BUILDING ON MARS

Research on In-Situ Resource Utilisation (ISRU) for a sustainable habitat

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Graduation thesis

Colophon

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Cover image
Layers and Sand on the Floor of Schiaparelli Crater, Mars.

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Building on Mars

Research on In Situ Resource Utilisation (ISRU) for a sustainable habitat which protects the crew on a Martian mission against the harsh environment.

Preface

This thesis is the sustainable graduation studio of the Master track Building Technology at the faculty of Architecture, Urbanism and Building Technology at Delft University of Technology.

I chose this subject because innovation, materialisation, sustainability and a hands-on approach are all subjects which have motivated me throughout my studies. The building industry often stays on the beaten track on specific aspects especially on materialisation and sustainability. This is partly because the known materials are already fit for the design task and because sustainability is difficult to define and translate into concrete design steps. Therefore choosing for a novel building material and a new way to think about sustainability within Building Technology has to come from a design task which differs entirely from the more traditional ones. Choosing for an extreme location like Mars demands an extreme yet feasible design with heaps of new possibilities. Here, material science and computational science can meet to create a new way of building with, for example, a new composite using additive manufacturing. Moreover, the way sustainability will unfold from this new task will be critical to the mission.

This research is all about finding an apt solution for a new problem using previous knowledge but also starting with a "clean slate".

Throughout this research, I was helped by many people whose enthusiasm inspired me as well as pushed the overall research forward. I firstly want to thank all of my mentors and the external delegate, who all supported me from the very start of this peculiar graduation thesis even through health troubles. Through detailed and critical questions, Fred Veer helped me push the subject further than I was expecting, and I wish to thank him for that and the time he took to help me destroy ice specimens. I would like to thank Paul de Ruiter for his great enthusiasm and aerospace expertise throughout the process, as well as Serdar Aşut for stepping in when Paul couldn't help me further. For our great morning talks about sustainability, Mars, exploration and the future we are heading towards, I also wish to thank David Peck.

Thanks to all of the TU Delft employees from different faculties who helped me find facilities and professional advice, especially Zu-Yao Chang for helping me with the freezer at EWI faculty. Without him my ice experiments would probably not have yielded as many results.

I also wish to thank two fellow students: Carlijn van der Werf and Nihat Mert Ögüt who both started with the subject of Building on Mars. Their advice and work helped me deal with the extreme requirements needed to build a habitat on Mars.

Last but not least, I wish to thank my friends, family and fellow Building Technology students who all, in one way or another, helped and supported me throughout this graduation. Many thanks especially to my father, who read and re-read my (long) thesis on a strict deadline; as well as my mother for providing the support only a mother can. Thank you all very much for that.

Abstract

Currently the possibilities of sending humans to Mars are being developed. This ambitious and exciting goal demands a broad range of new technologies, innovations and a fresh view on current challenges we are facing on Earth. This also applies to the field of Architectural and Building Technology.

To start with, the need for building a sustainable habitat is established, where sustainability is defined as being as independent as possible from Earth, considering the communication delay (22 min), the travel time (at least 5 months) and the scarcity of “launch windows”, which occur only once every 26 months. Therefore, being sustainable on Mars is vital. This aspect is leading to the research by focussing on using in-situ resources (ISRU).

Based on this insight, the research question was formulated: Which **in situ materials** and **forming techniques** are suitable to create an outer shell for a **sustainable habitat** on Mars which protects the crew from the **harsh Martian environment?** The Martian habitat will have to protect the crew from, among others, radiation and the extreme temperatures (ranging from 20 °C to -153 °C).

Literature study shows that ice provides an excellent shield against radiation. Moreover, ice is widely present on Mars. Hence, a number of experiments were performed to test the feasibility of using ice as a building material. These included a mixing test, a melting test and a compressive strength test. The experiments were done using different variables and environments. The results for all three tests were the same: the addition of sand or plastic does not upgrade the building properties of the ice. However, adding salt does improve the building properties. The outcome of the experiments indicates that up to 15 ppt of NaCl increases the compressive strength from an average of 1 MPa to 4 MPa. A higher percentage of sodium chloride does not influence the compressive strength. The experiments also indicated that the colder the testing environment (up to -70°C), the higher the compressive strength of the NaCl ice is. The warmer the environment (up to +25°C), the more ductile the NaCl ice behaves.

A further challenge to building a habitat on Mars is that it has to be built semi-remotely. This thesis singles out the use of robotic technology, which can perform all tasks necessary to build the habitat, ranging from mining the ice to assembling the building. A short analysis indicates that the use of additive manufacturing has great potential for the assembling of the building. In this thesis, preliminary studies and experiments have been conducted on additive manufacturing techniques for sodium chloride ice. The main outcome is that the ice structure has a greater overall strength due to the freezing of the ice layer by layer. This technique also enables the possibility of repair during the building phase as the water fills the possible cracks, and then expands upon freezing, creating a stronger structure.

Finally, a habitat has been designed to assess if the technological findings are useful and comply with the overall habitat requirements. The “Ice Hab” uses two different techniques of building with ice; one almost completely independent from Earth materials and another one with Earth technology for redundancy. Overall, the habitat design complies well with the requirements. Future studies will also have to deal with the power needed to build with ice, as the design currently exceeds the requirements.

This research answered the question by discovering a new material, sodium chloride ice, and a specific technique to process the ice via additive manufacturing. Further research is needed to determine the viability of those results, nevertheless, the results look promising.

Keywords: habitat, Mars, sustainability, ice composite , additive manufacturing

Glossary

ABBREVIATION	DEFINITION
ABS	Acrylonitrile butadiene styrene
AEROGEL	colloidal silica in the form of a fine lightweight powder with grains having minute pores that is made from silica gel and used chiefly as thermal insulation especially at low temperatures
AM	Additive Manufacturing
ANALOGUE	a chemical compound that is structurally similar to another but differs slightly in composition (as in the replacement of one atom by an atom of a different element or in the presence of a particular functional group)
ASTEROID	A relatively small, inactive (no atmosphere), rocky body orbiting the sun
ASTM	American Society for Testing and Materials
ASTM C39	Standardized test method for compressive strength of cylindrical concrete specimen
ASTRONOMICAL OBJECT	An astronomical object or celestial object is a naturally occurring physical entity, association, or structure that current astronomy has demonstrated to exist in the observable universe
ATM.	Atmosphere (unit of pressure).
CELESTIAL OBJECT	see astronomical object
CGF	Cryotropic gel formation
CL	Cargo Lander, see Lander
COMET	A relatively small, at times active, object whose ices can vaporize in sunlight forming an atmosphere (coma) of dust and gas and, sometimes, a tail of dust and/or gas
COPUOS	Committee on the Peaceful Uses of Outer Space
CRYOGEL	Cryogel are gel matrices that are formed by freezing and thawing process
CRYOGENIC	Freezing temperatures (or the science that studies it).
GYR	Gigayear
DELIQUESCENCE	The process by which a substance absorbs moisture from the atmosphere until it dissolves in the absorbed water and forms a solution
DRA 5.0	Design Reference Architecture 5.0: NASA mission design for human exploration of Mars
ECLSS	Environment Control and Life Support System
EDL	Entry, Descend, Landing
ESA	European Space Agency
ETFE	Ethylene tetrafluoroethylene, a high performance plastic
EVA	Extravehicular activity
FO	Forward Osmosis
FORWARD OSMOSIS	is a natural process in which the osmotic potential between two fluids of differing solute/solvent concentrations equalizes by the movement of solvent from the less concentrated solution to the more concentrated solution
GCR	Galactic Cosmic Radiation
G FORCE	G-force stands for either the force of gravity on a particular extra-terrestrial body or the force of acceleration anywhere. It is measured in g's, where 1 g is equal to the force of gravity at the Earth's surface, which is 9,8 meters per second per second.
HABITAT	A space habitat is a type of space station, intended as a permanent settlement or research specialized facility where humans can live and interact
HRL(S)	Habitation Readiness Levels
HYGROSCOPIC	The effect of attracting and holding water molecules from the surrounding environment
ICE	Isolated, Confined and Extreme environments
INDIGENOUS	Originating or occurring naturally in a particular region or environment, native
IN SITU	In architecture and building, in situ refers to construction which is carried out at the building site using raw materials
ISRU	In situ resource utilisation
ISS	International Space Station
JPL	Jet Propulsion Laboratory (NASA
JSC MARS-1A	Martian soil simulant
LANDER	A spacecraft designed to land on the surface of a planet or asteroid
LCA	Life Cycle Assessment
LUNAR	From the Earth's natural orbit, the Moon

LS	Martian solar longitude. The angle between the Sun and Mars, measured from the northern hemisphere
MANNED MISSION	see Manned Space Exploration
MANNED SPACE EXPLORATION	A space flight with a crew. Human spaceflight started with suborbital flights. Later goals reached were the launching of a single astronaut in orbit, the launching of several astronauts, the meeting and docking of two spacecrafts, making a lunar orbit, and landing of an astronaut on the Moon.
MC	Martian Concrete
MMS-1	Mojave Martian Simulant
NASA	National Aeronautics and Space Administration
N.D.	No date
NPOX	nanophase ferric oxide
PERMAFROST	In geology, permafrost is ground, including rock or (cryotic) soil, at or below the freezing point of water 0°C for two or more years
PLA	Polylactide acid
POI	Place of Interest
POR	Programme of Requirements
PVA	Polyvinyl alcohol
PYKRETE	Frozen composite made out of wood pulp and ice
R&D	Research & Design
REGOLITH	The layer of unconsolidated solid material covering the bedrock of a planet or asteroid
RFP	Rapid Freezing Prototyping
ROVER	A rover (or sometimes planetary rover) is a space exploration vehicle designed to move across the surface of a planet or other celestial body. Some rovers have been designed to transport members of a human spaceflight crew; others have been partially or fully autonomous robots
SLS	Selective laser sintering
SLS	Space Launch System
SNICE	Type of frozen water whose physical characteristics make it an intermediate between snow and ice: *snow-ice*
SPACE CRAFT	A spacecraft is a vehicle, or machine designed to fly in outer space
SPACE FLIGHT	Space flight is a ballistic flight into or though outer space. Spaceflight can occur with spacecrafts with or without humans onboard.
SPE	Solar Particle Event
SUBLIME (TO)	(of a solid substance) changes directly into vapour when heated, typically forming a solid deposit again on cooling
SV	Sievert. Unit which measures the health effect of low levels of ionizing radiation on the human body. Also used as millisievert (mSv)
THERMOPLASTIC	Is a polymer which is solid when cooled down and becomes pliable or mouldable above a set temperature
TRL(S)	Technology Readiness Level(s)
VAN ALLEN BELTS	The radiation fields surrounding the Earth, held in doughnut shapes by the Earth's magnetic field; the inner doughnut is mostly protons and the outer one mostly electrons; they were discovered by James Van Allen from the Geiger counter readings of Explorer I and Explorer III satellites
WT%	Percentage by weight

Glossary. All definitions with their entry in Merriam-Webster's dictionary, retrieved on November 25, 2017 from https://www.merriam-webster.com/

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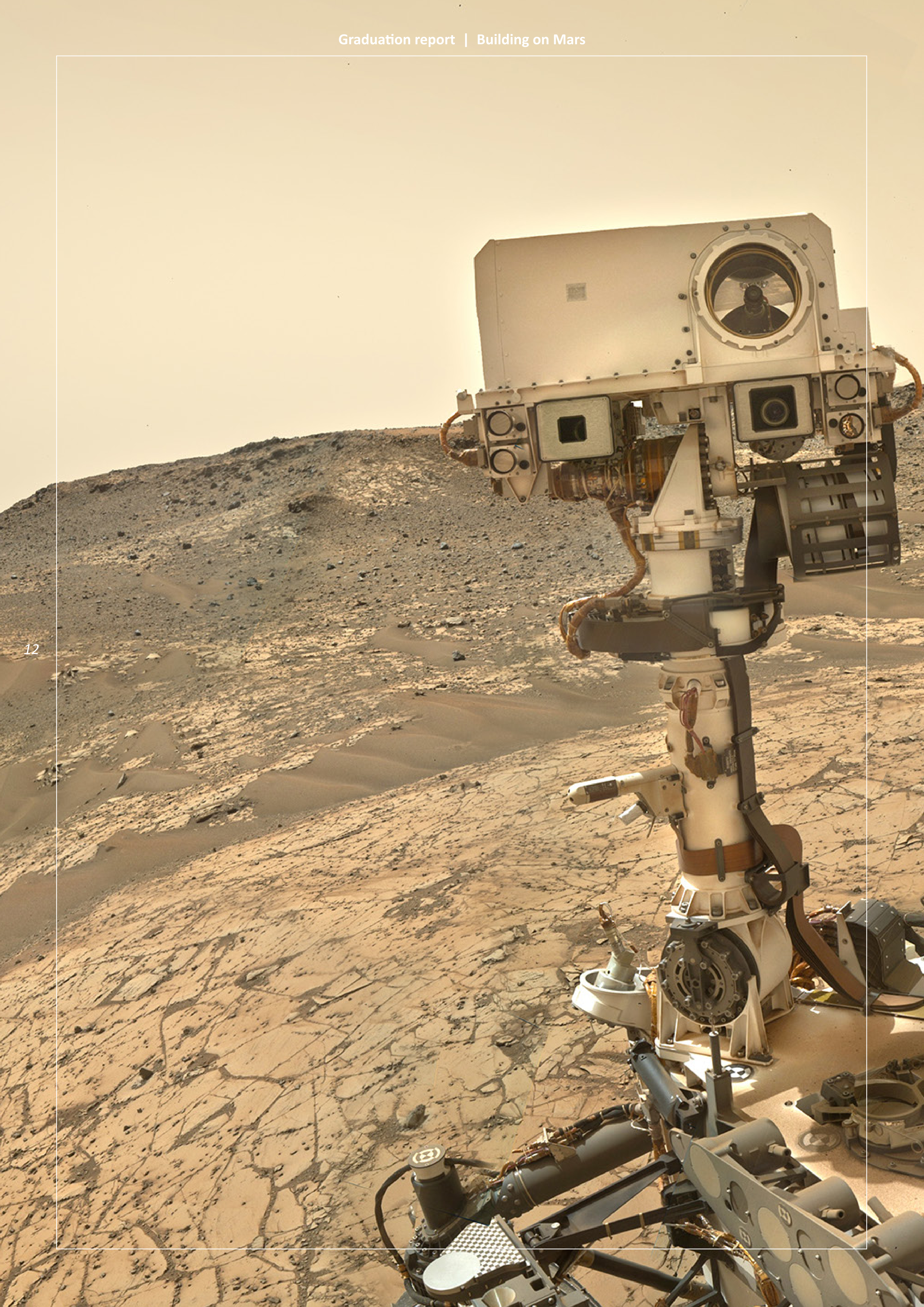
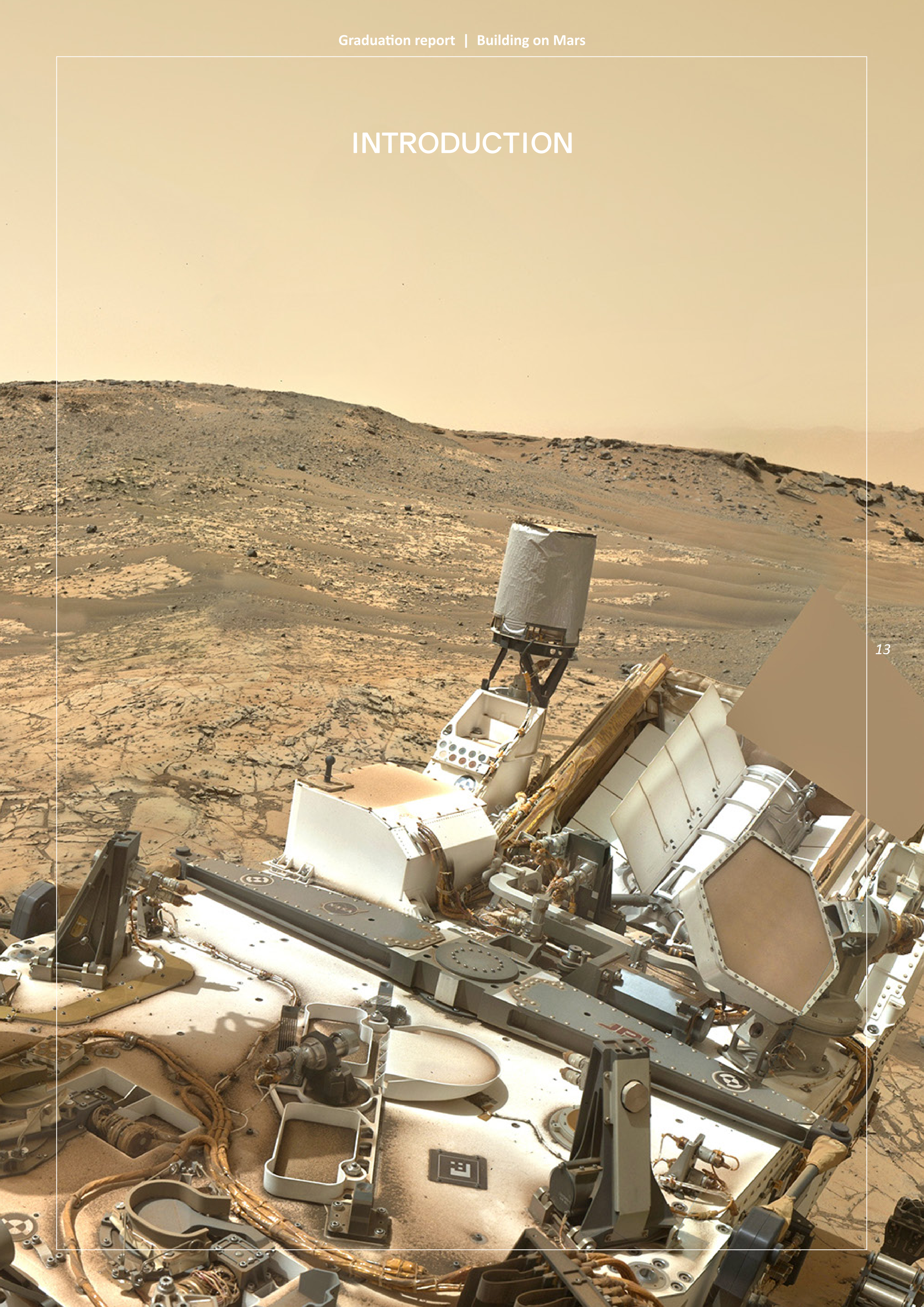


INTRODUCTION



"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

Kennedy, J.F. (September, 1962). Rice Stadium. Houston

1. Introduction

1.1 Context

1.1.1 Space exploration

Humans are curious by nature and it is one of the characteristics that defines us from other species (Kang, et al., 2009). Human curiosity led people to be fascinated by, among others, space and space travel. Arthur C. Clarke wrote in his book *Exploration of space* in 1951 that:

"The very conception of interplanetary travel was, of course, impossible until it was realized that there were other planets. [...] Although Mercury, Venus, Mars, Jupiter and Saturn had been known from the earliest of times, to the ancients they were simply wandering stars." (p.22).

This quote explains two different things; first, that "the ancients" have always been fascinated by space and second that in 1951 interplanetary travel was already being discussed as a possibility. Since 1951, the interest in the exploration of space has been growing and this led to a flourishing amount of resources and new technology on space travel and exploration (Dunbar, 2013).
However, this isn't only due to human curiosity. Interest in space has always had a military value, especially during the cold war which pushed space exploration to its apogee: landing a man on the moon. Interest in space is also growing economically in the last decade thanks to space tourism and moreover space mining. As our own resources are getting scarcer by the year, the possibility to get raw materials from outside our atmosphere changes the general interest of space exploration (DSI, n.d.).

In the last few years a huge number of spacecraft has been sent into space, some within our orbit like Earth satellites, like the Hubble telescope and the International Space Station (ISS). Some others have been sent further away in our solar system to gather data, like flybys and orbiters. A few landers and rovers have also been sent to the Earth's only natural satellite: the Moon, the Saturn moon Titan, the planets Mars, Venus and Mercury and to asteroids and comets. And finally numerous manned missions have been sent to the ISS for the past 18 years and to the Moon between 1969 and 1972 (Timeline of space exploration, 2017).

Today the main focus lies on manned missions with different large parties having different approaches. In Europe, the European Space Agency (ESA) set up the Moon Village global project. This project has as main goal to create a community to share interest and capabilities on different aspects of Moon exploration (e.g. exploration of the Moon itself but also deep space, first human settlements, space tourism, testing centre…) (Woerner, 2016).
In the United States, two large companies are also defining their goal and approach for manned space missions. The first company is The National Aeronautics and Space Administration (NASA) that started its programme: Journey to Mars. NASA intends to send the first humans to Mars in the 2040s to expand our knowledge of the Universe, of the planet Mars but also of our own planet. NASA's approach is to "follow the water" which was recently (2006) discovered to flow on the Red Planet in the hope to find traces of life (NASA, 2017). To support the human crew during their long term stay on the Red Planet, NASA is having a 3D printed Habitat Challenge to help prepare Mars for human exploration (NASA & Bradley University, n.d.).
The other large company interested in manned missions is SpaceX, a privately owned company, which has the goal of making life inter-planetary and to launch its first rocket to Mars in 2022, almost 20 years prior NASA's plans. The goal of this mission is to colonize Mars for the survival of our species (Musk, n.d.).

As the length of the different proposed missions varies from short term to long term, landing on an asteroid or planet implies that a crew could stay in space for as little as a few days to as long as up to a year (NASA, 2017). In order to host humans on planets and asteroids a habitat needs to be designed which can protect humans from the surrounding harsh environment. Currently, the greatest challenge is to deal with radiation, the (non) existent atmosphere, extreme temperatures, falling meteorites and dust containing perchlorates.

Space radiation has been defined as the main challenge the crew will have to endure as radiation is harmful to the human body when exposed to high doses or low doses for a long period of time (Durante & Cucinotta, 2011). Therefore, the habitat should provide shielding for the crew to ensure their safety and health. Shielding against radiation requires mass which can be a problem when landing on a planet with a (thin) atmosphere as mass tends to ignite when landing due to friction (Clarke, 1951). This atmosphere can also be a problem as only our own planet has one which is high in oxygen and thus breathable for humans. For example, Mars has a thin atmosphere composed predominantly of carbon oxide which is toxic for humans. The Moon on the other hand has no atmosphere and this prevents humans to breathe as well (Moon, 2017). Another challenge is the extreme temperatures found in space: most are extremely low when further away from the sun than we are, like on Mars where temperature drops to -130°C (Smith, n.d.). When no atmosphere is present, like on the Moon, temperature fluctuates extremely between day (+106°C) and night (-183°C) (Brown, n.d.). Thin or no atmosphere also allows larger meteorites to smash into the surface as they don't ignite as fast as in our thick atmosphere. Finally, a considerable challenge when going to Mars is dust. Mars is covered in fine dust which contains perchlorates. Perchlorates are salts which are found abundantly on Mars but are harmful to human health causing problems ranging from thyroid hyperplasia to the slowing of vital organs (Davila, Willson, Coates, & McKay, 2013). On top of that, this fine dust can block the human lung when ingested and impede the proper working of most of the equipment needed on Mars (NASA & Bradley University, n.d.).

Given all these dangerous aspects of the surroundings, it is critical to build a habitat which protects the human crew against the environment to ensure their safe stay on the planet or asteroid and safe return to our habitable planet.

Häuplik-Meusburger and Bannova (2016) describe a habitat as follows:

"A habitat is a critical element of human space flight, especially in long-term missions. It is the place where people live and work, it protects them from hazards of the environment, and it enables the crew to perform their tasks and operations." (p. 192)

1.1.2 Sustainability context

Sustainability is a hot topic at the moment; unfortunately, it is defined in many different ways. The Oxford dictionary (2017) states that sustainability is to be “able to be maintained at a certain rate or level”. On the website sustainability.com (n.d.), sustainability is explained as the “ability to sustain” or “the capacity to endure”. These definitions adjoin one another but are put simply and do not explain the whole concept. Yet, these are two of the first definitions you’ll find when looking for sustainability on the internet. Contal and Revedin made their own definition of it explaining the concept of sustainability in its whole in their book Sustainable Design II.

"We cannot allow sustainability to be reduced to the level of fashion or to be measured exclusively in terms of technological standards. Sustainability is a socio-political responsibility which must address the new challenges facing humanity: the provision of dignified housing for the growing global population; the need to understand, take seriously and upgrade informal settlements around the world and the creation of shared spaces which use the simplest means to facilitate communication and compassion or, put another way, “civicity”" (Contal, Revedin, Albrecht & Brusegan, 2011, p. 9).

There is a need to design and think in a sustainable way for every project, hence, even though a design is placed on another planet, there is a need to build in a sustainable way. Some might even say that because we have the chance to start from the beginning on another planet, we (humans) can learn from past mistakes and it is therefore essential to start “colonizing” other planets in a sustainable way. But the definitions of sustainability given above are specifically made for sustainability on Earth. Sustainability on another planet however has not yet been defined. This research aims to find how this concept can be defined regarding architecture on Mars.

1.2 Problem statement

Because long term manned missions are to be sent onto an asteroid or planet in the near future (2020s-2040s), the crew is in need of a protective environment, *a habitat*, where they can live and work without being harmed by the harsh asteroid or planetary environment. This habitat should protect the crew from:

- the surrounding (non) existing atmosphere
- radiation
- extreme temperatures
- falling meteorites
- dust containing perchlorates

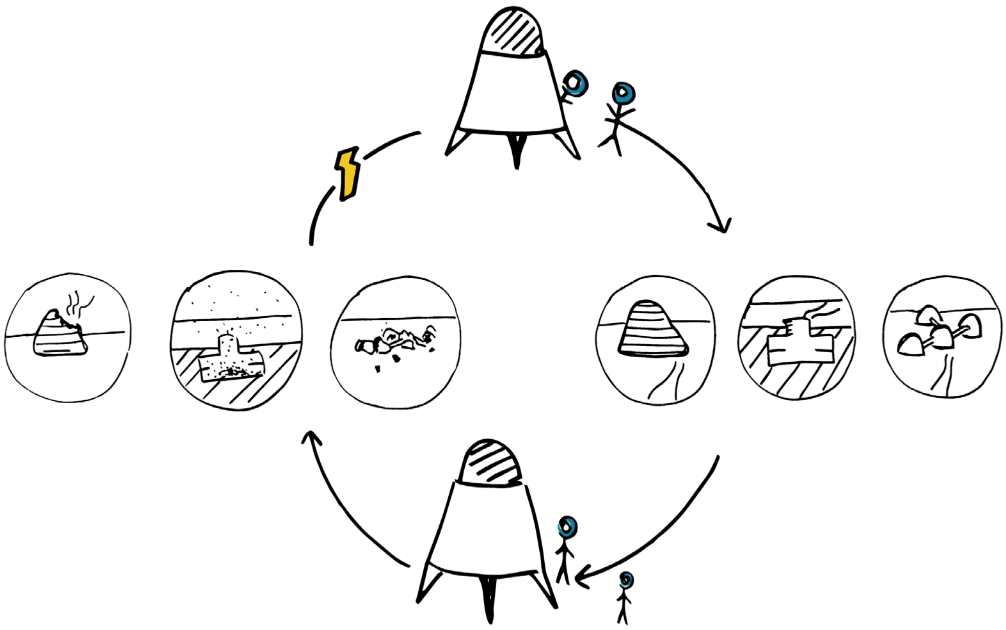


Figure 1. Problem statement. Current designs are only designed for one mission and don't consider the possible future use. The habitats are left behind to be damaged.

Few design ideas have been made on asteroids or planetary habitats but most of the ideas are novel and experimental, especially on ISRU methods. Furthermore, these designs are "only" tackling the environmental challenges without thinking about sustainability. Sustainability means that the crew can sustain itself and that next missions will be sustainable as well. There is therefore a need to design a sustainable habitat protecting the crew from the harsh environment.

1.3 Objectives

1.3.1 General objective

The general objective of this thesis is to investigate ISRU possibilities for the construction of a sustainable habitat which protects the crew from the harsh indigenous environment.

1.3.2 Sub-objectives

The main sub-objective is to define sustainability on the host asteroid or planet as well as its probable impact back on Earth. After sustainability is defined a method to assess the sustainability of new designs is developed.

1.3.3 Final products (deliverables)

The expected final product is a design for a habitat which is sustainable as well as a new sample material in combination with building methods of Martian ISRU. The deliverables will be presented through various means ranging from a sample report with mechanical properties to a computational design.

1.3.4 Hypothesis

The probable outcome for this research is the use of indigenous ice as building material for the outer shell. As ice itself isn't strong enough, reinforcement will be used to create an ice composite. The structure will probably be a dome of ice reinforced with Martian regolith, manufactured semi-autonomously by additive manufacturing.

1.3.5 Boundary conditions

Boundary conditions are set for this research based on the time available for this graduation study, which is nine months.

Constraints:

- **Why:** space exploration. Although it will be argued where in space a habitat should be designed, the question whether we should or should not put manned missions on asteroids or other planets is not discussed in this research.
- **When**: between 2020 and 2040[1]
- **How:** the energy is assumed to be delivered by solar panels and won't be further researched. Transportation will be assumed to come from (or to be similar to) the Space Launch System (SLS)[2]
- **Where**: one of these three Martian landing sites: Jezero Crater, NY Syrtis, Columbia Hills
- **Who**: a small crew of 4-6 people to begin with (as it is the intention of NASA to send a small crew of experts first)
- **What:** only the outer shell structure (as it specifically requires ISRU while the pressurized inner core can be prefabricated on Earth).

1 as 2020 is the scheduled launch time frame for SpaceX programme and 2040 is the scheduled launch time frame for NASA programme

2 The reason this rocket is chosen as reference is because it is a super heavy type rocket designed to carry humans into space with the Orion module (Moon and Mars) and because the blueprints for the rocket are available to the public.

1.4 Research questions & sub questions

The problem statement and objectives lead to the following research question:

Which **in situ materials** and **forming techniques** are suitable to create an outer shell for a **sustainable habitat** on Mars which protects the crew from **the harsh Martian environment?**

The research question leads to several sub questions which have to be answered in order to answer the main research question.

- What is the programme of requirements (POR) for a habitat on Mars?
- How to define sustainability on Mars?
- What potential building elements are found on Mars?
- Which of these elements are best suited to protect human beings against the harsh Martian environment?
- How is an outer shell constructed out of this (combination of) element(s)?

1.5 Approach & Methodology

These sub questions are the base of the research methodology as each question requires a different type of answer and a different approach.

	QUESTION	APPROACH	PRODUCT/ANSWER
A	What is the programme of requirements for a habitat on Mars?	Literature study	Programme of requirements
B	How to define sustainability on Mars?	Literature study	Set of requirements
C	What potential building elements are found on Mars?	Literature study	Excel sheet with map on where they are on Mars
D	Which of these elements protect best against the harsh Martian environment?	Literature study and Research by Design and simulations & physical tests	Table with elements against radiation, extreme temperatures, falling meteorites and dust containing perchlorates & Test specimen with three basic tests
E	How is an outer shell constructed out of this (combination of) element(s)?	Research by design and computational model simulations	Structural design

Table 1. Sub questions with their proposed approach to answer them as well as the probable form the answer will be (product).

Based on the previous methods and product table the approach and methodology wielded are as follows. First a literature study is carried out and precedents which have been assessed by external parties are analysed. This results in a programme of requirements (POR) for the design task. The POR can be divided into four categories: a habitat POR, a structural POR, a process and method POR and a POR regarding the material to be used. From these different programmes of requirements a design will be made which will then be tested and assessed on each of the four different briefs. The process will repeat itself until all the requirements are met in an iterative process.

As the use of ISRU is one of the biggest challenges, the research and design process starts with finding the right building material and thus answering the Material requirements. After the ideal material is found a process and building method will be researched which fits the process requirements as well as the properties of the selected material. When a suitable process is found a structural model is made meeting the appropriate requirements. When the ISRU method is fully analysed a design for the habitat will be made to assess if the newly found results can be applied for a whole habitat as well. However, the design of the habitat is not the focus of this research and will only briefly be made to assess the previous results of the ISRU method. All these results will then be evaluated and conclusions for further research will be drawn.

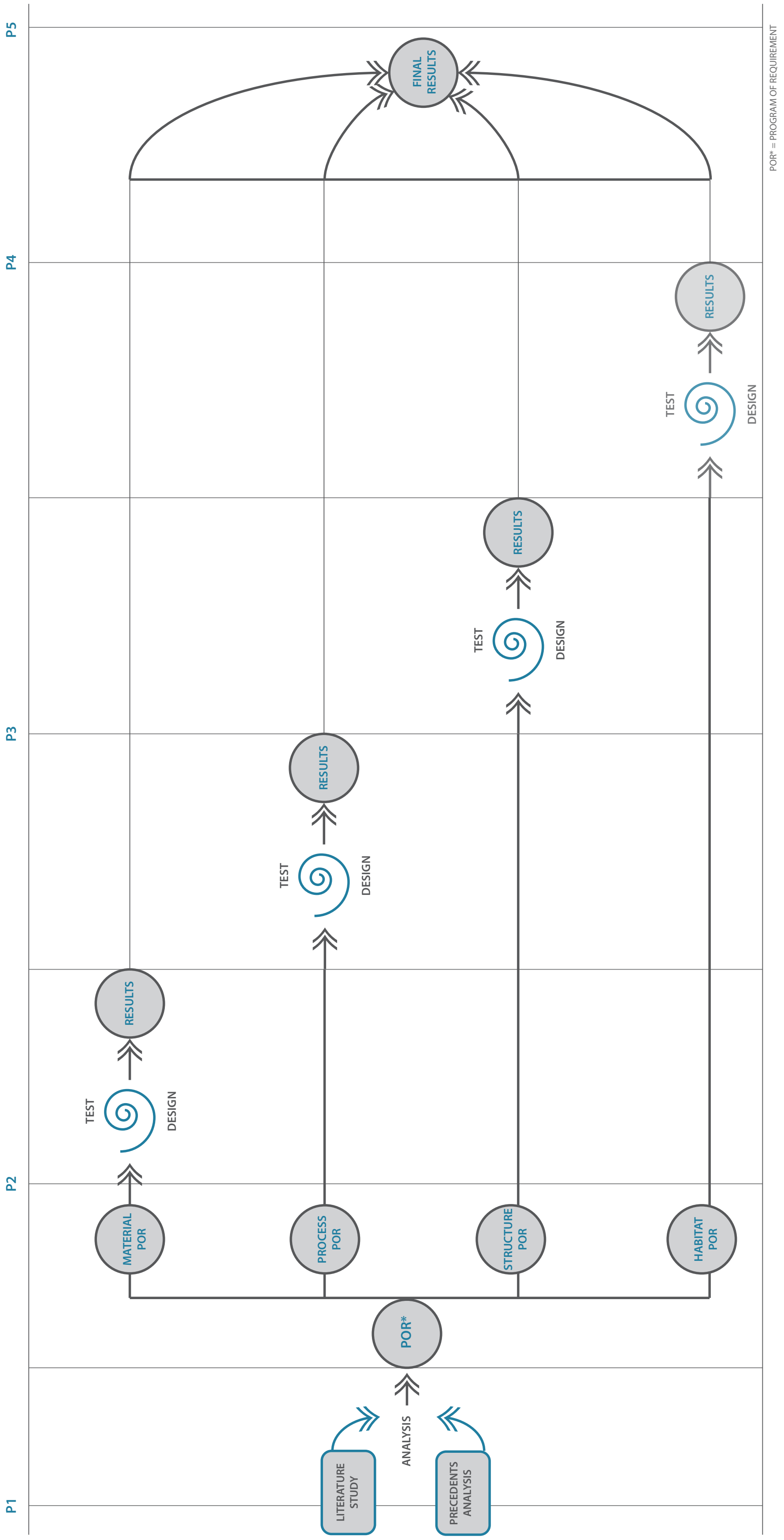


Figure 2. Methodology and approach of the research. First step is a literature study as well as a precedent analysis to define a programme of requirements (POR). This POR can be divided into four POR: Material, Process, Structure and Habitat. All these aspects are researched step-by-step using an iterative process of design and testing. This leads to a final design and research answer.

1.6 Report outline

The report is structured following the methodology and divided into eight main chapters: information about Mars, space travel, mission design and space architecture, sustainability, material, process, structure, and design. Each chapter starts with a literature study and then focusses on the specific topic of this research by drawing conclusions, making experiments, simulating or designing. At the end of each chapter a conclusion is drawn which are all combined in the final conclusions chapter.

1.7 Time planning

The time planning follows the methodology highlights with the project being divided into four parts:
- Material Research & Design
- Process Research & Design
- Structure Research & Design
- Habitat Research & Design

As mentioned in the methodology these parts aren't of equal importance, this gradation of importance is also reflected in the time planning where material and process R & D have a larger time frame than habitat and structure R & D.

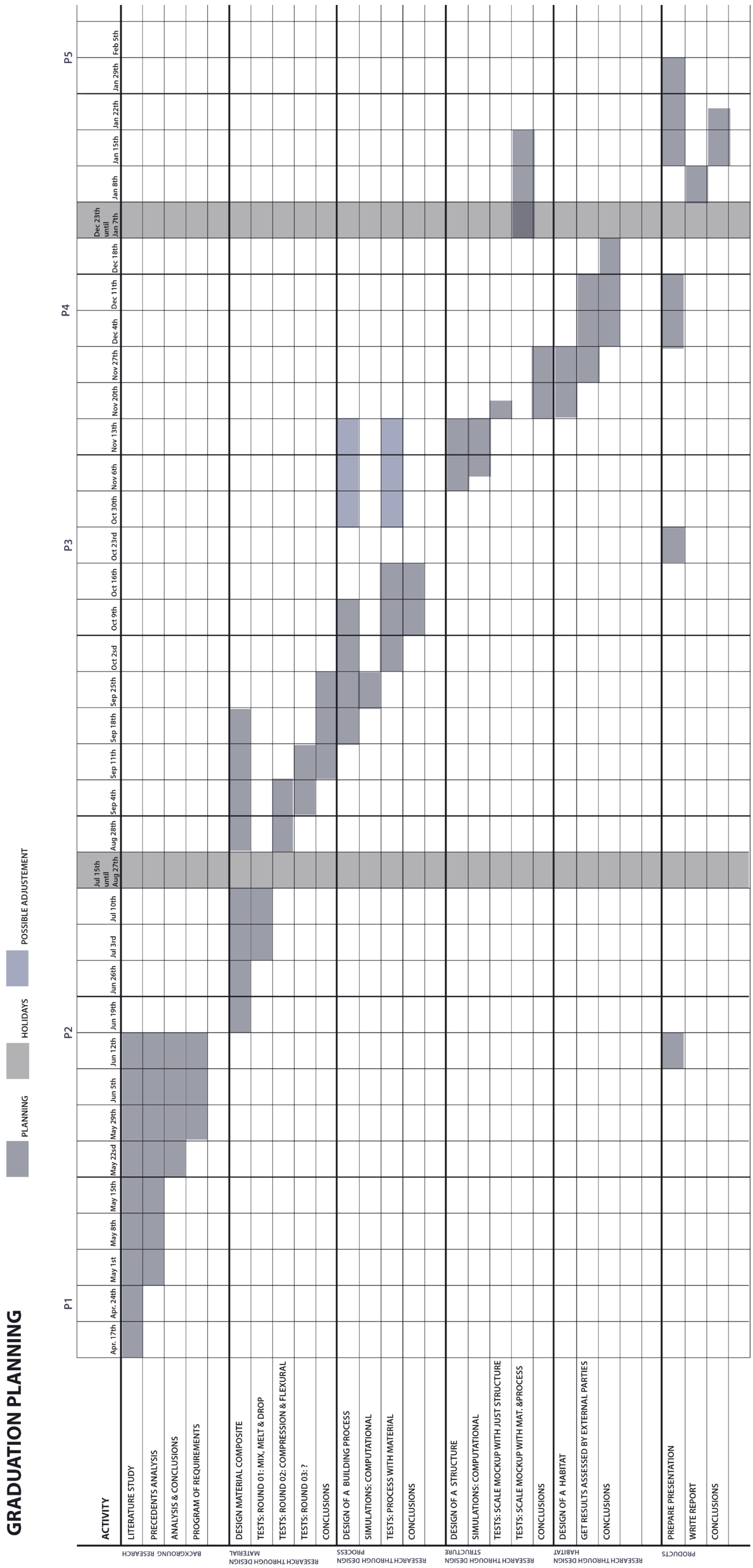


Figure 3. Graduation planning. Weekly tasks to perform to achieve the outcome stated in the research question following the methodology steps.

1.8 Relevance

Societal relevance

This graduation research offers a new perspective for architects and building engineers on outer space architecture and sustainability. Usually sustainability is about preserving our planet because we live on it. As asteroids and other planets aren't inhabited by humans (yet), sustainability isn't believed to be an important factor when designing structures. However, as humans are starting to colonize space, maintaining and sustaining the resources as well as the current situation becomes more important. Especially as space isn't owned by a specific party (e.g.. a state, a company, etc.) it is important to maintain this environment for everyone interested in space exploration. Moreover, just like Earth is our only Earth, the solar system is our only solar system. Building for a sustainable habitat has also economical relevance as the costs will greatly be reduced for follow-up missions.

Scientific relevance

The information gathered in this research can help design a new habitat for manned missions to Mars for interested parties. As some large space agencies (e.g. NASA, SpaceX) are planning to send manned missions onto Mars, the success of the mission depends on the wellbeing of the crew and on whether they survive the trip and stay on the planet. As outer space architecture isn't fully developed yet, every piece of information on how a habitat can be built will help protect the manned mission's crew.

● (green) **Full utilization in relevant environment** ● **Sufficient risk reduction in relevant environment** ⊙ **Initial feasibility validation/partial validation**	Earth	ISS/Low-Earth Orbit	Lunar Vicinity (Earth-Moon Lagrange Point (EML), Moon Orbit)	Moon Surface	Mars Vicinity	Mars Surface (Robotic Mission)
Beyond Low-Earth Orbit Crew Transportation			●	●	● (green)	
Heavy Lift Launch			⊙	●	● (green)	
Reduced Supply Chain		⊙	●	●	● (green)	
Autonomous Crew Operations	⊙	⊙	●	●	● (green)	
Deep Space Staging Operations			● (green)		● (green)	
Mars Ascent	⊙			⊙		⊙
Space Radiation Protection/Shielding		⊙	●	●	● (green)	
Life Support & Habitation Systems		●	●	●	● (green)	
Entry, Descent, & Landing Systems	⊙			⊙		●
Surface Power and Energy Management	⊙			● (green)		● (green)
Surface Mobility	⊙			●		●
Human Robotic Integration	⊙	●	● (green)	● (green)	● (green)	● (green)
Mars In-Situ Resource Utilization	⊙			⊙		●
Long Duration Human Health	⊙	●	●	●	●	
Deep Space Operation Techniques	⊙	⊙	●		● (green)	

Note: This table assumes critical capabilities will be provided by multiple agencies.

Figure 4. Risks of space exploration (ISECG, 2013, p. 21).

The research shows also a new approach to deal with challenges. As the requirements for a Martian habitat are extremely high and the resources available extremely limited, this research leads to innovative solutions which could be applied on Earth as well. Ice is an infinitely re-usable material and brines are largely available throughout the whole planet Earth. Finding a technique to build large structures with ice on Mars would highlight the possibilities to build with ice on Earth. When thinking of cold and remote environments like Antarctica and Siberia, using ice which, is widely available could be economically and environmentally interesting. The ice structure is designed for Mars which has a different conditions than Earth, this could lead to interesting results about building under different conditions like under the sea.

Relevance at TU Delft Building Technology

This research takes into account the research of two other TU Delft Building Technology students: Nihat Mert Ögüt and Carlijn van der Werf who both started their graduation project in November 2016 on building on Mars focussing on radiation shielding and on the programme of requirements, respectively. This research is focussing on a different aspect (ISRU materials and process with regard to sustainability) of the overall task which is: building on Mars. In a way this research is complementary to the two other master theses.

1.9 References

This research is guided by four supervisors of the Building Technology master track, each with a different specialisation who will add scientifical value to the research:

First supervisor:	Dr. ir. F. Veer – material science
Second supervisor:	Ir. P. de Ruiter – design informatics – period before P3
	Dr. Arch. Serdar Aşut – design informatics – period after P3
Third supervisor:	Dr. D. Peck – critical materials

The following persons have been contacted for their expertise on various topics related to this research:

NAME	AREA OF EXPERTISE	UNIVERSITY/COMPANY
C. VAN DER WERF	Building on Mars – POR	TU Delft - BT
N. ÖGÜT	Building on Mars – Radiation	TU Delft - BT
CHRISTIAAN	Building with ice – Sagrada	TU Eindhoven - BT
M. VAN PELT	Aerospace Engineering	ESA
I.L. TEN CATE	Astro biology	ESA
A. WIELDERS	Mars One	ESA
PAULO CRUZ	Ice reinforcement	Minho

Table 2. List of persons of interest for this research with their area of expertise.

Bibliography – Introduction

Sustainability [Def. 1]. (n.d.). In Oxford Dictionaries. Retrieved June 6, 2017, from https://en.oxforddictionaries.com/definition/sustainability.

Brown, G. M. (n.d.). Lunar Science- a post-Apollo view by S.R. Taylor: : Mineralogical Magazine 40(314) 1976 p.654-656.

Clarke, A. C. (1951). The exploration of space. New York: Harper.

Contal, M.-H., Revedin, J., Albrecht, B. A., & Brusegan, E. (2011). Sustainable design II: Towards a new ethics for architecture and the city. Arles: Actes Sud.

David, L. (2013). Toxic Mars: Astronaut must deal with perchlorates on the Red Planet. Space Insider. Retrieved from http://www.space.com/21554-mars-toxic-perchlorate-chemicals.html

Davila, A., Willson, D., Coates, J., & McKay, C. (2013). Perchlorates on Mars: a chemical hazard and a resource for humans. International Journal of Astrobiology, 1-5.

Dunbar, B. (2013, September 30). Beyong Earth: Why we explore (J. Wiles, Ed.). Retrieved June 7, 2017, from https://www.nasa.gov/exploration/whyweexplore/why_we_explore_main. html#. WTgcCOvyiUk

Durante, M., & Cucinotta, F. A. (2011). Physical basis of radiation protection in space travel. Reviews of Modern Physics,83(4), 1245-1281. doi:10.1103/revmodphys.83.1245

DSI. (n.d.). Asteroid mining. Retrieved June 8, 2017, from https://deepspaceindustries.com/

Häuplik-Meusburger, S., & Bannova, O. (2016). Space Architecture Education for Engineers and Architects: designing and planning beyond earth. Cham: Springer.

ISECG, (2013). The global Exploration Roadmap. National Aeronautics and Space Administration. Washington.

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., Mcclure, S. M., Wang, J. T., & Camerer, C. F. (2009). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. Psychological Science,20(8), 963-973. doi:10.1111/j.1467-9280.2009.02402.x

Moon (2017). In Wikipedia. Retrieved on November 25, 2017 from https://en.wikipedia.org/wiki/Moon

Musk, E. (n.d.). Making Humans a Multiplanetary Species. Retrieved June 6, 2017, from http://www.spacex.com/mars

NASA, & Bradley University. (n.d.). NASA's 3D-Printed Habitat Challenge. Retrieved June 8, 2017, from http://bradley.edu/challenge/

NASA. (2017, March 27). Journey to Mars Overview. Retrieved June 6, 2017, from https://www.nasa.gov/content/journey-to-mars-overview

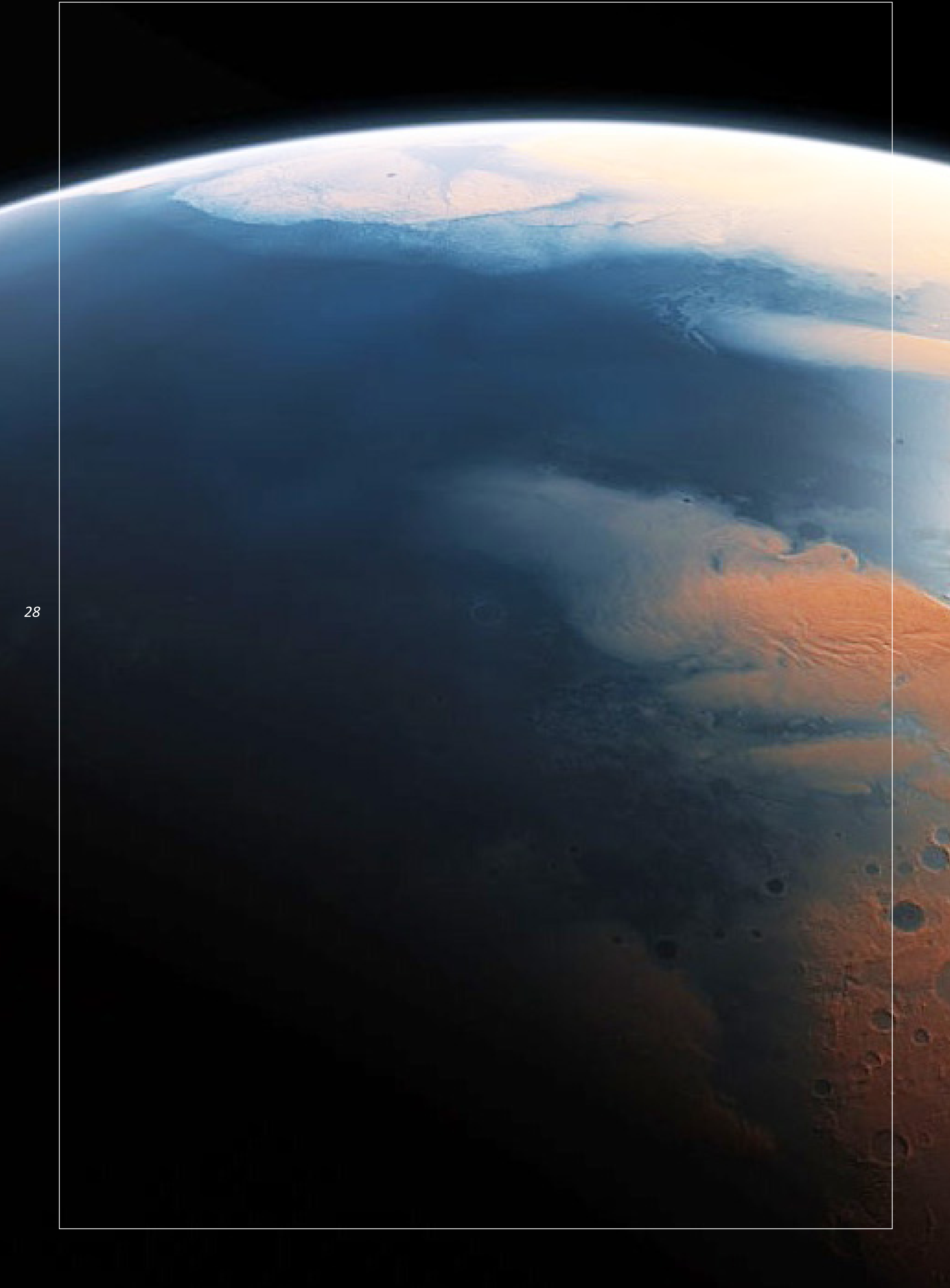
Smith, P. (n.d.). Mars/Earth Comparison Table. Retrieved June 6, 2017, from http://phoenix.lpl.arizona.edu/mars111.php

Timeline of space exploration. (2017, May 26). In Wikipedia. Retrieved June 6, 2017, from https://en.wikipedia.org/wiki/Timeline_of_space_exploration

Woerner, J. (2016, November 23). Moon Village: a vision for global cooperation and space 4.0. Retrieved June 6, 2017, from http://blogs.esa.int/janwoerner/2016/11/23/moon-village/

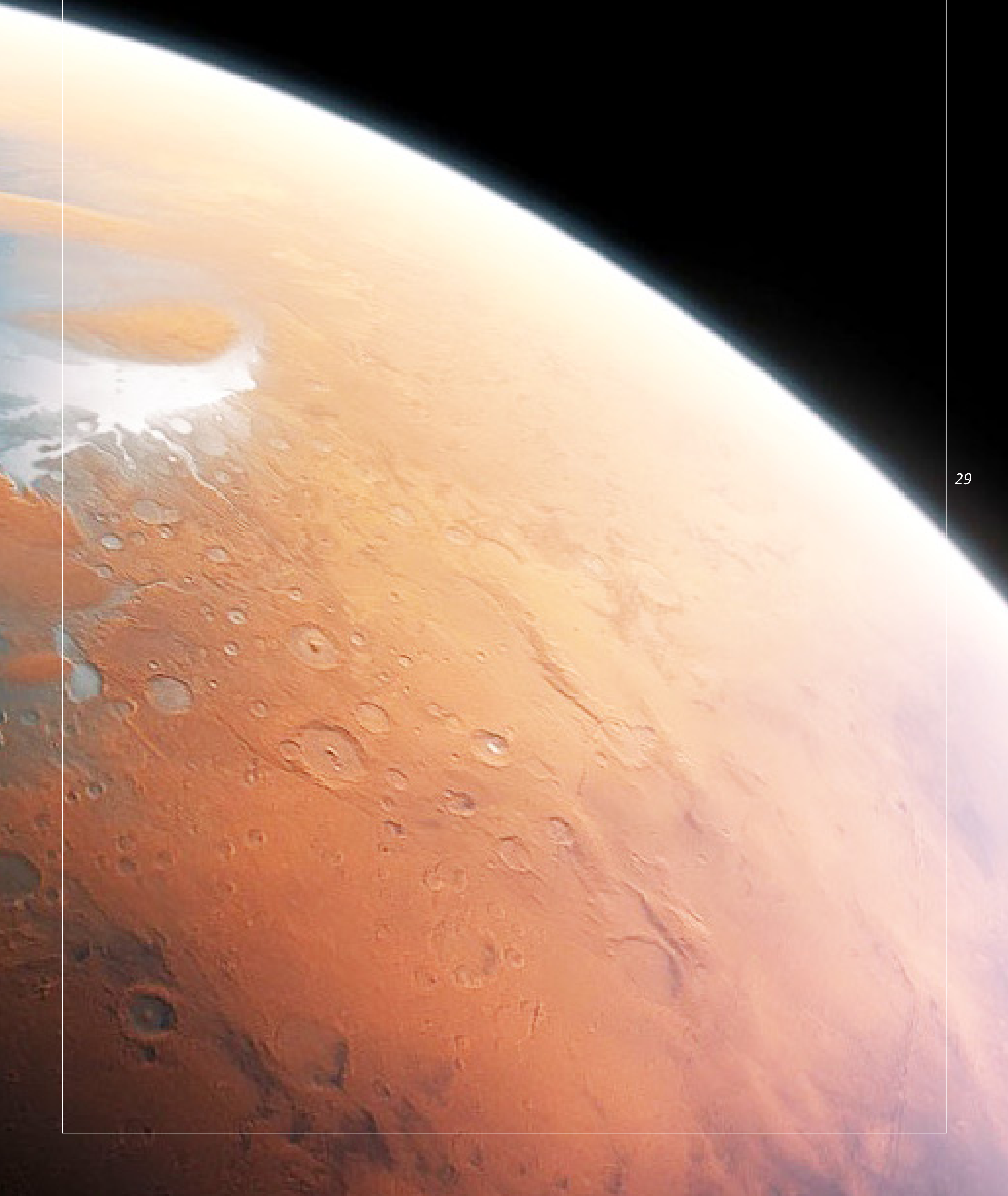
Other consulted documents:

National Geographic. (2015, January 26). The curious life of a Mars Rover. Retrieved June 6, 2017, from https://www.youtube.com/watch?v=7zpojhD4hpI&feature=youtu.be



PART A

DESTINATION: MARS



“I would like to die on Mars, just not on impact.”

Musk E., (March, 2013). At South by Southwest. Austin.

Part A is a summary of a literature study on space travel, the possible planets where habitats may be built as well as on mission design and architecture in space. This literature study on Mars forms the base of this research thesis. An analysis of precedents is also present within this part.

This chapter (partly) provides answers to the following sub-questions:

- What is the programme of requirements (POR) for a habitat on Mars?
- What potential building elements are found on Mars?

2. Mars vs. Earth's Moon

As is described in the introduction, the greatest challenge for the building of a habitat in outer space would be to build on the Earth's Moon or on the planet Mars. A few companies focussing on Moon exploration and on lunar habitats are ESA and the magazine Eleven which had, among others, an architectural engineering competition to design a lunar habitat named Moontopia. However, these projects are in an early phase and haven't any specifics yet. On the other hand, the exploration (and even colonization) of Mars has been the main focus of two large American companies for a few years: NASA and SpaceX. Great efforts are made to be the first to land a human on Mars, with NASA focussing on building a Martian habitat by hosting a centennial challenge (the 3D printed habitat challenge) at the moment (NASA & Bradley University, n.d.) and while SpaceX is focussing on sending the first humans on Mars by 2022 to start a Martian colony.
Mars and the Moon are two very different locations and building a habitat on either one of them will prove to be challenging and asks for a custom made design. Therefore, both celestial objects are analysed and compared to each other to define the design location of this research.

2.1 General information

2.1.1 The Moon

The Earth's moon (also referred to as *our* Moon or *the* Moon) is an astronomically inactive body that has an average distance of 384.400 km to the Earth. The Moon is believed to be formed by leftover debris from an impact between Earth and an ancient planet 4,51 billion years ago (right after Earth was formed). The Moon is an asteroid with no atmosphere but with a crust, mantle and core. The crust is formed by rocks with a top layer called regolith. The Apollo missions brought back lunar samples which helped determine the composition of this regolith which can be seen in table 3 (Brown, n.d.).

COMPOUND	FORMULA	COMPOSITION (WT %)	
		Maria	**Highlands**
SILICA	SiO_2	45.4%	45.5%
ALUMINA	Al_2O_3	14.9%	24.0%
LIME	CaO	11.8%	15.9%
IRON(II) OXIDE	FeO	14.1%	5.9%
MAGNESIA	MgO	9.2%	7.5%
TITANIUM DIOXIDE	TiO_2	3.9%	0.6%
SODIUM OXIDE	Na_2O	0.6%	0.6%
TOTAL		**99.9%**	**100.0%**

Table 3. Chemical composition of the lunar surface regolith (Moon, 2017).

2.1.2 Mars

Mars (also referred to as the Red Planet) is the fourth planet from the Sun in the Solar System and is situated at an estimated distance of 54,6 million kilometres from Earth. The planet was formed 4,6 billion years ago along with the rest of our solar system. Much like Earth, the planet has a (possibly) solid inner core made out of metallic iron and nickel, a mantle, a crust and an atmosphere. Mars gets its red colour from the rusting iron present in the rocks and dust forming the crust (Finlay, et al., 2010).

2.2 Properties

In table 4, the orbital and physical properties of the Moon and Mars are compared to the orbital and physical properties of Earth. It can be seen that the two planets have more in common with each other than the Moon and Earth.

			EARTH	MOON	MARS
	Properties	**unit**	**value**	**value**	**value**
ORBITAL	Semi major axis	km	149598023	384399	227987000
	Eccentricity	-	0.0167086	0.0549	0.0934
	Orbital period	days	365.256	27321661	686971
	Average orbital speed	km/s	29.78	1.022	24077
	Inclination	degree	1.578	5.145	1.67
PHYSICAL	Mean radius	km	6371	1737.1	3.389
	Flattening	-	0.0033528	0.0012	0.00589
	Circumference (equatorial)	km	40075.017	10921	21344
	Surface area	km2	510072000	$3,793x10^{7}$	144798500
	Volume	km3	$1,08321x10^{12}$	$2,1958x10^{10}$	$1,6318x10^{11}$
	Mass	kg	$5,97237x10^{24}$	$7,342x10^{22}$	$6,4171x10^{23}$
	Mean density	g/cm3	5.514	3.344	3.9335
	Surface gravity	m/s2	9.807	1.62	3.711
	Moment of inertia factor	-	0.3307	0.3929	0.3662
	Escape velocity	km/s	11.186	2.38	5.027
	Axial tilt	degree	23.4392811	1.5424	25.19
	Surface temperature av.	degree C	15	-53.15	-63
	Surface temperature min.	degree C	-89.2	-173.15	-143
	Surface temperature max.	degree C	56.7	116.85	35
	Surface pressure	kPa	101.325	1.00E-09	0.636

Table 4. Orbital and physical properties of the Earth, our Moon and Mars.

2.3 Magnetic field and Atmosphere

A magnetic field and an atmosphere are both essential to protect a planet from the different hazards found in space. These are thus important properties to look at when planning the design of a habitat for manned missions or for a space mission in general.
Geomagnetic fields are thus magnetic fields around a planet or asteroid that extend from the interior of the space object out into space where it protects the planet from the charged particles of the Sun arriving in the form of solar winds. Earth has a strong magnetic field ranging from 0,25 to 0,65 gauss because of its liquid conducting core which is composed of iron-nickel that rotates around its axis every 24 hours.
An atmosphere is a layer of gases which surrounds planets or other celestial bodies which is held in place by the gravitational field of the body. An atmosphere also protects its “host” by filtering out certain waves or physical bodies.

2.3.1 The Moon

The Moon has a magnetic field of about less than one-hundredth that of Earth. As magnetic fields hold an atmosphere together, the Moon has therefore a tenuous atmosphere which doesn’t protect against small or large asteroids or radiations or against extreme temperatures. Indeed, fluctuations between day and night are great on the surface of the Moon with a daily surface temperature varying between-183 ˚C at night and +106 ˚C during the day (Brown, n.d.).

2.3.2 Mars

Mars has a magnetic field which is less extensive than that of Earth because Mars has no inner dynamo to create this field. Therefore, the Martian atmosphere is also less thick than that of Earth with a gravitational force of 3,711 m/s^2. This thin atmosphere protects against small asteroids and, large temperature fluctuations but doesn’t protect against radiation and large celestial objects.

2.4 Properties in relation to missions

These characteristics not only define the conditions which will be found on these bodies in space but they are also defining the missions. As is mentioned before, building in space requires that everything needed from Earth comes within a space craft. Space flight and space crafts are different for different missions depending on the type of exploration (orbital, landing, roving, etc.) but also on the propitious times to fly due to the alignment of our planet with the destination. Mostly, the distance is of importance mainly due to communications. In table 5 these missions' aspects are described along with their impact on the design.

Missions aspects	Short missions (e.g. Orbital)	Medium missions (e.g. Lunar)	Long-term missions (e.g. to Mars)	Change of design considerations
Duration (months)	<6	6–12	>12	Habitat mass and volume
Distance to Earth (km)	300–400	350–400 K	60–400 M	Logistics mass and volume, increase of sustainability
Crew size	3–6	4≤	6≤	Size of habitat and logistics modules, privacy and social space
Degree of isolation and social monotony	Low to high	High	Very high	Interior design including privacy and social space (territorial issues)
Crew autonomy level	Low	Medium	Very high	Interior design with a certain flexibility to adjust to the crew needs
Emergency evacuation	Yes	Limited	No	Mission architecture and base/vehicle configuration
Availability of mission support				Mission architecture and habitat design, communication technology
Outside monitoring	Yes	Yes	Very limited	
Two-way communications	Yes	Yes	Very constrained	
Email up/down link	Yes	Yes	Yes	
Internet access	Yes	Yes	No	
Entertainment	Yes	Yes	Yes	
Re-supply	Yes	Very limited	No	
Visitors	Yes	No	No	
Earth visibility	Yes	Yes	No	Viewports

Table 5. Different mission's aspect ranging from short missions to long term missions (Häuplik-Meusburger and Bannova, 2016, p. 11).

2.5 Conclusion

The conclusion is that asteroids like our Moon and a planet like Mars have completely different properties and therefore demand a different building methodology. After a quick look into the properties of both celestial objects, it can be established that bringing heavy objects onto the Moon is possible whereas landing heavy objects to Mars is much more difficult due to its atmosphere[3]. This atmosphere protects Mars against small asteroids and extreme temperatures whereas the Moon has enormous differences between day and night. The Martian atmosphere however isn't thick enough to protect the surface of the planet from radiation; the Moon is also exposed to the problem of radiation.

Therefore to protect astronauts on the surface of those two objects a habitat must be created which shields them from those harsh conditions. Although Mars has a less difficult environment compared to the Moon, Mars doesn't allow heavy objects to land on its surface which implies that buildings should be made in situ whereas the Moon allows us to land a complete protective capsule which can be designed, built and tested on Earth. Therefore, building on Mars represents a different task but probably, whichever solution is found for a habitat on Mars will, with relatively few adjustments, be possible to build on the Moon too. Therefore, it is chosen to focus this research on building a habitat on Mars.

3 More in depth information about space travel and particularly the entry, descend and landing phases are explained in chapter 5.

3. Planet Mars

As Mars has been chosen as location for a habitat, a further in depth analysis is made of the planet to properly understand this extra-terrestrial environment.

3.1 General information

As is mentioned in 1.1, Mars is a planet next to us in the solar system. Mars is on an average distance of 225 million km from Earth with its shortest distance of about 54,6 million km and longest of about 401 million km. This huge variation is due to the planets' respective distance to the sun. These distances are of great influence for the properties of the planets but also for the relation between the two planets.
Although the planet is smaller than Earth and further away from the Sun, the Red Planet is comparable to our planet Earth regarding geological processes and land surface as both planets are within the habitable zone[4] of our solar system. Both planets have volcanoes, canyons and impact basins which imply that they both share some history (Smith, n.d.). A map of the planet is shown in figure 6 where those geological features as well as the different landing sites of rovers and landers can be observed. Landers are objects which land on the surface of the planet and observe the environment, however, they are unable to move. A rover is a lander which can move around to observe different sites around its landing site. Famous Martian rovers are Spirit and Opportunity, landed by NASA in 2004. Opportunity is still moving around the Red Planet today, having travelled for over 42 km on the surface of Mars (National Geographic, 2015).

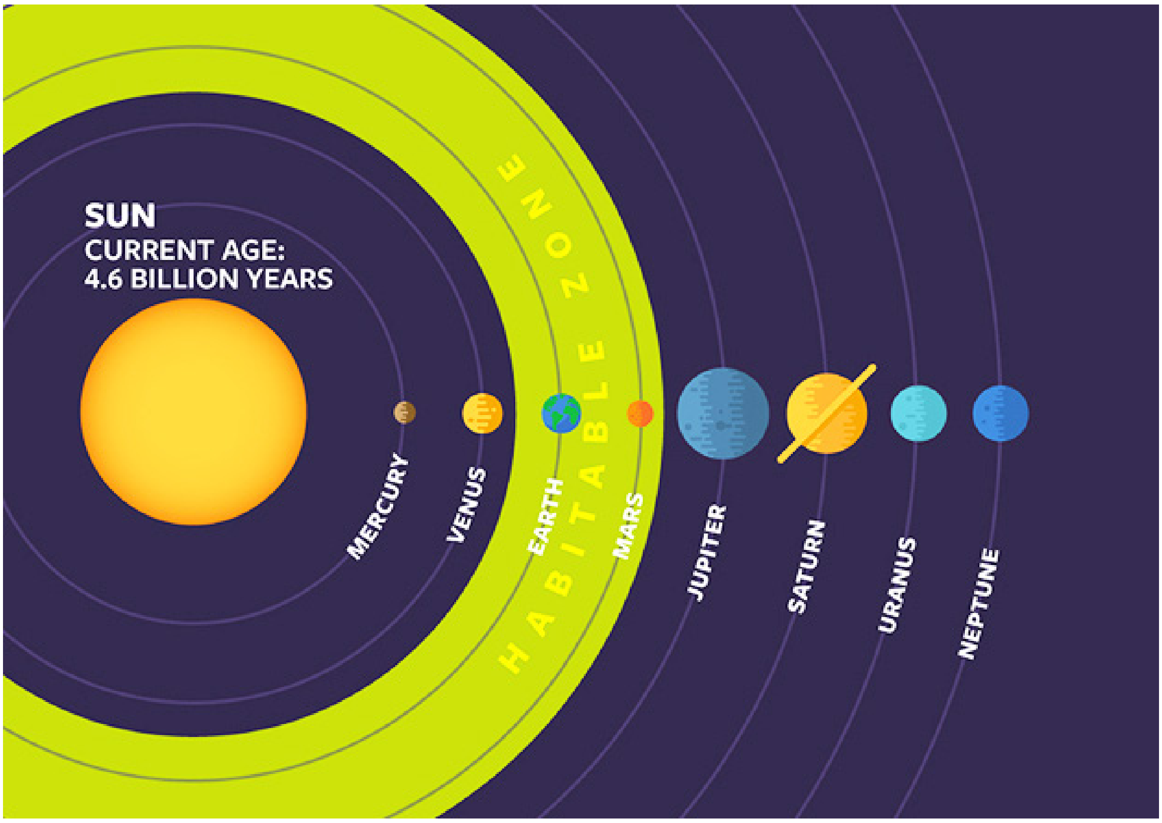


Figure 5. The solar system with Earth and Mars situated within the habitable zone (Retrieved from http://astrobiology.com/2016/05/hunting-for-hidden-life-on-worlds-orbiting-old-red-stars.html on October 7, 2017).

4 The habitable zone is a zone which is situated at a distance from the sun where temperatures allow water to exist, therefore also organisms.

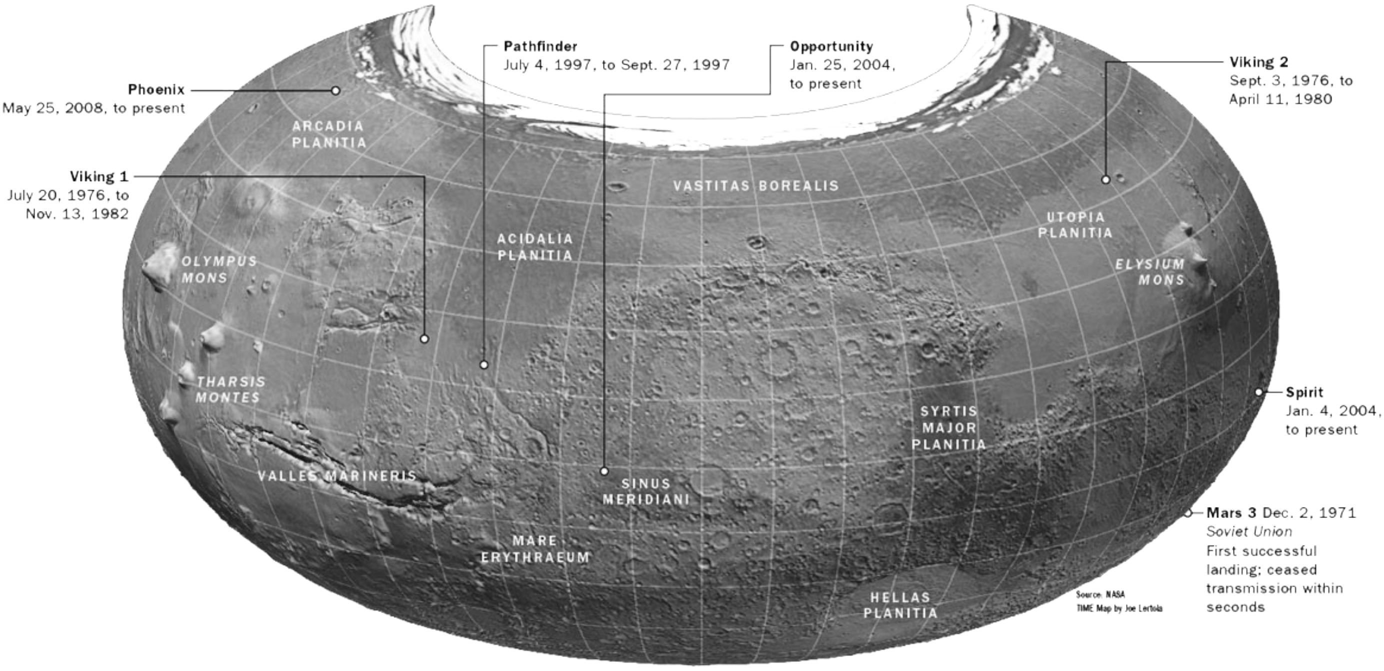


Figure 6. Map of Mars with its largest geological features such as craters, canyons and mountains as well as the landing site of manmade rovers and landers (NASA, 2017).

	Mars	Earth
Atmosphere (composition)	Carbon dioxide (95.32%) Nitrogen (2.7%) Argon (1.6%) Oxygen (0.13%) Water vapor (0.03%) Nitric oxide (0.01%)	Nitrogen (77%) Oxygen (21%) Argon (1%) Carbon dioxide (0.038%)
Atmosphere (pressure)	7.5 millibars (average)	1,013 millibars (at sea level)
Deepest Canyon	***Valles Marineris*** 7 km (4.35 miles) deep 4,000 km (2,485 miles) wide	***Grand Canyon*** 1.8 km (1.1 miles) deep 400 km (248.5 miles) long
Distance from Sun (average)	227,936,637 kilometers (142,633,260 miles)	149,597,891 kilometers (92,955,820 miles)
Equatorial Radius	3,397 kilometers (2,111 miles)	6,378 kilometers (3,963 miles)
Gravity	0.375 that of Earth	2.66 times that of Mars
Largest Volcano	***Olympus Mons*** 26 kilometers (16 miles) high 602 kilometers (374 miles) in diameter	***Mauna Loa (Hawaii)*** 6.3 miles high 121 kilometers (75 miles) in diameter
Length of Day (time required to make a full rotation on its axis)	24 hours, 37 minutes	Just slightly under 24 hours
Length of Year (time required to make a complete orbit of the Sun)	687 Earth days	365 days
Polar Caps	Covered with a mixture of carbon dioxide ice and water ice	Permanently covered with water ice
Surface Temperature (average)	-81 degrees F (-63 degrees C)	57 degrees F (14 degrees C)
Tilt of Axis	25 degrees	23.45 degrees
# of Satellites	2 (Phobos and Deimos)	1 (Moon)

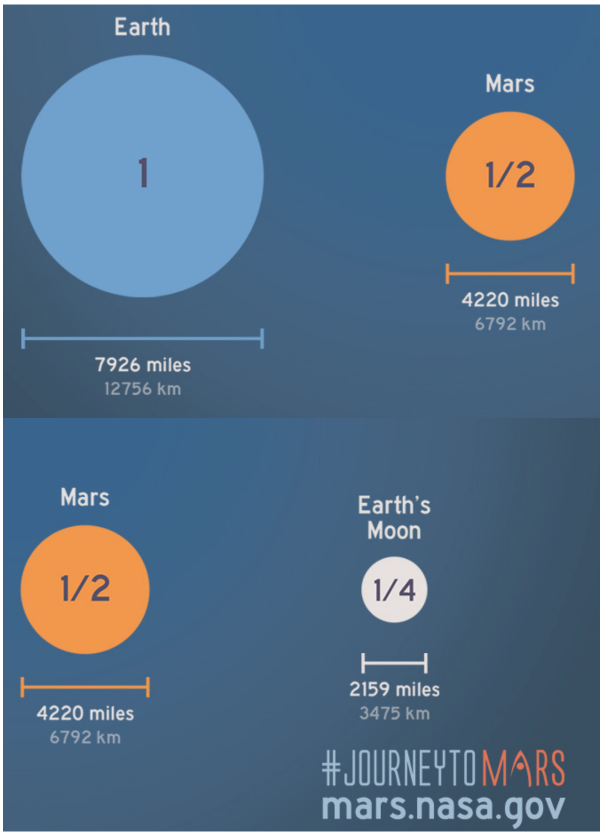


Table 6. Selected properties of Mars and Earth. Similarities can be seen in terms of geological history as well as differences due to the distance from the Sun (Smith, n.d.).
Figure 7. Comparaison Earth and Mars regarding the size of the planets (NASA, 2017).

Table 6 shows the differences and similarities between our planet Earth and Mars. Although our atmosphere is quite different from the Martian atmosphere today, their properties change over time. It is believed that a long time ago the Martian atmosphere was quite different from what it's now and probably resembled that of Earth. A lot of these properties show the similarities the two planets share like gravity, the length of a day, their respective polar caps, their satellites and the tilt axis. Other values influence each other and are in proportion to each other due to the distance from the sun. As Mars is further away the length of a year is longer and its temperatures are lower.

3.2 Composition

A complete (heavy) habitat can't be landed onto the surface of the planet Mars as resulting the friction would ignite the spacecraft. Therefore, In situ Resource Utilisation (ISRU) has to be analysed as well as the potential indigenous materials available. This heading is an inventory of the potential building materials available on the planet Mars.

3.2.1 Martian soil

Figure 8. Picture of the Kimberley formation made by Curiosity (NASA, 2017).

Martian soil, also called regolith, is mainly composed of fine dust and igneous rocks, the composition of which resembles that of Earth. The most abundant chemical elements are silicon and oxygen, iron, magnesium, aluminium, calcium and potassium. Less abundant chemical elements which compose the minerals of the planet are titanium, chromium, manganese, sulphur, phosphorus, sodium and chlorine. Hydrogen is present as H_2O ice and in hydrated minerals and carbon is mainly present as gas in the Martian atmosphere as CO_2, as well as dry ice on the pole caps of the planet (Foley, et al., 2008). Typical of Mars is the ultrafine dust layer which can cause potential health problems for astronauts as the dust could be ingested into the lungs as well as damage the Earth brought equipment.
As part of its Centennial Challenge, NASA released a list of indigenous materials which are found on Mars and can be used as potential building elements (NASA & Bradley University, n.d.). As this list isn't complete, a few extra elements were added.

MARTIAN SOIL	**NAME**	EXPLANATION
NASA LIST	CBI	crushed basaltic igneous rock (SiO_2 weight percent less than or equal to 57)
	BSR	basaltic sedimentary rocks (talus, alluvium with very little alteration/weathering, or mine tailings
	GSS	gypsum sand and siliceous sedimentary rocks (e.g., sand box sand, mudstone)
	CSR	carbonaceous sedimentary rocks (e.g. limestone, dolomite)
	IRS	igneous rocks with SiO_2 weight percent greater than 57 (e.g. granite)
	MR	Metamorphic rocks (e.g. slate)
NOT ON NASA LIST	H_2O	ice found in depth
	CO_2 ice	CO_2 ice (water) found on surface of mars (contains salts)
	ClO_4^-	Perchlorate: toxic for human health/ resource

Table 7. Material found in Martian soil which are mostly rocks forming regolith with ice found under the regolith layer.

3.2.2 Water

Mars has the most hospitable climate, after Earth, of our Solar System dixit NASA Jet Propulsion Laboratory (JPL). This statement is made because evidence has been found that liquid water has flowed on the surface of Mars billions of years ago. Life as we know it requires three things: organic compounds, energy (to synthesize complex geometric molecules) and liquid water, in the presence of those three elements life has been found even in extremely harsh environments, like the Atacama in Chile, the driest desert on Earth. Liquid water is thus essential for life and one of the reasons for manned missions on Mars. However, Mars' environment changed to a colder climate and a thinner atmosphere which doesn't support liquid water which sublimates immediately (NASA/JPL, n.d. & NASA, 2015b). Water is found on Mars at the moment either as ice or as vapour. Dry ice is found on the pole caps and underground ice can be found dispersed under the regolith. The gamma ray spectrometer (GRS) from the Mars Odyssey orbiter maps out the abundance and distribution of many elements from the periodical table. The hydrogen abundance has been mapped out and shows the potential for ground ice. Water vapour is also found although at lower altitudes and in lesser quantities. The water/ice present today on Mars contains a high percentage of salts which changes its freezing and boiling temperature thus allowing liquid "water" on Mars, known as brines (NASA, 2015a). Some of those salts are perchlorates.

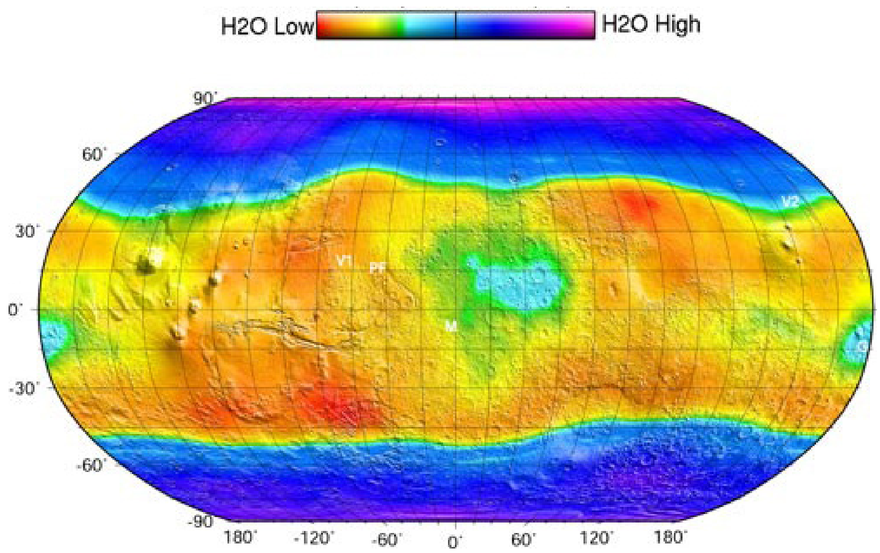


Figure 9. Map of Mars with the different concentration of H2O on the surface as measured by the MRO (Retrieved on October 22, 2017 from https://mars.nasa.gov/odyssey/images/odyssey/technology/h2o_map-br.jpg).

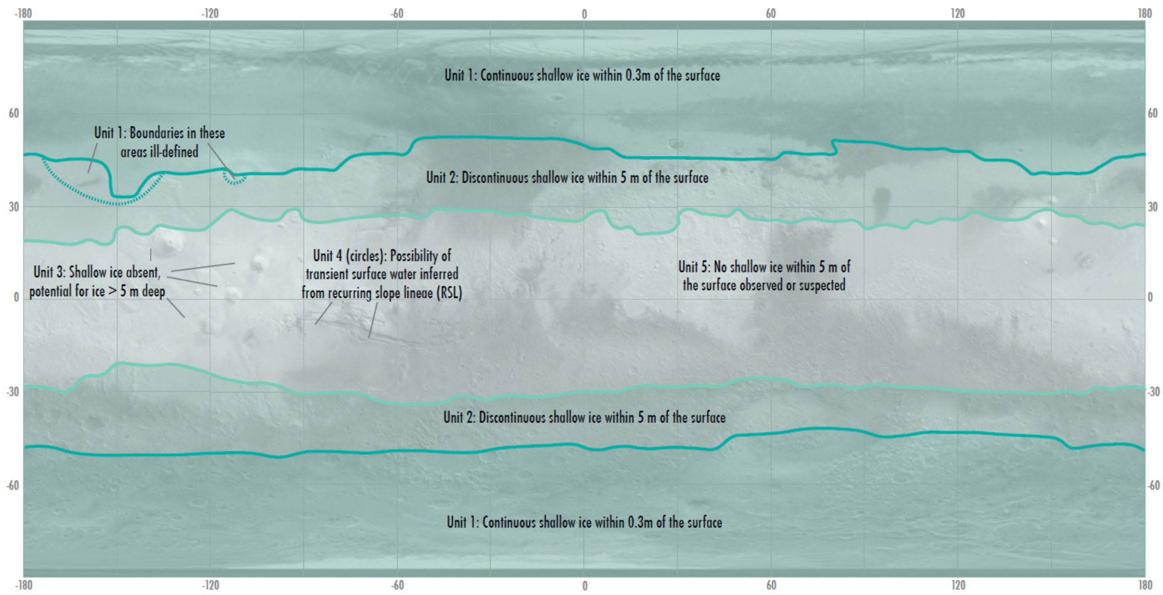


Figure 10. Map of Mars with the different ice layers (NASA, n.d.).

3.2.3 Perchlorates

In 2010, Perchlorates ($Cl0_4^-$) have been detected on at least two landing sites on Mars. Since then, the Mars Odyssey orbiter has determined that perchlorates are globally distributed on the top ten centimetres of the Red Planet's crust; the distribution of Cl within the top 1m of Mars' crust is shown on the map below.

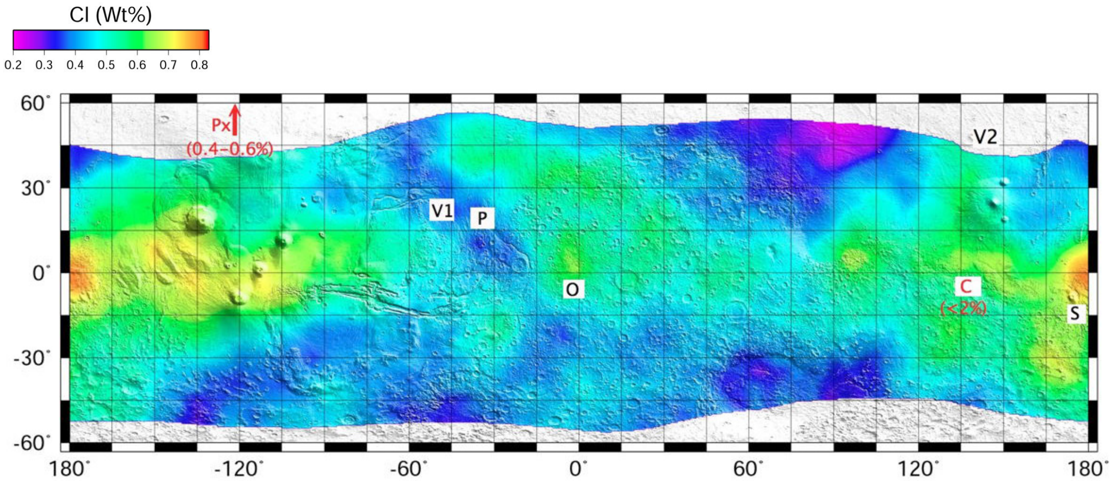


Figure 11. Map of Mars with the different concentration of Cl on the surface as measured by the MRO (Retrieved on October 22, 2017 from https://grs.lpl.arizona.edu/latestresults.jsp?lrid=27).

The discovery of perchlorates can't be ignored and measures need to be taken before sending humans onto the surface of Mars as perchlorates can be both a chemical hazard to human life as well as a resource. $Cl0_4^-$ is a hazard because it can cause malfunction of the thyroid by inhibiting the uptake of iodine ions leading to serious health problems like thyroid hyperplasia, goitre, decreased metabolic rates and a slowing of the functions of many vital organs. Another hazard is that $Cl0_4^-$ has been found in the regolith at polar altitude and it may thus be present in ground ice. But perchlorates could also be an important source of oxygen for life and operational support. Davila et al. (2013), developed a portable emergency O_2 system which can extract oxygen out of $Cl0_4^-$-rich simulated Martian soil using enzymes. The same process could be realised with $Cl0_4^-$-rich water or ice which could then be used for human consumption (Davila, Willson, Coates, & McKay, 2013). Another study by Fischer, et al., uses salts among which perchlorates to transform ice to liquid water by direct contact which could be done on the pole caps or by bulk deliquescence with vapour. A study has been made of two main tests which are focussing on two places where water ice can be found on Mars, on the polar caps and on the subsurface. A rough scheme of these two tests can be seen in figure 12. Results indicate that liquid brines are likely to form where water ice exists in the shallow subsurface of the Martian soil (Fischer, Martínez, Elliott, & Rennó, 2014). 39

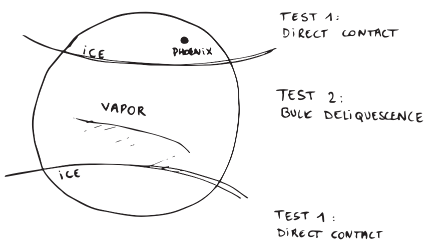


Figure 12. Map on where the two researched effect can take place on Mars with test 1 on the polar caps and test 2 around the equator.

3.3 Conclusions

To conclude, it can be said that Mars is an inhospitable planet for humans but it still has great potential as well. Its geology resembles that of Earth where roughly the same elements and rock formations can be found. These could possibly be used to land a manned crew as well as to build a habitat. Much can be learned by observing the Martian geology in situ as well as the properties of water and ice. Water presents an important potential resource for Martian life, human life and the building of a habitat. However, as ice sublimates on Martian surface due to its low pressure, water has to be "created". Different processes are available among which the use of perchlorates.

4. Jezero Crater

This chapter is an analysis of the specific habitat location: Jezero crater. This location is chosen based on different aerospatial and engineering criteria which are further explained in heading 6.1 Landing site.
In this chapter, the general geological features are explained and the climatology of the location is analysed in further depth especially concerning the composition of the surroundings.

4.1 General

Jezero Crater is situated within the Syrtis Major quadrangle at 18.855°N and 77.519°E. It is an impact crater with a diameter of +/- 49 km at an elevation of -2,5 km. The crater is a paleolake basin, meaning that it was a lake a long time ago, which has dried up over time. To be more precise, scientists think the crater was a river delta and was wet at two distinct moments in time and then dried up 3,5 to 3,8 billion years ago (Goudge, et al., 2015). This means that potentially life could have existed on this location which makes it a place of interest (POI) for scientific research. The map in figure 13 shows that there are a lot of different types of soil which makes Jezero Crater a scientific POI.

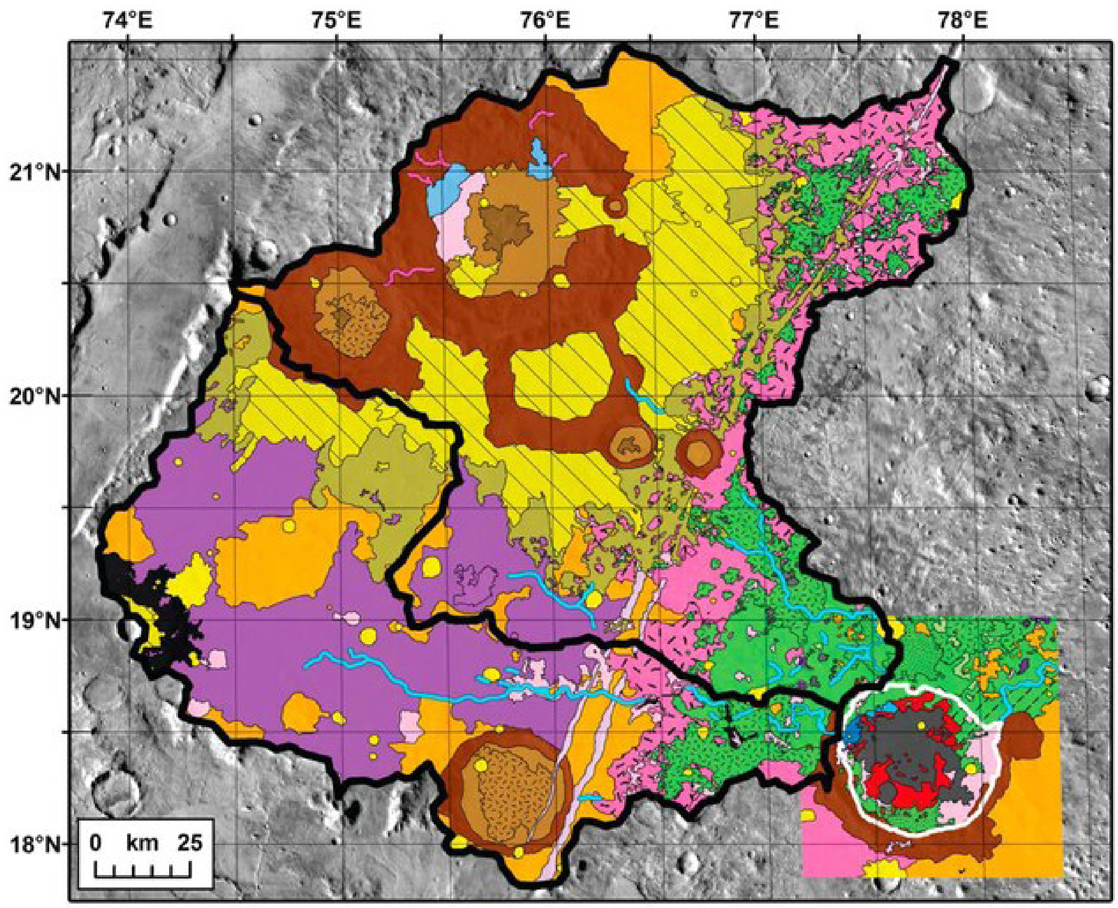


Figure 13. Different soil types near Jezero Crater (on bottom right) where the ancient water flows coming from the North West have left their mark in the soil composition (Goudge, et al., 2015).

4.2 Climatology

Just like on Earth, Mars has different climates on different locations and during different moments throughout the year and day. To determine the climate at different Martian locations, NASA has developed the Mars Climate Database v5.2 tool which indicates the temperature, pressure, solar flux and H_2O presence on a set location at a set date. This tool is used to analyse the climate at the habitat location: Jezero Crater. The tool plots a graph with a value for every hour during one sol[5], which is determined by the Solar Longitude Ls, see figure 13. To fully understand the database and general climate on Mars, the Martian seasons, solstices, months and days need to be understood. As Mars is tilted along its axis and it revolves elliptically around the sun, it has seasons just like Earth, however these seasons last about twice as long as on Earth as the Martian year lasts 668 sols (or 687 Earth days). The angle between the Sun and Mars is called the Martian Solar Longitude Ls. Table 8 below explains the relationship between the climate, seasons and the Ls. The northern summer solstice is at Ls=90 and the winter solstice at Ls=180. It can be seen that dust storms are common on Mars, in fact, these storms can be global and lasting for weeks, obscuring the whole surface.

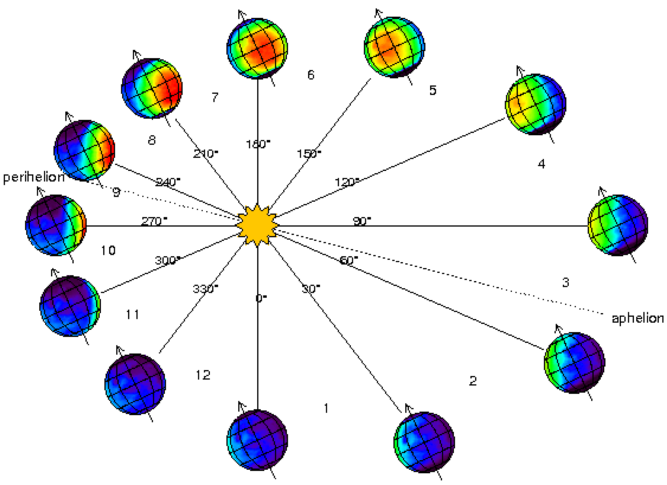


Figure 14. Solar longitudes Ls in relation with the sun. The northern summer solstice is at Ls=90 and the winter solstice at Ls=180 (Mars Climate Database, 2017).

Month number	Ls range (degrees)		Sol range		duration (in sols)	specificities
1	0	30	0.0	61.2	61.2	Northern Hemisphere Spring Equinox at Ls=0
2	30	60	61.2	126.6	65.4	
3	60	90	126.6	193.3	66.7	Aphelion (largest Sun-Mars distance) at Ls=71
4	90	120	193.3	257.8	64.5	Northern Hemisphere Summer Solstice at Ls=90
5	120	150	257.8	317.5	59.7	
6	150	180	317.5	371.9	54.4	
7	180	210	371.9	421.6	49.7	Northern Hemisphere Autumn Equinox at Ls=180 Dust Storm Season begins
8	210	240	421.6	468.5	46.9	Dust Storm Season
9	240	270	468.5	514.6	46.1	Perihelion (smallest sun-Mars distance) at Ls=251 Dust Storm Season
10	270	300	514.6	562.0	47.4	Northern hemisphere Winter Solstice at Ls=270 Dust Storm Season
11	300	330	562.0	612.9	50.9	Dust Storm Season
12	330	360	612.9	668.6	55.7	Dust Storm Season ends

Table 8. Seasons on Mars. Relationship between Martian months and the solar longitudes on the climate (Mars Climate Database, 2017).

5 A sol is a Martian solar day which lasts for about 24 hours and 37 minutes.

First, a general indication of Mars climate is plotted with the tool at the equator and the Phoenix landing site. The air temperature greatly fluctuates throughout the day going as low as 190K (-83,15°C) at 6.00 Martian hour and as high as 246K (-27,15°C) at 16.00 Martian hour. At 8.00 a H_2O ice layer of up to 0,30 kg/m^2 forms on the surface due to the peaking pressure. During the summer solstice (Ls=90), the lowest temperature is 197K and highest temperature is 245K. During the winter solstice (Ls=180), the lowest temperature is 196K and highest is 255K. All the plotted graphs can be found in appendix A.

Conclusion can be drawn that the air temperature at Jezero crater doesn't fluctuate much throughout the year, this is due to the proximity to the Martian equator. However the highest temperatures are around Ls= 150K and should be taken into account during the building phase as it gets close to 0°C.
The surface pressure ranges between 604 Pa during the night on the winter solstice to 687 during the day at the summer solstice.

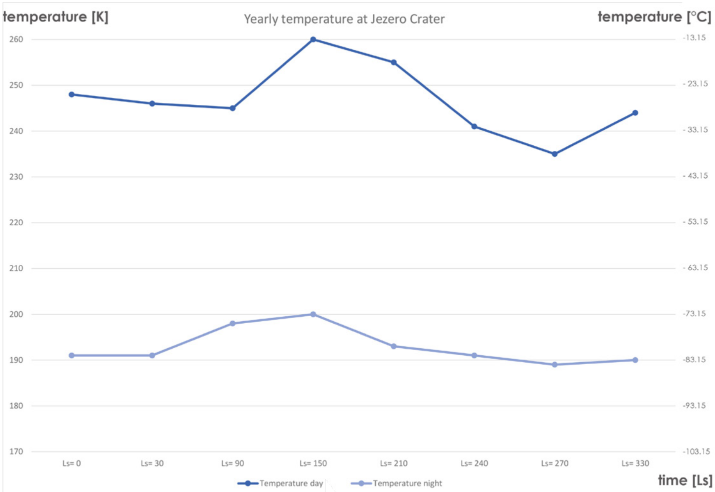


Figure 15. Yearly temperature flux at Jezero crater. Based on an analysis made in the Mars Climate Database.

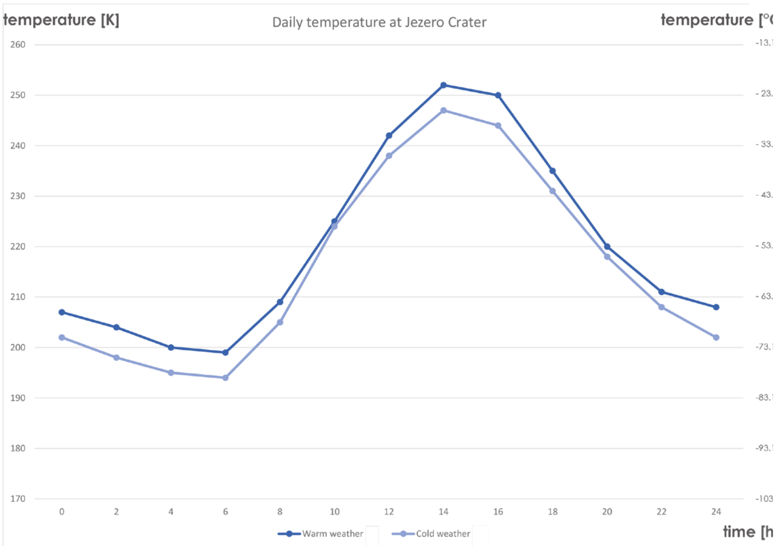


Figure 16. Daily temperature flux at Jezero crater. Based on an analysis made in the Mars Climate Database.

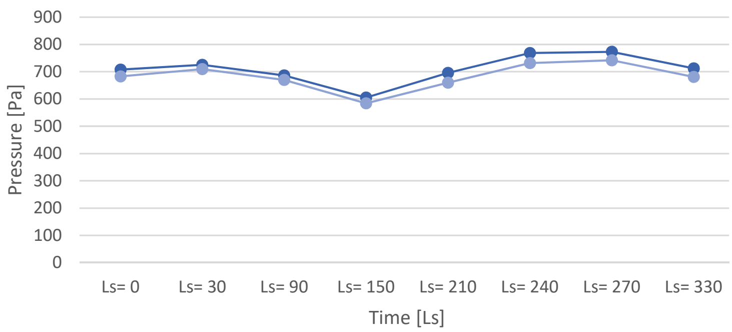


Figure 17. Yearly pressure flux at Jezero crater. Based on an analysis made in the Mars Climate Database.

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5. Space mission

In order to design a habitat on Mars, constraints due to space mission design are inventoried. Space missions rely on different technologies and aspects which often aren't flexible. Therefore the design of a habitat should comply to those quantitative criteria.

5.1 Space travel

Building on another planet means that transportation and fabrication are issues which should be addressed at the very beginning of the designing phase. As there are no human habitats outside the planet Earth, to create one, materials, tools and energy must be transported from Earth as well as the crew that is going to live in the habitat. This transportation to space is called Space travel and it can be defined in four main steps: launch, voyage, landing and return.

5.1.1 Launch

To properly understand how to launch objects from Earth into space, some physical properties of our planet Earth should first be explained.

Earth has a gravity equal to about 9,807 m/s^2 (or a *g* force of 1*g*). This *g* is the force which is pulling us towards the core of Earth, enables us to stand and sit. Gravity naturally attracts all objects around it, like Earth's only natural orbiter, the Moon. Gravity holds together another property of our planet: the atmosphere. The atmosphere is a layer of gases surrounding our planet which gets thinner as we move away from the core of the Earth but never stops. The atmosphere protects us from the harsh space environment and provides us with our sea level pressure. The top layer is called the heavy side layer and it protects the planet from falling meteorites. These phenomena make it difficult to launch heavy objects away from it and thus a great velocity must be achieved in order to escape this force: the escape velocity.

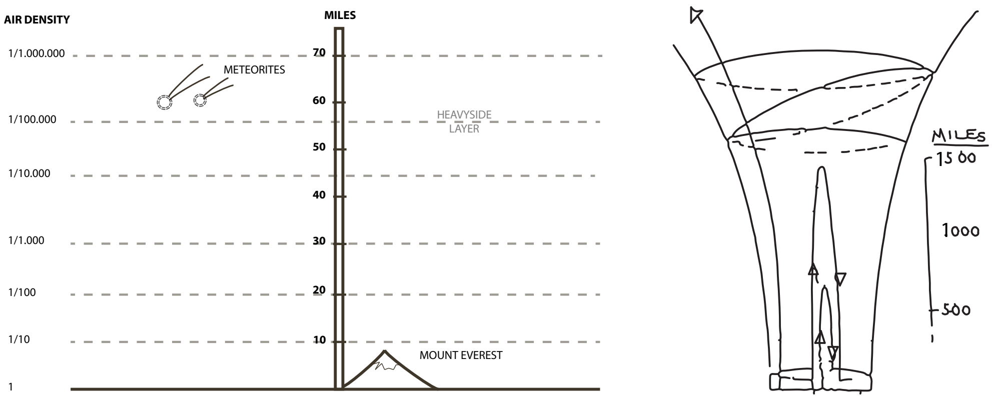

Figure 18. The different layers of our atmosphere on Earth and how a rocket escapes it, based on Clarke, 1951.

5.1.2 Voyage

The voyage to any destination is mostly "easy". Although one important aspect still has an impact on the travel and that is time. As our solar system is in constant movement, it means the Earth has shorter and longer distances to the other objects in our solar system. Therefore, some dates are more favourable to launch in order to reduce the time span of the voyage. Reducing the time span of the voyage not only shortens the mission but also reduces the exposure time to cosmic radiations[6] (Clarke, 1951).

As the Moon is at roughly the same distance from Earth throughout the year, launches to the Moon are relatively frequent. However launches to other objects must be timed. As example, NASA published possible launching dates for a journey to Mars (NASA, 2017). As can be seen in table 9, these dates are rare and therefore make the possible journey to Mars a rare occurrence.

6 Radiation and its dangers are explained in detail in heading 5.2

Date	Hour (UMT)	Min. Dist. (AU)	Min. Dist. (Gm)
May 22, 2016	11:11	0.50321	75.28
Jul 27, 2018	05:07	0.38496	57.59 (perihelic)
Oct 13, 2020	23:20	0.41492	62.07
Dec 8, 2022	05:36	0.54447	81.45
Jan 16, 2025	02:32	0.64228	96.08
Feb 19, 2027	15:45	0.67792	101.42
Mar 25, 2029	07:43	0.64722	96.82
May 4, 2031	11:57	0.55336	82.78
Jun 27, 2033	01:24	0.42302	63.28
Sep 15, 2035	19:33	0.38041	56.91 (perihelic)
Nov 19, 2037	09:04	0.49358	73.84
Jan 2, 2040	15:21	0.61092	91.39
Feb 6, 2042	11:59	0.67174	100.49
Mar 11, 2044	12:44	0.66708	99.79
Apr 17, 2046	18:01	0.59704	89.32
Jun 3, 2048	14:45	0.47366	70.86
Aug 14, 2050	07:46	0.37405	55.96 (perihelic)
Oct 28, 2052	06:28	0.44091	65.96
Dec 17, 2054	22:09	0.57015	85.29
Jan 24, 2057	01:26	0.65552	98.06
Feb 27, 2059	05:25	0.67681	101.25
Apr 2, 2061	12:47	0.63199	94.54

Table 9. Launching dates and duration of Martian missions according to NASA with the minimum distance in astronomical unit (AU) and in gigametres (Gm) (Genta, 2016).

5.1.3 Landing

Landing objects onto an asteroid or planet really depends on which asteroid or planet the landing takes place. Two different options are described: the first an asteroid, our Moon, and the second a nearby planet, Mars, as they are both mentioned for potential manned missions in heading 2.

Moon

Landing on the Moon is relatively easy as the *g* force of the Moon is low (0,164*g* compared to 1*g* on Earth) and therefore the Moon has no atmosphere which will heat the descending object. Landers can thus approach the surface with reduced velocity and land by firing a descent engine which assures a soft landing (Clarke, 1951).
This is how the Apollo missions have been landed on the surface of the Moon between 1969 and 1972.

Mars

Landing on Mars however is much more difficult due to its atmosphere. Heavy objects are therefore a challenge to land due to friction. Lightweight objects are landed either by parachuting and then “bounced around” (like the Spirit and Opportunity rovers) using special airbags or by retrorockets (like the Curiosity rover). Landing a heavier rocket, like a Cargo lander or crew lander however requires new technology.

5.1.4 Return

Landing isn’t always the end of the journey for space travel. Some rovers or landers need to continue their journey with collected samples and data and return these back to Earth for further research and analysis. But mostly, manned missions will be more likely to return to Earth after the mission in space has been accomplished. The return journey often resembles the launch step where the vehicle needs to escape the planet or asteroid’s *g* force.

5.2 Radiation

5.2.1 Origin

In our Solar System, radiation is a mixture of particles originating from the sun and galaxies with a broad range of energies. There are two different types of radiation, the ionizing and the non-ionizing. The latter is widely spread on Earth and has little to no health impact whereas the first type of radiation is harmful to human health. These ionizing radiations take their source from three distinctive events:

- Solar Particle Events (SPE): originating from the sun, during these SPE, solar flares release an enormous amount of energy.
- Galactic Cosmic Radiation (GCR): finds its origin outside our Solar System and produces intense ionization when passing through matter.
- Trapped radiation: created by the magnetosphere of our planet which forms two belts (Van Allen belts) where the inner belt contains protons and the outer belts electrons with a release of high energies.

Radiation can also be found on Earth which constitutes the X, α, γ, β rays of the spectrum whereas Space radiation is also formed by protons and heavy ions.

5.2.2 Impact on humans

Radiation is one of the most serious challenges for space exploration due to the health problems it causes. Radiation is measured in Sievert (Sv) and is a measure of the health effect of low levels of ionizing radiation on the human body (Sievert, 2017). Radiation causes mostly damage to human tissues and/or organs and the effect depends on the specific tissues and organs exposed as well as the radiation source, the amount of radiation and the exposure time. The Sievert is a unit which is more or less linearly related to the probability of cancer and genetic damage caused by radiation, with 1 Sv producing a 5,5 percent chance of developing cancer (Genta, 2016). The Sievert is a large value therefore it is often used as millisievert and calculated as rate per year (mSv/year).
When humans are sent to space they are thus exposed to this radiation. In the ISS, the annual maximum exposure is set at 200 mSv. On the surface of Mars the annual exposure is estimated at 230 mSv/year from GCR and 0,025 mSv from SPE which is above the ISS maximum dose (Morris, Ciardullo, Lents, Montes, Rudakevych, Sono, Yashar, 2016). This is also true as a crewed mission has first a long journey in space (ranging from 4 to 6 months) where exposure is much higher than under the (thin) atmosphere and mass of Mars (Genta, 2016).

Age	25	35	45	55
Male	0.7	1	1.5	2.9
Female	0.4	0.6	0.9	1.6

Table 10. Career limits for astronauts in Low Earth Orbit (LEO) expressed in Sv based on the National Council on Radiation Protection (NCRP) Report No. 98 in 1989 (Genta, 2016).

5.2.3 Designing against radiation

To protect humans from radiation, three methods are found: **increasing** the distance, **reducing** the time of exposure and **shielding**. In space, as cosmic radiation is isotropic, increasing the distance is not an option (Durante & Cucinotta, 2011). Shielding during space travel has found to be difficult, thus reducing the voyage time span to reduce the time of exposure and therefore the negative health impact on the space crew is the preferred method of protection.
However, on the surface of Mars, shielding is a viable option to protect the crew against radiation. As it is difficult to thoroughly protect the crew during the space flight, an increased protection is needed on Mars to compensate the time being exposed to space radiation. Hence a guideline of 50 mSv/ year is wielded. Shielding is done by placing lightweight materials between the crew and space radiation. Different materials have different shielding capacities with hydrogen being one of the lightest and therefore best radiation shielding elements. As can be seen in figure 18 and 19, water which is hydrogenated has excellent shielding properties. Hydrogen and other passive materials shield effectively against radiation but changes its particles creating secondary radiation which is as harmful to human health as (primary) radiation. Hence, a thick layer of material is needed to shield for both types of radiation.

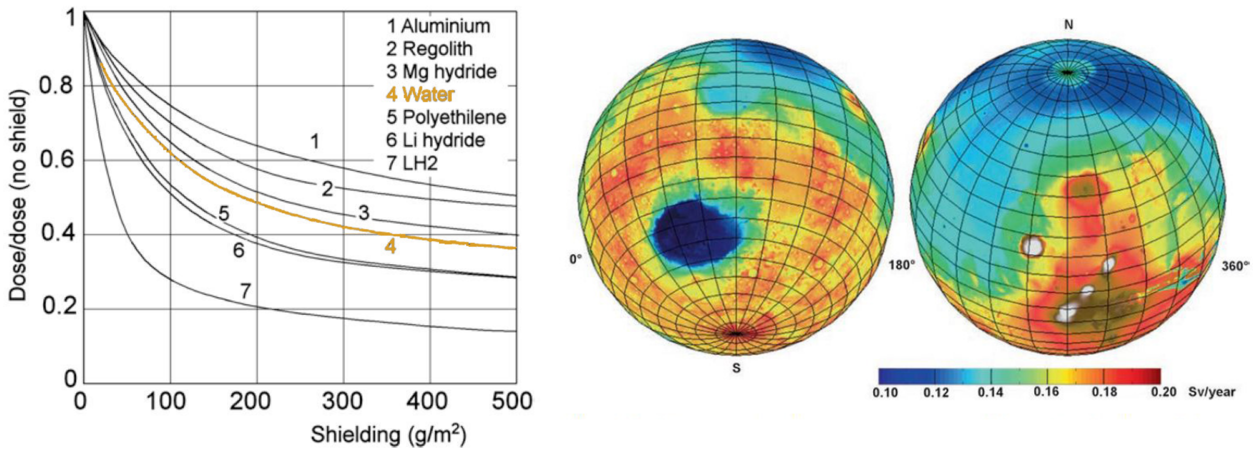

Figure 19. Left: Radiation shield comparison (Genta, 2016). Right: Effective radiation dose rate (in Sv/year) on the Mars surface (Genta, 2016).

Therefore, the thickness of the shield depends on two aspects: the material used and the amount of radiation. The amount of radiation on the surface of Mars depends on the specific location changing with the different latitude and altitude as can be seen in figure 19.
The previous figure 19 (as well as the Mars Climate Database tool) can be combined to determine the amount of material needed to shield the crew against all the harmful radiations. Water is used[7] as shield material for the specific location: Jezero Crater. Therefore, 30 g/cm needed (from figure 18) for a density of the salt ice (at -70°C) of 0,9233 g/cm³. Hence,

$$\text{Thickness}_{\text{salt ice}} = 30/\ 0{,}9233 = 32{,}5 \text{ cm}$$

Thus at least 325mm of salt ice is needed to protect the crew against space radiation following the NCRP health guidelines.

5.3 Mission Design and Constraints

Space travel and in particular the EDL methods used make up the mission design constraints. Different parties have different mission designs and therefore different constrains. This research is focussed on the mission design developed by NASA for three reasons: the first reason is that NASA has a mission design to go to Mars, which a lot of other space agencies, like ESA, don't have. The second reason is that NASA has an extensive experience (by landing the first man on the Moon, sending rovers to Mars, etc.) compared to other companies like SpaceX. And finally, most of NASA's data, designs and technologies regarding a mission to Mars are open source which is not the case for the Russian or Chinese space agencies.

NASA's latest mission design for Mars is called DRA 5.0: Design Reference Architecture 5.0. It is a sequence of two manned long-stay missions of about 500 days, which will span over seven years as can be seen in figure 20 and 22.

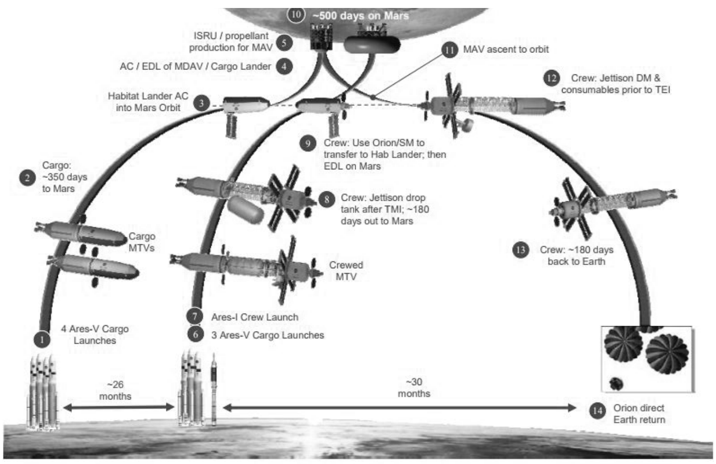

Figure 20. Mission sequence summary for DRA 5.0 (NASA, 2009, p. 5).

7 The material choice is extensively explained in PART C – Material.

5.3.1 Volume and mass

As stated before, every man made object arrives on Mars with a rocket. There are different types of rockets ranging from Intermediate, Heavy and Super-heavy which mostly relate to its payload. Every company has its own model but for this thesis the boundary was set on a NASA launch vehicle: the Space Launch System (SLS). The SLS is a super-heavy deep space rocket which is currently (begining of 2018) still under development. NASA designs this rocket specifically to send humans to Mars with two types of SLS: the cargo SLS and the crewed SLS with the Orion capsule. In the NASA mission design for a Journey to Mars, cargo landers are sent first with equipment for the ISRU for the Mars Ascent Vehicle (MAV) which is the rocket which will go back to Earth at the end of the mission on Martian surface. The cargo lander will also carry a habitat capsule along with all the necessary equipment to build it semi-autonomously from Earth. Only when all the equipment is set, will a crewed SLS arrive to Mars within the specialized Orion capsule. The cargo landers are one of the most important constraints for Space Architecture as it defines the maximum volume and mass that can be landed onto the surface of Mars.

The SLS block II Cargo design has a payload of maximum 130 mT (metric tons) and dimensions of 10m diameter and with a maximum of 31m height. Within this cargo, different technologies are placed and only a limited space is available for a habitat. This is visualised in figure 21 made by NASA (NASA, 2017)

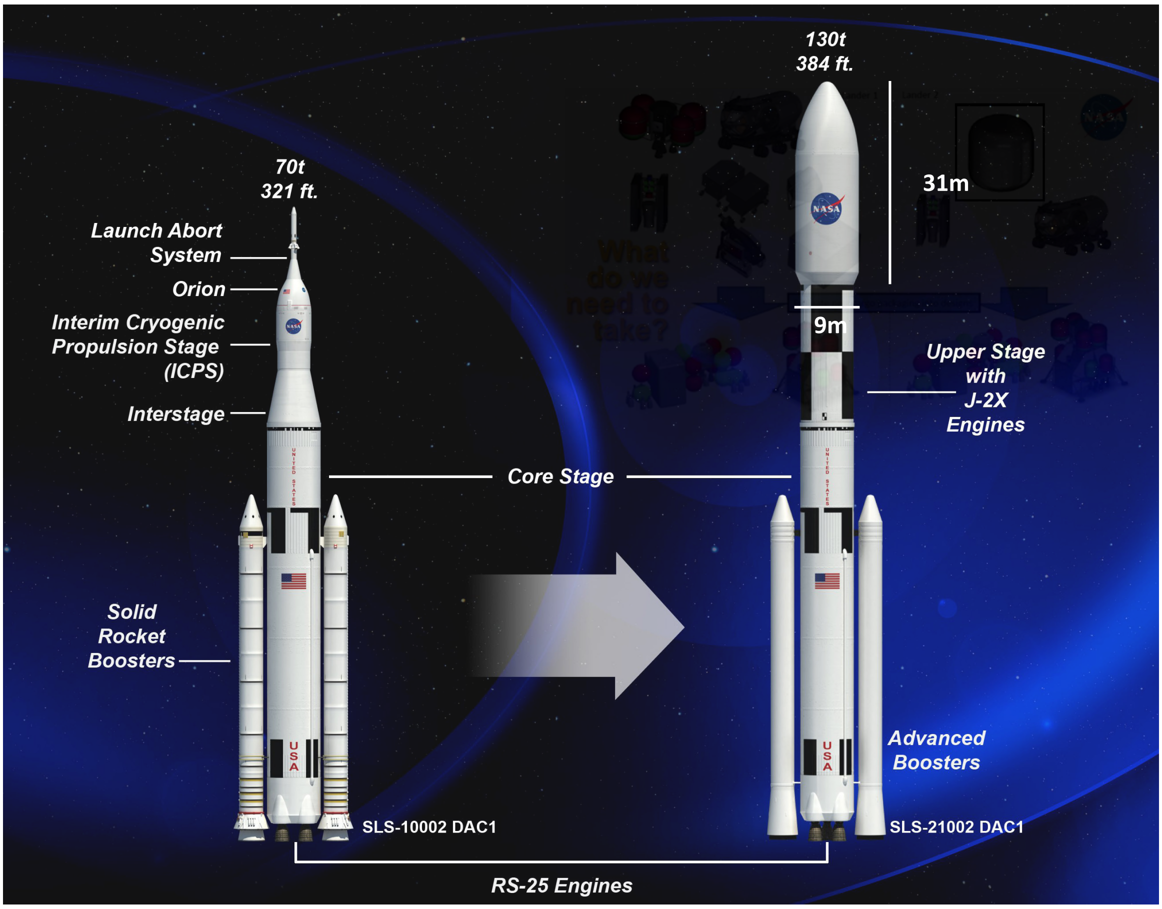

Figure 21. The SLS with a concept for two cargo capsules and the technology brought in (NASA, 2017).

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Surface Systems	Quantity	Habitat Lander System Mass (kg)	DAV Lander System Mass (kg)
Crew Consumables	-	1,500	4,500
Science	-	-	1,000
Robotic Rovers	2	-	500
Drill	1	-	1,000
Unpressurzed Rover	2	-	500
Pressurized Rover	2	8,000	-
Pressurized Rover Growth	-	1,600	-
Pressurzed Rover Power	2	-	1,000
Traverse Cache	-	-	1,000
Habitat	1	16,500	-
Habitat Growth	-	5,000	-
Stationary Power System	2	7,800	7,800
ISRU Plant	2	-	1,130
Total Surface Systems	-	**40,400**	**18,430**

Lander Systems	Quantity	Habitat Lander System Mass (kg)	DAV Lander System Mass (kg)
Ascent Stage 1 (no LOX)	1	-	12,160
Ascent Stage 2 (no LOX)	1	-	9,330
Descent Stage (wet)	2	23,760	23,760
Aeroshell	2	42,900	42,900
Total Wet Mass (IMLEO)	-	**107,060**	**106,580**

Table 11. The respective mass of each component with the habitat mass at 16500 kg and habitat growth at 5000 kg (NASA, 2009).

5.3.2 Time

Time is a constraint regarding the building process. The shortest distance between the Red Planet and our own planet Earth only occurs once every 26 months. This means that if we send a cargo lander with a habitat, 26 months later a crewed mission can arrive according to the launch windows. However, the DRA 5.0. states that it would be less costly and more efficient to have a shorter transit of the crew, therefore leaving less than 26 months to build the habitat. Furthermore, counting the time to set up the equipment and potentially run out, the construction time for the habitat should not exceed 17 (Earth) months.

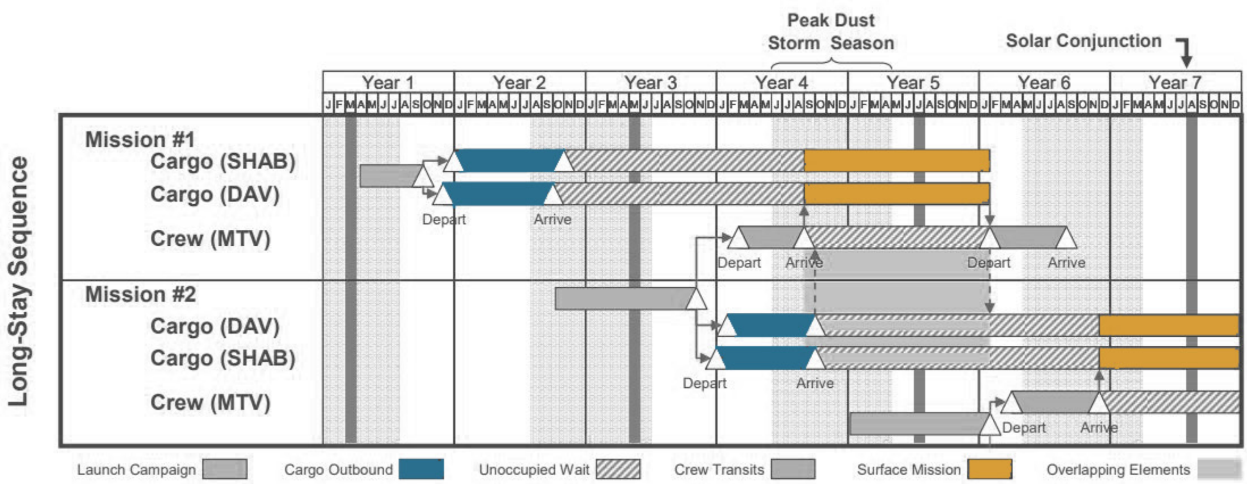


Figure 22. Mission sequence timelines for DRA 5.0 (NASA, 2009, p. 3).

5.3.3 Power

Power is an often overlooked constraint, however it is also an important one. Power on Mars can come from two sources: fission or solar. Power is needed to run the ISRU plant which is making propellant for the journey back to Earth with the MAV. Power is also used to build the habitat and, once the crew arrive to sustain it with the ECLSS[8], to run the different rovers, and to power the different necessities within the habitat (lighting, computers, laboratory equipment, etc.). This thesis has set a boundary on using solar power for the habitat design. However due to a greater distance between Mars and the sun than Earth and the sun, the efficiency of solar panels is lower than on Earth. Adding to that, global dust storms containing ultra-fine sand particles obstruct the sun on the surface of Mars for weeks in a row. Therefore the average solar radiation flux is 589 W/m^2 on the surface of Mars (Genta, 2016). Using high efficiency solar panels at 30% the maximum amount of power available for the building of the habitat would be around 7,36 W/m^2. Fortunately surface is widely available on Mars and therefore the amount of panels brought to Mars has as only limit its weight when transported from Earth. However, the amount of energy available with solar panels is thus extremely limited and would probably have to be coupled with a small nuclear reactor for redundancy. NASA is currently designing small fission units for space exploration with a design output of 40 kW (Genta, 2016). Taking both energy sources into account when designing the habitat is the most reasonable, however care must be taken that the power is also needed for the ISRU plant. How much power is needed for the IRSU plant depends on the mission design and the amount of crew members and is not yet known.

5.4 Conclusion

To conclude, heavy objects are difficult to send into space. Therefore, the less objects needed for mission and the more lightweight they are, the better. This holds especially for objects needed to build a habitat in contrast to Earth habitats where most of the time heavy building materials and tools aren't the main issue. However, to protect the crew from harmful radiation, mass is needed. As it can't be brought from Earth, local in-situ mass is needed to build the habitat which is time and power consuming. The boundaries of the mission (volume, mass, time and power) have therefore a leading impact on the programme of requirement for the design of the habitat.

8 ECLSS: Environmental Control and Life Support System. More information on this system is explained in heading 6.3 Design criteria under Structural Systems.

6. Architecture in Space

Two main concepts are defined by architecture in space. The architectural design of space crafts, like the ISS, and the architectural design of habitats on celestial objects. The focus of this paper is on the latter, architectural design of habitats on celestial object and therefore the literature analysis is also focussed on this particular aspect of space architecture.

6.1 Landing site

The first step of building a habitat on a celestial object, like Mars, is the location choice. Häuplik-Meusburger and Bannova (2016) consider these following aspects for the choice of a landing or building site:

- Safe distance from pre-deployed structures and elements
- Relatively smooth and flat terrain
- Close proximity to points of interest (POI) or scientific research and ISRU sites
- Ease of transportation to and from the landing site
- Availability of natural (landscape) protection from environment hazards

These criteria apply mostly to the terrain of the location, but other factors like the latitude and altitude are also of great importance. For example, to optimize solar power collection and to minimize temperature variations, an equatorial location is preferred. Regarding the return journey, launching from Mars requires less energy at the equator as well and is an important aspect of the mission. On the other hand, ground ice, which could be a resource for manned missions (Wilkinson, et al., 2016) is more widespread at higher latitudes. The latitude is also of influence on the angle at which solar radiation hits the habitat; therefore designing a habitat on lower latitudes would be different than on high latitudes.
NASA has set as priority to find microbial life and thus set the goal to "follow the water" which was the main aspect on choosing a landing site. After the workshop held in February 2017, NASA has narrowed down the choice of landing sites for the 2020 rover by three. The selected sites are the Jezero Crater, Columbia Hills (Gusev Crater) and NE Syrtis Major. The sites were selected for various reasons, but all three of them are within craters and equatorial latitudes.

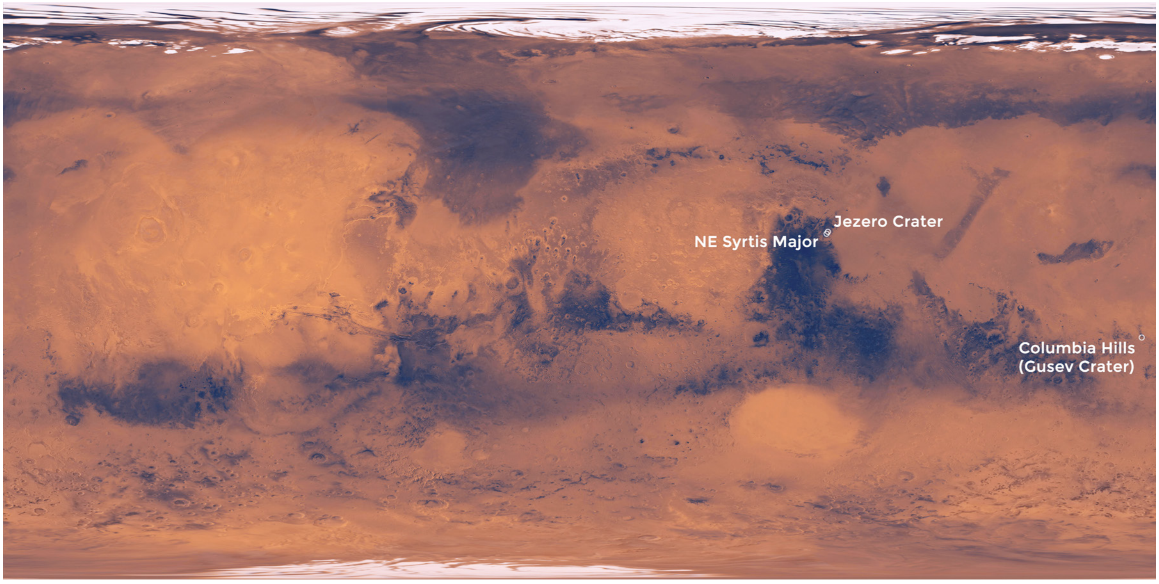


Figure 23. Final three landing site possibilities for the 2020 rover. The landing sites are all within a flat area and around the equator (NASA, n.d.).

- **Jezero Crater:** is a place where water once flowed, then dried up and went wet again which is scientifically interesting to understand the geology of the planet.
- **Columbia Hills, Gusev Crater:** home to Mars rover Spirit, which found evidence of hot springs flowing there.
- **NE Syrtis:** due to its volcanic activity, the place was once warm which caused ice to melt to create hot springs (NASA, n.d.).

However, these landing sites are selected for the rover 2020 mission and are thus not selected for a manned mission. Manned missions are usually planned to land near rover landing sites as site recognition and analysis need to be done before landing a crew. This paper focuses on one of these three landing sites: Jezero Crater. As the landing site has been determined, a rough plan of the site is drawn to determine the location of the habitat as well as the proximity of the powerplant and the distance between the habitat and the cargo landers and MAV.

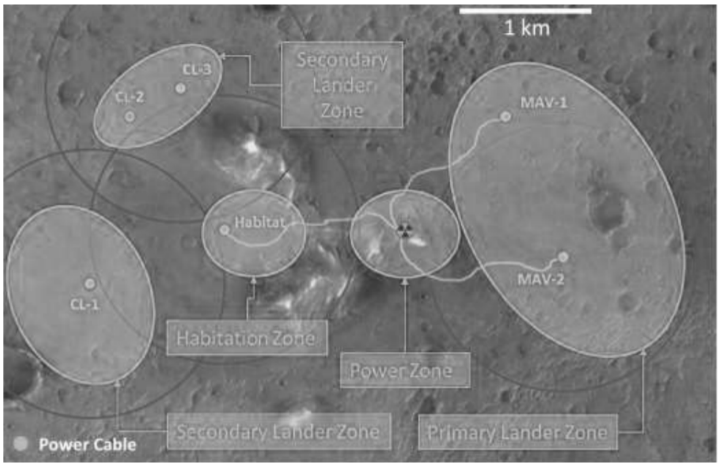


Figure 24. Plan for the Jezero Crater landing zone where the habitation zone is shielded from the power zone by natural landscape (hills within the crater) which are situated on the North East of the crater (NASA, 2017).

6.2 Technology Readiness Levels

The second step of building a habitat is to define the technology that is going to be sent onto the location. This is determined by the Technology Readiness Levels (TRLs) which scales from 1 to 9 with 9 being the most mature technology. The first four levels are the design steps, level five and six are the simulation steps and level seven through nine is when the design is assessed in a real world situation in an analogue environment. The criteria of the TRL table are slightly different for each company, but NASA and ESA have roughly the same criteria (Mankins, 1995) and those are the ones that are used during this research. The criteria are described in figure 25. 51

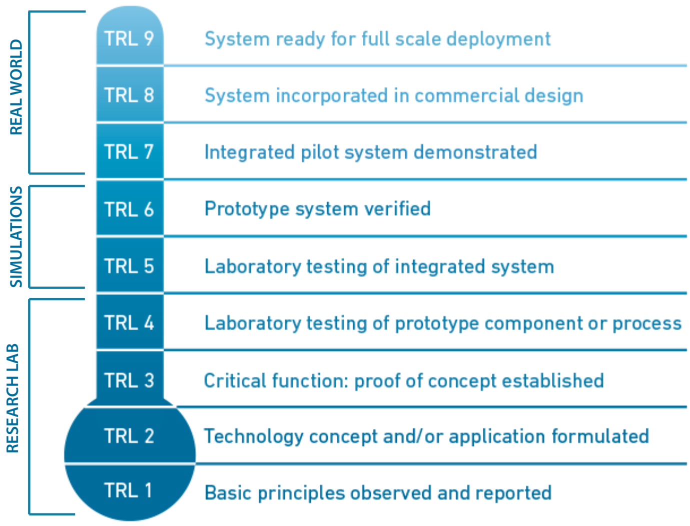


Figure 25. Technology Readiness Level's (TRL) as designed by NASA with the first four levels being design and research, levels five and six are simulations and the last three levels are real world tests.

Häuplik-Meusburger and Bannova (2016) state that the habitat is also assessed by classes ranging from Class I to Class III depending on the TRL and time.
Class I is a pre-integrated hard shell module.
Class II is a prefabricated module which is assembled at the destination.
Class III is an ISRU derived structure with integrated Earth components.
Most of the Martian habitat designs are ranging from class II to III with a strong emphasis on the latter option.

Other sources (Wilkinson, 2016) also indicate that the classes could go up to V where Class IV would be a module built only with local materials and with Class V being that both the module and process are using ISRU and are thus completely Earth independent.

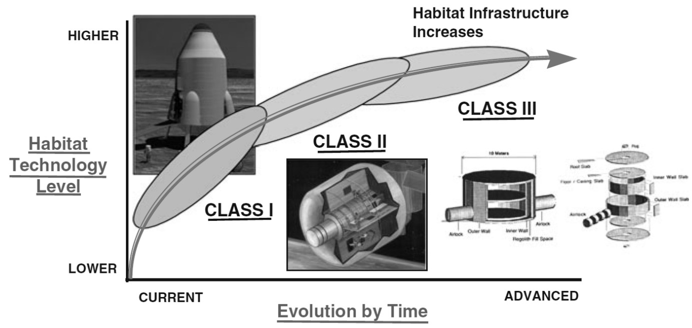


Figure 26. Habitat classification (Häuplik-Meusburger and Bannova, 2016, p. 231).

6.3 Design criteria

Building in space is different from Building on Earth, although the core concept stays the same: a building offers protection from the environment to its inhabitants. As is explained in the previous sections, the environment on Mars is different, and much harsher to us than the environment on our own planet. In the book *Space Architecture Education for Engineers and Architects* precise criteria are given to design habitats in space. The design phase of space architecture projects is related to the first four levels of the TRL.

6.3.1 Structural systems

Habitats in microgravity have to be pressurized, therefore Häuplik-Meusburger & Bannova (2016) described the following criteria:

- Moderate temperatures are provided for the crew inside the habitat
- Materials are selected on low outgassing
- Technical systems have minimal noise and vibration influence
- Materials and structure are to be fire and smoke proof
- Redundancy is vital in space

The system dealing with the physiological needs of the crew (air to breathe, pressure, temperature, humidity, etc.) is called the ECLSS (Environment Control and Life Support Systems) in aerospace engineering. This system is extremely complex and is used in different manned missions such as in the ISS. The ECLSS uses, for example, ISRU to provide O_2 from the Martian CO_2 and recuperate water from urine and cabin humidity (Genta, 2016). Main structural systems for space architecture can be divided in four categories: Pre-fabricated, Inflatable, hybrid and made by additive manufacturing (AM). Table 12 explains each category in more detail.

Construction methods/examples	Characteristics
Pre-fabricated Almost all realized space elements (Skylab, Mir, and ISS modules)	Design: standard, simple[a] to design Launch: many (1 for each module) Operation: immediate operational capabilities Installation: easy pre-integration of equipment and utility systems, can be installed and checked prior to launch Materials: have been demonstrated, good structural integrity and reliability Engineering: easy integration of windows Constraints: habitable volume of internal capacity increased only by adding modules
Inflatables (Bigelow's Genesis I and II, BEAM)	Design: system has been demonstrated in space Launch: can be compactly packaged Installation: can afford some pre-integration Materials: multi-layered envelope, each layer with special features Architecture: larger habitable volume on site; not divided into smaller volumes
Hybrid	Design: inflatable and conventional elements are combined Materials: combination of hard and soft elements/combination of prefabricated and in-situ-produced materials Installation: pre-integration of utilities and equipment is partly possible Architecture: larger habitable volume and/or optimized habitability features
Emerging technologies	3D printing methods; active magnetic radiation shielding (electromagnetic interference (EMI) and radio frequency interference (RFI) Shielding); nanomaterials for radiation protection; biological protection through the use of new therapeutic gases; etc.

Table 12. The four different structural techniques for habitat in outer space: pre-fabricated, inflatables, hybrid and emerging technologies (mostly AM) (Häuplik-Meusburger & Bannova, 2016, p.178).

Not only is the structure important but structural openings are potential dangers for air leakage and a target for micro meteorites and should thus be minimalized.

Another structural design aspect is radiation shielding where the crew should be protected from radiation hazards as well as micrometeoroids following the “As Low As Reasonable Achievable” (ALARA) principle. As radiation is one of the most dangerous hazards in space, effective shielding using mass is required. Two options are available, one is creating mass on the surface and the other, preferable, one is to assume a cave habitat (Häuplik-Meusburger & Bannova, 2016).

Available with current technologies and potential ISRU applications	Emerging technologies
Water shelters: deployable and permanent	MF (Magnetic Field) shielding using superconducting magnets
Regolith	ION shielding
Polyethylene	Nanotubes (hydrophobic or hydrophilic)
Natural landscape	Lava tubes (would require advanced technologies)

Table 13. Different radiation shielding techniques (Häuplik-Meusburger & Bannova, 2016, p.112).

Though, as Mars has a (thin) atmosphere, micrometeoroids shouldn’t be a great problem as the particles will ignite in the atmosphere before touching the Martian surface. The protection against radiation is still a relatively new technique but it will have a great impact on the mission. A great amount of developing techniques is proposed and each can be applied in different situations.

6.3.2 Habitation concepts

Häuplik-Meusburger and Bannova (2016) describe the following design parameters based on the 1996 design parameters for orbital, planetary and mobile habitats from Cohen.

Design parameter	Orbital habitat	Planetary habitat	Mobile habitat
Radiation shielding	Water is possible, but must be launched from Earth	In situ resources can be used for radiation shielding (Lunar and Martian regolith). It can be attached externally to the habitat or elements can be printed	Mass of shielding material is relevant
Pressure ports	Ports can be at distal axial ends	Ports with dust control are necessary	Ports with dust control are necessary
EVA airlock	May incorporate an airlock and zero gravity optimized suits	Can be landed separately and assembled on the surface	Inflatable airlock is a possibility
Countermeasures against micro gravity	Diverse types of exercise equipment required, countermeasures such as a small diameter, human-powered centrifuge	Less important in the 0.38G on Mars and 0.6G on the Moon, more spatial solutions are possible (on the surface). Exercise equipment needed	Less important for mobile habitat if mission duration is limited
Gravity orientation	Has to be optimized for 0G operations	Has to be optimized for partial G operations	Has to be optimized for partial G operations
Life support	Physical/chemical closed loop system with possible plant-growth unit	Physical/chemical system that includes local resources with CELSS component. Water can be extracted from the Mars CO_2 atmosphere through the Sabatier process. A large greenhouse is possible	Physical/chemical systems that can be connected to the ‘main’ habitation system. A small portable greenhouse is optional
Power systems	Solar panels, batteries	Solarfields with solar panels, batteries, possibly nuclear power generators	Solar cells and batteries (volume and mass)
Other	Interior orientation and navigation cues	Dust control and clean rooms	Mobility system, motor, and mechanism

Table 14. Different habitat concepts based on their purpose: orbital habitat, planetary habitat and mobile habitat. The planetary habitat criteria are applicable in the case of this research (Häuplik-Meusburger & Bannova, 2016, p.194).

However, Apollo missions and psychological studies (Häuplik-Meusburger & Bannova, 2016 & Genta, 2016) show that the crew should not only “survive” the environment but that the habitat should be designed for habitability. Häuplik-Meusburger and Bannova describe a habitat as:

“A habitat is a critical element of human space flight [...]. It is the place where people live and work, it protects them from hazards of the environment, and it enables the crew to perform their tasks and operations.”(Häuplik-Meusburger & Bannova, 2016, p. 192).

Especially for long missions of a year or over, the psychological need of the crew increases over the physiological needs. To design for habitability, the crew should have a sense of where they are by having a visual contact with the exterior environment whether direct or via screens. The plan and routing of the habitat should also be flexible to allow the crew to personalise the environment to their liking. A sense of control over lighting, interior and temperature positively influence the work efficiency of the crew. Another design aspect is that private, public and semi-public spaces should be designed thoroughly. It is necessary for each crew member to have his/her own quarter where he/she can be alone to communicate with their relatives on Earth or read a book; in summary, to be able to retreat. However, to avoid having the crew growing apart from each other, there should also be a social gathering space where the crew can meet without it being a lab or workspace. These two different activities of working and living should be as much separated as possible as well (Genta, 2016). These aspects are vital for the wellbeing of the crew and thus the mission’s success.

6.3.3 Modules

In space, habitats should be built along with an emergency system or expansion possibility which often translates itself in modules which can be attached to each other.
The book *Space Architecture Education for Engineers and Architects*, gives a large overview on different typologies of space habitats. The following drawings (figure 27) are just a few examples on how these modules could be designed with as main criteria redundancy ,microgravity and the modularity of the elements (Häuplik-Meusburger & Bannova, 2016). The modules are connected to the outdoor environment via a hatch which allows for EVA (Extra Vehicular Activities) either with a spacesuit or a pressurized or unpressurized rover (Genta, 2016). These hatches can be combined with other (future) modules to form (possible) connecting corridors.

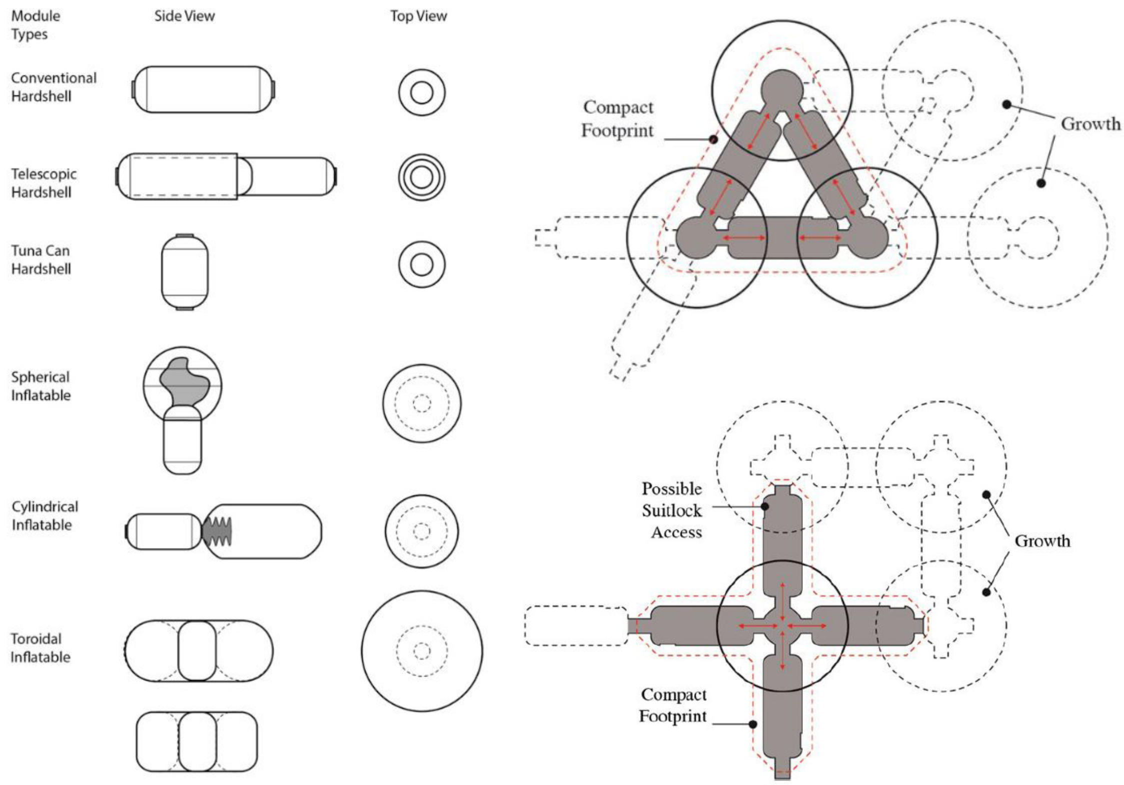


Figure 27. Different habitat typology where modules provides redundancy and possibility for expansion (Häuplik-Meusburger & Bannova, 2016, p.207 & 209).

6.4 Mission Materialisation

As mentioned in the previous sections, the use of ISRU has an important role in building a habitat with low impact upon the planet. However, ISRU is limiting and sometimes manmade materials are needed for different purposes. Therefore, mission recyclables can be used as well to build a habitat. Mission recyclables are materials (mostly brought in from Earth) that are only needed for a specific task (e.g. Entry, Descend and Landing: EDL). After use, they are often discarded, thus re-using them for architectural purposes would help reducing the mission's waste. A list of mission recyclables (as listed by NASA for the Centennial Challenge) is inventoried in table 15.

NAME	EXPLANATION	**DENSITY**	**MELTING POINT**
		(g/cm³)	(°C)
LDPE	Low density polyethylene # 4	0,910-0,940	105 - 115
HDPE	High density polyethylene # 2	0,93 - 0,97	120 - 180
PET	polyethylene terephthalate # 1	1.38	260
NY	Nylon #7	1.15	220 - 265
PP	Polypropylene # 5	0,895 - 0,92	160
AF	Aluminium foil	2.7	660
PS	polystyrene # 6	0,96 - 1,04	240
VY	vinyl # 3	0,920 - 0,924	100 - 260

Table 15. Mission recyclables. Different type of polymers which are brought by rockets and not used after EDL.

But these are just polymers, and most probably, a habitat will also have organic materials on site such as a farm and food and thus organic waste which could also be added to the list of mission recyclables. Here, strategies to try to close the loop on material flows could be applied to counteract the material scarcity of the environment.

6.5 Mission Assessment Strategies

Following the design phase, an assessment phase is needed to correlate with TRL's five to nine. These assessments are usually done making use of simulation (model, VR...) and mock up models. Depending on the technology to be assessed and on the type of tests needed, locations with different characteristics are chosen. Habitats are sometimes tested within a facility like the ESA/ESTEC facility in Noordwijk (The Netherlands) where structures can be tested, among others, under micro gravity and extreme temperatures. Most of the habitats though are tested in analogue environments which are isolated, confined and extreme (ICE) environments where each different ICE location has its strength and limitations.

Some ICE locations are:
- Polar research Stations (Arctic and Antarctic)
- Underwater Analog Habitats
- Desert research Stations (e.g. Atacama Desert, Chile)

Another way to assess a new technology is to analyse existing technologies and design ideas of previous habitats, whether they have been built or not (Häuplik-Meusburger & Bannova, 2016).

6.6 Conclusions

The first step of building in space, much like on Earth, is to define the location of the building. At this stage of the research it is decided to build on one of the three Martian sites selected by NASA: Jezero Crater. The next step in building a habitat is to define the design criteria which are based on the mission design and space architecture literature and are summarized in table 16. These criteria will help design a habitat as well as assess it at the end of the research.

	Themes		Criteria
1.0	**Landing site**	1.1	Safe distance from pre-deployed structures
		1.2	Relatively smooth and flat terrain
		1.3	Close proximity to POI
		1.4	Ease of transportation to and from landing site
		1.5	Constant temperature through day and night
		1.6	H_2O present near the landing site
2.0	**Structural systems**	2.1	Moderate temperatures are provided for the crew inside the habitat (short sleeve environment)
		2.2	Materials are selected in on low outgassing
		2.3	Technical systems have minimal noise and vibration influence
		2.4	Materials and structure are to be fire and smoke proof
		2.5	Redundancy
		2.6	Minimal structural openings
		2.7	Radiation shielding following ALARA
		2.8	Resistance against meteoroids following ALARA
		2.9	Resistance against perchlorates following ALARA
		2.10	Mass: 130 mT
		2.11	Volume: max diameter: 10m and max height: 31m
3.0	**Typology**	3.1	Pressure ports with dust control
		3.2	EVA airlocks
		3.3	Gravity orientation
		3.4	Energy harvesting near or within the habitat
		3.5	Possible expansion
		3.6	Habitat for 6 crew members
4.0	**Sustainabi lity**	4.1	use of ISRU
		4.2	Class IV technology
		4.3	low impact on Mars upon departure (waste)
		4.4	Re-use of organic matters
5.0	**Life support**	5.1	Physical/chemical systems to provide O2
		5.2	Extraction system for H2O
		5.3	Greenhouse
6.0	**Psychologi cal**	6.1	visual contact with exterior environment
		6.2	Flexible plan, furniture, lighting, temperature
		6.3	Separating work and leisure, private and public
		6.4	Private crew quarters for each member

	Themes		Criteria
7.0	**Assessment**	7.1	TRL 1
		7.2	TRL 2
		7.3	TRL 3
		7.4	TRL 4
		7.5	TRL 5
		7.6	TRL 6
		7.7	TRL 7
		7.8	TRL 8
		7.9	TRL 9
8.0	**Material**	8.1	ISRU at least 70%
		8.2	recyclables
		8.3	thickness of at least 325 mm of H_2O
9.0	**Process**	9.1	semi-autonomous
		9.2	lightweight machinery
		9.3	min. amount of machines needed > machinery is multipurpose
		9.4	time: should not exceed 17 months
		9.5	power: max 40 kW

Table 16. Programme of requirements made based on the literature study. It is divided in requirements specific for the habitat itself but also specific to the structure, the materials and process of the habitat.

7. References

The NASA Centennial challenge enabled architecture and engineering firms to design habitats for Mars and an increase in space architecture is noticed over the past few years. A few recent examples are explained below. It is beyond saying that these design have not been built on Mars (yet).

7.1 Mars Habitat

Figure 28. The Mars Habitat by GAMMA Team (Wilkinson, Mosil, Dierckx, Gallou, & Kestelier, 2016).

The Mars Habitat is one of the entries for the NASA Centennial challenge and proposes a habitat created by autonomous additive swarm construction. It proposes a hybrid habitat which is composed of different pre-fab inflated modules. These modules are connected to each other and have different functions but they are designed to still be able to work individually if needed. The inflated modules are then covered by an in situ regolith layer of 1,5m above the sleep/work modules and 2,5m above the communal space modules to protect the crew against radiation and extreme temperatures. The regolith shield is built with three types of robots having each a different specialisation: excavation, transportation and melting. To maximize crew protection, the modules are entirely covered in regolith with the exception of the entrances. This doesn't allow view or daylight to come through. Daylight is replaced by artificial circadian rhythm lighting (Wilkinson, Mosil, Dierckx, Gallou, & Kestelier, 2016).

Advantage(s):
- Three simple robots which distributes the risks over three objects.
- Structure which protects the structural holes and allow the robots to finish the construction.

Disadvantage(s):
- High energy demand to melt the regolith
- Different robots are needed thus higher transportation costs.
- No visual connection with exterior
- No natural daylight
- Regolith contains perchlorates

7.2 LAVAHIVE

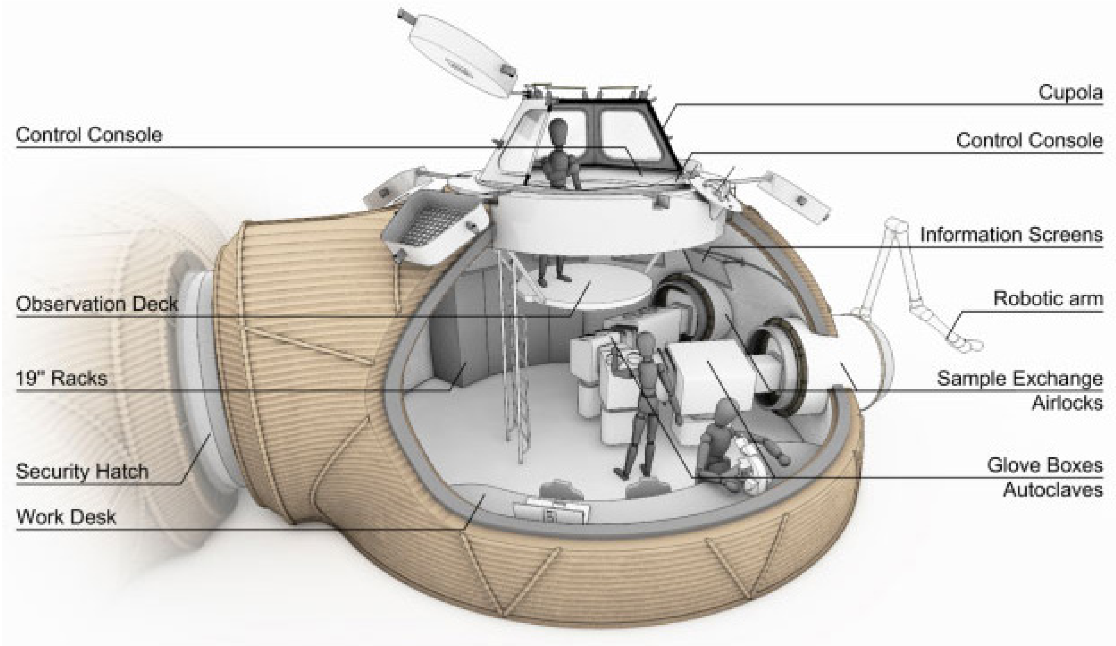


Figure 29. LAVAHIVE by Liquifer Systems group (Liquifer System Group, 2017).

LavaHive won the third prize in the NASA Centennial Competition. The concept behind this design is to create a modular additive manufactured Martian habitat using a novel "lava casting" construction technique as well as using recycled space craft materials. The habitat is divided into modules which are first "printed" by sintering the regolith which means by heating up the regolith to create glass. The prints are supported by loose regolith which can be removed at a later stage and replaced by a pressurized membrane (Liquifer System Group, 2017).

Advantage(s):	- Low energy is required as it uses direct sunlight to sinter the regolith
Disadvantage(s):	- High energy demand to melt the regolith - No visual connection with exterior - No natural daylight - Regolith contains perchlorates

7.3 Mars Ice House

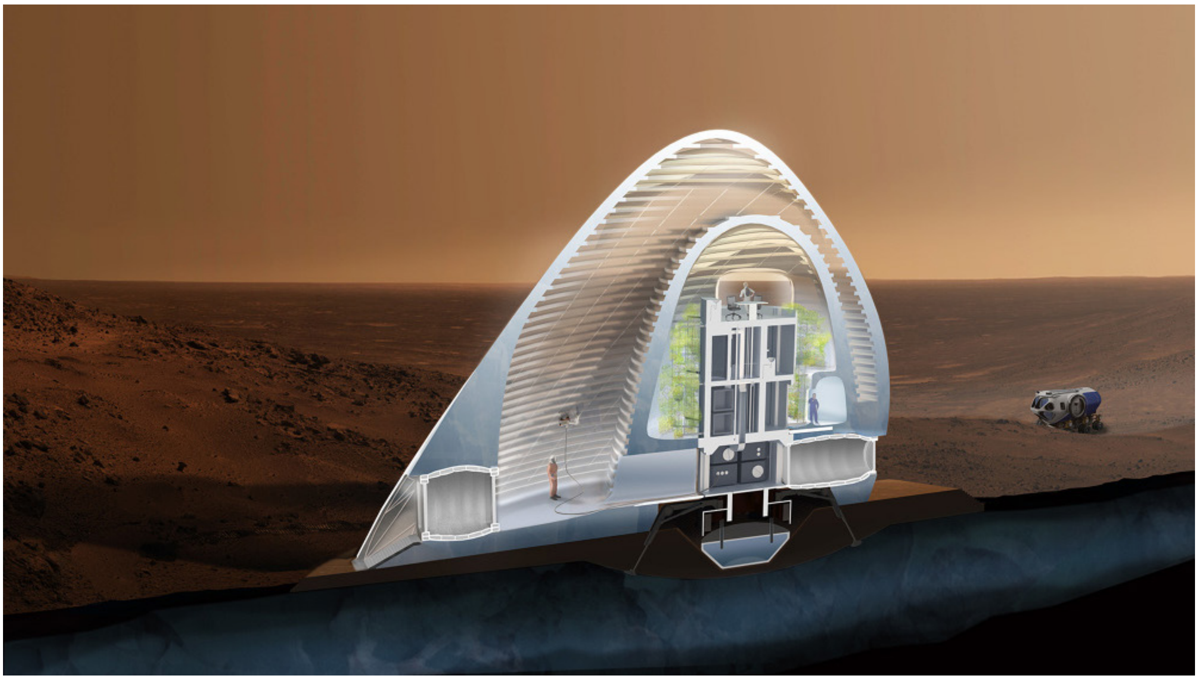


Figure 30. Mars Ice House by Clouds AO (Morris, at al., 2016).

Mars Ice House is the entry to the Centennial Challenge that won the first prize. The design team proposes to build a hybrid structure out of ground ice. Just like the other references, the capsules first lands and deploys a pressurized membrane. The concept behind building with ice is that ice is transparent but is also a great radiation shield as H_2O contains lots of hydrogen; on top of that ice is largely available in the subsurface of the Red Planet. As the habitat is made out of ice, a specific location is needed where: ice is abundant in the shallow ground (within 20cm – 1m), surface temperatures remain below the freezing point and still with maximum solar exposure (solar panels).
In this design proposal the membrane is made out of translucent Ethylene tetrafluoroethylene (ETFE) and reinforced with Dyneema strands. ETFE is a high performance plastic with high corrosion and temperature fluctuation resistance. This membrane prevents the ice from sublimating; the whole process makes use of phase change in H_2O. The subsurface ice would be collected in the vapour form through solar radiation which allows the H_2O to be filtered. After it has been collected, the water is then printed using "minibuilders": robots connected mechanically to water storage and which use vacuum gripping to hold onto the ceiling or roof construction while using additive manufacturing to build the structure. The materials used to create the structure are: water, fibre reinforcement and aerogel (used for insulation). The fibre reinforcement is still experimental and two main fibres have been considered: pykrete (ice reinforced with wood pulp) which has proven to have great tensile strength and a fibrous silica additive which, on top of improving the tensile strength of the structure, still allows daylight through (Morris, at al., 2016).

Advantage(s):	- One printing robot - Transparent structure - Great radiation shielding
Disadvantage(s):	- Isolation is needed to have a warm (+20˚C) interior and make sure the ice construction doesn't melt. Right now the design uses translucent ETFE sheets. - Ice has the tendency to sublimate thus precautions must be taken which are difficult to test on Earth.

7.4 Mars Ice Home

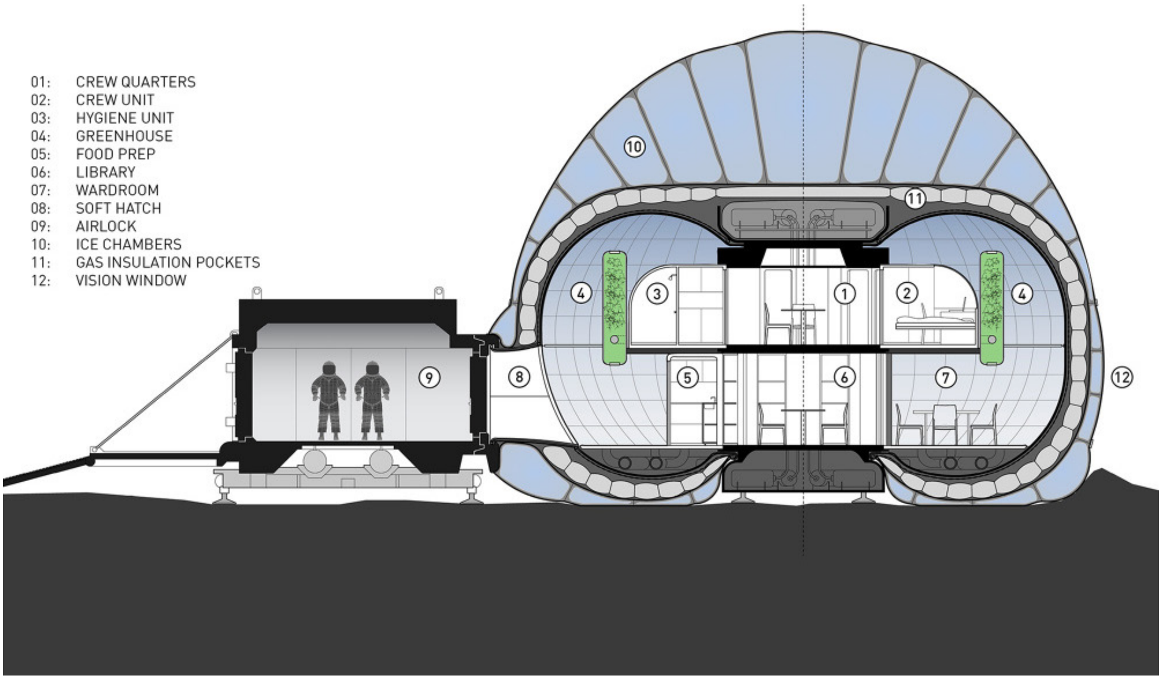


Figure 31. Mars Ice Home by NASA/Cloud AO (Clouds AO, 2017).

The Mars Ice Home is the development of the Mars Ice House concept. The overall shape of the habitat is due to its location, indeed at such latitudes solar radiation is more intense from above which is why the top of the habitat has an extra insulation pad. In this advanced concept, the ice isn't printed between ETFE membranes anymore but put directly into membrane pockets (Clouds AO, 2017).

Advantage(s):	- Transparent structure - Great radiation shielding
Disadvantage(s):	- Ice has the tendency to sublimate thus precautions must be taken which are difficult to test on Earth.

7.5 NASA Water walls

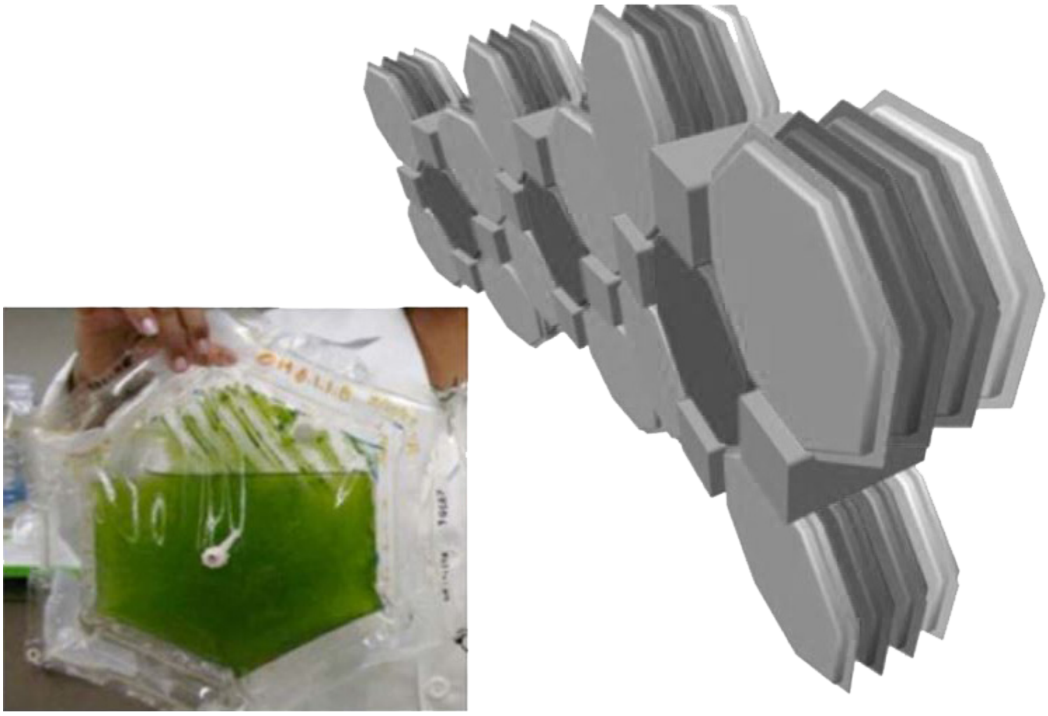


Figure 32. Water wall by NASA (Häuplik-Meusburger & Bannova, 2016, p.215).

The water wall is a concept applying passive Forward Osmosis (FO) technology. It isn't a whole habitat but a non-structural wall which shields from radiations as well as producing O_2 out of CO_2, treats human waste (grey water and urine) and allows for defined climate control. The walls are made out of plastic bags filled with liquid and algae (Häuplik-Meusburger & Bannova, 2016).

Advantage(s): - Passive system: no life threatening mechanical failure
- Combines different function in one

Disadvantage(s): - Requires a pressurized environment

7.6 Conclusions of the references

A few conclusions can be drawn from this reference study. The first is that most habitats are composed of two structures: a prefab pressurized (often inflatable) core with an ISRU outer shell which protects the core from the harsh environment (high temperature fluctuations, radiation, meterorites, etc..).

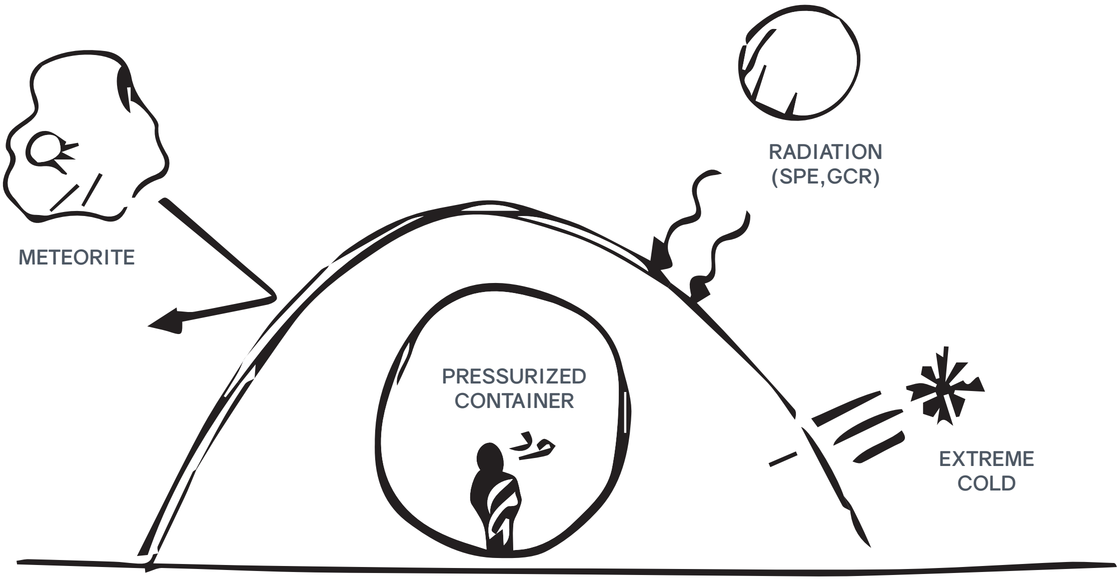


Figure 33. Typical design for a habitat. Two main structures: one pressurized inner core and an ISRU outer shell which protects the inner core from extreme temperatures, falling meteorites and radiation.

The focus of this research is on the outer shell and ISRU technologies as most prefab pressurized environments are already in use for different applications like the ISS. The materialisation of this outer shell is what usually distinguishes the different habitat designs from one another. The main materials used are regolith and ice as they are both excellent radiations shielding materials. However, regolith contains perchlorates which can be harmful for human health. Moreover, often large and multifunctional machinery is required to build the habitat out of this material. Regolith as building material isn't discarded right away but the first choice, for now, for the outer shell of the habitat is building with ice as ice can also be translucent and thus allows natural light to flow through the structure without needing structural cuts. Ice also requires significantly less energy to process. In the next heading, the materialisation is further researched.

8. Conclusion part A

Part A is a summary of a literature study on space travel, the possible planets where habitats may be built as well as on mission design and architecture in space. This literature study on Mars forms the base of this research thesis. An analysis of precedents is also present within this part.

This chapter (partly) provides answers to the following sub-questions:

- What is the programme of requirements (POR) for a habitat on Mars?
- What potential building elements are found on Mars?

8.1 What is the programme of requirements (POR) for a habitat on Mars?

The following POR is based on the literature study for the habitat as well as for the structure, building material and processing method. This list will assess if the design complies to the research question.

	THEMES	NUMBER	CRITERIA
1.0	**Landing site**	1.1	Safe distance from pre-deployed structures
		1.2	Relatively smooth and flat terrain
		1.3	Close proximity to POI
		1.4	Ease of transportation to and from landing site
		1.5	Constant temperature through day and night
		1.6	H_2O present near the landing site
2.0	**Structural systems**	2.1	Moderate temperatures are provided for the crew inside the habitat (short sleeve environment)
		2.2	Materials are selected in on low outgassing
		2.3	Technical systems have minimal noise and vibration influence
		2.4	Materials and structure are to be fire and smoke proof
		2.5	Redundancy
		2.6	Minimal structural openings
		2.7	Radiation shielding following ALARA
		2.8	Resistance against meteoroids following ALARA
		2.9	Resistance against perchlorates following ALARA
		2.10	Mass: 130 mT
		2.11	Volume: max diameter: 10m and max height: 31m
3.0	**Typology**	3.1	Pressure ports with dust control
		3.2	EVA airlocks
		3.3	Gravity orientation
		3.4	Energy harvesting near or within the habitat
		3.5	Possible expansion
		3.6	Habitat for 6 crew members
4.0	**Sustainability**	4.1	use of ISRU
		4.2	Class IV technology
		4.3	low impact on Mars upon departure (waste)
		4.4	Re-use of organic matters
5.0	**Life support**	5.1	Physical/chemical systems to provide O2
		5.2	Extraction system for H2O
		5.3	Greenhouse
6.0	**Psychological**	6.1	visual contact with exterior environment
		6.2	Flexible plan, furniture, lighting, temperature
		6.3	Separating work and leisure, private and public
		6.4	Private crew quarters for each member

	THEMES	NUMBER	CRITERIA
7.0	**Assessment**	7.1	TRL 1
		7.2	TRL 2
		7.3	TRL 3
		7.4	TRL 4
		7.5	TRL 5
		7.6	TRL 6
		7.7	TRL 7
		7.8	TRL 8
		7.9	TRL 9
8.0	**Material**	8.1	ISRU at least 70%
		8.2	recyclables
		8.3	thickness of at least 325 mm of H_2O
9.0	**Process**	9.1	semi-autonomous
		9.2	lightweight machinery
		9.3	min. amount of machines needed > machinery is multipurpose
		9.4	time: should not exceed 17 months
		9.5	power: max 40 kW

Table 17. Programme of requirements made based on the literature study. It is divided in requirements specific for the habitat itself but also specific to the structure, the materials and process of the habitat.

8.2 What potential building elements are found on Mars?

The following potential building elements are found on Mars:

MARTIAN SOIL	NAME	EXPLANATION
NASA LIST	CBI	crushed basaltic igneous rock (SiO_2 weight percent less than or equal to 57)
	BSR	basaltic sedimentary rocks (talus, alluvium with very little alteration/weathering, or mine tailings
	GSS	gypsum sand and siliceous sedimentary rocks (e.g., sand box sand, mudstone)
	CSR	carbonaceous sedimentary rocks (e.g. limestone, dolomite)
	IRS	igneous rocks with SiO_2 weight percent greater than 57 (e.g. granite)
	MR	Metamorphic rocks (e.g. slate)
NOT ON NASA LIST	H_2O	ice found in depth
	CO_2 ice	CO_2 ice (water) found on surface of mars (contains salts)
	ClO_4^-	Perchlorate: toxic for human health/ resource

Table 18. Materials available on Mars.

However, when a manned mission lands on Mars, recyclables will also be available and should also be taken into account as potential building elements. The following elements can be used:

NAME	EXPLANATION	DENSITY	MELTING POINT
		(g/cm³)	(°C)
LDPE	Low density polyethylene # 4	0,910-0,940	105 - 115
HDPE	High density polyethylene # 2	0,93 - 0,97	120 - 180
PET	polyethylene terephthalate # 1	1.38	260
NY	Nylon #7	1.15	220 - 265
PP	Polypropylene # 5	0,895 - 0,92	160
AF	Aluminium foil	2.7	660
PS	polystyrene # 6	0,96 - 1,04	240
VY	vinyl # 3	0,920 - 0,924	100 - 260

Table 19. Mission recyclables by NASA.

Bibliography – PART A

Brown, G. M. (n.d.). Lunar Science- a post-Apollo view by S.R. Taylor: : Mineralogical Magazine 40(314) 1976 p.654-656.

Clarke, A. C. (1951). The exploration of space. New York: Harper.

Clouds AO (2017). Mars Ice Home. Retrieved on November 25, 2017 from http://www.cloudsao.com/MARS-ICE-HOME

Davila, A., Willson, D., Coates, J., & McKay, C. (2013). Perchlorates on Mars: a chemical hazard and a resource for humans. International Journal of Astrobiology, 1-5.

Durante, M., & Cucinotta, F. A. (2011). Physical basis of radiation protection in space travel. Reviews of Modern Physics,83(4), 1245-1281. doi:10.1103/revmodphys.83.1245

Fischer, E., Martínez, G. M., Elliott, H. M., & Rennó, N. O. (2014). Experimental evidence for the formation of liquid saline water on Mars. Geophysical Research Letters,41(13), 4456-4462. doi:10.1002/2014gl060302

Foley, C.N. et al. (2008). Martian Surface Chemistry: APXS Results from the Pathfinder Landing Site, in The Martian Surface: Composition, Mineralogy, and Physical Properties, J.F. Bell III, Ed. Cambridge University Press: Cambridge, UK, 42-43, Table 3.1.

Genta, G. (2016). Next Stop Mars: The Why, How, and When of Human Missions. Springer.

Goudge, T.A., Mustard, J.F., Head, J.W., Fassett, C.I. Wiseman, S.M. (2015). Assessing the mineralogy of the watershed and fan deposits of the Jezero crater paleolake system, Mars. Journal of Geophysical Research: Planets, 120, 775-808, doi:10.1002/2014JE004782.

Häuplik-Meusburger, S., & Bannova, O. (2016). Space Architecture Education for Engineers and Architects: designing and planning beyond earth. Cham: Springer.

Hodgkinson, J. M. (2000). Mechanical testing of advanced fibre composites. Boca Raton, FL: CRC Press.

Liquifer System Group (2017). LavaHive. Retrieved on November 25, 2017 from http://www.liquifer.com/lavahive/

Mankins, John C. (1995). Technology Readiness Levels: A White Paper. NASA, Office of Space Access and Technology, Advanced Concepts Office.

Martínez, G. M., & Renno, N. O. (2013). Water and Brines on Mars: Current Evidence and Implications for MSL. Space Science Reviews,175(1-4), 29-51. doi:10.1007/s11214-012-9956-3

Mars Climate Database (2017). Mars Climate Database v5.2: The Web Interface. Retrieved on November 25, 2017 from http://www-mars.lmd.jussieu.fr/mcd_python/

Morris, M., Ciardullo, C., Lents, K., Montes, J., Rudakevych, O., Sono, M., Yashar, M. (2016). Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O. Aiaa Space 2016. doi:10.2514/6.2016-5528

Musk, E. (n.d.). Making Humans a Multiplanetary Species. Retrieved June 6, 2017, from http://www.spacex.com/mars

NASA, & Bradley University. (n.d.). NASA's 3D-Printed Habitat Challenge. Retrieved June 8, 2017, from http://bradley.edu/challenge/

NASA. (2017, March 27). Journey to Mars Overview. Retrieved June 6, 2017, from https://www.nasa.gov/content/journey-to-mars-overview

NASA. (n.d.). Picking a Landing Site for NASA's Mars 2020 Rover. Retrieved June 6, 2017, from https://mars.nasa.gov/mars2020/mission/timeline/prelaunch/landing-site-selection/

NASA. (2015a). NASA Mars Rover's Weather Data Bolster Case for Brine. Retrieved June 6, 2017, from https://www.nasa.gov/jpl/msl/nasa-mars-rovers-weather-data-bolster-case-for-brine

NASA. (2015b). NASA confirms evidence that liquid water flows on today's Mars. Retrieved June 6, 2017, from https://phys.org/news/2015-09-evidence-brine-mars.html

NASA. (2009). Human Exploration of Mars: Design Reference Architecture 5.0. Texas.

NASA/JPL. (n.d.). Mars, Water and Life. Retrieved June 6, 2017, from https://mars.jpl.nasa.gov/msp98/why.html

National Geographic. (2015, January 26). The curious life of a Mars Rover. Retrieved June 6, 2017, from https://www.youtube.com/watch?v=7zpojhD4hpI&feature=youtu.be

Sievert. (2017, November 13). In Wikipedia. Retrieved November 19, 2017, from https://en.wikipedia.org/wiki/Sievert

Smith, P. (n.d.). Mars/Earth Comparison Table. Retrieved June 6, 2017, from http://phoenix.lpl.arizona.edu/mars111.php

Wilkinson, S., Mosil, J., Dierckx, J., Gallou, I., & Kestelier, X., De. (2016). Concept Design of an Outpost for Mars using Autonomous Additive Swarm Construction. Specialist Modelling Group: Foster Partners.

Other consulted documents:

Hecht, M.H. (2002). Metastability of Liquid Water on Mars. Icarus, (156), 373-386.

Ögüt, N.M. (2017). Building on Mars: construction of a radiation shielding Martian habitat with in-situ materials via suitable construction methodologies. Graduation thesis at TU Delft Architecture and the Built Environment faculty.

Van der Werf, C. (2017). Building on Mars: an evolvable design strategy for the architectural engineer. Graduation thesis at TU Delft Architecture and the Built Environment faculty.

PART B

SUSTAINABILITY

"We cannot allow sustainability to be reduced to the level of fashion or to be measured exclusively in terms of technological standards. Sustainability is a socio-political responsibility which must address the new challenges facing humanity [...]"

Contal, Revedin, Albrecht & Brusegan, (2011). *Sustainable design II: Towards a new ethics for architecture and the city*, p. 11. Arles: Actes Sud.

Part B is a summary of a literature study on sustainability in relation to building a habitat on Mars. The outcome of this study is a definition of sustainability for Mars and some criteria which are applied during the design phase of this research.

This chapter provides an answer to the following sub-question:

- How to define sustainability on Mars?

9. Defining sustainability

After analysing the conditions under which building on Mars has to take place, sustainable building on Mars should be discussed. The broad definition mentioned in the introduction 1.1.2 of sustainability is “to be able to sustain”. Hence it has two implications in the case of building on Mars. First, as we are sending technology from Earth to Mars, it has an impact on our planet Earth and secondly it has an impact on the host planet Mars. Thus sustainable building in space has to be sustainable on Earth as well as on the host object, in this case: Mars.

Sustainability has already been defined on Earth and although it still is subject to discussion, most designers follow a standard. Many standards exist for the building environment like BREEAM, LEED etc. However, building a habitat on Mars is multidisciplinary and requires more than just sustainable building guidelines. Life cycle assessment (LCA) is a way to assess almost every design on the impact the whole life cycle of the design has on the environment. The LCA method starts with a Life Cycle Inventory (LCI) where an inventory of the emission of the used materials towards air, water and soil is made. The next step is to make a Life Cycle Impact Assessment (LCIA) where the inventory from the LCI is given a single value of impact. This is quite difficult to express scientifically and is therefore usually done by environmental specialists (Vögtlander, 2013).

As mentioned before, this research will focus on the materials and processes needed to build the habitat but not on the transport. It is defined that the building has to be designed to be as small and as light as possible regarding interplanetary transportation in order to reduce the cost of the mission. Therefore, the responsibility for the efficiency and sustainability of the transport itself will be left to the aerospace engineers.

10. Sustainability in Space

The impact of the habitat and the crewed mission inhabiting it on the Red Planet is analysed. A lot of instruments from Earth are already present in space and many more will be sent in the future onto, among others, the surface of Mars. These are measuring instruments, landers and rovers, solar panels, landing parachutes and airbags and possibly a habitat. This research will focus mainly on the habitat and the process of building and the impact it has on the planet. First, sustainability in relation to space travel is not a well-defined and well known subject. One of the reasons is that Space is an open terrain which belongs to everyone and no one at the same time. Therefore, the General Assembly of the United Nations created a committee in 1959 to govern the use of space for the benefit of all humanity: the Committee on the Peaceful Uses of Outer Space (COPUOS). The aims of the committee are peace, security and development. COPUOS created a set of guidelines concerning long-term sustainability of outer space activities. Those guidelines define space sustainability as follows:

"The conduct of space activities in a manner that balances the objectives of access to the exploration and use of outer space by all States and governmental and non-governmental entities only for peaceful purposes with the need to preserve the outer space environment in such a manner that takes into account the needs of current and future generations." (Clean Space, 2017)

Another party which is involved in space sustainability is ESA which created the Clean Space initiative. Clean Space shares goals with the COPUOS and it particularly tries to tackle man-made space debris.
Clean Space focusses on three steps: actively removing man-made space debris, assessment of the impact of old and new technologies and the creation of novel technologies. These three steps are depicted in figure 34.

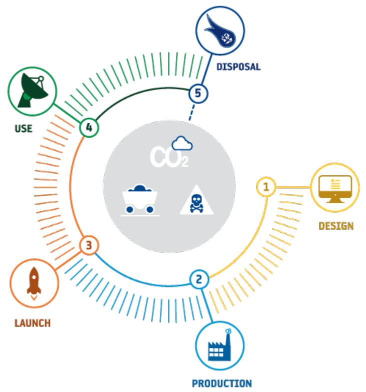


Figure 34. Proposal for a sustainable use and design of space (Clean Space, 2017).

The interesting part for this research is the eco design part which is applicable for satellites but also for other objects sent into space. The eco design methods assess the impact on CO_2, natural resources and hazard for life of every step of the process starting with the design and production phase to the launch and use phase and even on the disposal (end of life) phase.

The design is assessed following the publication of ESA on the Life Cycle Assessment (LCA) tool where guidelines are provided to reduce the impact of the different phases of the design. Following this multi criteria and multi-step analysis, the design can be assessed on its impact on Earth.

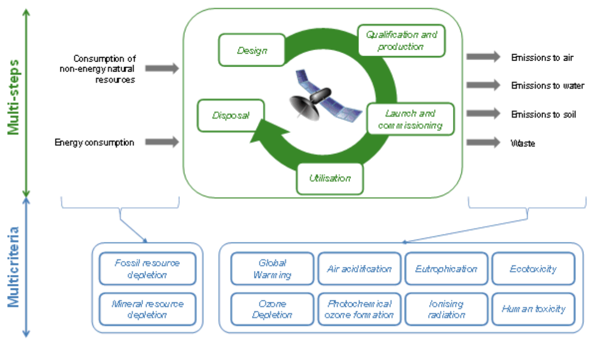


Figure 35. Life Cycle Assessment tactics of ESA (Clean Space 2017).

11. Sustainable on the surface of Mars

The two researched topics of sustainability on Earth and sustainability in Space both don't encompass the whole complexity of building a sustainable habitat on the surface of another planet. The term sustainability and the need for ecological measures on Earth became an urgency mainly due to climate change (Contal, Revedin, Albrecht & Brusegan, 2011).

Mars does not have a population (yet) and it is not currently experiencing climate change. As a matter of fact, the Red Planet was hotter and wetter some 3,6 gigayears (Gyr) ago and has therefore already experienced "climate change". It is therefore not useful to apply sustainable principles used on Earth to counteract climate change to design a sustainable habitat on Mars.
The core concept behind sustainability is "to be able to sustain". This concept is closely linked to the concept of redundancy which are both essential if a crew is sent to Mars. This crew will have to survive the harsh Martian environment having a 22 min delay in communications with Earth and a possibility for a voyage every only 26 months at best. This distance between Earth and the Martian surface is why redundancy and sustainability are not only important but are crucial for the crew's survival and the completion of the mission. Following this logic, to be able to sustain would mean being as much independent from Earth as possible, therefore allowing problems (real and potentials) to be handled in situ without any time delay. Hence being sustainable on Mars means being independent from Earth and its resources.

The use of ISRU for the design of a habitat can be divided into the five previously mentioned classes with class V indicating a complete independency from Earth. The precedent designs analysed in chapter 7 are all categorized as class III habitats: an ISRU derived structure with integrated Earth components. Each of these classes can be compared to the TRL, with the lower the class the higher the TRL. Therefore, as those two aspects need to be taken into account, the requirement set for this research is to have a habitat in between class III and IV, meaning that a class III habitat is designed with some class IV technologies which are tested in situ. This enables the class IV technology to have a higher TRL for the next Martian surface habitat as more missions will probably be sent after the first one. Combining technologies from both classes allow redundancy and possible sustainable expansion of the habitat following the principles set by Häuplik-Meusburger and Bannova (2016).

12. Requirements for the habitat.

The sustainable design requirements for a Martian habitat are linked to independency from Earth. This can be quantified by the habitat classes, with the higher the class the most independent the habitat is. This means that the sustainable goal for habitats will be to achieve a class V habitat. However, this technology isn't near being ready and this extreme sustainable standard can only be achieved in steps and by testing other classes within the Martian environment. Therefore, the requirement for this research (which is focussed on the first Martian habitat) is that the habitat is in between class III and IV. Meaning that class IV technologies are used to test their efficiency for future use but class III technology is also used as redundancy.

TRL	CLASS	DEFINITION
8-9	CLASS I	pre-integrated hard shell module.
5-8	CLASS II	prefabricated module which is assembled at the destination.
3-5	CLASS III	ISRU derived structure with integrated Earth components.
2	CLASS IV	module build only with local materials.
1	CLASS V	both the module and process are using ISRU and are completely Earth independent.

Table 20. Requirement for a sustainable habitat: between class 3 and class 4.

13. Conclusion part B

Part B is a summary of a literature study on sustainability in relation to building a habitat on Mars. The outcome of this study is a definition of sustainability for Mars and some criteria which are applied during the design phase of this research.

This chapter provides an answer to the following sub-question:

- How to define sustainability on Mars?

Sustainability on Mars means being independent from Earth for redundancy as contact with Earth is extremely limited. This can be directly related to the habitat technology classification as well as the TRL, the higher the class, the higher the Earth independency. Therefore a class V habitat is desirable. However, this research will focus on designing and testing a class IV habitat as this has not been done yet.

Bibliography – PART B

Clean Space . (2017). Clean Space, the UN and the sustainability of space activites. ESA. Retrieved from http://blogs.esa.int/cleanspace/2017/03/10/clean-space-the-un-and-the-sustainability-of-space activities/

Contal, M.-H., Revedin, J., Albrecht, B. A., & Brusegan, E. (2011). Sustainable design II: Towards a new ethics for architecture and the city. Arles: Actes Sud.

Häuplik-Meusburger, S., & Bannova, O. (2016). Space Architecture Education for Engineers and Architects: designing and planning beyond earth. Cham: Springer.

Sustainability. (n.d.). Retrieved June 6, 2017, from http://sustainability.com/

Sustainability [Def. 1]. (n.d.). In Oxford Dictionaries. Retrieved June 6, 2017, from https://en.oxforddictionaries.com/definition/sustainability.

Vögtlander, J. (2013, April). Rekenen aan duurzaamheid met de methode van de eco costs/value ratio. CostandVALUE, 14-21.

PART C

MATERIAL

"Each sample or test specimen is [...] unique, and derived data must be regarded just to it, rather than to the material in general."

Hodgkinson, J. M. (2000). Mechanical testing of advanced fibre composites. P. 5.

Part C is focussing on finding the adequate material which complies to the set requirements. First a literature study is made on materials which are available on Mars with their "building" properties. Then, a research is made to find the material composition which will comply to the requirements.

The literature study and research (partly) provides answers to the following sub-questions:

- What potential building elements are found on Mars?
- Which of these elements are best suited to protect human beings against the harsh Martian environment?

14. Literature study

The conclusion from previous chapters points to three materials which have great potential for the building of a Martian habitat. Two ISRU materials, regolith and ice, which are both abundant and have excellent radiation shielding properties, and one mission recyclable material, nylon, which is used in parachutes to absorb the EDL shocks. Further research is made for these three materials regarding their ability to be used as construction material for a Martian habitat.

14.1 Ice

14.1.1 Properties

States

Ice is the solid state of H_2O. In the phase diagram below, the different states of water are depicted. Water has different states depending on temperature and pressure. As the pressure on Earth is roughly constant at 1 atm (atmosphere), water becomes solid at its freezing point at 0˚C and becomes gaseous at its boiling point at 100˚C. However, there are many different types of ice which are formed under different temperature and pressure.

As the pressure on the surface of Mars is different from that on Earth, the boiling and freezing points of water on Mars differ too. As can be seen in figure 36, liquid water cannot occur on the surface of Mars, therefore ice immediately sublimates.

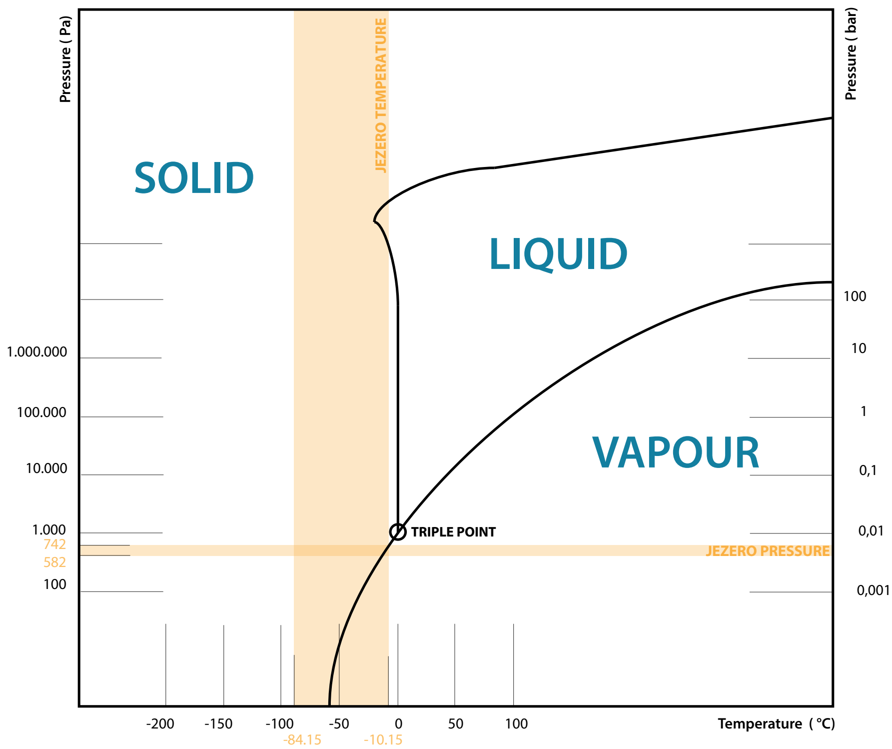


Figure 36. Phase diagram of H2O. Different states of H2O where the conditions at Jezero crater can be analysed. It can be seen that Mars is close to the triple point and that therefore special conditions need to exist in order to have liquid water on Mars.

However, brines, largely found on Mars (NASA, 2015a) have a different phase diagram and would allow deliquescence[9]. Brines are a solution of water and salt. The salt content is expressed in practical salinity units (psu) or in parts per thousands (ppt). A well-known brine is sea water which has a salinity of 35 parts per thousand (ppt). Per 5 ppt increase of the brine the freezing point decreases by 0,28°C. Different salts have different impacts however the most common is sodium chloride: NaCl which has a minimum freezing temperature of-21,1°C.

9 Deliquescence: the process by which a substance absorbs moisture from the atmosphere until it dissolves in the absorbed water and forms a solution (Deliquescence, n.d.).

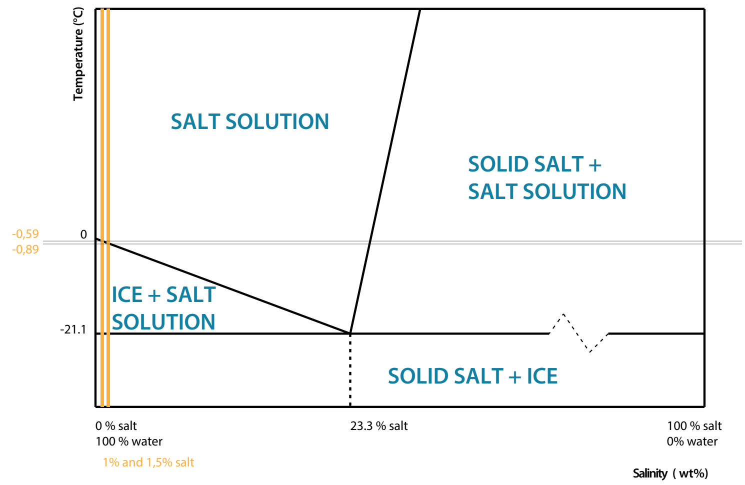


Figure 37. Phase diagram of NaCl brines at 1atm. where the four states of NaCl brines can be observed. The yellow lines indicates the different states of the solution at 1 % and 1,5 % salinity. Plotting the pressure would require a 3D diagram which is unnecessary as the ice type stays the same no matter the pressure when exposed to very low temperatures (like the temperatures found on Mars).

The minimum temperature at which a solution can be liquid is called the eutectic temperature (T*e)* of the solution. This is also true for brines of given salts and their salt concentration at T*e* is called the eutectic concentration *χeut*. In the table below the eutectic temperatures of liquid brines probably found on Mars are given along with their eutectic concentrations expressed in wt%. Especially the perchlorates brines are important as they are abundant on Mars subsurface and allow liquid water to be found on Mars. Their T*e* is 206K and 236K for $Mg(ClO_4)_2$ and $NaClO_4$ respectively (Martínez & Renno, 2013).

Salt	T_e (K)	*DRH* (%)	χ_{eut} (wt%)
H_3PO_4	203	41	60
LiCl	206	48	24
$Mg(ClO_4)_2$	206	53	44
KOH	210	50	32
$AlCl_3$	214	53	25
$ZnCl_2$	221	58	52
$CaCl_2$	226	60	30
$NiCl_2$	230	64	30
$NaClO_4$	236	52	68

Table 21. Eutectic points of brines likely to be present on Mars. The eutectic temperatures of these salts are exceeded at low and mid latitudes over the entire year, and at polar regions during spring and summer. The threshold relative humidity DRH for these salts to deliquesce is theoretically reached on the surface only poleward of ±60˚ and during the spring, when the water vapour content of Martian atmosphere peaks (Martínez & Renno, 2013, p.37).

Structural properties
Depending on the formation (or freezing process) of ice, single crystals or polycrystalline ice forms. These crystals determine if the ice is anisotropic or isotropic which depends on the orientation of the crystals. Thus, the process in which the ice is formed strongly influences the properties of the ice. One set of properties which are relevant when considering building with the material is the mechanical properties (Janssen & Houben, 2013).

Mechanical properties
Ice is very inhomogeneous resulting in varying strength. However, in general, it can be stated that ice is stronger in compression than in tension. Therefore most ice constructions are made to optimize the compressive strength like arches and domes. So ice behaves a bit like concrete which has a tensile strength of 1/10th that of its compressive strength. The average tensile strength of ice is 1,43 MPa (between -10˚C and -20˚C). Both the tensile and compressive strength of ice increase when the temperature the ice is subjected to decreases as is shown in figure 38.

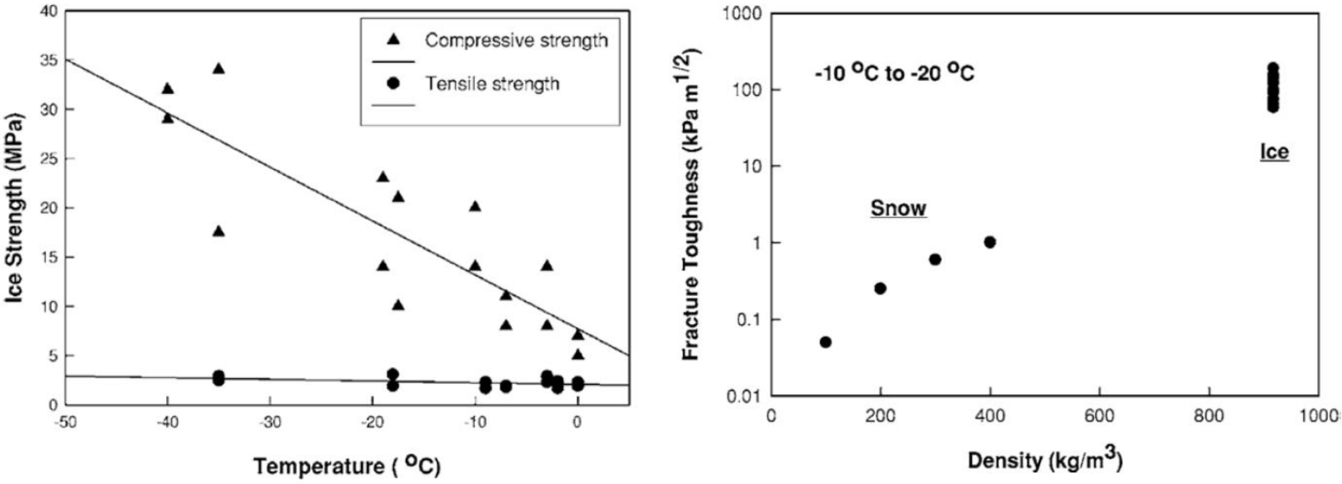


Figure 38. Left: Strength of ice versus temperature of the ice. Where compressive strength is higher when the ice is colder (JJ Petrovic, 2003 from Janssen & Houben, 2013, p. 35). Right: Fracture toughness of ice verus its density. It can be seen here that the fracture toughness stays roughly the same (Janssen & Houben, 2013, p. 37).

Depending on the microstructure, the state of the material and the rate of loading, ice can behave as a ductile as well as a brittle material. As it has a hexagonal symmetry, it can be considered as stacked layers with brittle fractures at high deformation rates when under tension and with slow deformation when exposed to high temperatures. One of the most specific properties of ice is that it creeps especially at high stress levels. Creep may appear under high stress but also when it is near its melting point (-5˚C and-10˚C) and depends on the nature of the stress, the grain size and the impurity content (impurities being generally water or air bubbles). Ice becomes thus stronger and denser at temperatures well below its freezing point; however it also becomes more brittle. Ice freezes from the outside in thus putting great pressure on the outer ice layer. To avoid this brittleness, proposed methods are to either build up the ice out of thin layers or to keep the water moving under the surface (like a river would). This way the ice is clear of impurities and the formation of cracks is prevented. Another aspect which can lead to the cracking of the ice is thermal shock. Thermal shock mainly appears when temperatures are really low and the inside of the ice block is hotter than the outside leading to high pressure and finally cracks. Therefore solar radiation can be a limitation when using ice as structural element (Janssen & Houben, 2013).

All these mechanical aspects depend on different types of ice whether it’s the formation process, the temperature, the type of ice or the crystal structure, which means that every aspect must be carefully examined. However, a mechanical property of ice which is quite constant is the fracture toughness as can be seen in the graph below (Janssen & Houben, 2013).

To conclude, ice is a relatively weak material prone to creep. Although it doesn’t seem like the ideal building material, it is still a widely available and cheap material in artic regions on Earth as well as on Mars (although slightly different than on Earth of course). To improve the mechanical properties of ice, fibrous reinforcement has been proved to be a cheap and adequate solution, as will be explained in the next heading.

14.1.2 Ice composites

Types

There are different types of composites as well as different types of ice composites. The first ice composites were igloos which were traditionally reinforced with lichen by inhabitants of northern regions. No other ice composite was made for a long time after that until WWII where an ice fleet was proposed to be made using “pykrete” a mixture of ice and wood pulp. Ever since then a number of studies has been made that showed that fibrous materials are best to reinforce ice (Vasiliev, 1993). The different type of composite can be divided in two categories derived from the reinforcement method: microscopic and macroscopic (Vasiliev, Pronk, Shatalina, Janssen, & Houben, 2015). The macroscopic method uses the tensile strength of another material. By placing that material in the direction of the tensile forces, the ice is reinforced. An example of macroscopic reinforcement is a steel cable placed in one direction much like reinforced concrete. Microscopic reinforcement works against the crack formation of the ice which determines its tensile strength. The reinforcement material is then mixed up with the water to create an isotropic composite. An example of microscopic reinforcement is wood pulp which is added to water to create pykrete (Janssen & Houben, 2013).

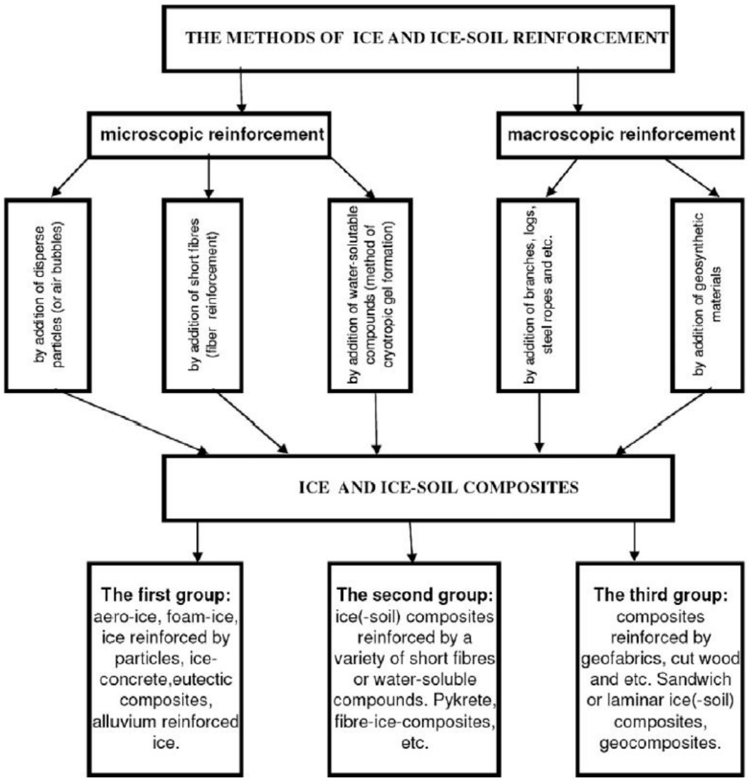


Figure 39. Methods of Ice and Ice-soil reinforcement where two types of ice composites are described: microscopic and macroscopic reinforcement (Vasiliev, et al., 2015, p. 2).

In the past years, a great interest was given to wood, fiberglass and asbestos (Vasiliev, 1993) as a reinforcement material. At the moment, wood as pykrete and cryotropic gel formation (CGF) are the most researched materials due to low costs and low impact on the environment as wood is a natural material and CGF is often used with xanthan gum and polyvinyl alcohol (PVA) (Vasiliev, et al., 2015). The properties and tests results of these two categories of ice composites are further explained.

Pykrete

Pykrete is a frozen composite made out of wood pulp and ice and was first used during WWII. Vasiliev tested the material on numerous occasions (Vasiliev, 1993 & Vasiliev, 2015) and found out that fibrous materials are the most effective ice strenghteners. The strength can be calculated with the following formula:

$$\sigma_c = \mu E_2 \varepsilon \phi_2 + \sigma'_1 (1-\phi_2)$$

with σ_c = the strength of the ice composite

μ = the Krenchel coefficient (indicating the fibre orientation and distribution)

E_2 = the elastic modulus of the reinforcing fibres

ε = the failure strain of the composite

ϕ_2 = the volumetric content of the reinforcing fibres

σ'_1 = the failure stress

As can be derived from the formula, fibres with high strength and elastic modulus are best for ice composites (Vasiliev, 1993). However this formula is quite experimental and should be used as a starting point rather than a known fact. As ice properties depend on many factors (as explained in the previous section), to determine the strength of ice composites, simulations and physical tests are needed. There haven't been many studies done with regard to properties of ice and even less on reinforced ice. Moreover, the studies that were made give varying results which makes it difficult to rely on the literature findings. Figure 41 shows the crushing strength, tensile strength and density of pykrete done by Goeffrey Pyke in 1943 (Janssen & Houben, 2013).

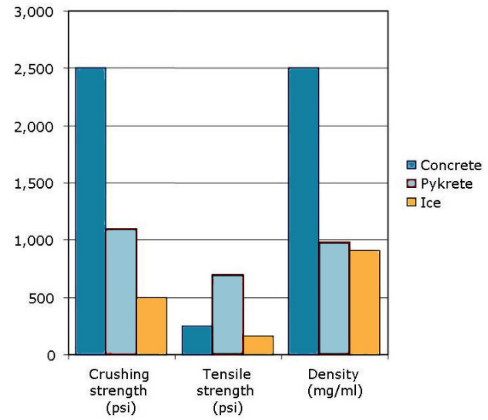


Figure 40. Mechanical properties (crushing strength, tensile strength and density) of concrete, pykrete and ice. Concrete has a better compressive strength however pykrete has the best tensile strength.

A few conclusions, can however still be drawn from the few tests made on fibre reinforcements in ice. For example, to reinforce ice with a fibre, the **critical length** is an important factor. The critical length depends on the diameter of the fibres and its ultimate strength and usually ranges from 20 to 150 times the diameter of the fibre. Another conclusion is that **low percentage** of fibre reinforcement has already a great impact on the bending and compressive strength, with 2% of fibres already improving the strength by a factor 2 to 3. The improved strength also has a positive impact **against creep**. In the case of pykrete, the melting rate is slowed down due to the low conductivity of the wood pulp (Janssen & Houben, 2013).
Although pykrete is one of the best reinforcement for ice composites, it has a major drawback which is that wood pulp is often unavailable in subfreezing conditions, leading to high transport costs.

Cryogels

Cryogel are gel matrices that are formed by a freezing and thawing process. They are made to present the same properties as silica aerogels in terms of monolithicity, density, porosity and surface area. Aerogels are known for their excellent insulating properties (thermal, electrical and acoustical) but the most common way to create them is through supercritical drying which is complex, expensive and carries health issues. Pons (2012) tested the properties of cryogels with four different solvents: ethanol, methanol, acetone and *tert*-bethanol. The results were promising as can be seen in table 22 (Pons, Estop, Molins, Harris, & Xu, 2012).

Properties of selected samples (the same samples as Table 2). V_{bulk}: total volume of pores; V_m SP: volume of mesopores from single point (at the maximum attained pressure); $\langle Ø_m \rangle = 4\cdot(V_m\ SP)/S_{BET}$: mean mesopore diameter; $V_m\ \beta_s$: mesopore volume from β_s-plot; $\langle Ø_m \rangle_\beta$: mean mesopore diameter from β_s-plot; V_m: mesopore volume from BdB–FHH method; $Ø_{ads}$ and $Ø_{des}$: maxima of the mesopore size distributions inferred from adsorption ($Ø_{ads}$) and desorption ($Ø_{des}$) isotherms from BdB–FHH method; $F_M = 100\cdot(V_{bulk} - V_m)/V_{bulk}$: macroporosity percentage. Numbers within brackets indicate uncertainties.

Data from:	Bulk	Single-point	4V/A	β_s-plot	β_s-4V/A	BdB–FHH			Bulk and BdB–FHH
Label	V_{bulk} (cm³/g)	V_m SP (cm³/g)	$\langle Ø_m \rangle$ (nm)	$V_m\ \beta_s$ (cm³/g)	$\langle Ø_m \rangle_\beta$ (nm)	V_m (cm³/g)	$Ø_{ads}$ (nm)	$Ø_{des}$ (nm)	F_M
Aerogels									
M	7.9(7)	5.1	46	–	–	5.3	72	18	33(6)
A2	6.6(6)	2.4	20	2.1	21	2.5	72	26	62(4)
E6	4.8(3)	3.7	62	–	–	3.8	101	45	21(5)
A3	3.9(4)	1.9	20	1.6	17	2.0	57	17–31[a]	49(6)
A5	1.7(2)	1.8	17	1.6	19	1.7	22	9	0
Monolithic cryogels									
Tm	8.1(7)	2.3	27	–	–	2.3	76–141[a]	41	72(3)
M	7.0(6)	1.7	14	1.4	14	1.8	8–12[a]	9	74(3)
E6	4.5(3)	0.6	11	0.4	11	0.6	8	7	87(1)
Fragmented cryogels									
M	10.4(1.0)	1.9	18	1.4	20	2.0	19, 108[b]	27, 65[b]	81(2)
E6	6.1(7)	1.8	9	0.7	8	1.9	C[c]	C[c]	69(4)
A3	4.0(6)	2.4	11	1.9	12	2.6	99	37	35(10)
A2	3.9(1.0)	1.8	8	–	–	1.9	C[c]	C[c]	51(13)
A5	1.9(3)	1.4	6	1.1	8	1.6	27–35[a]	8	16(13)
Xerogels									
M	0.5(1)	0.5	4	0.5	5	0.5	4	4	0
A2	0.1(1)	0.3	3	0.2	3	0.1	3	3	0

[a] Broad maximum.
[b] Bimodal distribution.
[c] Broad and complex distribution.

Table 22. Properties of different cryogels created from different solvents (Pons, at al., 2012, p.5).

Vasiliev explored the possibility to use cryogels as reinforcement for ice and ice soil composites using cryotropic gel formation (CGF). Vasiliev uses cryogels made from polyvinyl alcohol (PVA), which is a white polymer with no smell or taste. The reason for PVA cryogels is that PVA is widely available and it has excellent mechanical and thermal properties. These gels are also used in the medical environment which, according to Vasiliev, proves their ecological cleanness. In an earlier study, the improvement of the relative strength of cryogels as ice reinforcement was proved (Vasiliev, Ivanov, Sokurov, Shatalina, & Vasilyev, 2012).

Relative strength *k* at bending of ice composites depending on various additives of water-soluble polymers (at temperature — 20 °C) (Vasiliev, 1988).

The type of polymer	Weight content,%	Relative strength, *k*
Polyethylene glycol	4	0.85
Carboxymethylcellulose	4	0.25
Oksyethylcellulose	4	0.40
Methylcellulose	1	0.85
PVA	4	1.35
PVA with glycerine weight content 0.5%	4	2.00

Table 23. Relative strength of ice composites (Vasiliev, 1988 in Vasiliev, et al., 2012).

In a recent study, it was proven that some factors are important when using PVA in CGF and that, when taking these factors into account an ice composite can be improved on strength and crack formation. These factors are:

- Quality and quantity of the PVA
- Time of thawing
- The number of freezing and thawing cycles
- The type of ice used

In general, ice composites have more strength when subjected to a few freeze and thaw cycles much like it does in cold climate throughout the seasons (Vasiliev, et al., 2015).

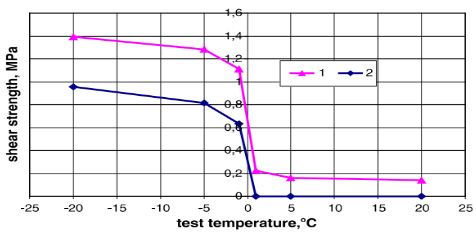


Fig. 4. Shear strength of the ice–soil composite (1) and control soil (2) vs. test temperature during and after 1 cycle of freezing and thawing.

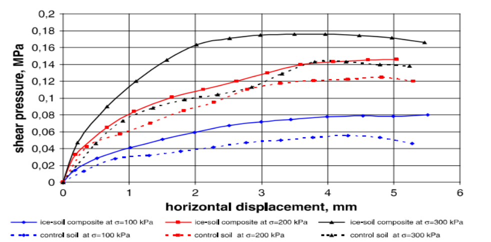


Fig. 5. The shear diagrams at the positive temperature (+20 °C) for different soils at various σ-normal pressure: the ice–soil composite or in this case cryogel–soil composites samples obtained by method of CGF and the control soil samples.

Figure 41. Shear strength and horizontal displacement of ice composite (1) and the control soil (2) (Vasiliev, et al., 2015).

14.1.3 Building with Ice

Building with ice hasn't be done on Mars yet but a few examples have been made on Earth. One of the oldest examples are igloos which have been used by people living in the North for centuries. Traditionally built with snow, the air between the snow particles is a great insulator. In regions where the outside temperature can be as low as-45˚C, the igloo provides a comfortable inside temperature of around 0˚C (Janssen & Houben, 2013). Janssen and Houben analysed almost every known type of ice structure built to date (in 2013) and assessed the structures using twelve criteria, ranging from the construction techniques used to the reinforcement material. The criteria as well as the buildings are depicted in the matrix (Janssen & Houben, 2013).

After assessing each case, Janssen & Houben created a matrix with the most common choices of variables. It was clear that most buildings were made for recreation purposes and with a limited life span of a few months. The most common technique to build the structures is spraying and blowing a mixture of water and snow (snice) which can be done from a distance by hand. Another notable fact is that not much reinforcement is used in these structures, when reinforcement is needed, steel cables or woven fabrics are used (Janssen & Houben, 2013).

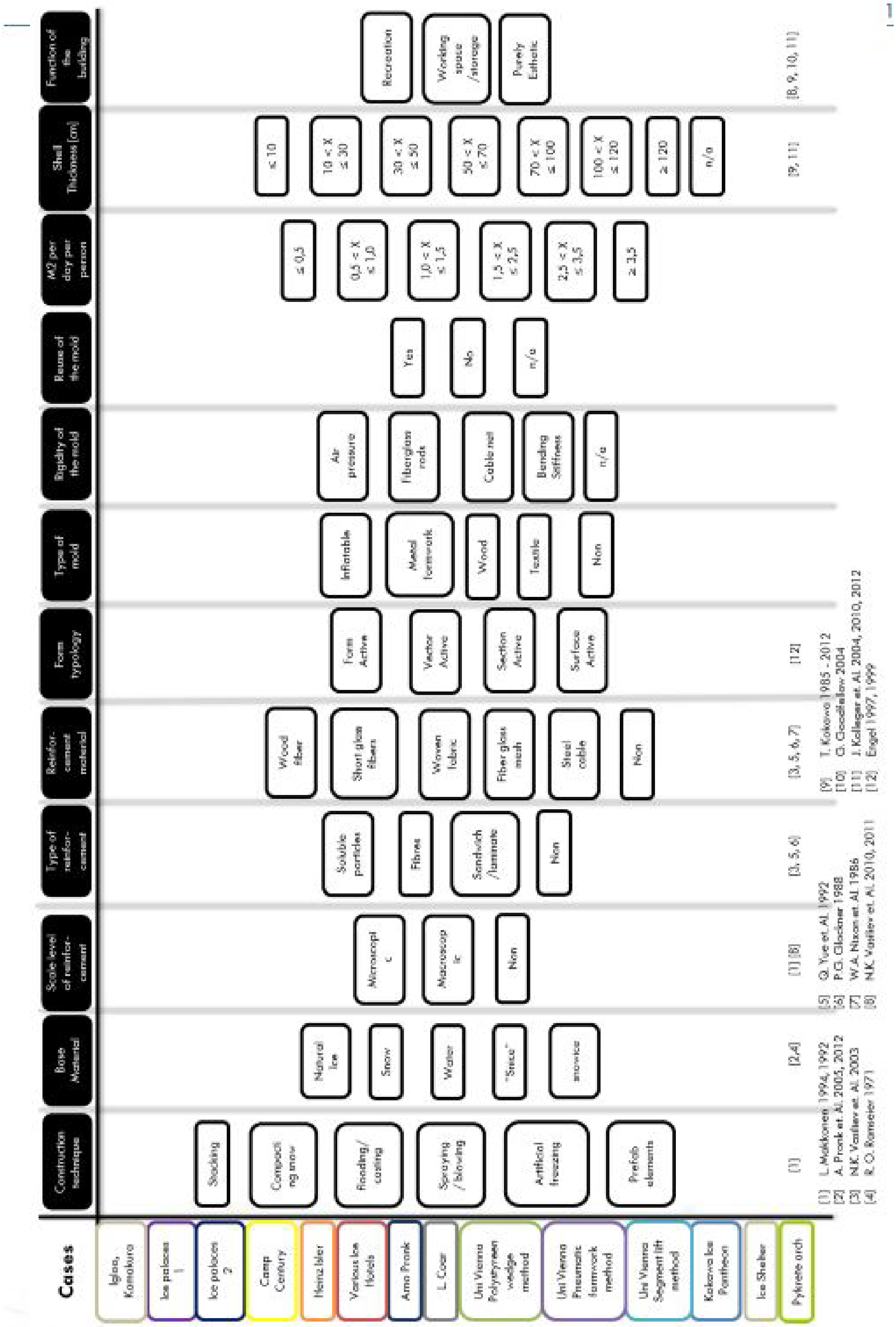


Figure 42. Table of assessment for ice structures (Janssen & Houben, 2013, p. 75).

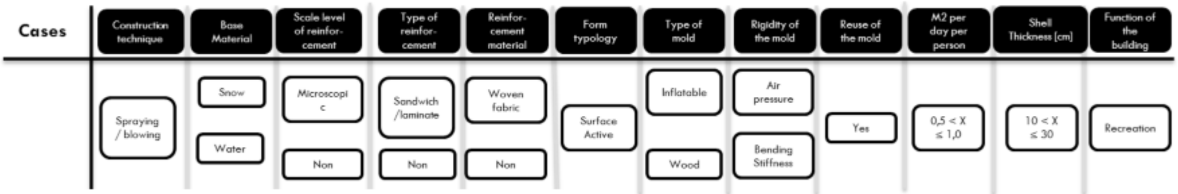


Figure 43. Matrix of the most chosen techniques analysed by Janssen and Houben (Janssen & Houben, 2013).

14.1.4 Conclusions

Ice is an inhomogeneous and complex material. A few properties are important when considering ice as building material. First, it has a better compressive than tensile strength, the latter being equal to 1,43 MPa. Ice is often compared to concrete for its mechanical properties, being sometimes ductile as well as brittle. However ice melts and the lower the temperature, the higher its strength. Besides having positive effects, the higher the stress (e.g. heat) the higher the chance of creep. The formation process is also of influence on the strength. Since ice freezes inwards from the outside, the strength will be higher if the ice is formed layer by layer or with a constant water flow.

To improve the strength and the reliability of ice, reinforcements can be used. As this is a quite novel technique only few reinforcement options have been tested and used with the most promising reinforcement being fibrous materials. Two reinforcement types have a low environmental impact: pykrete and cryogels with PVA. Both are great reinforcements with pykrete being the most reliable source with a few examples of large structures being built like the pykrete dome in Juuka, Finland which has a 30m span. However wood pulp isn't found in artic regions and even less so on Mars. PVA is an excellent material for CGF and improves the strength and decreases crack formation of ice.

The properties of reinforced ice, much like ice itself, depend on the fabrication process and the properties of the reinforcement. In the few built examples, spraying snice is the most common method. On Mars, habitats should be autonomously built which means this method isn't possible and that a new building method is needed.

14.2 Regolith

Regolith is the layer of unconsolidated fine material that covers the solid rocks of a celestial object. Its chemical composition on Mars is 45,41 wt% SiO_2, 16,73 wt% Fe_2O_3 and FeO, 8,35 wt% MgO, 6,37 wt% CaO, etc. Martian Regolith is known to comprise extremely fine dust. This dust contains substantial quantities of nanoparticles of iron oxides and oxyhydroxides, known together as nanophase ferric oxide (npOx). This npOx gives its reddish hue to Mars (Chow, Chen, Zhong, & Qiao, 2017).

14.3 Nylon

Nylon is a thermoplastic which is made out of repeating units which are linked with each other by covalent chemical bonds, also called a polyamide. Nylon 6,6 is the most widespread type of nylon an its properties are given in the table below.

PROPERTY	VALUE	UNIT
DENSITY	1,15	g/cm^3
ELECTRICAL CONDUCTIVITY	10^{-12}	S/m
THERMAL CONDUCTIVITY	0,25	W/(m.K)
MELTING POINT	190 - 350	˚C

Table 24. Properties of Nylon.

Nylon is very polar and therefore forms hydrogen bonds. It is also hygroscopic which will affect its properties when soaked in water. It is a generally durable material with a high resistance to chemicals and organic matter. However, nylon is weak in the presence of sulfuric acid. As thermoplastic the material has no strength properties in itself, it all depends on the form it is given. It is used as fabric but more often as filament for various purposes as fishing filaments, food packaging, toothbrushes (Jahnke, 1996) and more recently as additive manufacturing filaments.

14.4 Conclusions

To conclude the three different analysed materials have very different mechanical and structural properties leading to certain advantages and disadvantages for all of them. As their properties strongly depend on the fabrication process of the final product (structure), different possibilities should be analysed.

15. Assessment of materials

Literature study on material composition and process methodology provides a solid base for design but the findings need to be validated by means of tests and simulations. To assess the new composites, the overall behaviour of the composite as well as its mechanical properties have to be tested. These properties have been tested following different methodologies. First the material itself is tested and redesigned and then the different possible structures are assessed.

A few researches on composites are used as example: the tests used for ice composites for The Pykrete Dome (Janssen & Houben, 2013), the assessments tests used by the NASA Centennial Challenge (NASA & Bradley University, n.d.) and the tests described in the Mechanical testing of advanced fibre composites (Hodgkinson, 2000). Hodgkinson (2000) describes that for fibrous composites to be evaluated some primary mechanical properties are essential to test. Those properties are:

- Tensile modulus
- Compressive modulus
- Flexural modulus
- Lateral contraction ratios
- Tensile strength
- Compressive strength
- Flexural strength
- Apparent interlaminar shear strength
- Fracture toughness

These properties are first tested on a test specimen which becomes a sample then material then end product (Hodgkinson, 2000). The above mentioned properties don't need to be tested all right away with the test specimen which saves time.

TEST SPECIMEN → SAMPLE → MATERIAL → END PRODUCT

Janssen and Houben (2013) run some basic tests first to make quick decisions on which reinforcement is the most effective. Those tests are:

- A mixing test: to assess which materials mix well together and which don't
- A melting test: to see if the reinforcement improves the material and which reinforcement is best at different weathering conditions
- A drop test: where the composite is dropped to quickly compare the difference in strength

After these basic tests have been run, a specific composite should come out as best from the test which can then be further tested. Further tests to test the compression and flexural strength of the composite are described by NASA in their Centennial Challenge. These tests give precise criteria that the material has to meet. The material is tested in different shapes ranging from an easier (cone) to a more complex (dome) structure which is then assessed by standardized compressive and tensile tests.
The cone has a standard size of 300mm in height and a diameter of ø=150mm and is tested with the ASTM C39 Compression Test. ASTM C39 is a standardized test method for compressive strength of cylindrical concrete specimens. As it is usually used for concrete a weight factor is added by the Centennial Challenge committee to assess the specimen. The minimal compression load the cone has to withstand is 450 kgf which is 44 MPa in the International System of Units (SI unit).
The beam (length: 650mm and cross section: 200x100mm) is tested with the ASTM C78 test and NASA here specify that the beam should have a minimum load failure of 750 kgf which is 73 MPa in SI units. ASTM C78 is the standard test method for flexural strength of concrete (using simple beam with third-point loading).
The last geometry tested is a dome which is also placed under compressive force and has to withstand 625 kgf or 61 MPa in SI units (NASA & Bradley University, n.d.).

Students from Eindhoven Technical University also tested ice and pykrete cylinders and beams under compressive strength in a cooling chamber. Their specimens are 150 mm in height and have a diameter of 95 mm. The average compressive strength of the 100 % water ice is 3,18 N/mm^2 or 3,18 MPa (all the specific data concerning this experiment can be found in the appendix C).

The collected data can help assess the samples but as Hodgkinson (2000) mentions in his book:

"Each sample or test specimen is […] unique, and derived data must be regarded just to it, rather than to the material in general." (p.5).

To conclude the assessment of the material is added to the table of requirements.

	THEME	NUMBER	CRITERIA
10.0	Assessment	10.1	Mixing test of a brick
		10.2	Melting test of a brick
		10.3	Drop test of a brick
		10.5	Compression test (ASTM C39) of a cylinder (diam: 150 - height: 300mm) min. load failure at 450 kgf = 44 MPa
		10.6	Compression test (ASTM C78) of a beam (100x200mm 650mm) min. load failure at 750 kgf = 73 MPa
		10.7	Compression test (ASTM C78) of a dome min. load failure at 625 kgf = 61 MPa
		10.8	Flexural strength (tpb test) of a beam (100x200mm 650mm)
		10.7	Compression test (ASTM C78) of a dome min. load failure at 625 kgf = 61 MPa
		10.8	Flexural strength (tpb test) of a beam (100x200mm 650mm)

Table 25. Programme of requirements for the assessment of the material.

16. Materialisation for a habitat on Mars

Heading 14 and 15 of chapter C concluded that a new material needs to be found to design a sustainable habitat on Mars. Conclusion is that an ice composite is the most promising solution to add strength to the already existing qualities of ice as a structural material in the particular case of a sustainable Mars habitat.
Finding a new composite requires research and physical testing. The literature study on building on Mars is explained in part A of this report and concludes that physical experiments are needed to find a composite which will comply to the set requirements. This part is thus about the physical testing of a new composite including the requirements, methodology used, the testing set-up and the results.

16.1 Requirements

The requirements for the new material are taken from heading 14 and are summarized in the following material requirement table.

	REQUIREMENT	VALUE
1	ISRU	at least 70%
2	Compressive strength cylinder	44 MPa (450 kgf)
3	Compressive strength dome	61 MPa (625 kgf)
4	Translucency	Daylight must be let through: min 150 lux

Table 26. Requirements for the building material based on the literature findings.

16.2 Methodology

Finding a new material requires finding its properties, in this case especially the ones useful for building a structure. Therefore the compressive and tensile strength are of critical importance to determine if the new composite will comply with the set requirements. The tensile and compressive strength are found through a series of different tests which are designed to find out which particular reinforcement material or combination of materials and in which quantities are complying best with the requirements.
The performed tests are divided into two experiments, the first experiment consists of simplified, time constrained, small scale, but scalable, preliminary pilot studies. The tests will establish if the used method and experiments are robust and are believed to yield useful results. The second experiment is a series of advanced tests which will verify the first steps and give a more elaborated result. The main thought behind this methodology is that creating an analogue for Mars is costly and time consuming. As explained in heading 15 and 3, Mars is an extreme environment and recreating it on Earth proves difficult, costly and time consuming. Therefore simple tests are performed in an Earth like environment to obtain preliminary conclusions which then can be tested in an analogue Martian environment. This focused method saves time but is not completely reliable and some important conclusions may be missed. The whole experimental phase of the project is based on a trial and error method where the first test helps building the set-up and methodology for the second test which in turn builds up the set-up and methodology for the third one etc.

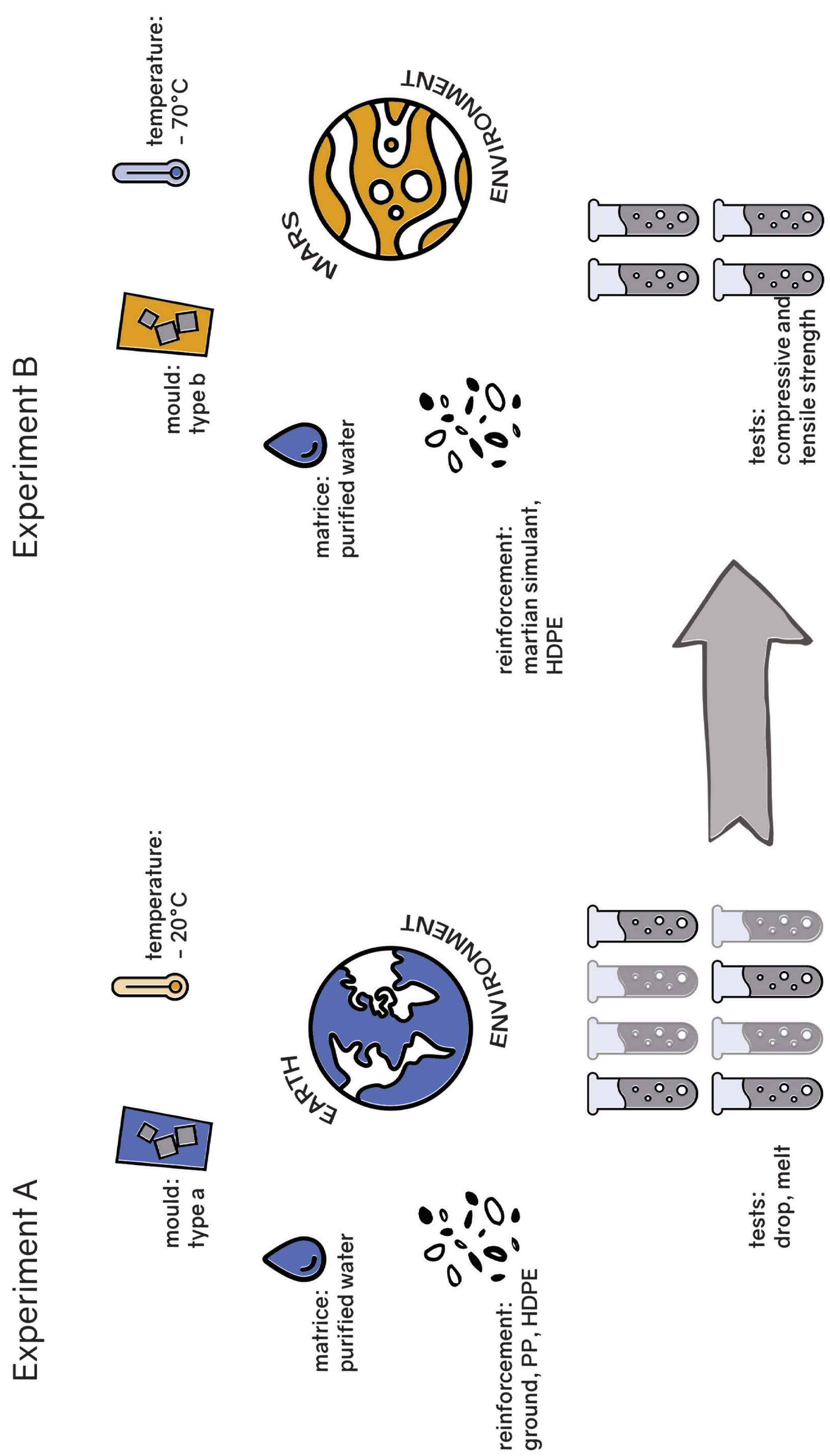


Figure 44. The relationship between experiment A and experiment B. Experiment A being a pilot study processing a lot of variables and tests to draw some preliminary conclusions to restrain the variables of experiment B.

16.3 **Experiment A**: Earth environment tests

16.3.1 Aim and objective

The aim for the first series of tests is to find out which material or combination of materials has the highest potential as building material for a habitat on Mars.
The objective of this test is to confirm the conclusions drawn at the end of part A. The goal of the test is to compare rather than to obtain specific values.

16.3.2 Set up

Matrix

As the specimens are ice composite, the matrix is purified H_2O. The water is purified because, as stated in heading 14, the resulting ice is stronger as it has homogeneous clarity and translucence. In this experiment, the water is purified by boiling it twice to reduce the amount of gas and impurities that are contained.

Fibres

The fibres used for this experiments are mission recyclables and sand. The sand will indicate how minerals behave within the ice matrix, which is an analogue for the Martian soil simulant. The mission recyclables used are two different types of plastic: PP and HDPE. The plastics are recycled containers (like drinking bottles) which are shredded into small pieces of roughly 3 mm. The fibres are used in different quantities to find out which percentage complies best to the requirements. The exact amount is stated in the variables heading in table 28.

Fibres	Density [g/cm3]	Tensile strength [Mpa]	Youngs modulus [Gpa]	Compressive strength [MPa]
Polypropylene (PP)	0,89-0,91*	27,6 - 41,4*	0,896 - 1,55*	25,1 - 55,2*
High Density Polyethylene (HDPE)	0,94 - 0,96*	20,7 - 44,8*	0,621 - 0,896*	19,7 - 31,9*
Sand	0,08 - 0,1			

Table 27. Fibres properties used for the experiment.

Ice composite formation

The samples are made out of two different moulds. First a handmade rectangular foam mould (M001) is used for specimen A0.001 and A0.002. However this mould isn't watertight and it broke when taking of the ice, therefore another mould is used: a basic plastic drinking cup (M002). Both moulds are placed into a regular kitchen freezer at-20°C. The samples are made out of purified H_2O and vary in the fibre type (materials) and quantities.

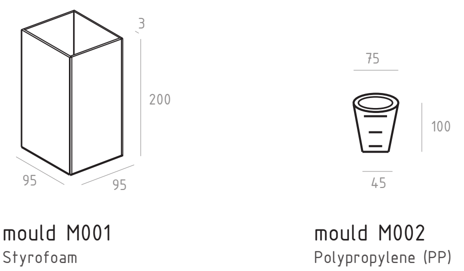


Figure 45. Moulds used during experiment A. M001 is a rectangular mould made specifically for the experiment out of Styrofoam. M002 is a plastic PP cup bought in a convenience store.

Tests performed

Test A01: mix test.
The first test is to mix the reinforcement(s) with the water and visually observe how the elements mix at room temperature (+/- 22°C) before putting them into the freezer (-20°C) and visually observe the resulting ice. The observations are reported in a table for each sample.

Test A02: drop test.
The second test consists of dropping the sample from a height of about 1m40 onto the ground at ambient temperature (+/- 1°C 13°C) and atmosphere (1 bar). The behaviour of the ice is then visually observed and reported in a table for each sample. This test is a way to find out how well the fibres are “attached” to the H_2O ice in the different samples. This test is first performed with regular ice with no reinforcement to have a base-line result which is used to compare the different samples. The drop test also gives information about the strength of the samples.

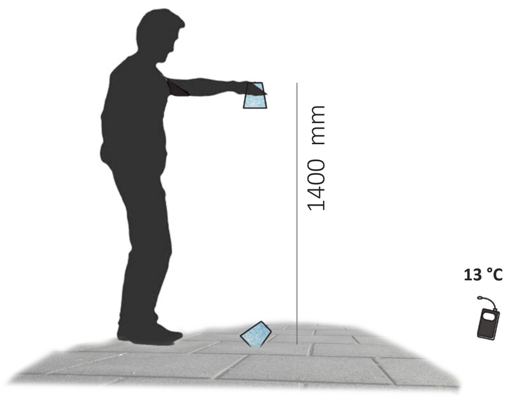


Figure 46. Test A02 setup.

16.3.3 Variables and constants

The test variables define the number of tests performed, these variables are defined by the literature findings and the results of the first tests. As the tests are meant to be compared to each other, constants are also important to define.

Experiment A has four different variables which determine the amount of composite samples created.
The first one is the type of fibre used as reinforcement which is either a plastic recyclable PP and HDPE as they are the most common plastics used for packaging daily use products (Siracusa, Rocculi, Romani & Dalla Rosa, 2008) or sand which is a rough analogue for Martian regolith. The second variable is whether the water used for the ice is pure H_2O or a NaCl brine, similar to the type of ice found on the location. The third variable is the freezing time which will be determined by the previously mentioned samples and experiments. The last variable is the amount of fibre used to reinforce the composite, from the literature research, we know that low quantities of fibres already have a great impact on the properties of the new composite.

The environmental constants which will be used to assess the variables are:
- Orientation of the fibres (all randomly oriented fibres),
- The mould is the same thus the specimens have the same dimensions
- Freezing temperature (-20°C)
- Testing temperature (outside) +/- 1°C 13°C
- Drop surface (paving stones)
- Drop height (1m40)

Variables Experiment A

Fibre	Plastics (PP & HDPE)				Sand	
NaCl	0 teaspoon		1 teaspoon		2 teaspoons	
Freezing time	16 hours				36 hours	
Percentage fibre	1,0	2,5	5,0	10,0	20,0	50,0

Table 28. Variables of experiment A.

16.3.4 *Zero measurement*

The zero measurement, also called null or baseline measurement, is a measurement made without any variables in order to obtain a reference value. This enables comparisons between the variables and allows conclusions to be drawn. For both experiments the zero measurement sample is a pure H20 ice block made in the mould used for each experiment. The tests performed are the same as the tests performed on the other samples.

The first test is the mix test which isn’t relevant in this case as the mixture is only made out of one element. The second test, the drop test, has no defined result but is used to compare the behaviour of the ice upon impact with the mixed ice upon impact.

16.3.5 *Results*

Observations

Early observations are that adding salt changes the structure of the ice which has a more granular structure which does not break as fast as pure H_2O. The ice breaks only on the impact part while the purified H_2O ice cracks and sometimes the whole structure breaks. This is also true when adding different fibres: plastics and sand. While adding salt and sand to the matrix, the brine mixes better and has a more uniform structure than the just the purified H_2O mixed with sand samples. However a percentage of the salt concentrates on top of the ice creating a brine which does not freeze at -20°C. Both the sand and plastic fibres don’t add much strength to the structure and are difficult to mix with the purified H_2O or brine as their density is higher than that of water or the brine tested.
All the results as well as all the imagery taken can be found in the test data table in the appendix D.

Figure 47. Experiment A. f.l.t.r Sample 003: Zero measurement – Sample 004: Plastic PP & HDPE – Sample 005: Plastic PP & HDPE and NaCl.

Figure 48. Experiment A. f.l.t.r Sample 006-008-010: Ice with different concentrations of sand – Sample 007-009-011: Ice with different concentrations of sand and 5gr of NaCl

Analysis

The variables of experiment A are plotted against the design requirements and the result of the experiment are scored in the matrix according to three "values".
The aim of this experiment was to define the best (combination) of materials to comply with the set criteria to allow further in depth research with experiment B. As can be seen in the table, the salinity of the ice has a positive influence on all criteria and a longer freezing time has a positive influence on at least two criteria. However plastics only have a positive influence on the translucency on the material and the sand on the ISRU criteria. The values for the plastic and sand ice composites are topped by plain ice by itself therefore there is no point to put in extra effort in overcomplicating the ice.

	REQUIREMENT	SALINITY	PLASTIC	SAND	LONGER FREEZING TIME	LESS THAN 1/3 FIBRES
1	ISRU	v	X	v	-	v
2	Compressive strength cone	v	X	X	v	v
3	Compressive strength dome	-	-	-	-	-
4	Translucency	v	v	x	Not determined	v

Table 29. Influence of the variables on the table of requirements.
V= greatly complies to the criteria compared to the other variables
X= does not comply (well) with the criteria compared to the other variables
- = does not apply/ no value found

Conclusion

The conclusion is that the salinity of the ice has a great influence on the structure and the strength of the ice and that a percentage of salt is preferred. The exact percentage will be defined with experiment B. Another conclusion is that plastic and (earth) sand are not reinforcing the structure in any way and will therefore not be used in experiment B.

16.4 **Experiment B**: Mars analogue tests

16.4.1 Aim and objectives

The aim of this series of tests is to find out which material or combination of material is the strongest in compression and tensile strength.
The objective of this series of tests is to confirm the conclusion reached in experiment A and to get a value for the new composite which can be used for the further steps of the research: the design of a process, structure and habitat.

16.4.2 Set up

Matrix

The matrix is different from the one used in experiment A, as the conclusion was that salinity is an important factor, demi water is used. Demi water is short for demineralized water, which means salts are no longer present in the water therefore a specific quantity salt can be exactly measured and added without other salts influencing the results.

Fibres

The fibres used for experiment B are indigenous materials and high-performance earth materials. The mission recyclables (plastics under three forms: PET, HDPE and PP) are no longer used as experiment A showed no increased value using them. The indigenous material used is a simulant for Martian regolith. As was concluded in the first part of the thesis, Martian regolith is a potential reinforcement for a ISRU habitat on Mars. However as no Martian regolith sample has been brought back to Earth, a simulant is used. In this research the Mars Mojave Simulant MMS-1 is used. The simulant is a chemical analogue developed by NASA and the JPL. The simulant is available as rocks (coarse, particles larger than 1mm, with a majority within 3-5mm range) , sand (fine, particles smaller than 1mm) and dust (superfine, particles smaller than 0,6mm). The simulant is close to the observed regolith and the differences and similitudes are seen in figure 49.

Actual Mars Regolith	**MMS-1 Mojave Mars Simulant**
Silicates: 44%	**Silicates**: 49%
Iron Oxide: 18%	**Iron Oxide**: 11%
Aluminum Oxide: 9%	**Aluminum Oxide**: 17%
Magnesium Oxide: 7%	**Magnesium Oxide**: 6%
Calcium Oxide: 6%	**Calcium Oxide**: 10%
Sulfates: 6%	**Sulfates**: <1%
Trace: 10%	**Trace**: 7%

Figure 49. Chemical comparison between actual Mars regolith and the MMS-1 Mojave Mars simulant (retrieved on November 25, 2017 from themartiangarden.com).

The high-performance material used is aerogel for its great insulating and lightweight properties. The specific material used is the Lumira silica Aerogel LA 1000 with a particle size of 0,4mm. However this material is highly hydrophobic and therefore mixing it with water needs careful planning and design.

Fibres	Density [g/cm3]	Tensile strength [Mpa]	Youngs modulus [Gpa]	Compressive strength [MPa]
Polyethylene terephthalat (PET)	1,38	48,3 - 72,4*	2,76 - 4,14*	62,2 - 68,5*
Mojave Mars Simulant MMS-1	1,18	nk	nk	nk
Lumira aerogel LA1000	0,06 - 0,15	nk	nk	nk

Table 30. Fibres properties used for the experiment.

Ice composite formation

During the second step tests, Martian conditions are simulated and standard testing methods are used. Martian conditions mainly vary from Earth conditions regarding the outside pressure and temperature (see chapter 2 and 3). However, the pressure isn't of great importance regarding the making of ice as long as the temperature is well below zero as can be derived from the phase diagram of water (see figure 36). To simulate Martian air temperatures the mean temperature of the habitat location at Jezero crater is needed. This data can be derived from heading 4.2 Climatology, which indicates that air temperature ranges from-83°C during the night to-13°C during the day. These temperatures are simulated within a freezer going up to-70°C at the Electronic Instrumentation Laboratory of the EWI faculty (TU Delft). The mould used for this experiment is a plastic cylindrical mould (M003) which has a watertight lid. This mould is used because it has roughly the same dimensions as the moulds used by Janssen & Houben to make and test their ice. Therefore, results can be compared.

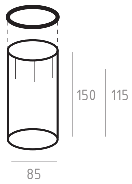


Figure 50. Mould used during experiment A. M003 is a cylindrical mould with dimensions based on the experiments made by NASA and Janssen and Houben.

Tests performed

The aim of this experiment is to know the compressive strength of the samples. Therefore two tests will be performed: the ASTM C39 test and a melt test.

B01: Compression test.
In most tests found in the literature, the cone has a standard size of 300mm in height and a diameter of ø=150mm. During this experiment however, the size of the samples is different due to the size restrictions of the equipment. The ASTM C39 Compression Test is a standardized test method for compressive strength of cylindrical concrete specimen. As it is usually used for concrete, a weight factor is added by the Centennial Challenge committee to assess the specimen and will also be used in this experiment.
The parameters for the machine are set at:

Speed start	10	mm/min
path	none	
Pre-load	10	N
Speed pre-load	5	mm/min
Test speed	1	mm/min
Force shutdown	80	%

B02: Melt test.
The second test is designed to test the resistance to warm temperatures of the sample. The samples are put at ambient temperatures to melt (+/- 25°C). The time required for the samples to melt is compared to the time regular H_2O ice takes to melt completely.

16.4.3 Variables and constants

The test variables define the amount of tests to be performed, these variables are defined by the literature findings and the results from the first tests. As the tests are meant to be compared to each other constants are also important to define.

Experiment B has only two variables left: the amount of NaCl to be used and the freezing settings. The other variables were ruled out by experiment A.

The constants which will assess the variables are:

- Orientation of the fibres (all randomly oriented fibres),
- The mould is the same (M003) thus the specimen have the same dimensions and form,
- Freezing temperature

- Testing temperature (outside)
- Testing machinery
- Testing settings (see table ...)

Variables Experiment B

NaCl	1,4 ppt	2,8 ppt	5,7 ppt	14,3 ppt
Freezing temperature	In stages up to -70°C		At once at -70°C	

Table 31. Variables of experiment B.

16.4.4 Zero measurement

The zero measurement, also called null measurement, is a measurement made on a standard sample without any variables to have a reference value. This enables comparisons between the variables and allows conclusions to de drawn. For both experiments the zero measurement sample is a pure H_20 ice block made in the mould used for each experiment. The tests performed are the same as the tests performed on the other samples. The test is performed three times to determine the differences found.

The tested specimens are all compared to a plain water ice specimen on which the same tests are executed, which yields a null value allowing comparison between the specimens and variables.

16.4.5 Results

Observations

The first four samples indicate that adding salt makes the ice structure more dense and therefore less cracks occur even when the ice is subjected to extremely low temperatures (-70°C). The non-salt ice takes less time to melt than the salt ice. The structure also seems less cracked when put directly into a cold air environment rather than decreasing the temperature gradually.

Figure 51. Difference in crack formation between water ice and salt water ice. The picture on the left shows how the specimen are observed, the picture in the middle shows specimen B0.001 which has great cracks going through the whole structure as opposed to small restrained cracks in the salt water ice of specimen B0.002 on the right picture.

B0.001
tapwater

B0.003
tapwater

B0.002
tapwater
table salt

B0.004
tapwater
table salt

Figure 52. Difference between the melting shape and rate of the water and salt water ice.

To perform the compression tests the specimen had to be sanded on the top side as the ice expanded non homogeneously. A simple sanding machine was used and proved to be a quick (few seconds needed) and effective solution which prevents the ice from melting. However it is quite challenging to hold the ice tight as the sanding of specimen B0.005 proved by slipping away and shattering on the floor before it could be tested. The compression tests were performed at the Mechanical, Maritime and Materials Engineering faculty (3mE) of the Delft Technical University. The resulting force of the compression test are constant between 15673 N (2,76 MPa) and 17398 N (3,06 MPa) which indicates that the amount of salt added does not have much influence. However specimen B0.006 had only a strength of 6778 N which could indicate that 1,43 ppt of salinity is not enough. However, it has to be taken into consideration that the machine settings were not set right and that the speed of the forces was ten times greater than during the other tests. As specimen B0.005 couldn't be tested to compare the values, this outcome should be taken as non-conclusive.

All specimens though broke in long vertical pieces which could mean that the structure should be reinforced in the horizontal plane. However tensile strength tests are needed before making any design decisions.

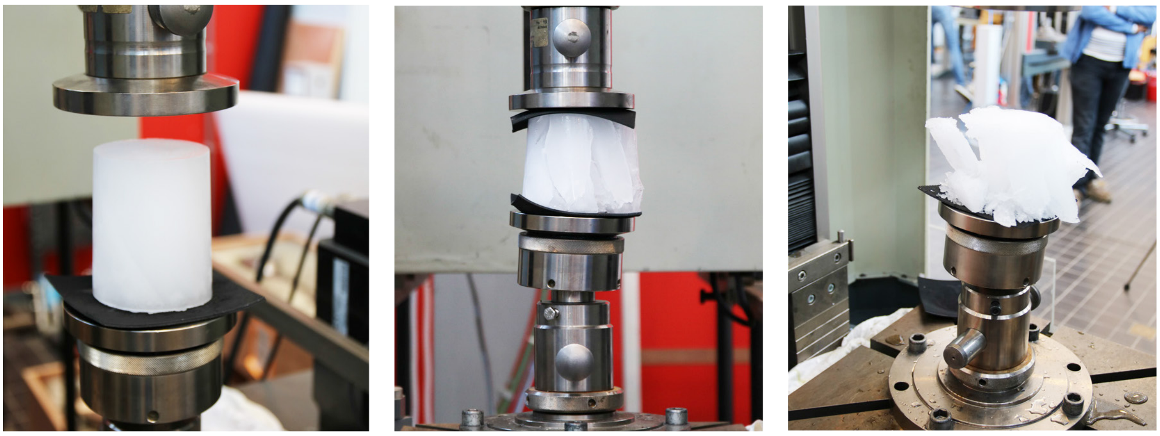


Figure 53. Testing of specimen B0.012 with the test set up before the test, during the test and after the test was performed.

The deformation and standard force graph shows that the higher the salinity the more plastic the ice is. Indeed, the first specimens, B0.006, B0.007, B0.008 and B0.009, which have a lower salt concentration have a more brittle behaviour comparable to standard brittle materials like concrete. This could also be due to the fact that the first specimens were still colder than the latter ones, meaning the higher the temperature of the ice, the more ductile it behaves. This theory matches the literature findings.

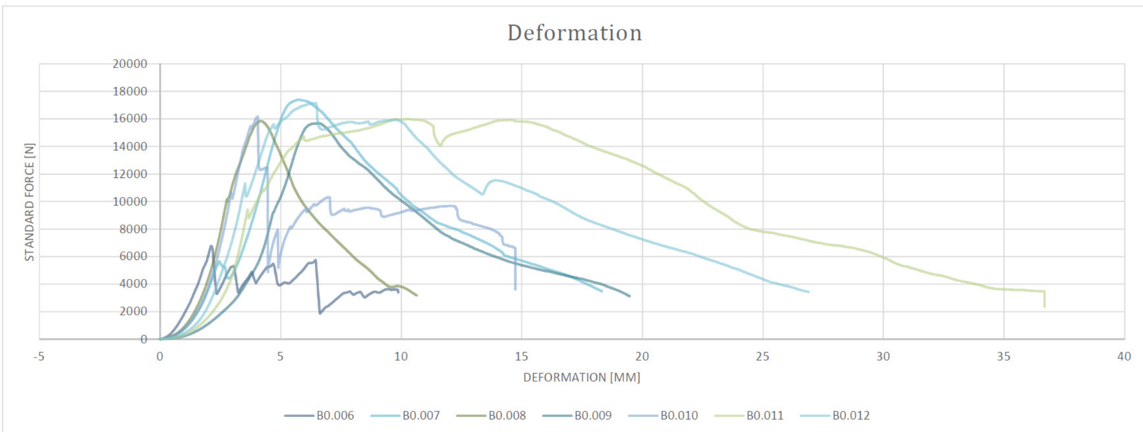


Figure 54. Graph with the results of the standard force and deformation from experiment B. The graph shows that specimen B0.011 and B0.012, which are both ice with a salinity of 14,3 ppt, have a higher plastic deformation.

Analysis

The value of the compressive strength found in our experiments differs by a factor 10 from the values for plain ice. However even the literature indicates that ice is a peculiar material which does not behave regularly in the same manner. The compressive strength of ice is also influenced by the strain rate (S^{-1}) (Janssen, Houben, 2013). Still the values for the compressive strength of the specimen from experiment B (about 3 MPa) differ greatly from the values found in the following table.

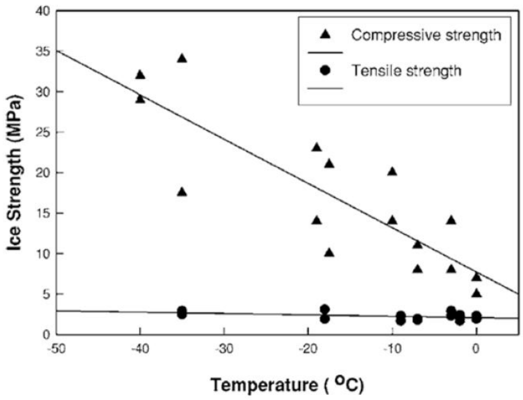


Figure 55. Strength of ice versus temperature of the ice. Where compressive strength is higher when the ice is colder (JJ Petrovic, 2003 from Janssen & Houben, 2013).

Four different aspects have been found to be of influence. These aspects could give a probable explanation for the deviation in values. The four aspects are highlighted the following heading.

Crystal size of the ice

The size of the crystals that forms the ice has a direct influence on the compressive strength of the ice following this formula:

$$\sigma = 9{,}4 * 10^5 * (d^{(-1/2)} + 3|\theta|^{0,78})$$

with
σ= compressive strength of ice (Mpa)
d= crystal size (cm)
θ= temperature (°C)

Stress due to sanding

The specimens were tested vertically and one side was sanded to ensure a flat surface for the compression test. The sanding might have caused extra stress on the structure and therefore influenced its test performance.

Thermal conductivity of ice

As the values found in our experiments differs by a factor 10 from the values found in the literature, the thermodynamic properties of ice and brines are analysed. The table shows that the thermal conductivity and density of the ice increases when the temperature decreases and the specific heat decreases. Unfortunately the specimens weren't correctly measured and weighted during this experiment, therefore the density couldn't be calculated.

ice	Temperature (t)	Density (ρ)	Thermal conductivity (k)	Specific heat (Cp)
	[°C]	[kg/m3]	[W/mK]	[kJ/kgK]
water	0.01	999.8		
	0	916.2	2.22	2.05
	-5	917.5	2.25	2.027
	-10	918.9	2.3	2
	-20	919.4	2.39	1.943
	-30	920	2.5	1.882
	-40	920.8	2.63	1.818
	-50	921.6	2.76	1.751
	-60	922.4	2.9	1.681
	-70	923.3	3.05	1.609
	-80	924.1	3.19	1.536
	-90	924.9	3.34	1.463
	-100	925.7	3.48	1.389
	Formulae	**definition**	**unit**	**value for design**
Brines				
(NaCl)	λb= (1-0,14.Ms).λw			
with	λb	thermal conductivity brine	[W/mK]	3.04390244
	Ms	kg salt/kg brine	[kg]	0.01428
	λw	thermal conductivity water	[W/mK]	3.05

Table 32. Result of experiment B compared with the compressive and tensile strength of other common material.

Temperature fluctuation

The specimens have experienced great temperature fluctuation before being tested which could also have put the structure under stress.

Conclusions

Conclusion is that the addition of NaCl improves the compressive strength of the ice and that the higher the specimen temperature, the more ductile the ice behaves. However, the zero values aren't corresponding to the literature so a new experiment is needed where the four afore mentioned aspects are taken into account.

The variables of experiment B are tabled against the design requirements and the result of the experiment are put in the matrix according to three "values".
The aim of this experiment was to define the best (combination) of materials to comply to the compressive and tensile strength criteria.

	REQUIREMENT	SALINITY	FREEZING GRADUALLY	FREEZING AT ONCE
1	ISRU	V	x	V
2	Compressive strength cone	x	-	-
3	Compressive strength dome	-	-	-
4	Translucency	x	-	-

Table 33. Influence of the variables on the table of requirements.
V= greatly complies with the criteria compared to the other variables
X= does not comply (well) with the criteria compared to the other variables
- = does not apply/ no value found.

16.5 **Experiment C**: Mars analogue rectification tests

The conclusion made from experiment B is that the zero values are far away from the values found in the literature and therefore the tested values aren't considered as reliable. Therefore a new experiment is needed where the inconsistency of experiment B are rectified.

16.5.1 Aim and objectives

The aim of this series of tests is to find out which material or combination of material is the strongest in compression.
The objective of this series of tests is to rectify the experiment inconsistency from experiment B and get zero values which are close to the literature.

16.5.2 Set up

Matrix

The matrix is the same as the one used in experiment B, demi water is used. Demi water is short for demineralized water, which means salts are no longer present in the water therefore a specific quantity salt can be exactly measured and added and without other salts influencing the results.

Fibres

The only added element for experiment C is NaCl in different concentrations like experiment B as there was no issue with the fibres used. In experiment B, the highest concentrations of 14,3 ppt offered the highest compressive strength. In this test, only two different types of salinity are tested: 10 and 15 ppt.

Ice composite formation

The main difference between test B and C are the conditions of the ice formation and the tests performed. The specimens will be formed within an insulated box with an open lid in the same freezer as in experiment B at-70°C.
These temperatures are simulated within a freezer going up to -70°C at the Electronic Instrumentation Laboratory of the EWI faculty (TU Delft). The mould used for this experiment is a plastic cylindrical mould (M003) which has a watertight lid.

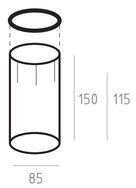


Figure 56. Mould used during experiment A. M003 is a cylindrical mould with dimensions based on the experiments made by NASA and Janssen and Houben.

Tests performed

The aim of this experiment is to determine the compressive strength of the samples and if the tested method and environment are accurate enough.

C02: Compression test.
The compression test is performed at the faculty of 3ME (TU Delft). The main difference with experiment B is that the specimen will be transported from the EWI faculty to the 3ME testing lab within an insulated box and will then be placed under compression at a temperature of-70°C (both the specimen and testing machine are within a freezing element). The specimens are first made at-70°C within an open insulated box which is closed when taken out of the freezer. The specimens are then transported to the 3ME faculty and led to gradually warm up for 30 min. The specimens are then demoulded, one by one, by placing the mould in water at room temperature (about 22°C). All the demoulded specimen are then placed within the testing cooling chamber at-70°C and one is placed under the compressive machine. The specimen are let to settle for 20 min before the first test is performed on specimen C0.001. Once the specimen fails, it is quickly taken out, observed and the following specimen is placed under the compressive foot. The test starts after 5 min of stabilisation after the door has been opened. This procedure is repeated for all specimen.

The parameters for the machine are set at:

Speed start	10	mm/min
path	none	
Pre-load	10	N
Speed pre-load	5	mm/min
Test speed	1	mm/min
Force shutdown	80	%

16.5.3 Variables and constants

The test variables define the amount of tests to be performed, these variables are defined by the literature findings and the results from the first two tests. As the tests are meant to be compared to each other, constants are also important to define.
Experiment C focusses on the percentage of salt needed and this will therefore be the only variable tested. As there are only three different variables: 0 ppt, 10 ppt and 15 ppt salinity, three specimens of each variable have been tested to have a more accurate comparison of the values.

The constants which will assess the variables are:

- Orientation of the fibres (all randomly oriented fibres),
- The mould is the same (M003) thus the specimen have the same dimensions and form,
- Freezing temperature (-70°C)
- Testing temperature (-70°C)
- Testing machinery
- Testing settings

Variables Experiment C

NaCl	0 ppt	10 ppt	15 ppt

Table 34. Variables of experiment C.

16.5.4 Zero measurement

The zero measurement, also called null measurement, is a measurement made on a standard sample without any variables to have a reference value. This enables comparisons between the variables and allows conclusions to de drawn. For both experiments the zero measurement sample is a pure H_20 ice block made in the mould used for all of the experiments. The tests performed are the same as the tests performed on the other samples. The test is performed on three specimens to determine the differences found.

The tested specimens are all compared to a plain water ice specimen on which the same tests are executed, which yields a null value allowing comparison between the specimens and variables as well as comparing values to the literature.

16.5.5 Results

Observations

The visual observations of the formed ice are similar to the observations made in experiment B. As the ice was made under similar conditions, this is reinforcing the conclusions drawn then, that the higher the salinity, the less cracks the structure presents.

Figure 57. The picture on the left shows all the specimen from experiment C with the three specimens on the left being ice with a salinity of 15 ppt, the three in the middle ice with a 10 ppt salinity and the three specimen on the right being a 0 ppt salinity ice. This picture shows the difference in ice translucency. The picture on the right shows specimen C0.001, full of cracks even before demoulding.

The results of the compression tests, hoewever, differ greatly from the compression tests from experiment B. The deformation curve goes up steadily with two breaks. After the definitive failure of the test we can see the deformation line dropping immediately pointing towards a brittle behaviour. Indeed when looking at the ice specimens after the test, a smooth clean cut can be seen in the horizontal plane. The higher the salinity the cleaner the cut. It is also noticable that the last two specimen, and especially C0.009, behave more plasticilly. Specimen C0.003 was not tested as the specimen broken upon demoulding.

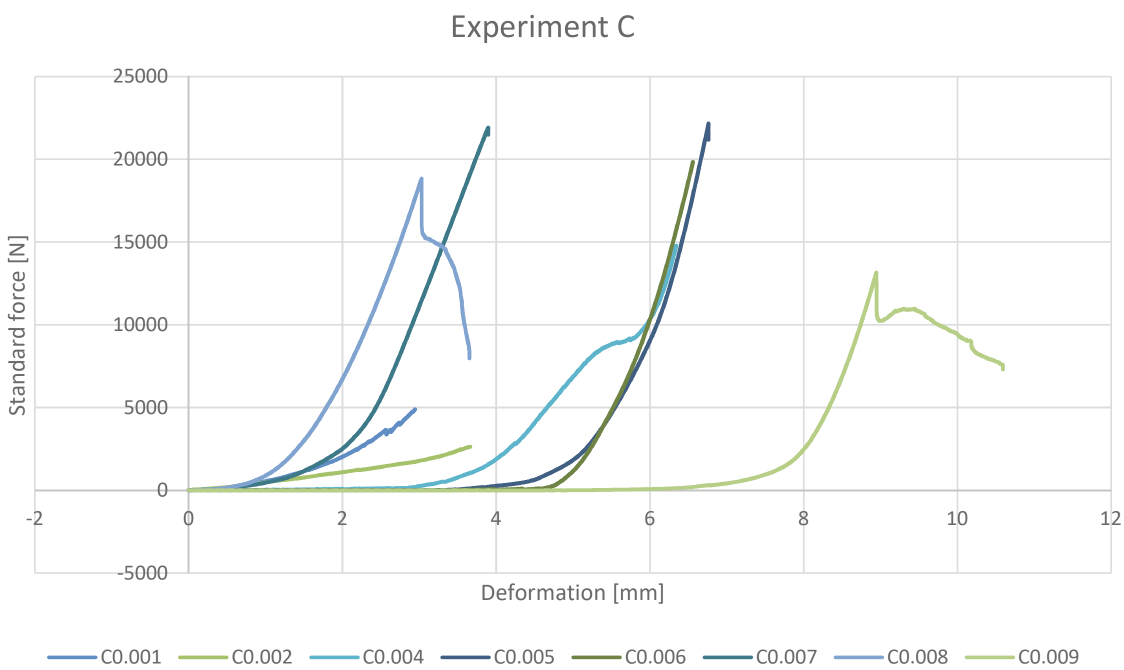


Figure 58. Graph with the results of the standard force and deformation from experiment C.

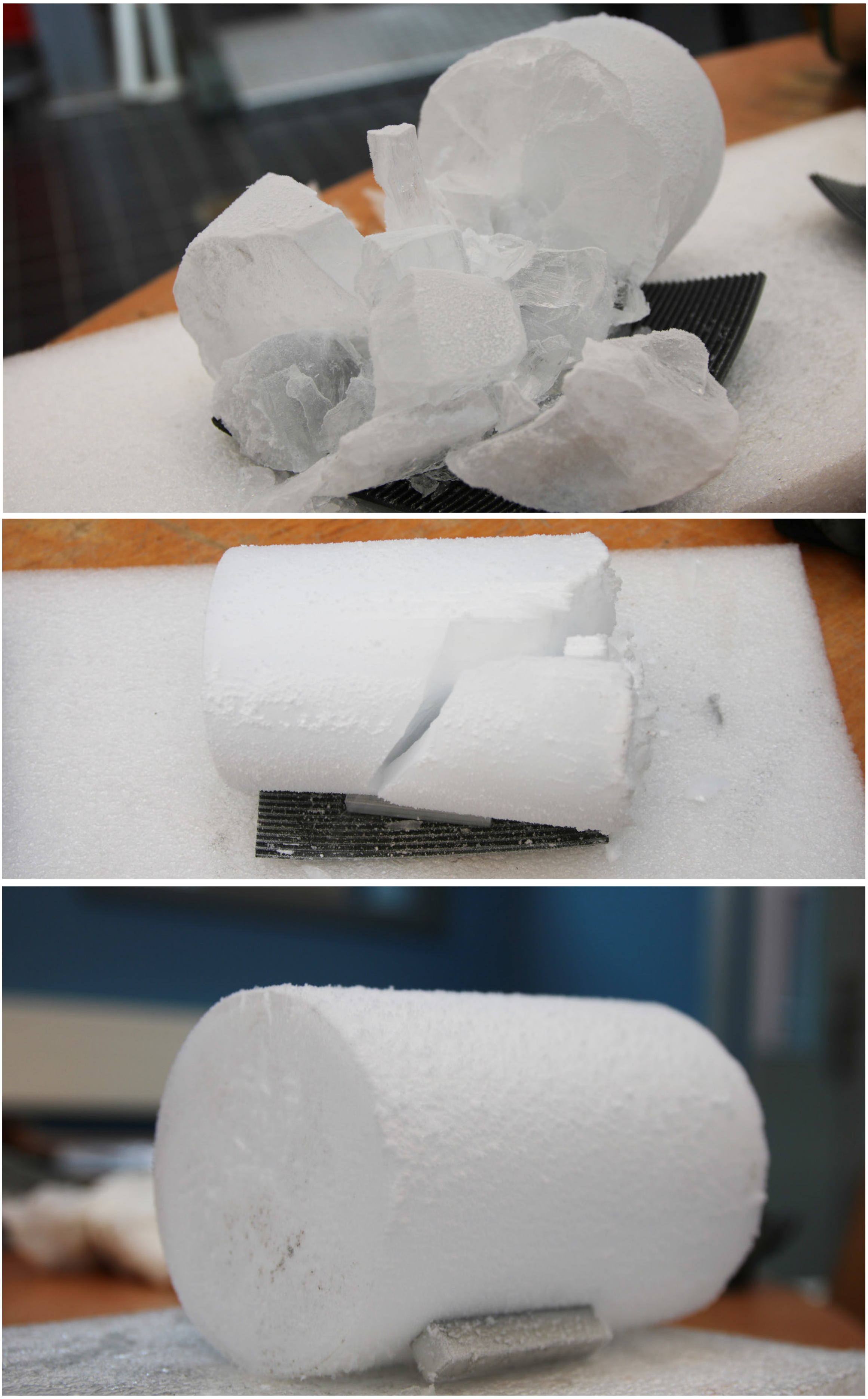


Figure 59. Specimens after compression test at-70 °C. Above, C0.001, in the middle C0.004 and on the bottom C0.007.

Analysis

Upon observing the deformation graphs, it can be seen that a break occurs at a quite low force and that the curve then peaks steadily again. This is apparently due to the non-uniform shape of the ice. Indeed, the cone is a bit truncated to allow stacking and easy demoulding. When the ice is placed horizontally, the machine makes first contact on the larger diameter until the "top" breaks off, allowing an even application of the force and therefore a higher support for compressive strength.

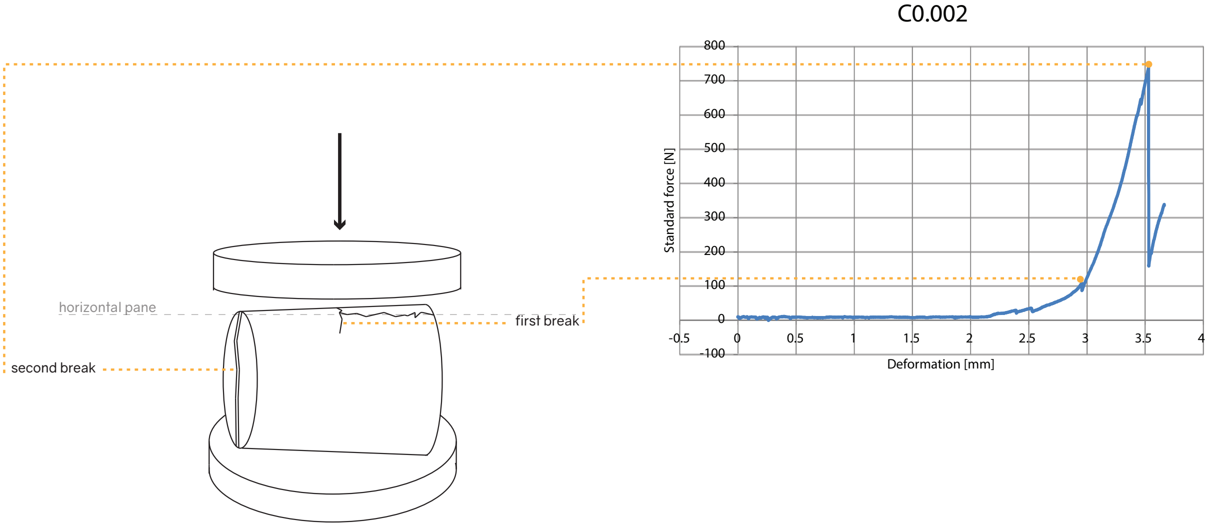


Figure 60. Visual representation of the first and second break in relation to the resulting deformation graph.

As said in the observation heading, the last two specimen (C0.008 and C0.009) have a more plastic deformation which can be compared to the deformation lines resulting from experiment B. This is probably due to the increase in temperature in the cooling chamber. Indeed, after specimen C0.006 was tested, the liquid nitrogen used to cool down the cooling chamber ran out. Therefore, the following specimens were not tested at-70°C but specimen C0.007 at-50°C and specimens C0.008 and C0.009 at-20°C. These are the values of the air temperature, most probably the ice specimens themselves were still much cooler. But the sudden rise in temperature indicates that the ice behaves differently when exposed to different temperatures. Therefore both experiments B and C indicate the behaviour of ice at different outside air temperatures which reflects how ice would behave through different moments of the day and year.

Conclusions

The specimens have a brittle behaviour when exposed to temperatures of-70°C. The added NaCl increases the overall compressive strength. However the increase in salinity from 10 ppt to 15 ppt does not increase the overall compressive strength of the specimens, however the failure behaviour is more clean in the specimens with 15 ppt salinity.

The variables of experiment C are tabled against the design requirements and the results of the experiment are put in the matrix according to three "values".

The aim of this experiment was to define the best (combination) of materials to comply to the compressive strength and translucency criteria. The best results were performed by the specimens with a salinity of 15 ppt.

	REQUIREMENT	SALINITY GENERAL	SALINITY 10 PPT	SALINITY 15 PPT
1	ISRU	V	V	V
2	Compressive strength cone	x	X	XV (better but still does not comply)
3	Compressive strength dome	-	-	-
4	Translucency	X	-	-

Table 35. Influence of the variables on the table of requirements.
V= greatly complies with the criteria compared to the other variables
X= does not comply (well) with the criteria compared to the other variables
- = does not apply/ no value found

17. Conclusion part C

Part C is focussing on finding the adequate material which complies to the set requirements. First a literature study is made on materials which are available on Mars with their "building" properties. Then, a research is made to find the material composition which will comply to the requirements.

The literature study and research (partly) provides answers to the following sub-questions:

- What potential building elements are found on Mars?
- Which of these elements are best suited to protect human beings against the harsh Martian environment?

Ice is the selected material to build a habitat on Mars. The reasons for this material choice is that ice is providing mass against radiation but still allowing daylight to go through the structure therefore, complying to the quantitative as well as the qualitative criteria set for the habitat. However, ice can be a weak material without reinforcement. On Earth wood pulp is often used, however it is not available on Mars, hence a new ice composite is needed.

Tests are made assessing ice reinforced with in situ materials such as regolith and salt and recyclables such as plastic. The most promising results came from the ice combined with sodium chloride and further tests were made to assess if this salt ice complies to the set requirements. Overall, the specimens tested do comply with the ISRU requirement but do not comply with the compressive test requirements and the specimens were not tested on translucency with measurement tools but only assessed with visual observations. To be able to thoroughly test for compliance with the set requirements more tests would be necessary. However due to time constraints of this research and capacity constraints of the facilities on the TU Delft campus, this will not be possible within this graduation research.

The experiments did give useful information about the overall behaviour of ice under different circumstances and with different fibres (plastic, sand and salt). The results show that the behaviour of the ice changes with the outside air temperature and thus the temperature of the material itself: the colder the ice the more brittle the ice is but the more load it can withstand. The behaviour and appearance of the ice also changes when adding salt to the water. The ice behaves more like toughened glass and it is therefore easier to predict failure.
This information is useful for the next phases of the project: the processing of the ice, the structural design and the habitat design phases.

However, as is mentioned at the beginning of this chapter, the values found for each specimen are valid for the specific specimen and making assumptions for the overall behaviour of a material should be made with caution.

Bibliography – PART C

Chow, B. J., Chen, T., Zhong, Y., & Qiao, Y. (2017). Direct Formation of Structural Components Using a Martian Soil Simulant. Scientific Reports,7(1). doi:10.1038/s41598-017-01157-w

Deliquescence. (n.d.).In Britannica. Retrieved November 25, 2017, from https://www.britannica.com/science/ deliquescence

Hodgkinson, J. M. (2000). Mechanical testing of advanced fibre composites. Boca Raton, FL: CRC Press.

Jahnke, T. S. (1996). Nylon Plastics Handbook Edited by Melvin I. Kohan (MIK Associates). Hanser: Cincinnati, OH. 1995. Journal of the American Chemical Society,118(34), 8186-8186. doi:10.1021/ja9655808

Janssen, F., & Houben, R. (2013). Reinforced ice structures: a research on the building method for the application of ice composites. Master's thesis, Eindhoven University of Technology, Eindhoven.

Mankins, John C. (1995). Technology Readiness Levels: A White Paper. NASA, Office of Space Access and Technology, Advanced Concepts Office.

Martínez, G. M., & Renno, N. O. (2013). Water and Brines on Mars: Current Evidence and Implications for MSL. Space Science Reviews,175(1-4), 29-51. doi:10.1007/s11214-012-9956-3

NASA, & Bradley University. (n.d.). NASA's 3D-Printed Habitat Challenge. Retrieved June 8, 2017, from http://bradley.edu/challenge/

NASA. (2015a). NASA Mars Rover's Weather Data Bolster Case for Brine. Retrieved June 6, 2017, from https://www.nasa.gov/jpl/msl/nasa-mars-rovers-weather-data-bolster-case-for-brine

Pons, A., Estop, L., Molins, E., Harris, K., & Xu, M. (2012). A new route to aerogels: Monolithic silica cryogels. Journal of Non-Crystaline Solids,358, 461-469.

Siracusa, V., Rocculi, P., Romani, S., & Dalla Rosa, M. (2008). Biodegradable polymers for food packaging: a review. Trends in Food Science & Technology, 19 (12), 634-643.

Vasiliev, N. (1993). On development of fibre-ice-composites. Cold Regions Science and Technology,21(2), 195-199. doi:10.1016/0165-232x(93)90007-u

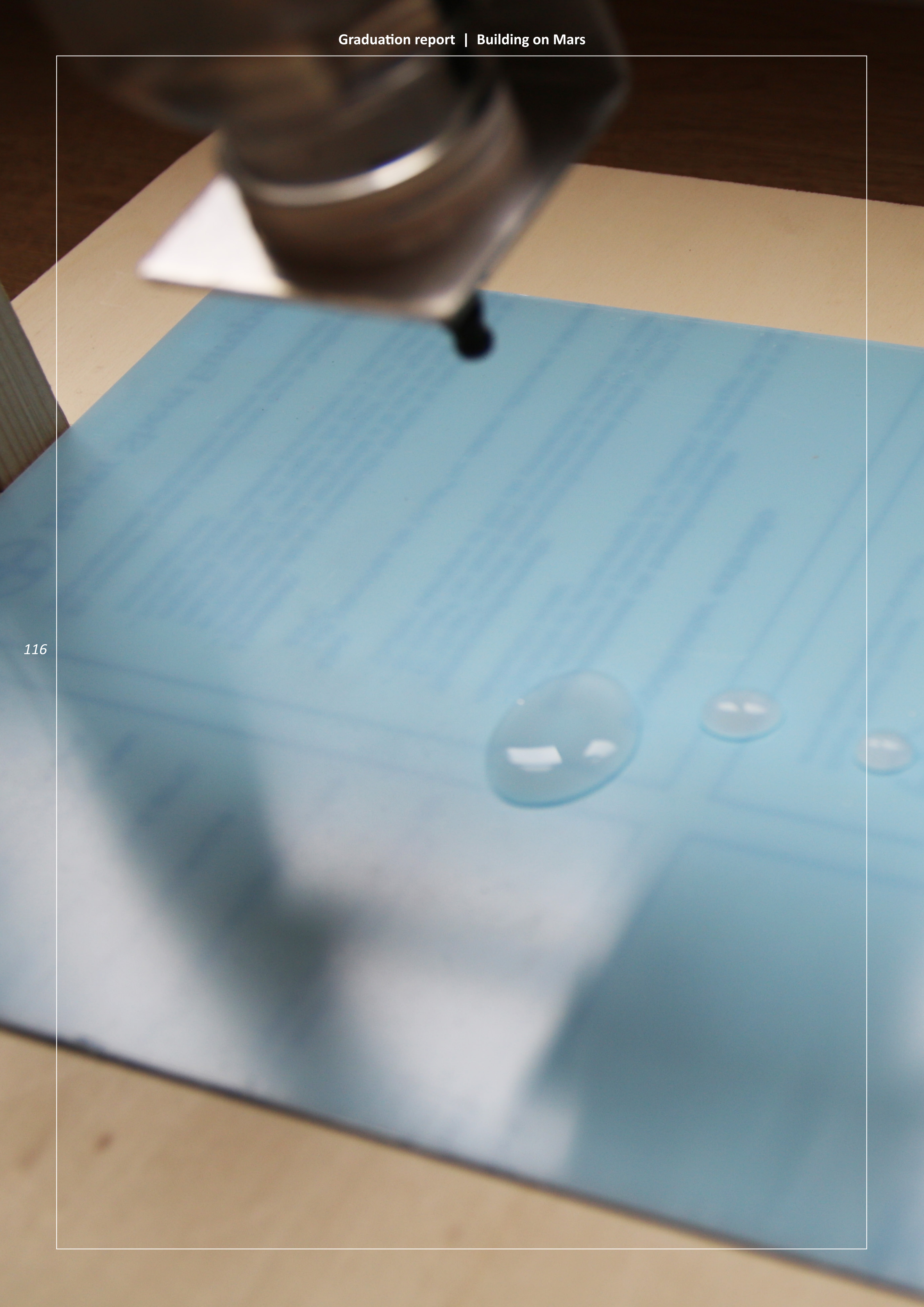
Vasiliev, N., Ivanov, A., Sokurov, V., Shatalina, I., & Vasilyev, K. (2012). Strength properties of ice–soil composites created by method of cryotropic gel formation. Cold Regions Science and Technology,70, 94-97. doi:10.1016/j.coldregions.2011.09.003

Vasiliev, N., Pronk, A., Shatalina, I., Janssen, F., & Houben, R. (2015). A review on the development of reinforced ice for use as a building material in cold regions. Cold Regions Science and Technology,115, 56-63. doi:10.1016/j.coldregions.2015.03.006

Other consulted documents:

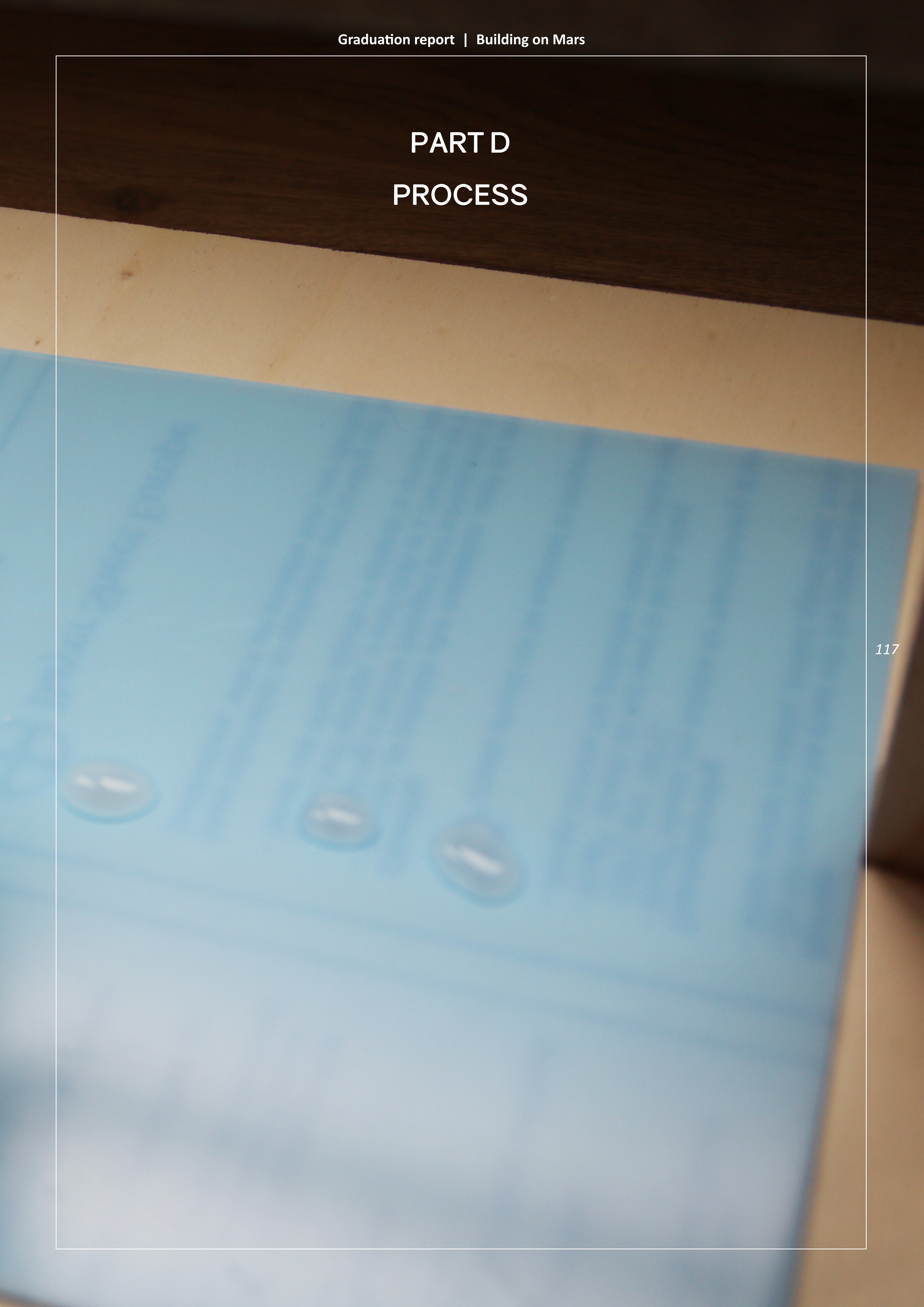
Hecht, M.H. (2002). Metastability of Liquid Water on Mars. Icarus, (156), 373-386.

Warmflash, D. (2015, September 28). Water on Mars: Astrobiology Implications Must be Taken with a Grain of Salt. Retrieved June 6, 2017, from http://www.visionlearning.com/blog/2015/09/28/water-mars-sounds-good-life-forms-problem/



PART D

PROCESS



Hallatt, A. (May, 2014). It's not fun to be a penguin if your neighbours are killer whales In Artic circle. Retrieved on November 26, 2017 from http://arcticcirclecartoons.com

Part D is focussing on finding the adequate process which meets the set requirements. First a literature study is made on the different semi-autonomous processes which are currently used for the different available Mars materials described in the previous chapter. Then, a research is made to find the best building process for the chosen material (NaCl and H_2O ice) which will comply with the requirements.

This chapter (partly) provides an answer to the following sub-question:

- How is an outer shell constructed out of this (combination of) element(s)?

18. Literature study

Due to the different properties of the materials explained in the previous chapter, different technologies are used to process and form the materials into habitable structures.

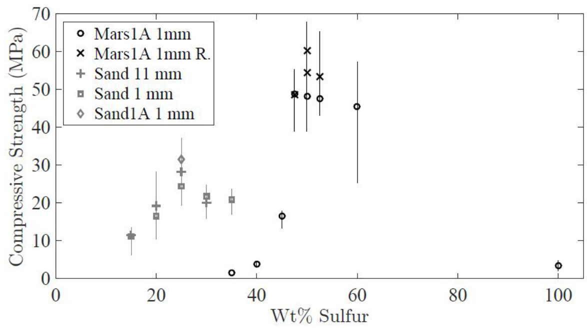
18.1 Forming techniques

18.1.1 Regolith

Regolith hasn't be used to build structures (yet) but some studies have been made in the prospect of building on Mars or the Moon. This chapter however will focus on developing techniques specific for Martian conditions.
The need for ISRU is high on Mars and therefore not only is the core material of importance but also the binders and process should be ISRU as much as possible. Most techniques to build a habitat out of regolith make use of calcination which is energy intensive or needs additive bonding agents from Earth (Chow, et al., 2017). However, two techniques have been developed using only ISRU to process, form and bind Martian regolith.

Sulphur binding

A study by the Northwestern University binds regolith with available sulphur to create "Martian Concrete" (MC). Initially the idea of sulphur binding was used to create Lunar concrete, however due to the lack of atmosphere of the Moon; sulphur sublimates which leads to a weak concrete structure. To test their theory that the atmosphere of Mars will avoid this problem the Martian soil simulant JSC Mars-1a was used. The "Martian concrete" is based on Earth sulphur concrete and is made by hot mixing, casting and cooling down of 50% sulphur and 50% JSC Mars-1a. The sulphur reacts with the rich metals present in the soil which improves the strength of the MC. The resulting properties of the MC are shown in the table below. To obtain these properties, especially the strength, the particle size distribution has a great influence (Wan, Wendner, & Cusatis, 2016).



Boundary Condition of Compressive Loading	Quasi-static Compaction		Dynamic Compaction	
	Average Flexural Strength (MPa)	Optimum Peak Compression Pressure (MPa)	Average Flexural Strength (MPa)	Impact Pressure (MPa)
Rigid	10	720	13	~400
Free	27	800	40	>800
Flexible	25	360	50	~400

Figure 61. Compressive strength of sulphur concrete based on the wt% of sulphur in the component (Wan, et al., 2016, p. 10).
Table 36. Difference of the boundary conditions (rigid, free and flexible) on flexural and compressive strength of the material (Chow, et al., 2017, p. 2).

Pressure forming

A study by the University of California demonstrated that subjecting Martian soil simulant to high pressure compression results in solids. Usually, basaltic particles do not adhere to each other when compressed unless heat is applied. In this case, the study determine that the nanophase ferric oxide (npOx) present in the Martian soil acts as a binding agent under the right pressure. To determine this result, a widely used soil simulant JSC Mars-1a with a chemical composition of 43,48 wt% SiO_2, 16,08 wt% Fe_2O_3 and FeO, 4,22 wt% MgO, 6,05 wt% CaO, etc. was used the same simulant used to test the MC in previous heading). The tests were conducted with a piston which applied two rates of loading (quasi static and impact) from the top and with three different lateral boundary conditions, rigid, free and flexible. The results were compact disc-shaped geometries which were cut into beams and then tested in a three point bending test. The results are shown in table 36. As can be seen, the particle size is not of influence under quasi static loading. However, the lateral boundary conditions have great impact on the flexural strength and shape of the compacted elements. The free and flexible boundaries resulted in a *R* of nearly three times higher than the rigid boundary. Even more, at R ≈30 MPa the flexible boundary shows a 150-200% greater strength than the free boundary (Chow, et al., 2017).

18.1.2 Ice

Saw (igloo)

The most traditional ice building method is to saw building blocks out of snow. This method is how igloos are built using only snow, a saw and a snow spade. Once blocks are created they are stacked hemispherically on top of each other like in the picture below. The cracks that appear between the blocks are filled with snow. Once the igloo is built a fire is lit inside and when the walls/roof starts to melt the fire is put out and a ventilation hole is created which freezes the melting snow into a thick and impermeable layer of ice. This method is quick and requires few tools but it only works for relatively small shelters as large structures will collapse due to the own weight of the snow (Janssen & Houben, 2013).

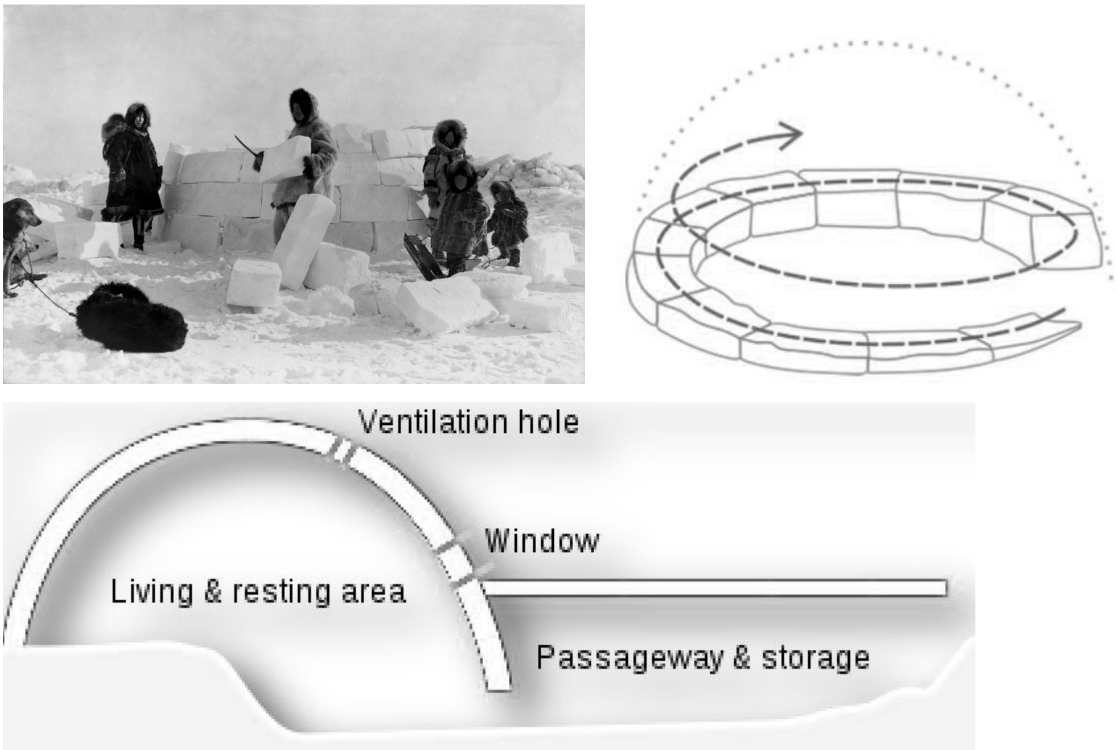


Figure 62. Above: Construction method for an igloo: sawing ice blocks and stacking them hemispherically (Igloo, 2017). Under: Construction method for an igloo: hemispherical stacking of ice blocks and section of the climate principle (Janssen & Houben, 2013, p. 77).

Natural ice blocks

The most common ice building method today is harvesting natural ice which forms on lakes or rivers. The ice is sawed which creates ice blocks which are strong enough to be stacked on top of each other. The best ice is made by rivers as the water is flowing underneath it which allows it to freeze equally creating translucent blocks of ice. This building method is used to build ice palaces and hotels from Canada to Russia where the first ice palaces were built in the eighteenth century. This method creates strong and simple buildings. The main drawback however is that natural ice can't be found everywhere and weather conditions need to be favourable (Janssen & Houben, 2013), which gets tougher every year due to climate change.

Figure 63. Ice blocks being harvested from a frozen lake for the Ice Bar London. Retrieved from https://twitter.com/ICEBARLONDON

Spraying water

The most recent methods spray water or a water composite on top of a membrane. The membrane is either a cloth or an inflatable and reusable plastic membrane. This method is relatively new and still very experimental but it allows a free form design. The main component used is a high pressure duct which sprays thin particles of water. To reinforce the structure, the water is sometimes mixed with snow or wood pulp to create pykrete as is mentioned in the material chapter (Janssen & Houben, 2013). This method of reinforcement and spraying allows large structures to be built like the pykrete dome and a replica of the Sagrada Familia.

Figure 64. Building of a scale Sagrada Familia from ice in Juuka, Finland by TU Eindhoven students. Retrieved from http://www.elmenymuhely.hu/megfejtettuk-a-da-vinci-kodot-4dframe-elmenymuhely-a-jeg-hatan-is-finnorszagban/?lang=en

18.2 Additive manufacturing

For its Journey to Mars mission, NASA plans on sending a space craft with the building materials first and then sending the crew which can then directly move into the habitat (NASA, 2017). This means that the habitat should be autonomously or semi autonomously built. An autonomous and multifunctional technology is additive manufacturing (AM). The term additive manufacturing overlaps many technologies including: 3D printing, rapid prototyping, direct digital manufacturing, layered manufacturing and additive fabrication (Amazing AM, n.d.). These forms of AM would have to be incorporated onto robots or rovers or be added at the end of a robotic arm to allow a habitable structure to be built. The AM techniques used depend primarily on the material used and secondly on the structure which has to be built. A few AM techniques are tested in the ISS, among which the Zero-G Printer which demonstrates that building in zero *g* is much the same as at 1*g*.
The most used materials in AM are thermoplastic polymers like Polylactide acid (PLA) and Acrylonitrile butadiene styrene (ABS), however these aren't available on Mars, thus, the AM potential of the available in situ materials is analysed.

18.2.1 Nylon

Nylon is one of the mission recyclables and is considered as reinforcement material for other ISRU. As polymer Nylon is therefore often used as printing filament because of its qualities. The most important qualities are durability, low friction coefficient and a high tensile strength. It is therefore a really flexible material with a lot of freedom of design and already lots of applications (Amazing AM, n.d.). However, it is a mission recyclable therefore it is only available in small quantities on Mars.

18.2.2 Ice

As PLA is the most used material for AM, a table first compares the properties of ice with those of PLA.

specs	unit	Ice (at -70°C)	Polylactic Acid (PLA)
Density	g/cm3	0,9233	1,21 - 1,43
Melt temperature	°C	0	157 - 170
Injection Molding temperature	°C	5 - 10	178 - 240
Tensile strength	MPa	nd	61 - 66
Compressive strength	MPa	3 - 10	48 - 110
Shrink rate	%	-0,0035*	0,37 - 0,41
specific heat	kJ/kgK	1.609	
thermal conductivity	W/mK	3.05	0,13
viscosity	mPas	1,308 (water)	

* ice does not shrink but expands

Table 37. Properties of ice compared to polylactic acid (PLA) to assess the potential AM possibilities.

A few examples of AM with ice are already widespread. As the material is cheap and widely available, 3D printing with ice becomes more popular. However, building a machine that can achieve this can prove problematic. Pieter Sijpkes et al., built a machine capable of printing ice (Barnett, Angeles, Pasini, & Sijpkes, 2009) which was used for the scale model of the Mars Ice House by Clouds AO (Morris et al. 2016). The process of AM with ice is called Rapid Freezing Prototyping (RFP) with water (Zhang, Leu, Ji, & Yan, 1999). Scientists from McGill University made a prototype for a RFP machine. They used a normal RP machine but replaced the screw-driven nozzle with two valve nozzle systems. One is to extrude water under pressure of at least 30 kPa and at 10 ˚C. The other valve nozzle is to extrude brine as support of the structure which can later be melted without melting the ice due to its lower melting point. The whole system needs to be insulated to prevent the ice and brine to freeze within the tubes as well as at the exit of the valve. The printed water is frozen by contact with the previously deposited ice and with the freezing air temperature. An important aspect of RFP compared to other AM technologies is that the material expands greatly. Therefore, the CAD model should be designed to leave enough spacing to allow the expansion without putting the structure under unnecessary stress (Zhang, et al., 1999; Barnett, et al., 2009).

The paper written by Barnett et al. in 2009 also includes a complete table of the building parameters of the machine used to 3D print ice structures (one a brandy glass and one a snowflake wall). These designs are all made with a cartesian setting which is ideal for small objects, but difficult for bigger structures like a habitat. This would indeed imply a large machinery which would have to be even larger than the structure to be build. Another technique is usually used for larger AM structures using a robotic arm which has more flexibility and can even be mounted on a moving robot (Khoshnevis et al., 2005). However, this technique has not been applied yet with ice as building material.

BUILD PARAMETERS FOR THE FAH AND THE COBRA

Parameter	Range[a]	Ex. 1[b]	Ex. 2[c]
Nozzle diameter (D, mm)	0.05–0.25	0.10	0.05
Path width (w_p, mm)	0.5–1.5	1.0	0.8
Path height (h_p, mm)	0.05–0.5	0.47	0.10
Path speed (v_p, mm/s)	0–100	15	25
Gauge Pressure (p, kPa)	0–55	30	30
Valve duty cycle (N, %)	0–50	30	30
Valve frequency (Hz)	0–450	150	250
Freezer temp. (°C)	-23	-23	-23
Water/brine temp. at nozzle tip (°C)	0–20	10	5
KCl concentration (kg/m^3)	0–280	80	80

[a] Range of values attainable with the hardware we currently have.
[b] Parameters for the brandy glass shown in Fig. 6.
[c] Parameters for the Koch snowflake structure shown in Fig. 7.

Table 38. Building parameters of the FAH and the COBRA machines for RFP (Barnett, Angeles, Pasini, & Sijpkes, 2009).

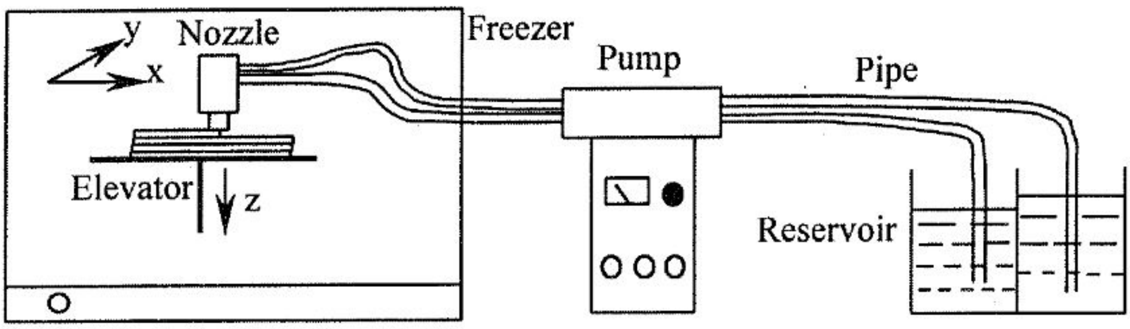


Figure 65. Scheme for a RFP prototype using under pressure water (Zhang, et al., 1999, p. 187

18.2.3 Regolith / Sand

Techniques using AM for sand usually require high heat. The Solar Sinter project uses AM techniques and sintering techniques by using direct solar radiation to directly melt sand to create glass objects by a process known as selective laser sintering (SLS). This method was tested in the Sahara Desert in Egypt and in Morocco. By harvesting solar rays into a glass ball lens a new kind of laser is created which melts the desert's sand into glass. This method is quite energy neutral as the energy used is only solar for the laser as well as for the electronics required to move the sand using pv cells (Kayser, 2011). This method is promising and is used in the LAVAHIVE concept to create Martian habitats. As the Martian regolith is finer than desert sand, possibly less energy would be required.

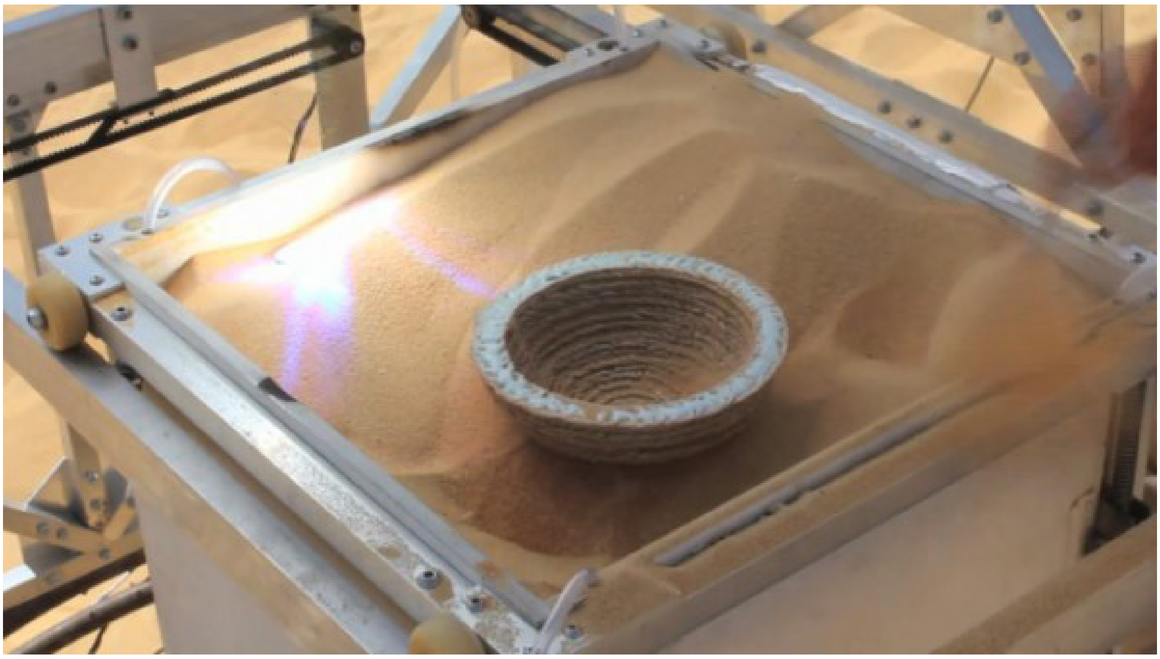


Figure 66. Bowl made out of sand from the desert by solar sintering (Kayser, 2011).

Another technique for additive manufacturing with sand/clay is contour crafting. Contour crafting has been developed by Behrokh Khoshnevis to reduce the overall costs and building time for housing. Khoshnevis uses a large cartesian printer which prints structural elements as well as walls and floors. However this machinery is far too large and heavy to use in space as the volume and mass requirements are strict (see chapter 5.3: mission constraints). Therefore, the contour crafting company worked together with NASA to produce a robotic arm capable of printing structural elements in space, mainly on the Moon. However, the scale prototype was made in two steps, therefore the technology to make the top of the dome is not ready yet (Khoshnevis, et al., 2005).

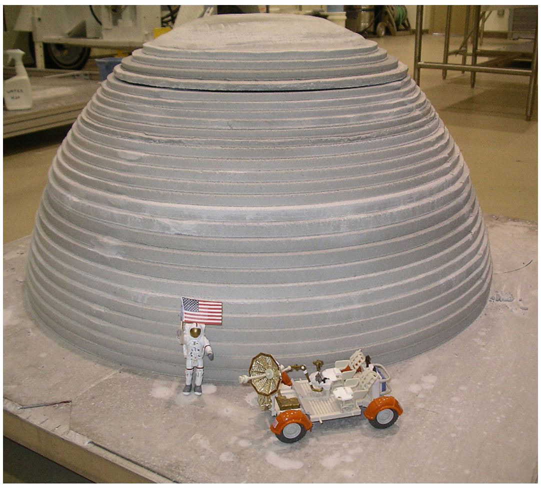


Figure 67. Prototype of a lunar habitat build with lunar regolith simulant using CC (Khoshnevis, et al., 2005).
Figure 68. The Grip Minibuilder mounting the structures it is building (Stott, 2014).

The Institute for Advanced architecture of Catalonia, the IAAC, is also analysing AM techniques and invented the Minibuilder. Minibuilders are small scale robots which mount the structure they printed in order to keep the size of the robot small and still build large scale structures like buildings. This task is performed by different robots: the Base robot (building the base), the Grip robot (building the rest of the structure) and the Vacuum robot (which adds strengthening to the structure) (Stott, 2014). This is still experimental but the principle looks promising for the construction of a full scale habitat on Mars.

18.3 Conclusions

Lots of different promising techniques are researched and used on Earth to build with ice, regolith and nylon. However, Martian conditions are different from Earth conditions. Therefore autonomous processes are favoured over semi-autonomous processes. Most AM techniques are promising but are tested at conditions very different from Martian conditions, especially the pressure would be of great influence on machinery as well as on final product.

METHODS - MATERIALS	SULPHUR BINDING	PRESSURE FORMING	NATURAL HARVESTING (SAW)	SPRAYING	AM	RESULTS
ICE	0	1	1	1	1	**4**
PYKRETE	0	0	0	1	0	**1**
CRYOGELS	0	0	0	1	0	**1**
REGOLITH	1	1	0	0	1	**3**
NYLON	0	0	0	0	1	**1**
RESULTS	**1**	**2**	**1**	**3**	**3**	

Table 39. Different potential building materials tabulated against different potential building methods. The results indicate that Ice and regolith are the most flexible material in terms of processing method and that spraying and AM are the most flexible method in terms of applicability to the materials.

19. Construction process for an ice habitat for Mars

This chapter focusses on a building process principle for a salt ice structure on Mars. The research is based on the previously found material properties of the sodium chloride ice.

19.1 Requirements

The requirements of the processing of the ice are summarized based on the literature study and research done in part C.

	REQUIREMENT	VALUE
1	(Semi) autonomous	100 %
2	Machines amount	ALARA (As Low As Reasonably Achievable)
3	Weight capsule	500 kg
4	Volume capsule	⌀ = 9m and h= 30m max
5	Time	700 sols

Table 40. Requirements for the process of a habitat for a sustainable habitat on Mars based on the literature findings.

19.2 Research based on the material properties

19.2.1 *Freezing time of the ice: calculations and experiment.*

As time is a constraint, the building time of the habitat is of great importance. When using water which will freeze when exposed to the cold Martian environment, the freezing time has to be calculated. The heat conduction and resulting R-value of the ice dome on Mars has been calculated and were found to be 9616,9855 W/m²K and 0,000104 respectively.

FORMULAE	DEFINITION	UNIT	VALUE FOR DESIGN
Q= P.C.ΔT.V			
Q	absorbed heat	Jm^3	1946796.208
P	density of air (Mars)	kg/m^3	0.02
C	specific heat (Mars)	J/kgK	1016
ΔT	temperature difference	K	70
V	Volume	m^3	1368.67
Q=A.(T1-T2).A			
Q	heat conduction	W/m^2K	9616.9855
A	mean thermal conductivity	$Jm^{-1} s^{-1} °C^{-1}$	3.05
T1	temperature of the object (ice)	K	274.15
T2	temperature outside	K	203.15
A	area	m^2	44.41
R= 1/Q	R value	Km^2/W	0.000103983

Table 41. Calculations of the heat conduction of a 650 mm ice dome on Mars.

These values differ greatly from more typical R-values found in the built environment on Earth. The following table is an example of a typical insulated Dutch cavity wall.

MATERIAL	THICKNESS	THERMAL CONDUCTIVITY	R-VALUE
	m	W/mK	m^2K/W
SAND STONE	0,02	1,3	0,0154
CAVITY (AIR)	0,04	0,024	1,66
MINERAL WOOL	0,22	0,034	6,47
R_E	-	-	0,04
R_I	-	-	0,13
R_C VALUE WALL			8,32

Table 42. Typical insulated Dutch cavity with its thickness and thermal conductivity and the resulting R-value.

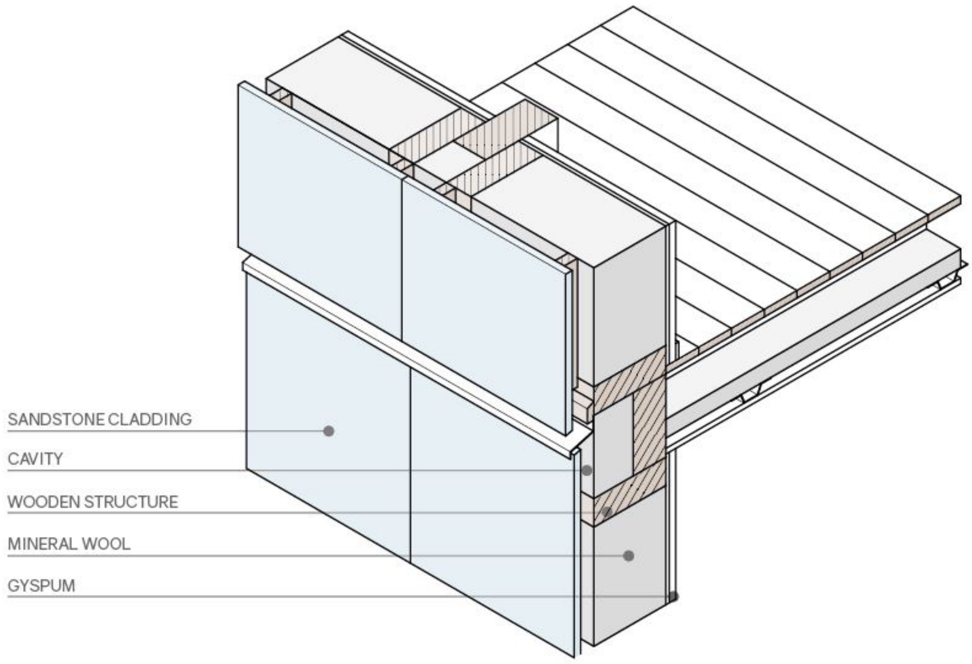


Figure 69. Three dimensional detail of a typical Dutch cavity wall (based on drawing by Schouten, N. 2017).

As the values differ greatly while we ignore if this is due to the material properties or the peculiar properties of the Martian environment, a physical test is executed to validate the hand calculations.
A plastic cylinder is put in a freezer at -20°C on Earth with a diameter of 850 mm. The cylinder is first filled with sand to simulate the ground on Mars and then it is filled with different water layers. The first layer of water of 200 mL is put on in the cylinder to freeze. It takes 32 min to freeze completely. The next layers are approximatively 5 mm in height (25 mL) and take roughly 28 min to freeze. The hand calculations for this experiment are found in table 43.

These findings indicate that the ice will freeze rapidly especially when the temperatures are lower. Therefore it would be more efficient to print when temperatures are at their lowest: during the night. This means that solar energy is not the most effective solution and that fission power might be more useful in this case. The printing during the night also means that the ISRU plant for the return journey fuel could work more effectively during the day.

FORMULAE	DEFINITION	UNIT	VALUE FOR DESIGN
Q= P.C.ΔT.V			
Q	absorbed heat	Jm^3	13.80232
P	density of air (Earth)	kg/m^3	1.225
C	specific heat (Earth) at 250K (-23°C)	J/kgK	1.006
ΔT	temperature difference	K	20
V	Volume	m^3	0.56
Q=A.(T1-T2).A			
Q	heat conduction	W/m^2K	28.1064
A	mean thermal conductivity	$Jm^{-1} s^{-1} °C^{-1}$	2.39
T1	temperature of the object (ice)	K	274.15
T2	temperature outside	K	253.15
A	area	m^2	0.56
R= 1/Q	R value	Km^2/W	0.035579085

Table 43. Calculations of the heat conduction of a Ø=850 mm ice layers in a freezer (-20°C) on Earth.

19.2.2 Sublimation rate of pure water ice.

The freezing rate of the ice is important to build the structure, however, once it is built it should stay in the solid state for as long as possible. As the temperatures and pressure are so low, the ice won't melt into a liquid. These conditions, however, make sublimation into a gas state possible, therefore damaging the built structure. Hence the sublimation rate of the ice wall is estimated.

In Ingersoll (1970) the sublimation rate of ice is determined following the next equation:

$$E_s=0,612*\Delta\eta*\rho_{atm}{}^{D}*[((\Delta\rho/\rho)*g)/v^2]^{1/3}$$

With
E_s= sublimation rate [mm/h]
Δη= concentration difference at the surface of a sample and at distance
ρ_{atm}= atmospheric density [kg/m^3] = 0,02 for Mars and =1,225 for Earth
D= diffusion coefficient for water in CO_2= $1,4*10^{-3}$ m^2/s
v= kinematic viscosity CO_2= $6,93*10^{-4}$ m^2/s
g= acceleration due to gravity [ms^{-2}]

This equation gives the following table of loss rate of pure water ice. This table is for ice on Earth (g ≈ 1) therefore if these values are used for Martian ice, the pressure needs to be taken into account. The table was made in 1970 and only goes to a minimum temperature of 255K, far above the lowest temperature found at Jezero crater.

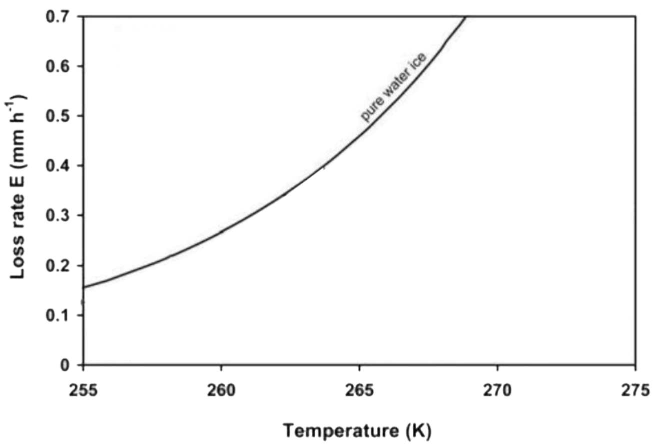


Figure 70. Loss rate of pure water ice and of ice under a regolith layer based on Chevrier, et al, 2007.

Therefore finding the sublimation rate of the pure water ice at Jezero requires adapting the values of the table to the multiple different temperatures and pressures values of Jezero. As these values are constantly fluctuating, three ranges are determined: a high value (which is the worst case scenario in terms of sublimation), an average value (which is deduced from the values most commony found at Jezero) and a low value (which is the best case scenario). The temperature and pressure for the three ranges are determined from the climatic database.

High (peak during the day): 773 Pa and 260 K
Average: 670 Pa and 220 K
Low (peak during the night): 583 Pa and 190 K

These values translate to a loss rate of[10]:

High (peak during the day): 773 Pa and 260 K → 0,0804 (from the table 0,28 mm/h on Earth at 260K)
Average: 670 Pa and 220 K → 0,0335 (assuming 0,05 mm/h on Earth at 220K)
Low (peak during the night): 583 Pa and 190 K → 0,0000 (assuming 0 mm/h on Earth at 190K)

Considering the daily temperature flux presented in chapter 3.2 Climatology, the daily average loss rate is calculated:

High (peak during the day):	6h → 0,0804*6	= 0,4824 mm
Average:	12h → 0,0335*12	= 0,40200 mm
Low (peak during the night):	6h → 0,0000*6	= 0,00000 mm
		= 0,8844 mm /day

Assuming the minimum radiation requirements for an ice wall of 325 mm thickness, the whole structure would take 367,48 (Earth) days to sublimate. In the current design, there are two ice walls, one is protected and will therefore not sublimate and the other one is unprotected with a thickness of 650 mm. This unprotected wall will take 734,96 (Earth) days to entirely sublimate.

This means that during a 550 days mission, the wall would still be thick enough to protect against radiation even at the end of the mission. However, these are values for pure water ice and not for a NaCl brine which is used for the design of the ice wall. It has to be taken into account, that these calculations (and therefore conclusion) are all experimental and based on a lot of assumptions. Hence, these are an indication rather than value to base a design on.

19.2.3 Thermal expansion of the ice.

Building a dome out of water is not done by "just" printing it. A dome requires small cantilevers when the shape is build going up, this is easily done with materials that have high viscosities like clay as the cantilever is quite small and the clay dries faster than it takes to fall. However, water will fall rapidly making it impossible to use regular AM techniques.

10 assuming the line continues to decrease with a decrease in temperature which other studies suggest (Chevrier, et al, 2007).

Figure 71. Building a dome out of water layers which freezes into ice requires a design solution for the cantilever part.

A first design idea is to use the thermal expansion of the ice to make this small cantilever as water expands when freezing into ice. Ice has a linear expansion which can be calculated with the following formula:

$$\Delta V/V = \alpha * \Delta T$$

With $\alpha \sim 50*10^{-6}$ deg^{-1}

$$\Delta V/V = \alpha * \Delta T = 50*10^{-6} * 70 = 0{,}0035$$

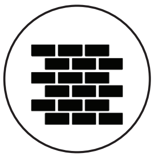
Figure 72. Using the thermal expansion of the ice could be one solution to the problem.

The feasibility of this preliminary design idea depends on the method used to build the habitat. Therefore a process principle is chosen in the next heading.

19.3 **Experiment D**: Process principle

19.3.1 Process principle

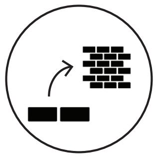
The five process principles used for building with ice on Earth and the one principle used in the design of the Mars Home are now all assessed. Each principle is assessed with the set requirements for a building process on Mars as well as with the sustainability requirements set out in part B. As can be seen in figure 73, the principle which complies best with the set requirements are: filling vacuum pockets, spraying onto a membrane and spraying onto itself (AM). However, from a feasibility point of view, spraying fine water particles onto a membrane will not work as the harsh Martian conditions (extremely low temperature and low pressure) will make the particles freeze or sublimate in mid-air. The two lasts options are good options to further investigate.
In part B of the report, the sustainability ambition level for the habitat is a class IV technology. The principle of spraying the ice onto itself by AM which would expose the ice bare to the Martian environment would classify as technology class IV and will therefore be chosen for further development. Redundancy is critical in space and this technology will not provide that. Therefore it is chosen to combine both options of vacuum filling pockets (which has a high TRL due to the controlled environment of the pockets) with an extra AM ice wall to ensure redundancy as well as that the high sustainability ambitions are met.



Stacking blocks I

requirements

(semi) autonomous	v
machine amount	v
weight	x
volume	x
time	x



Stacking blocks II

requirements

(semi) autonomous	v
machine amount	x
weight	x
volume	x
time	x

Filling vacuum pockets

requirements

(semi) autonomous	v
machine amount	v
weight	v
volume	v
time	x

Spaying on membrane

requirements

(semi) autonomous	v
machine amount	v
weight	x
volume	v
time	v

Spraying onto itself

requirements

(semi) autonomous	v
machine amount	v
weight	v
volume	v
time	x

"Air" balloon

requirements

(semi) autonomous	v
machine amount	x
weight	v
volume	x
time	x

Figure 73. Building process principles based on the literature findings on building with ice on Earth. Each is assessed on the design requirements set with v=complies to the requirements, x= does not comply to the requirements.

19.3.2 Methodology

The spraying of water droplets onto the structure (spraying onto itself) is the selected method based on the theoretical compliance with the set criteria (see figure 74). To assess the feasibility of the method with the designed salt ice tested in part C, physical tests are needed. Just as the experiments made during the design of the material phase, the process experiments are a proof of concept rather than reflecting the reality. This is mainly due to time and budget constraints. This method is similar to AM techniques.

19.3.3 Aim and objective

The aim for the test is to find out which process principle has the highest potential to build a habitat on Mars with the salt ice.
The objective of this test is to find out the freezing rate of the ice composite and compare them to the manual calculations. The second objective is to find out how the ice layers bond with each other and if they can be "stacked". The goal of the test is to compare rather than to obtain specific values.

19.3.4 Set up

As building a three dimensional robotic arm which can "print" the ice is time consuming and costly, a linear system has been built. The systems consist of two main elements: a frame and a water dispensing bottle. The bottle has the water drop at a constant rate via a micro drip system which is mounted on the bottle. This drip system allows only a few droplets to fall down instead of a water stream. The rate of the droplets is made constant by an air inlet tube placed within the water (based on the Mariotte's bottle principle). The bottle is mounted on a rail which is in turn attached to a frame. The rail allows the bottle to make a linear movement which can then be repeated to "print" a wall structure. The bottle moves with help of two weights of similar mass which, when given an extra push, allow linear constant movement. The frame and bottle is placed in a freezer going to -30°C to "print" the layers. The outcome of the test is visually assessed.

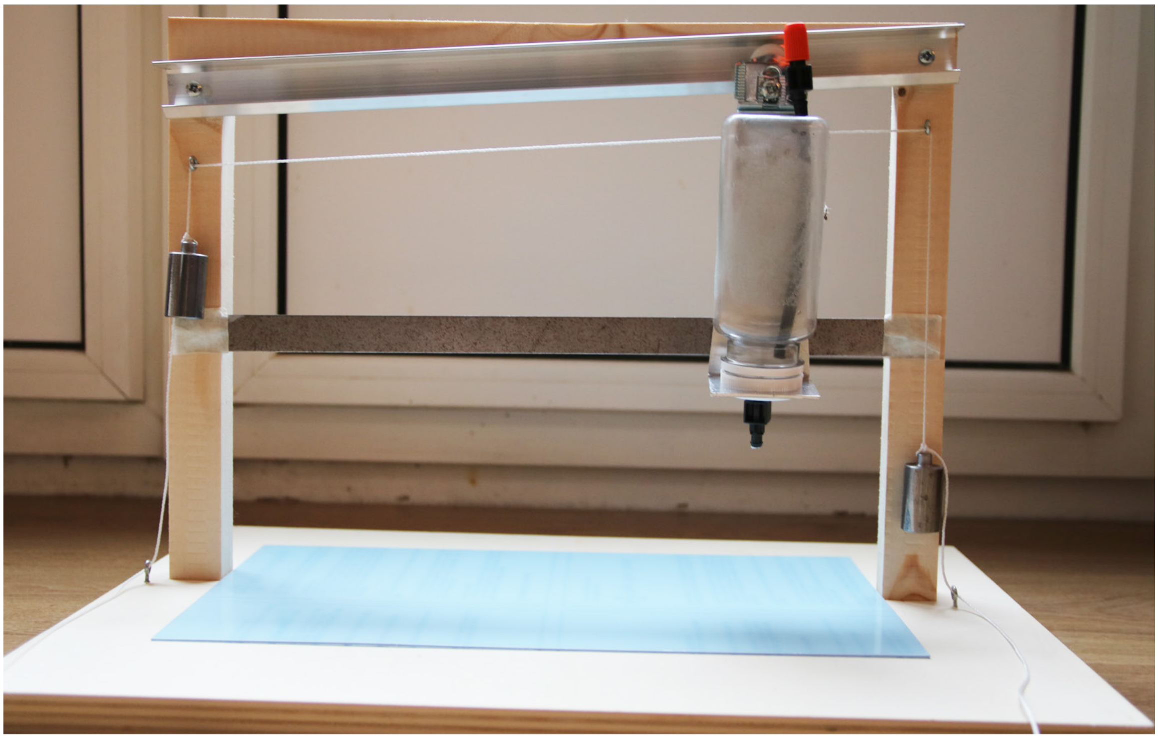


Figure 74. The test set up. The linear frame with the Mariotte's bottle with the micro drip system mounted on the frame.

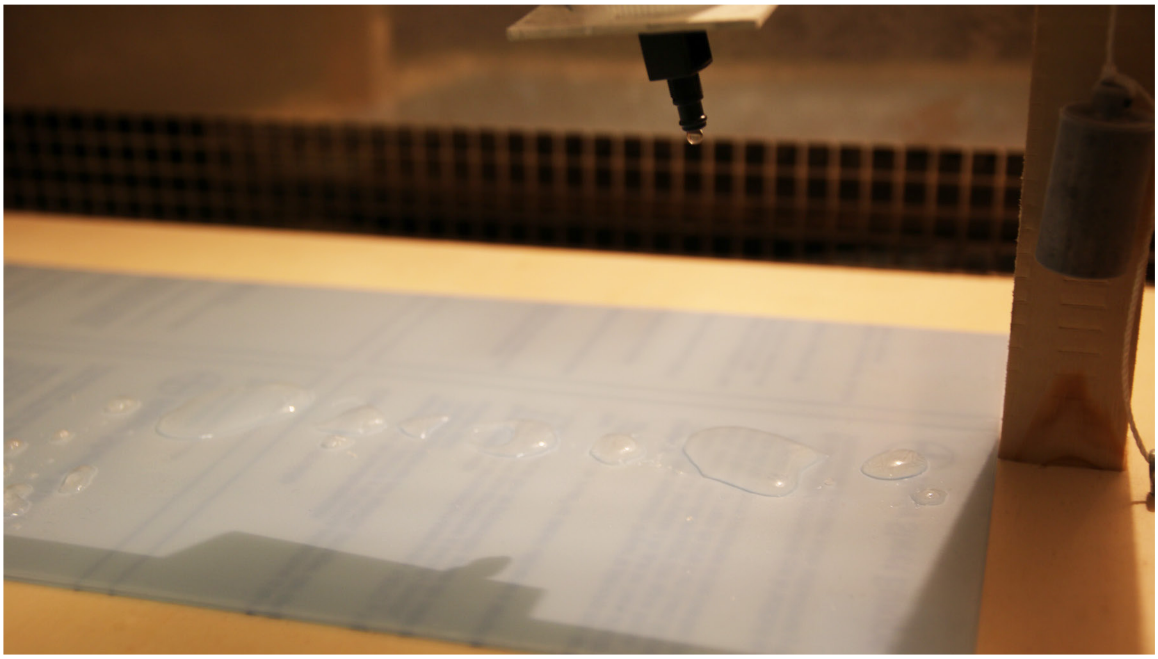


Figure 75. The first layer is "printed". The water forms different sizes of droplets as some drops merged together to create larger drops.

19.3.5 Results

Observations

The first “printed” layer formed large droplets which merged together rather than creating a continuous line. This first layer creates different droplets of different sizes with the smallest having a diameter of approximatively 2 mm to the biggest having a diameter of +/- 35 mm. However, after “printing” the other layers, the ice formed a linear shape. The increase in layers decreased the freezing time as well as the overall width of the linear structure creating a slightly sloped “wall”. The last printed layer created a crack in the ice structure underneath, probably due to the difference in temperature of the water/ice.

Once all the layers were printed (9 in total), the structure was left in the freezer overnight at a temperature of -70°C. After 12 hours, the ice sample was taken out of the freezer and observed. The crack formed by the last layer is gone and the water droplets formed by the first layers are clearly visible. The overall transparency of the ice changed when exposed to-70°C, the ice has a more milky colour.

Analysis

The different freezing time of each layer is put in a graph. It can be seen that the freezing time decreases with each layer. The cause is probably that the inside of the freezer and the equipment are getting colder over time as well as the heat conduction differs for ice and plastic. This applies to the previously printed layers which then offer a colder and more conductive under surface which exctrats energy to the freshly printed layer, therefore decreasing the freezing time of each subsequent layer.

The ice structure left overnight in the freezer is quite strong, considering that it is made out of very irregular layers. The “repair” of the crack is probably due to the fresh layer of water running through the crack and expanding while freezing, thereby reinforcing the part. The structural strength of the ice structure was tested with a short but effective method: the structure was put under stress until it broke. The break was clear and linear, exactly in the middle of the structure. This is quite peculiar as the all the layers were quite irregular, the assumption was that the ice would break around the water droplets. The outcome of this simple test is promising for the overall strength of the final structure as creating the ice layer by layer could maybe make the overall structure less fragile. This is also stated in literature, that the ice formed by lakes is stronger as the ice freezes from inside out, the smaller the layer, the stronger the ice.

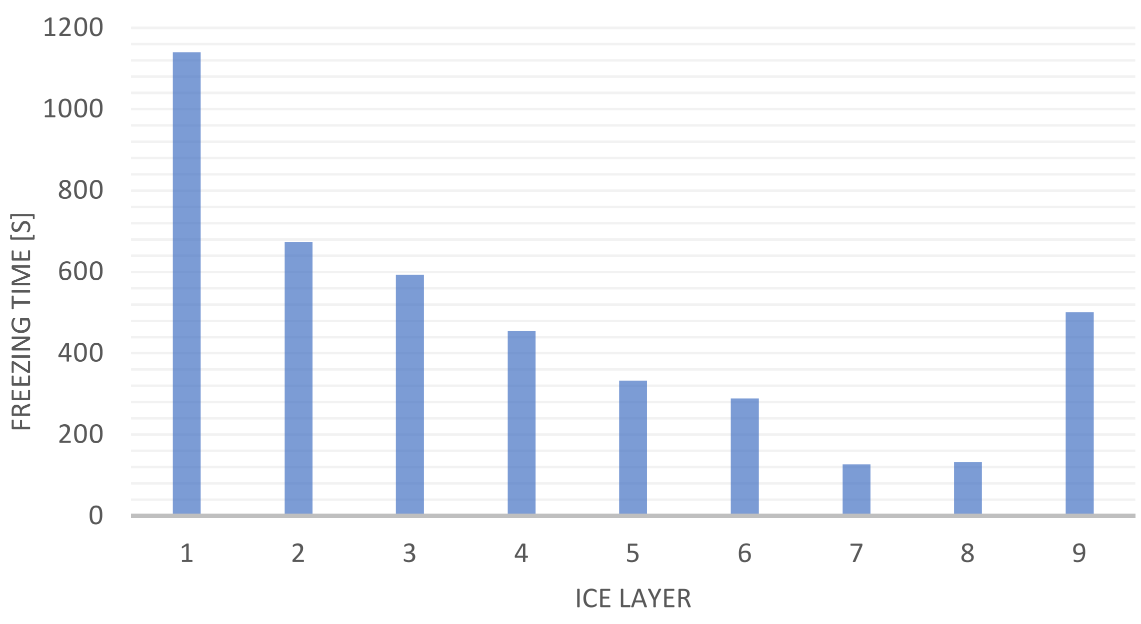
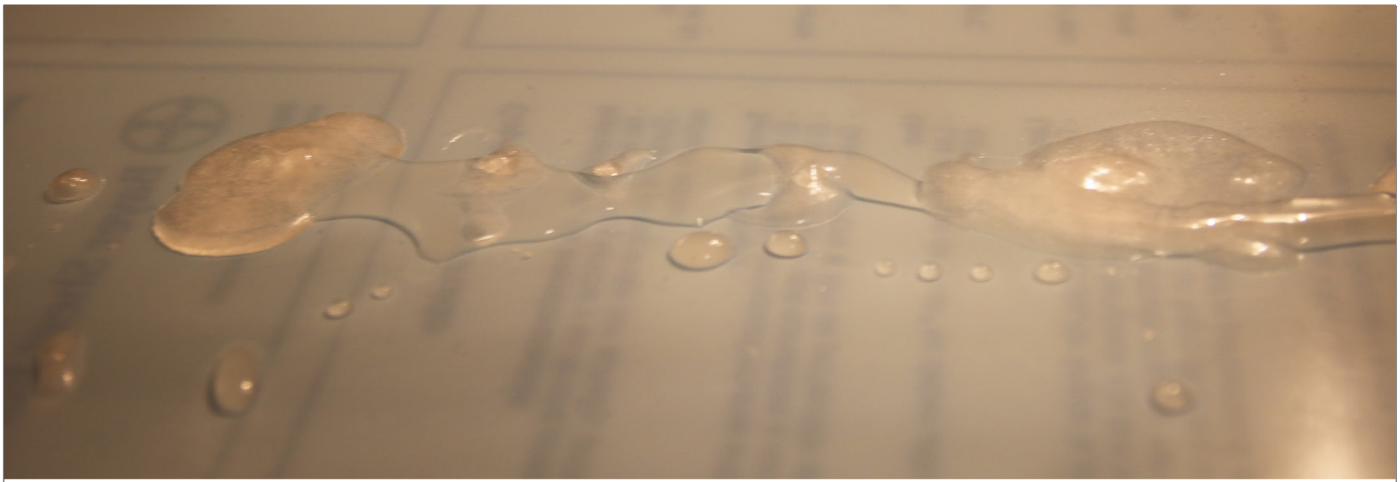
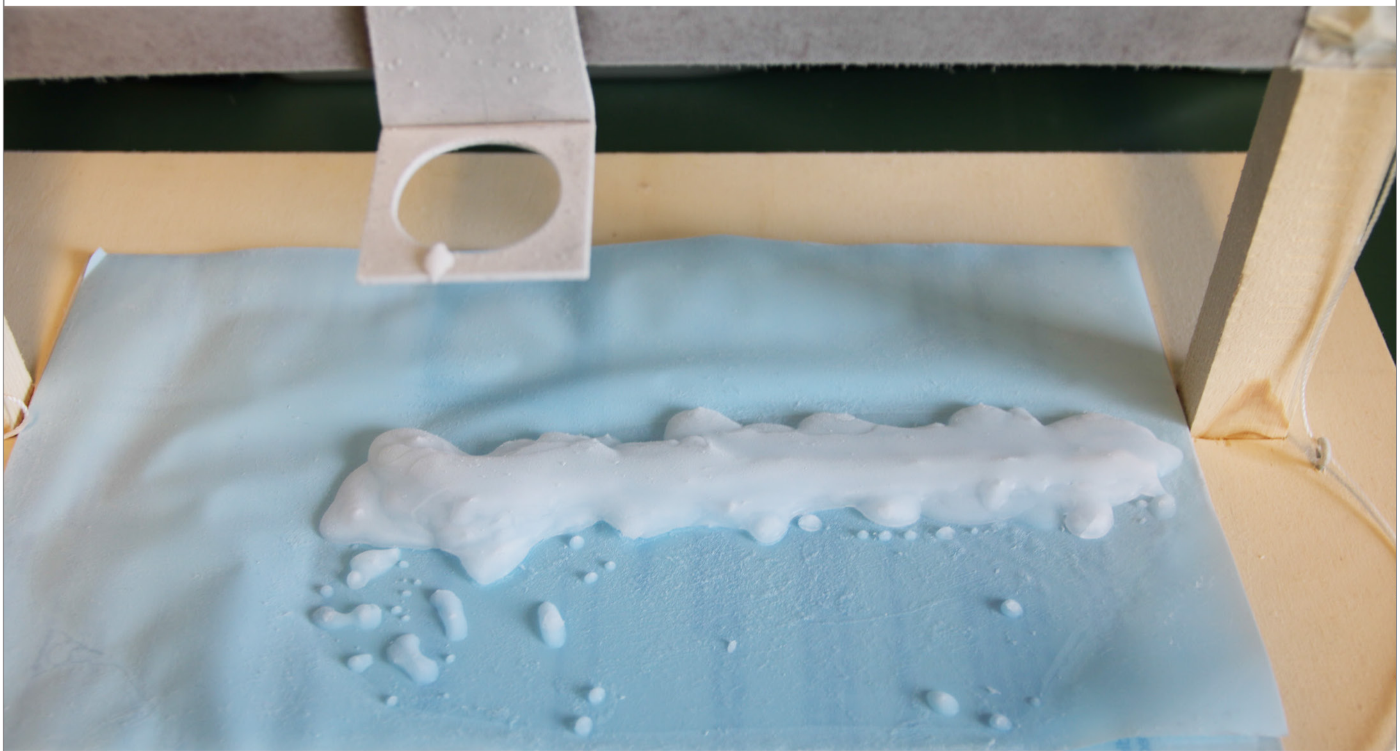


Figure 76. Bar graph of the freezing rate for each printed ice layer.





Conclusion

Conclusion can be drawn that the ice can be quickly printed as the ice freezes rapidly, even at only -30°C, indicating an even faster rate at decreasing temperatures. The overall strength of the printed ice structure seemed as well increased by using small layers to build it, as it both freezes more evenly and repairs the possible cracks.

	REQUIREMENT	TEST RESULT
1	(Semi) autonomous	v
2	Machines amount	v
3	Weight capsule	-
4	Volume capsule	-
5	Time	V

Table 44. Influence of the variables on the table of requirements.
V= greatly complies to the criteria compared to the other variables
X= does not comply (well) with the criteria compared to the other variables
- = does not apply/ no value found

19.3.6 Possible design of the AM robot

The salt ice "printing" robot would have to be small to climb onto the build structure. It should be a "climbing" robot with a robotic arm instead of a cartesian system which would be bulky and heavy for such a large structure (therefore not complying to the volume and mass requirements). The design of the robot could be based on the vacuum clamping Minibuilder from the IAAC. However, this option should be analysed using ice as material instead of clay.
A possible solution for the cantilever problem of the water would be to custom-make a robot with a support structure where the water is deposited onto the small portable structure. When the water has frozen into ice, the structure would be removed to print the next segment of the habitat. This technique could be energy and time extensive and requires more research for feasibility.

Figure 77. Possible other solution using the printing robot as support.

20. Conclusion part D

Part D is focussing on finding the adequate process which complies to the set requirements. First a literature study is performed on the different semi-autonomous processes which are currently used for the different available Mars materials described in the previous chapter. Then, a research is caried out to find the best building process for the chosen material (NaCl and H_2O ice) which will comply with the requirements.

This chapter (partly) provides an answer to the following sub-question:

- How is an outer shell constructed out of this (combination of) element(s)?

Forming a shell out of salt ice which complies with the sustainability requirements as well as the other overall requirements has a low TRL. Therefore, two overall principles are selected to further investigate this. Firstly a class IV technique which is the most promising but has a low TRL: using AM to "print" a dome. Secondly, a class III technique with a higher TRL is also explored: filling an ETFE (high performance plastic) membrane with the ice. Therefore the ice is within a protected environment (the membrane) and won't easily sublimates.

The focus of this chapter is on the first option. Different calculations are made to know how rapidly the ice will freeze thus indicating the building time needed. As ice is a peculiar material, an experiment was made to find out the freezing rate. Overall the ice freezes rapidely (in a matter of minutes) even at-30°C which would allow the ice structure to be built within the time available. The building time however does not only depend on the freezing rate but on the overal design of the habitat as well. This is further explored in the next two chapters.

The experiment also indicates that the ice structure might be stronger when printed with small layers as the ice freezes from inside out, therefore adding to the overall strength and redundancy of the habitat. Indeed, as each layer is printed, in the event of damage on the already printed structure, the new layer inserts itself within the damaged parts, therefore repairing the structure.

The sublimation rate of the ice is also calculated and plotted against the freezing rate, thereby indicating the life expectancy of the structure. The ice sublimates at a rate of 0,8844 mm /day. Considering that it takes about 10 minutes to freeze this amount of ice, we see that sublimation will hardly affect the building process. and freezes about the same amount in just under 10 minutes.

Bibliography – PART D

Amazing AM. (n.d.). What is Additive Manufacturing. Retrieved June 6, 2017, from http://additivemanufacturing.com/basics/

Barnett, E., Angeles, J., Pasini, D., & Sijpkes, P. (2009). Robot-assisted Rapid Prototyping for ice structures. 2009 IEEE International Conference on Robotics and Automation. doi:10.1109/robot.2009.5152317

Chevrier, V., Sears, D. W. G., Chittenden, J. D., Roe, L. A., Ulrich, R., Bryson, K., Billingsley, L., & Hanley, J. (2007). Sublimation rate of ice under simulated Mars conditions and the effect of layers of mock regolith JSC Mars-1. Geophysical Research Letters, 34. doi:10.1029/2006GL028401.

Chow, B. J., Chen, T., Zhong, Y., & Qiao, Y. (2017). Direct Formation of Structural Components Using a Martian Soil Simulant. Scientific Reports,7(1). doi:10.1038/s41598-017-01157-w

Igloo (2017). In Wikipedia. Retrieved on December 28, 2017, from https://en.wikipedia.org/wiki/Igloo

Ingersoll, A. P. (1970), Mars: Occurrence of liquid water, Science, 168 (3934), 972–973.

Janssen, F., & Houben, R. (2013). Reinforced ice structures: a research on the building method for the application of ice composites. Master's thesis, Eindhoven University of Technology, Eindhoven.

Kayser, M. (2011). Solar Sinter. Retrieved June 6, 2017, from http://www.markuskayser.com/work/solarsinter/

Khoshnevis, B., Bodiford, M.P., Burks, K.H., Ethridge, E., Tucker, D., Kim, w., Toutanji, H., Fiske, M.R., (2005). Lunar Contour Crafting – A Novel Technique for ISRU-Based Habitat Development, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Nevada.

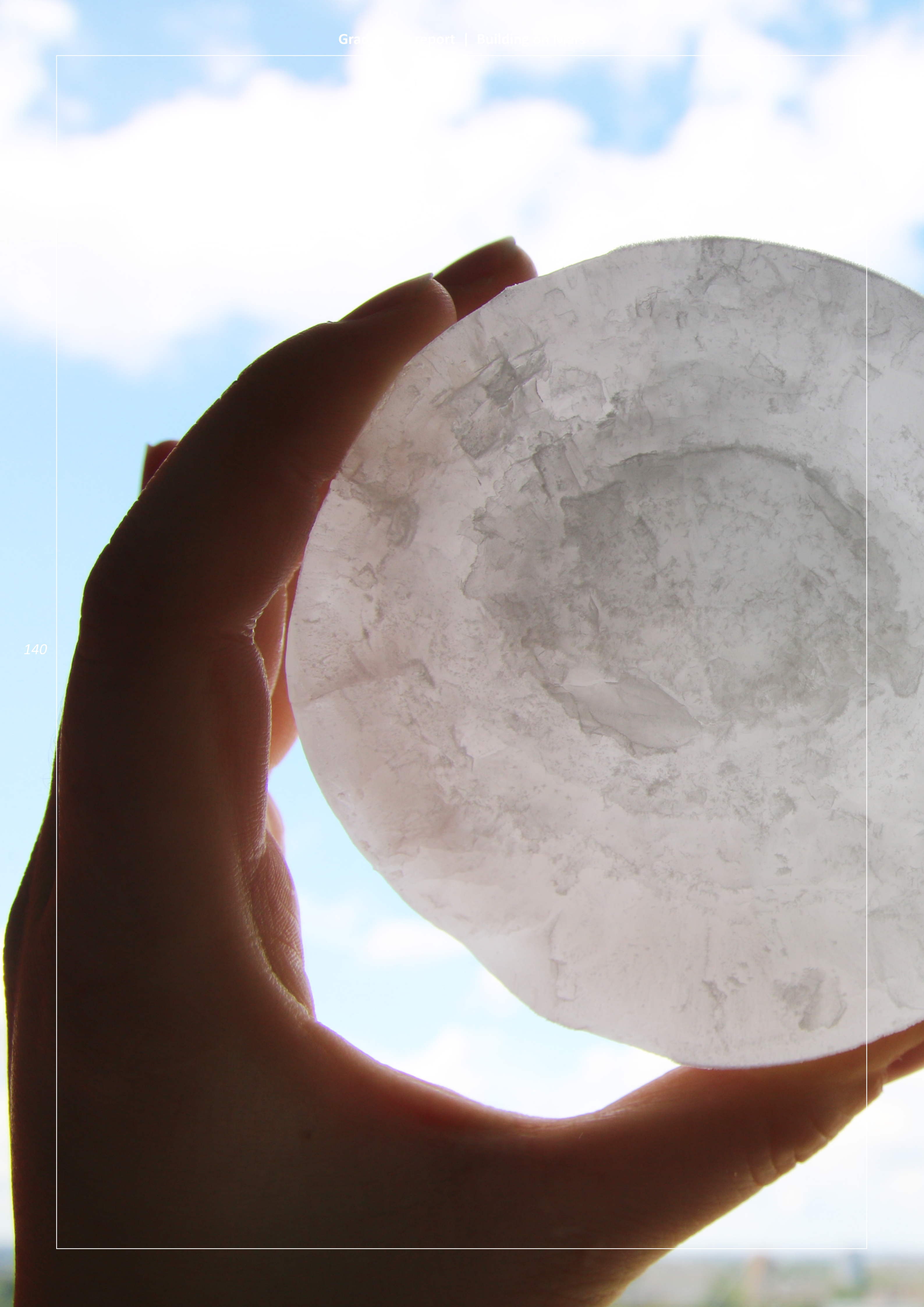
Morris, M., Ciardullo, C., Lents, K., Montes, J., Rudakevych, O., Sono, M., Yashar, M. (2016). Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O. Aiaa Space 2016. doi:10.2514/6.2016-5528

NASA. (2017, March 27). Journey to Mars Overview. Retrieved June 6, 2017, from https://www.nasa.gov/content/journey-to-mars-overview

Stott, R. (2014). IAAC Invents a Family of Robots to 3D Print Structures of Any Size. ArchDaily. Retrieved on November 30, 2017 from https://www.archdaily.com/517378/iaac-invents-a-family-of-robots-to-3d-print-structures-of-any-size

Wan, L., Wendner, R., & Cusatis, G. (2016). A Novel Material for In Situ Construction on Mars: Experiments and Numerical Simulations. Construction and Building Materials.

Zhang, W., Leu, M. C., Ji, Z., & Yan, Y. (1999). Rapid freezing prototyping with water. Materials & Design,20(2-3), 139-145. doi:10.1016/s0261-3069(99)00020-5



PART E

STRUCTURE

"Problem is (follow me closely here, the science is pretty complicated), if I cut a hole in the Hab, the air won't stay inside anymore."

Andy Weir in The Martian. *(Weir, 2014)*

Part E has its focus on the structural optimisation of the Martian habitat using the previously found salt ice material and AM processing technique to build it. A limited literature study is done to set requirements to the structure of the habitat focussing on redundancy and radiation shielding. Then a structural analysis is made using a computational model which is the base for a future habitation design.

This chapter provides the second part and complete answer to the following sub-question:

- How is an outer shell constructed out of this (combination of) element(s)?

21. Literature study

It can be concluded from the literature and experiments conducted in part C that ice is strong in compression and weak in tension. Therefore a compression structure is chosen for the ice habitat. The most common three dimensional compressive structures built on Earth are catenary arches, domes and vaults which are further analysed.

21.1 Catenary arch

A catenary arch is an inverted catenary curve. The catenary curve is the path a flexible cable follows when hung by its extremities. When turning this curve upside down, a catenary arch is formed. The main advantage of such a structure is the ability to withstand its own weight by having a structure in compression. Catenary arches redirect the force of gravity into compression forces by pressing along the curve of the arch. When uniformly loaded, the arch's line of thrust runs through the centre (Catenary arch, 2017).

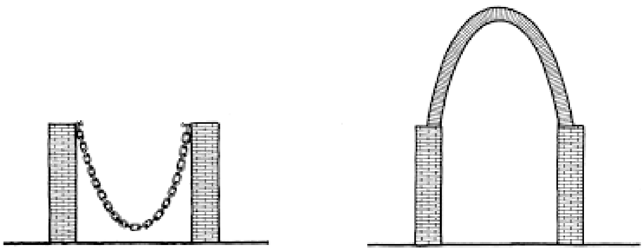


Figure 78. A catenary arch is the inverted catenary curve of a flexible cable (Mud House Design, 2017).

The Catenary arch has been widely used on Earth in vernacular architecture as well as in modern and contemporary structures and buildings. One example of vernacular architecture using catenary arches are the Musgum mud huts in Cameroon. These huts are catenary arches built out of mud, which can withstand maximum weight with a minimum amount of material. The top of the hut is left open for climate control purposes. This type of building was widely spread worldwide as no tools are necessary to build the structures, only bare feet and hands, earth and water (Musgum mud huts, 2017). As can be seen in the section, the walls are quite thin compared to the overall structure. It should be noted that the habitat on Mars needs mass, especially on top, to shield against radiation. Therefore it should be assessed whether adding mass on top of the structure is still possible with this technique of using catenary arches.

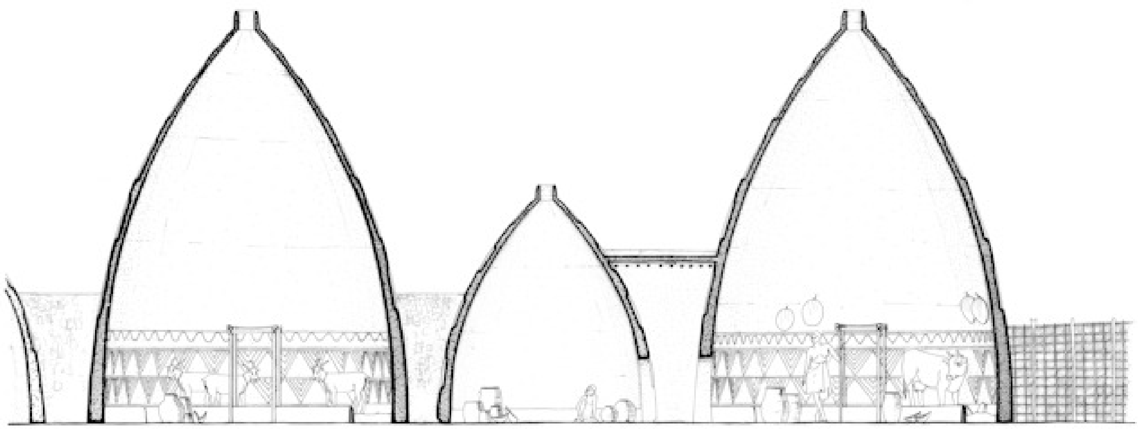


Figure 79. Section of a Musgum Mud Hut (Learning from vernacular, n.d.).

21.2 Dome

The most common compression structure is a dome. A dome has many different shapes but the compression/ tension line is defined by an angle. An angle of 51,49° determines where the dome is under compression with α= 90° – 51,49° = 38,51° where the dome is under tension (Wurm, 2007).

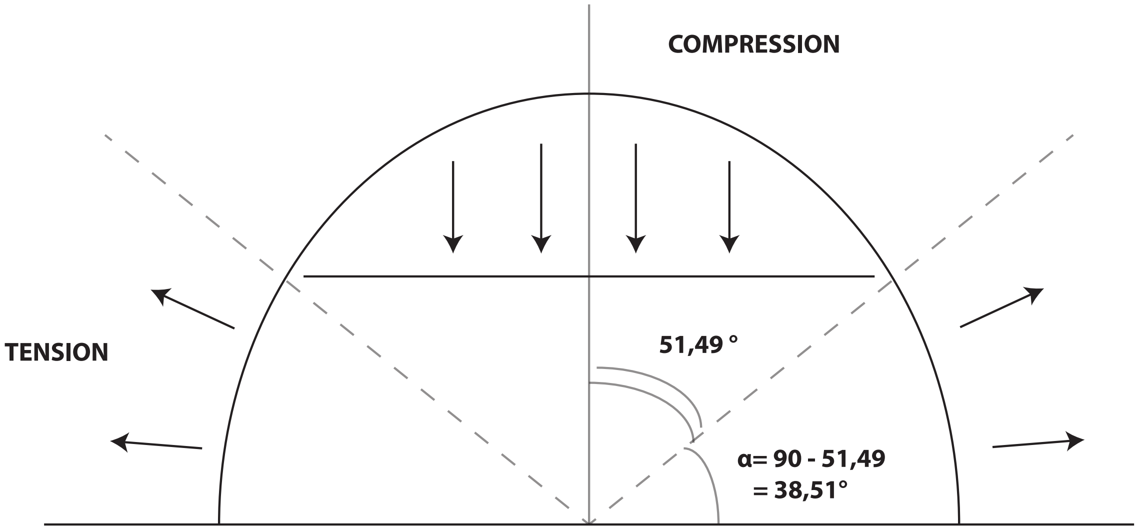


Figure 80. Principle of tension and compression in a dome.

Thus different shapes determine whether the dome is mostly under compression or tension as can be seen in the small study in figure 81.

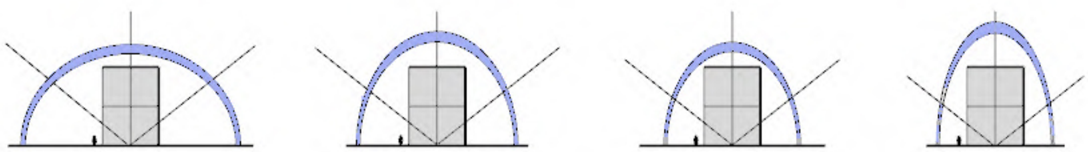


Figure 81. Different dome shapes with the higher the dome, the more in compression the structure is.

As explained in chapter 14, Inuits built igloos from snow in the shape of a dome by stacking snow blocks hemispherically. However this structure has a very limited span as the thickness of the wall is large therefore the dome collapses due to its own weight when spanning large dimensions.

There are also other reasons for building a dome than having a mainly compressive shape. Principally, a dome structure is resistant against the exterior environment as it has no hard corners and it is a self-supporting structure. This is critical as a Martian habitat should not be pointy to protect the habitat from point loads caused by flying particles or falling meteorites. The dome shape is also resistant against potential (Mars) quakes of which little is known but because of redundancy, the worst case scenario is taken into account.

A dome has eminent properties which fit the design requirements, however, openings weaken the structure greatly. For the habitat design, at least a few EVA hatches are needed and a possibility for expanding the habitat by connecting another module is an essential mission design criterium.

21.3 Vault

Another compressive structure which, here, allows openings are vaults. The ETH Zurich is pioneering in the research of vaults, creating large thin structures. A vault is a compression shell which exerts lateral thrust which requires counter resistance (Vault, 2017). Vaults were built in the earliest of times by the Sumerians and Egyptians and were later widely spread in Europe during the Middle Ages when typically built as ceilings in churches and cathedrals. A vault requires a support structure which is demounted once the last stone is set. This technique is used by the Block Research group at ETHZ to create incredibly thin stone structures like the Armadillo Vault build for the Venice Biennale. To design this vault, the VAULT plugin for the software Rhinoceros is used to optimize the shape (Block Research Group, 2017). The vault has as main advantage that it allows for openings within the structure which is needed when building a habitat with structural openings for the different hatches.

Figure 82. The Armadillo Vault for the Venice Biennale 2016. It comprises of 399 limestone panels with a minimum thickness of 5 cm spanning 16 m (Block Research Group, 2017).

22. Structural analysis for an ice habitat on Mars

This chapter focusses the structural optimisation of the salt ice habitat.

22.1 Requirements

The requirements for the structural design of the habitat are summarized based on the literature study done in part A and the research done in part C and D.

	REQUIREMENT	VALUE
1	Redundancy	-
2	Minimal structural openings	ALARA
3	Radiation shielding	Thickness min.
4	Protection against impacts and vibrations (quakes and meteorites)	-
5	Compression	AHARA
6	Possible expansion	At least 1 extra module
7	Visual contact with exterior	Daylight must be let through: min 150 lux

Table 45. Table of requirements for the structural design of the dome.

22.2 Research based on domes

22.2.1 Overall shape

To define the exact shape of the dome for a Martian habitat, a restrained shape analysis is made in the modelling software Rhinoceros. Using the ETHZ VAULT plugin allows to find the horizontal and vertical equilibrium of any given shape. First a general shape is made around the habitat capsule to provide the minimal dimensions needed. The shape is cut open at the places where hatches are needed. When these settings are set, the tool calculates the horizontal and vertical equilibrium of the structure until a stress free shape is obtained.

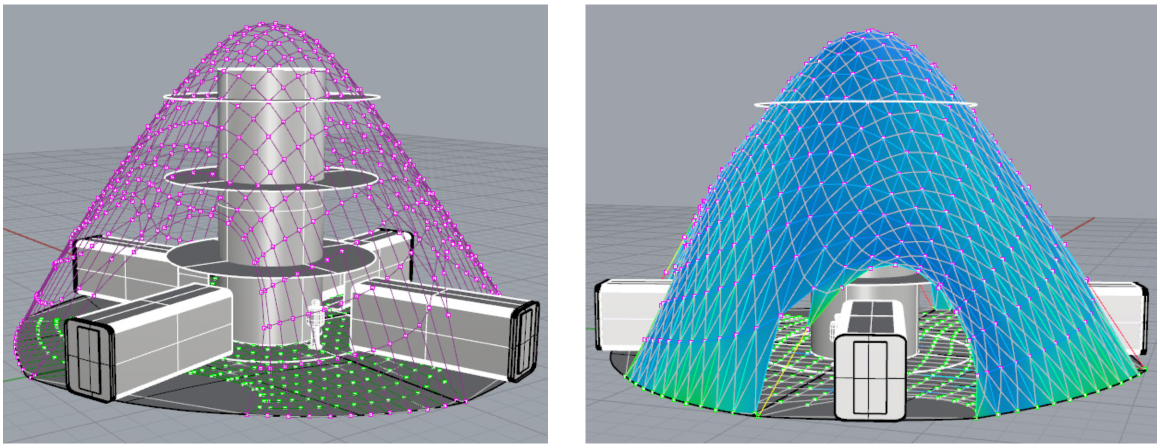


Figure 83. The shape of the dome created by the VAULT tool in the computational programme Rhinoceros.

22.2.2 Radiation shielding

The shape is then plotted with the required minimum thickness for radiation shielding. The thickness of the ice is predetermined, however due the equatorial latitude of the location, most radiation comes from a high angle meaning that the dome should be thicker on top. This puts the most weight on the most vulnerable part of the structure. Hence, an extra layer of ice is added under the structure , on top of the core capsule which is strong enough to support the weight of the ice.

22.2.3 Martian Gravity

Another important design aspect which varies from a typical Earth environment is the Martian gravity. As gravity on Mars is only 3,711 m/s^2, the dome should be able to withstand greater forces and adding mass on top of the structure should not be as big a problem as on Earth.

23. Conclusion part E

Part E has its focus on the structural optimisation of the Martian habitat using the previously found salt ice material and AM processing technique to build it. A limited literature study is made to set requirements to the structure of the habitat focussing on redundancy and radiation shielding. Then a structural analysis is made using a computational model which is the base for a future habitation design.

This chapter provides the second part and complete answer to the following sub-question:

- How is an outer shell constructed out of this (combination of) element(s)?

Ice is strong in compression, therefore a computational optimization is made to put the structure under compression. The overall shape is quite high which allows more mass to be used on top of the capsule hence protecting effectively against radiation from above (where most radiation is coming from at Jezero crater). This optimization also made positive use of the structural cuts for the six hatches used for EVA's, coupling of the habitat modules and possible expansion of the habitat.

Bibliography – PART E

Block Research Group (2017). Armadillo Vault, Venice, Italy. Retrieved on November 26, 2017 from http://www.block.arch.ethz.ch/brg/project/armadillo-vault-venice-italy

Catenary arch (2017). In Wikipedia. Retrieved on November 30, 2017, from https://en.wikipedia.org/wiki/Catenary_arch

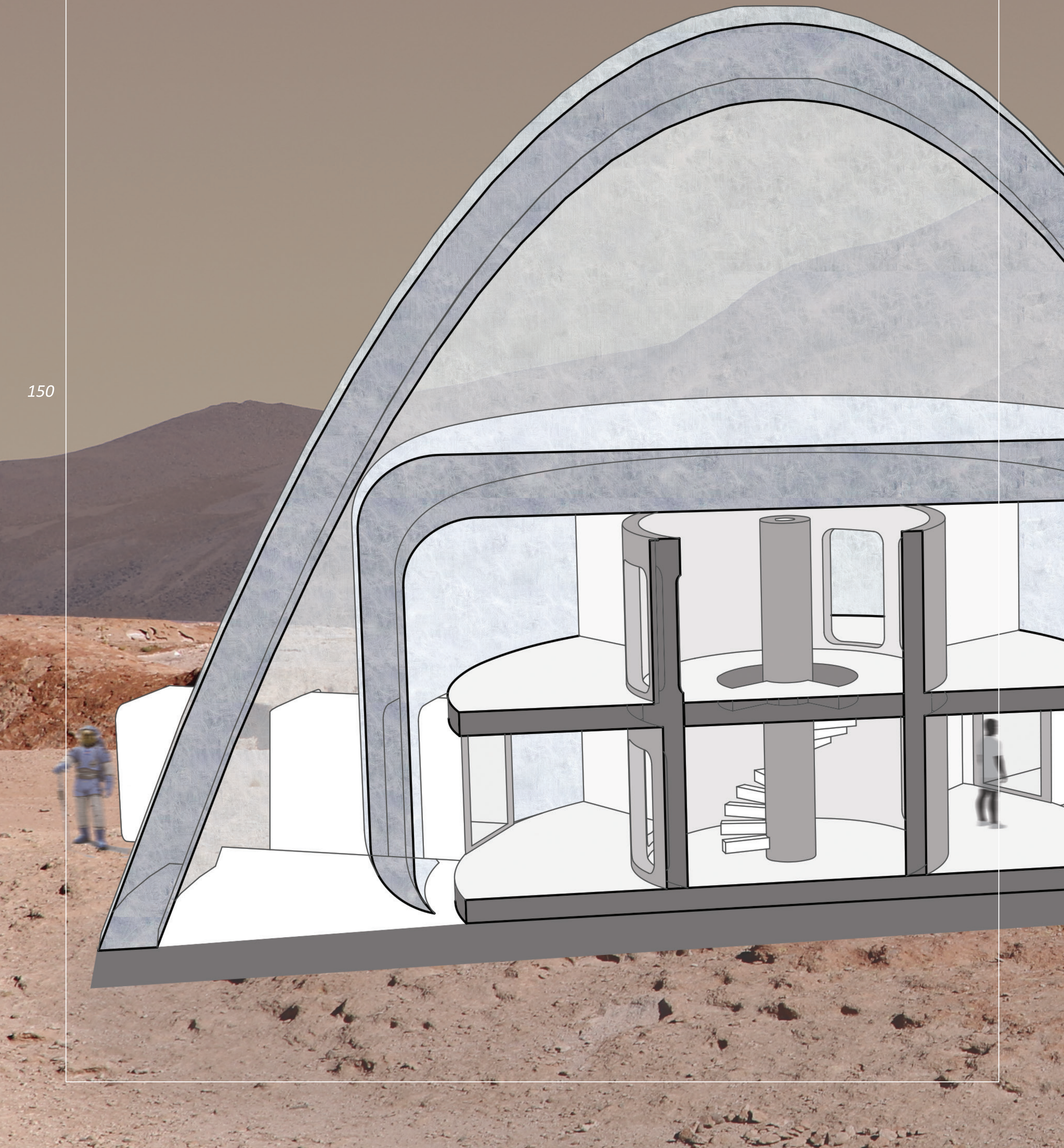
Learning from vernacular (n.d.). Retrieved on November 30, 2017, from http://archiveweb.epfl.ch/learning-from-vernacular.epfl.ch/

Musgum mud hut (2017). In Wikipedia. Retrieved on November 30, 2017, from https://en.wikipedia.org/wiki/Musgum_mud_huts

Vault (Architecture) (2017). In Wikipedia. Retrieved November 26, 2017, from https://en.wikipedia.org/wiki/Vault_(architecture)

Weir, A. (2014). The Martian. United States: Crown Publishing.

Wurm, J. (2007). Glass structures: design and construction of self-supporting skins. Basel: Birkhäuser



PART F

the "ICE HAB"

"We do not create the work. I believe we, in fact, are discoverers."

Glenn Murcutt

Part F is the resulting design which is based on the previously performed research. The design aims at verifying if the findings made during the research phase of the project can still be applied into context: building a sustainable habitat on Mars.

This chapter provides an answer to the main research question:

Which **in situ materials** and **forming techniques** are suitable to create an outer shell for a **sustainable habitat** on Mars which protects the crew from the **harsh Martian environment**?

24. Habitat design

To assess the findings made during this research, a design, the Ice Hab, is made for a sustainable Martian habitat using the techniques found in the previous chapters. The design is then assessed with the criteria set in the programme of requirements.

24.1 Geographical context

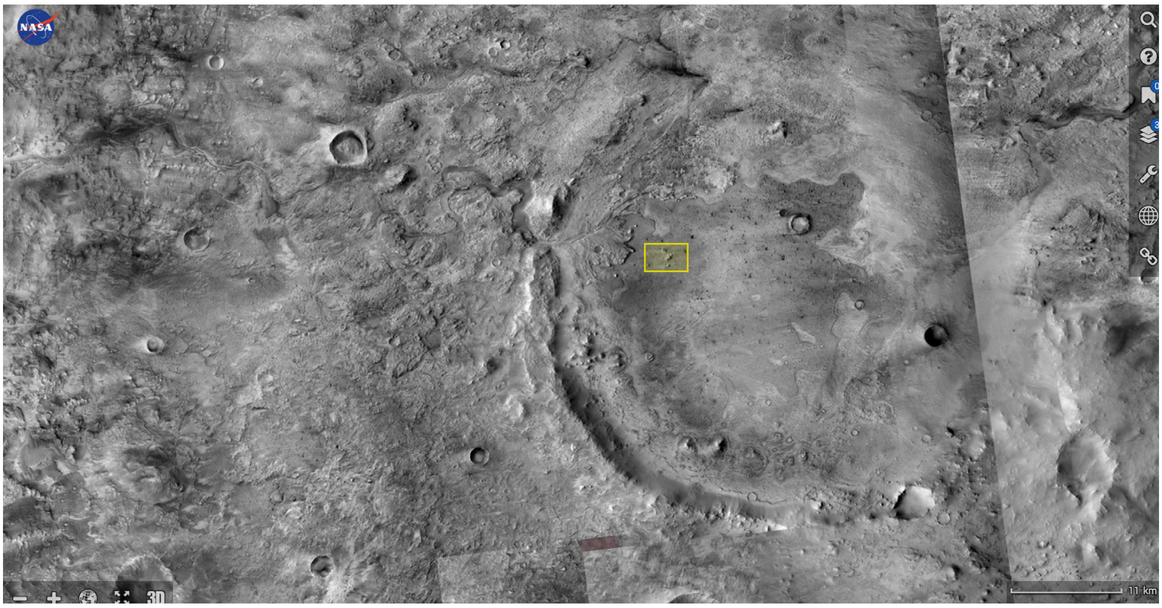


Figure 84. Map of Jezero crater with the North west design location for the habitat in the yellow square (Retrieved on September 5, 2017, from the NASA Explore Mars map tool from https://mars.nasa.gov/maps/explore-mars-map/fullscreen/).

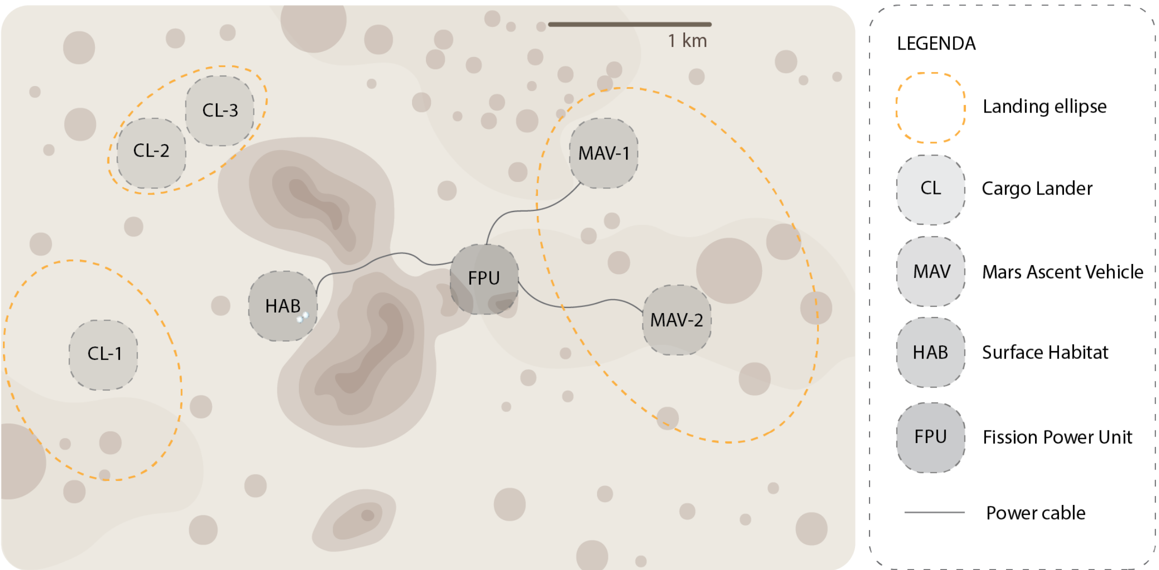


Figure 85. Geographical context of the ice hab.

The geographical context of the habitat is defined by the DRA 5.0 architecture configuration. The location is set at the North West rim of the Jezero crater. The habitat is set on a relatively flat ground (by orbital assessment of MRO) near the landing zones for the cargo landers (CL) and next to the crew landers. The habitat has two modules: mostly for redundancy but also because the maximum floor span only leaves possibilities for small modules to be built. Hence two modules are thought to be best also regarding psychological factors of routing and separating work and living functions.

The Ice Hab is oriented as to receive as little radiation as possible from the sun; it is mainly facing North and protected by the natural environment hills. Those hills also protects the habitat from the fission power unit following the design requirements set by NASA in the DRA 5.0.

Figure 86. Global map of Mars with Jezero crater highlithed.

24.2 Building timeline

The mission timeline defines the building time frame: a maximum of 18 months (but less time is preferred as it has to be finished and assessed before the 18 months deadline). There are different building steps to take when building the habitat in order to ensure the harsh environment does not have a negative influence on the building of the Ice Hab. Each of these steps has a different time frame which needs to fit within the overall building time.

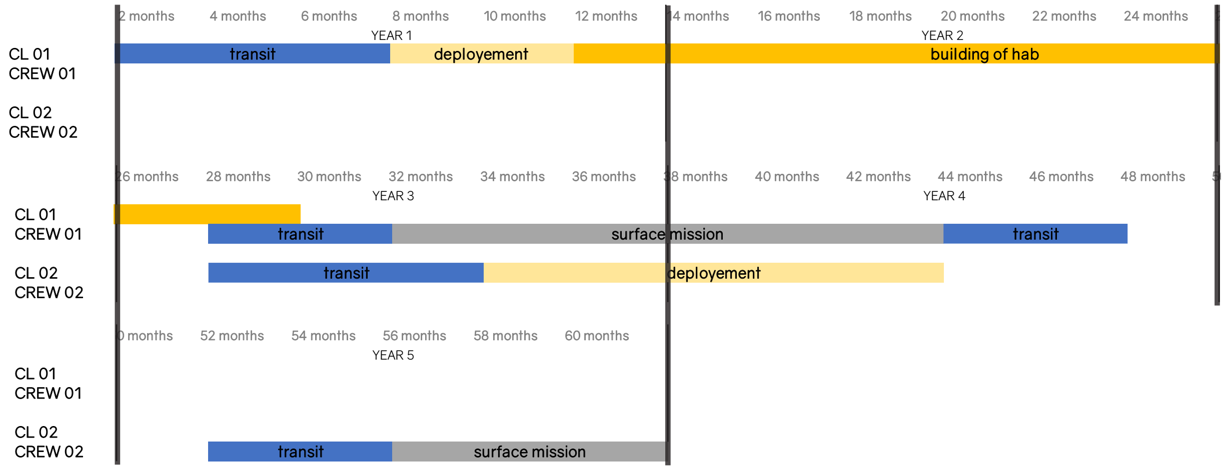


Figure 87. Mission timeline based on DRA 5.0 with two manned surface missions.

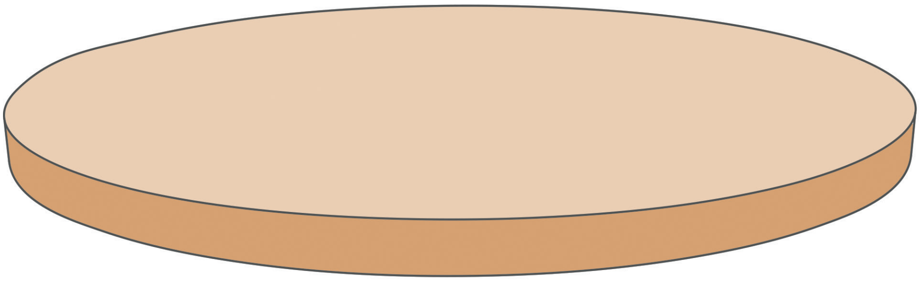
building of hab				
capsules are put close to each other	inflatable membrane, airlocks, floor, interior	furniture + insulation aerogel	pockets are filled	exterior dome is printed
H20 and NaCl is harvested and stored			H20 and NaCl is harvested and used in real time	

Figure 88. Building timeline.

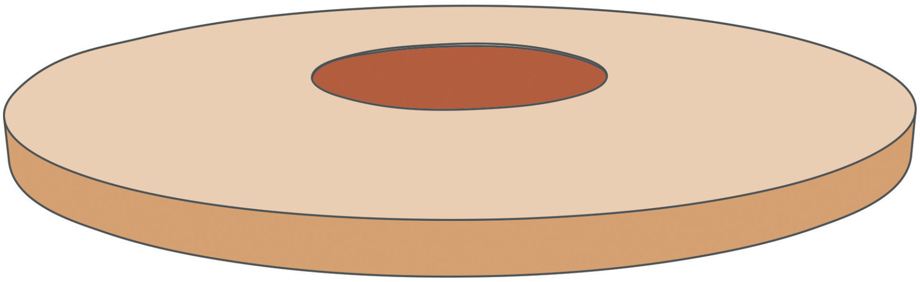
The different building steps are, with their respective time:

1. The two habitat capsules land within the CL with the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) EDL.
2. A relatively flat ground is located by small rovers (2a) and once found, the ground is flattened even more by excavation (2b). Laser sintering is then used to form a building platform, which is able to support the habitat (2c). Time: about 1 month.
3. H_2O, CO_2 and NaCl are harvested nearby in parallel to the other following building steps.
4. Capsules are put in place next to each other using retro propulsion. Time: about 1 month.
5. The inflatable ETFE membrane is inflated keeping constant pressure of 1 kPa inside the membrane. The airlocks are simultaneously deployed as they are attached to the membrane to prevent air leaks. Time: about 2 weeks.
6. The floors are deployed from the original capsule within the pressurized membrane. The floor system is similar to the system designed by NASA where floors and interior walls are pre-integrated in the capsule and can be autonomously unfolded. Time: about 0,5 week.
7. The interior walls and interior plan is unfolded and deployed autonomously as well. Time: about 0,5 week.
8. The insulation layer is filled with silica aerogel for thermal insulation (another option: the layer is already filled with aerogel on Earth, however the feasibility of this option needs further research). Time: about 2 weeks.
9. The vacuum pockets are filled with the harvested water and sodium chloride, beginning by filling the lowest layer, waiting until it freezes completely then proceeding to the next layer until all the pockets are filled. Time: about 4 months.
10. The exterior dome is printed out of the harvested water and sodium chloride, thin layer by thin layer, this process takes place at night. Time: about 8 months.

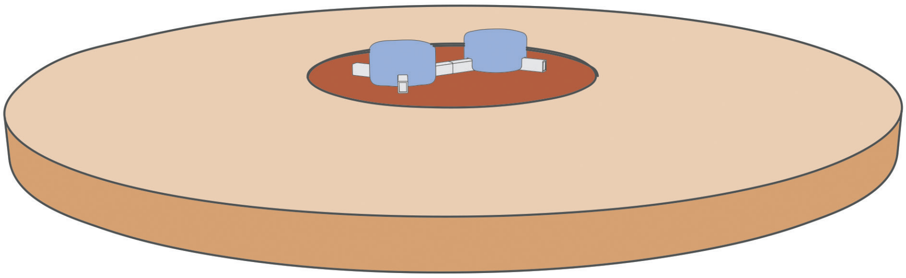
Building steps



2a. A relatively flat ground is located by small rovers

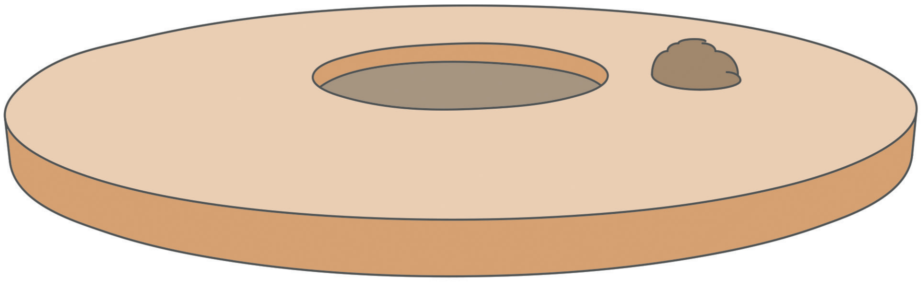


2c. The regolith is laser sinterised to form a building platform.

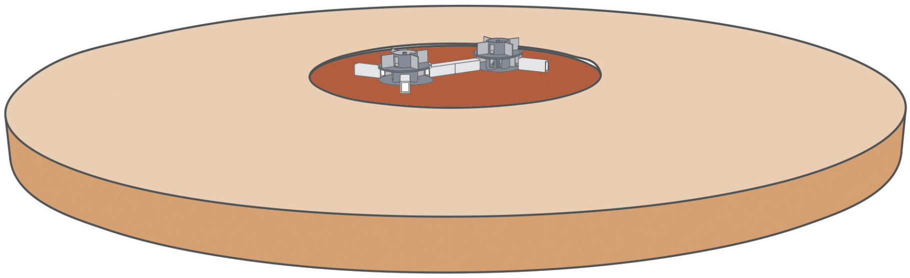


8. The insulation layer is filled with silica aerogel for thermal insulation.
9. The vacuum pockets are filled with the harvested water and sodium chloride, beginning by filling the lowest layer, waiting until it freezes completely then proceeding to the next layer until all the pockets are filled.

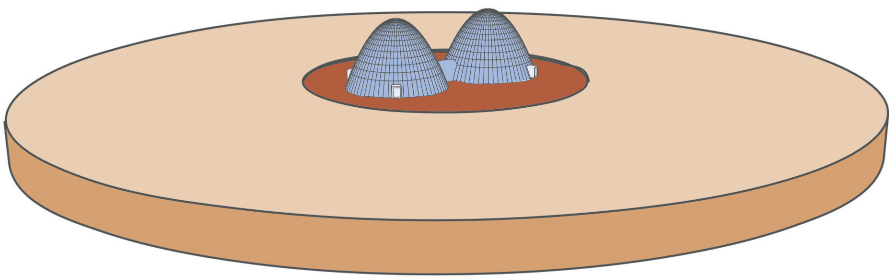
Figure 89. Schematic depiction of the main building steps.



2b. The ground is flattened even more using RASSORs



4. Capsules are put in place next to each other using retro propulsion.
5. The inflatable ETFE membrane is inflated as well as the airlocks.
6. The floors are deployed from the original capsule.
7. The interior walls and interior plan is unfolded



10. The exterior dome is printed out of the harvested water and sodium chloride, thin layer by thin layer, this process takes place at night.

24.3 Plans and interior

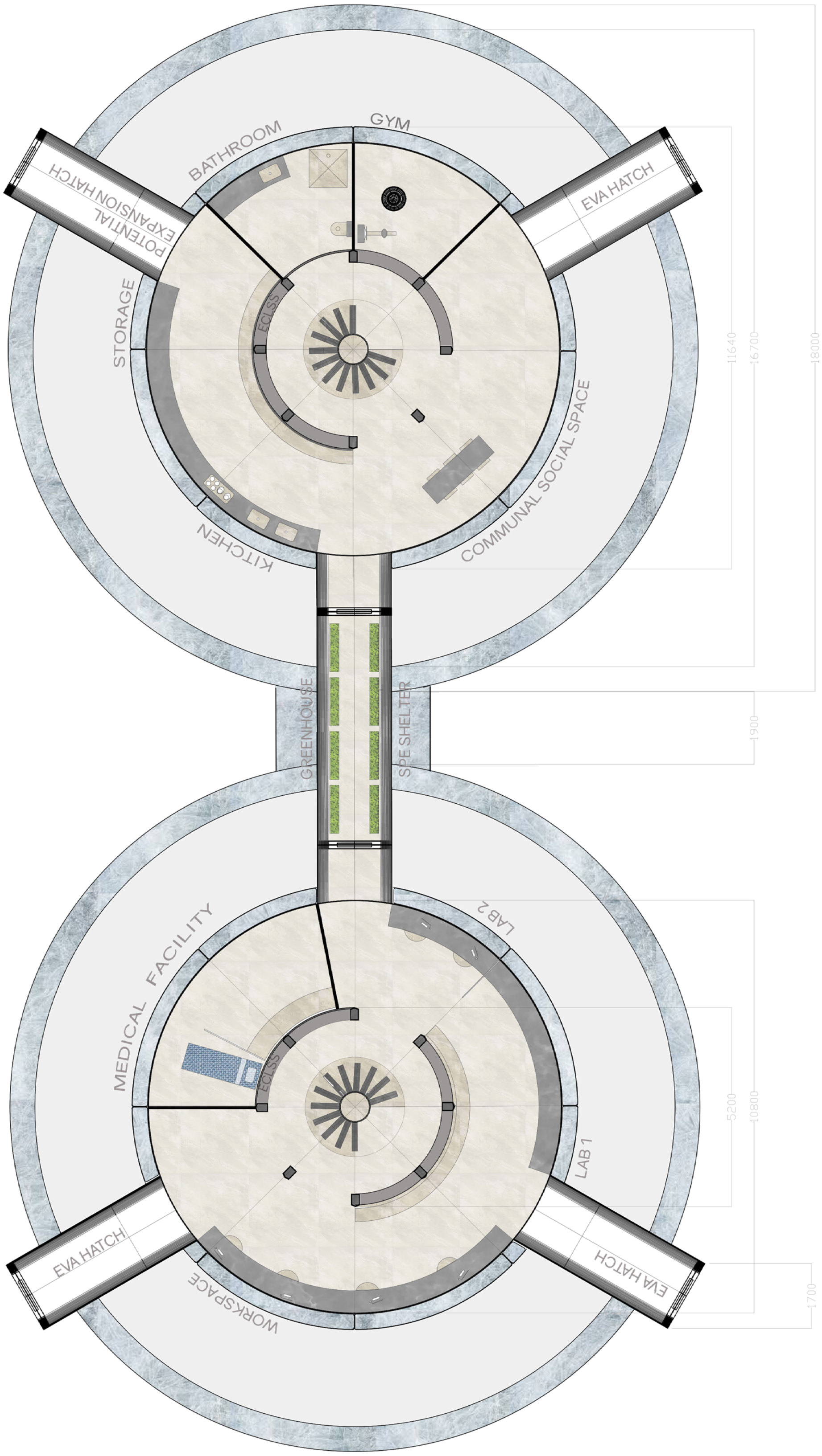


Figure 90. Plan of the Ice Hab, no scale, level GF.+0

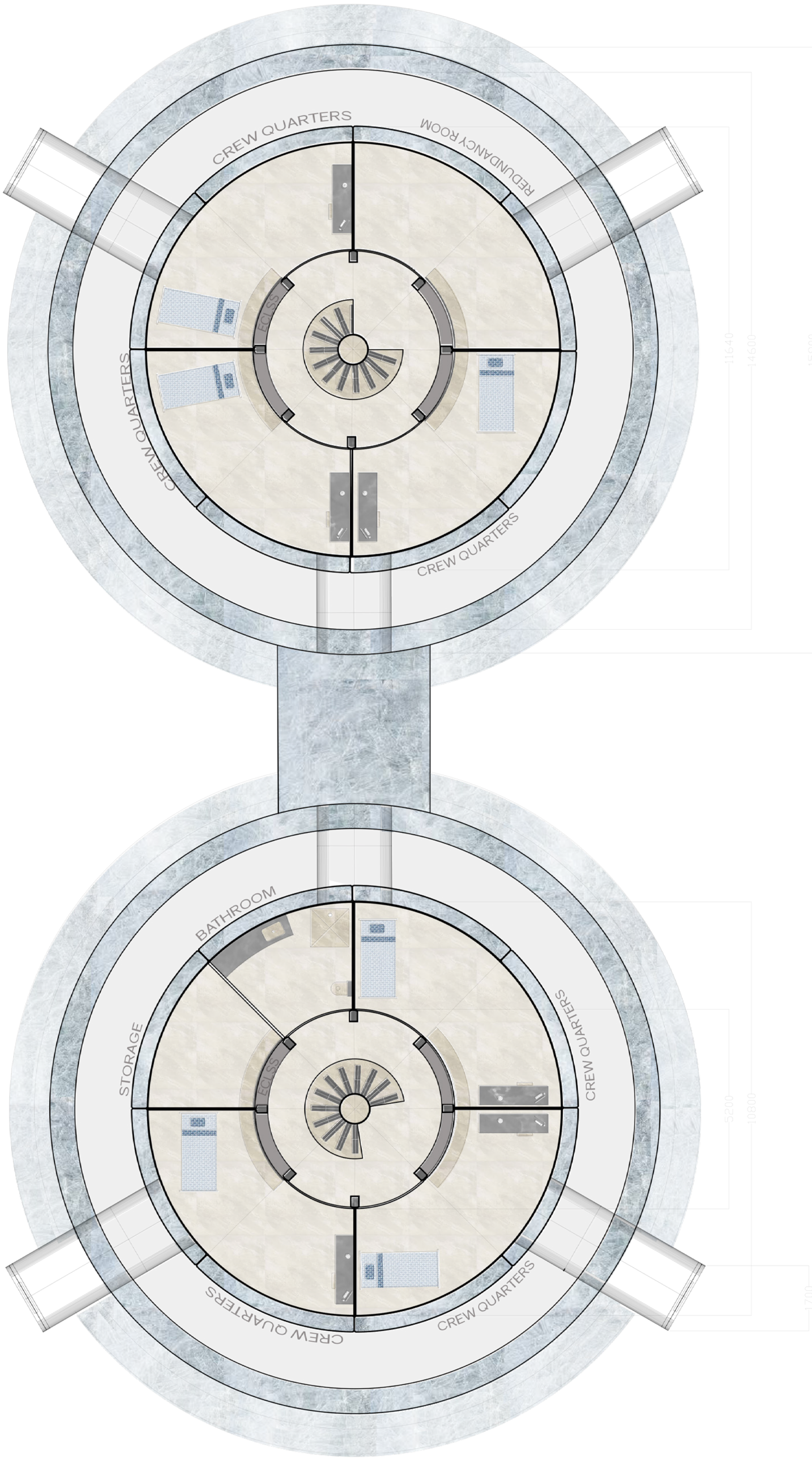


Figure 91. Plan of the Ice Hab, no scale, level 1.+2800.

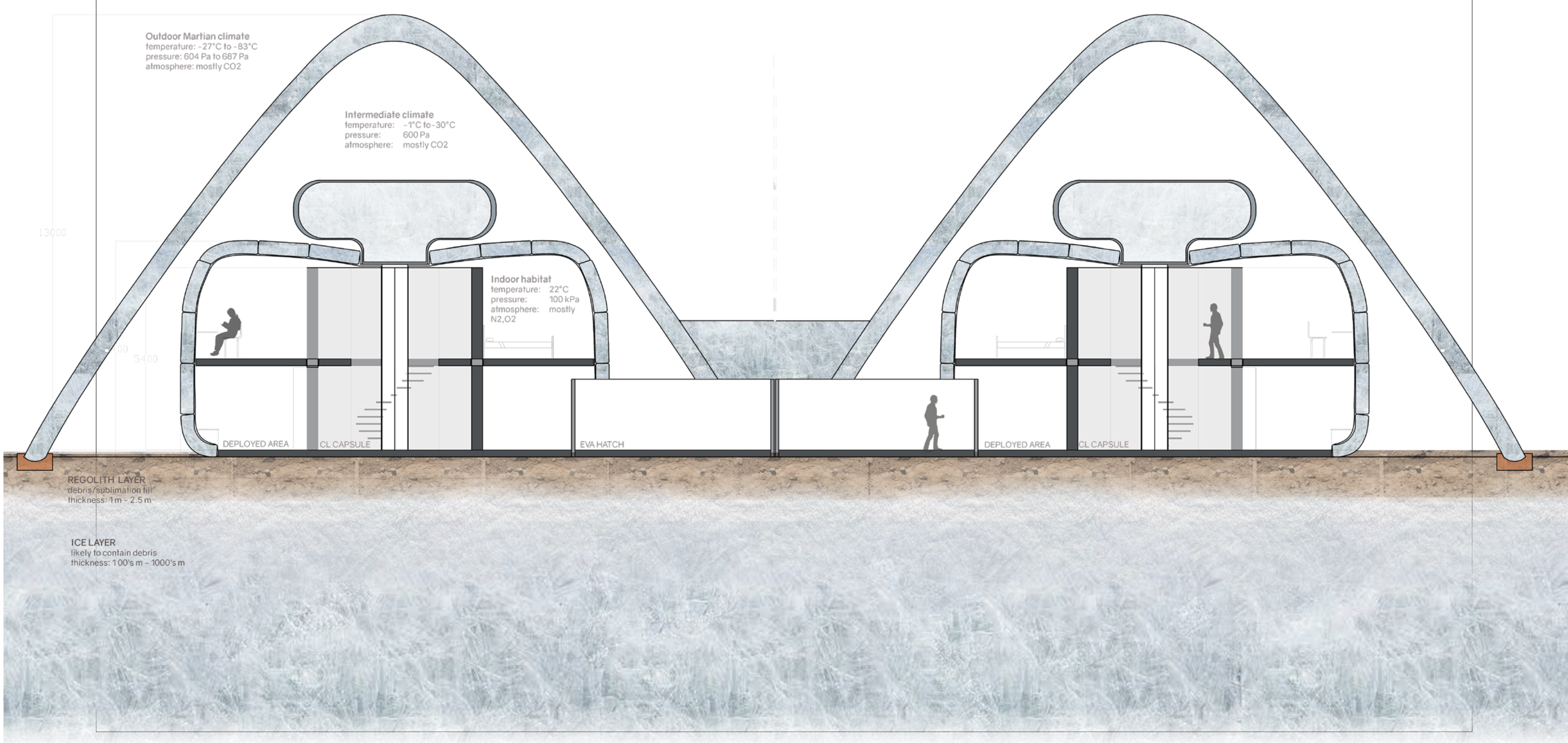
24.4 Routing and interior

The two modules are designed taking both quantitative and qualitative criteria into account. The interior plans are strongly influenced by the psychological needs of the crew and these were carefully taken into account in the design. The two main activities, working and living, are separated both physically and mentally by putting both functions within different modules. Therefore, the crew can separate both functions as to not “bring work home” or vice versa. The living area comprises both social communal spaces and private quarters for each crew member. The overall plan is designed is such a way that interacting with the crew is necessary but having a moment alone is also possible through different routing within the Ice Hab, this also helps preventing boredom.

The interior plans are however still flexible and the crew is still able to move furniture, change the interior walls and the functions of some rooms (sanitary and medical facilities are however anchored and can’t be moved). The volume and area of the design are based on the volue study made by Adams in 1999 and can be found in Appendix E.

The hatch between the two modules serves two purposes: it is the greenhouse where food can be grown and biological experiments can be carried out as well as being a storm shelter. As the hatch itself is structurally strong (due to its prefabrication on Earth, and the protection offered by the two domes) it can be covered by a large amount of ice. This thick ice layer shields the crew from radiation during high SPE.

On top of the planning of the interior, the structural design also complies to the qualitative criteria. The ice walls allow some natural light to come through the structure which helps the crew differ days from nights and even assess a little of the surroundings.



24.5 Detail of the line of defence

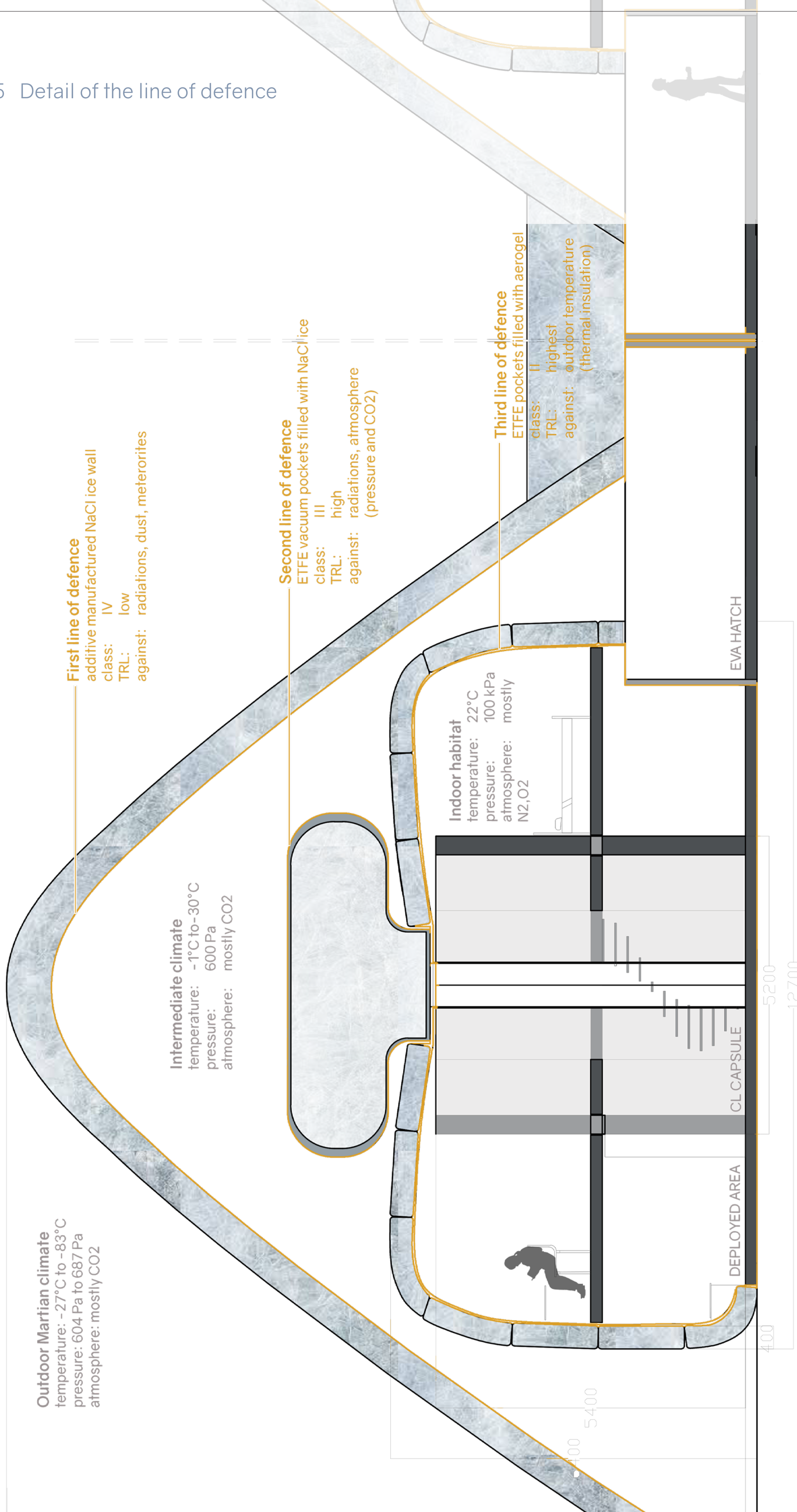


Figure 92. Section 1:500 of the Ice Hab with the three line of defence.

This section shows the two walls concept design. The first ice wall is printed on the surface using a robotic arm mounted on a small Mini Builder robot. This wall is made with 100% in situ materials, using only underground H2O and NaCl. This means that the wall is a class IV technology, therefore complying to the sustainability requirements. The shape is based on the structural simulation made in the VAULT plugin for Rhinoceros to place the shape under compression rather than tension as ice has a much stronger compressive strength. The ice is exposed to the harsh Martian environment, meaning that it will slowly sublimate into the atmosphere. The sublimation rate is still slow and the structure will "survive" for about 45 months which is well above the time the crew will be staying on Mars (maximum 12 months). As the Martian atmosphere is also containing H2O particles it could also mean that the wall has the ability to repair itself especially during the day when the ice behaves more plastic due to higher temperatures. The wall will also increase in strength over time as the ice melts during the hot hours of the day and refreezes during the freezing hours of the night, therefore exposing the structure to different thawing and freezing cycles, increasing the overall strength of the ice.

However, there are still many unknowns for the protecting properties of the ice, the building capabilities and survival rate of the wall. As redundancy in space is vital, this wall will serve as an in situ experiment for follow up missions, and another wall with a higher TRL (but also lower class of III) will be built. This second wall is built within a protective environment: the ETFE membrane. The wall is built by inserting water into the vacuum pockets of the inflatable ETFE membrane. The water then freezes when exposed to the cold Martian environment. The ice is separated from the warm habitat environment by a layer of aerogel which insulates the habitat and therefore thermally separates the ice wall from the interior of the Ice Hab. The ETFE layer filled with aerogel also acts as acoustical insulator and fire retardant due to the extraordinary properties of both materials.

This ensures that the ice wall, which is 400 mm thick, acts as a shield against radiation independently from the temperatures and pressures inside and outside the habitat.

On top of the prefab capsule, a large water tank is installed to act as reservoir as well as extra radiation shielding as most of the radiation comes from directly above at equatorial regions. It is also close to the crews private quarters where the crew will be spending a lot of time.

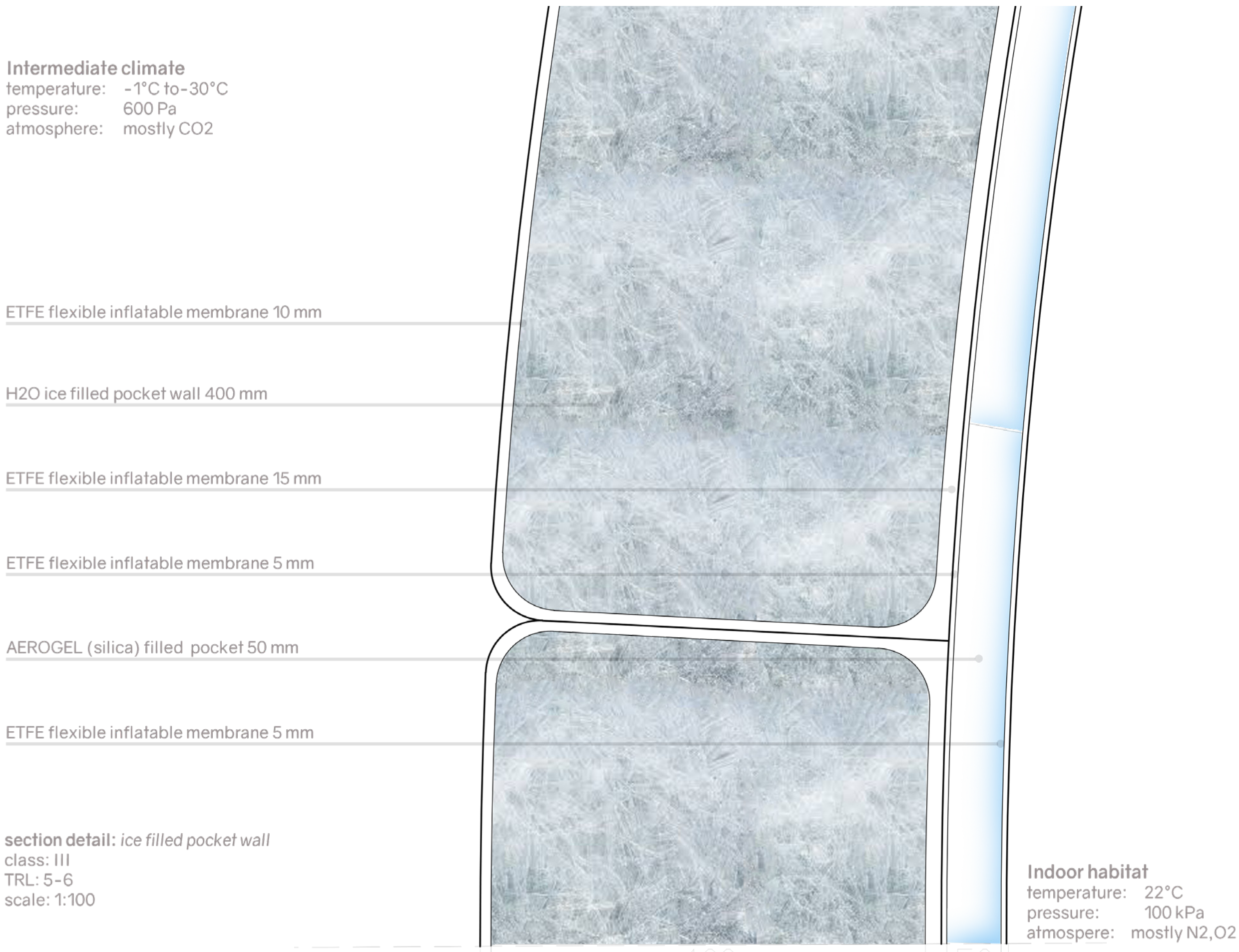


Figure 93. Section 1:100 of the vacuum pockets filled with ice.

In a typical Dutch cavity wall there are different lines of defence against the exterior environment. There is a first line of defence, a second thermal insulation line, and a third airtightness line. In this design, the first line of defence is against meteorites, dust containing perchlorates and radiation. The second line is again a radiation shielding line (redundancy) as well as pressure and airtightness line. The last line of defence is the thermal aerogel layer against the extreme temperatures from Mars as well as acoustical insulation. All these lines of defence can be connected to different classes and TRL, therefore the need for redundancy.

This design uses aerogel insulation, another option would be to use CO_2 as insulation layer. This would increase the ISRU percentage of the Ice Hab, however, the thickness of the insulation layer would increase as well as CO_2 does not have the same good thermal insulation properties as silica aerogel.

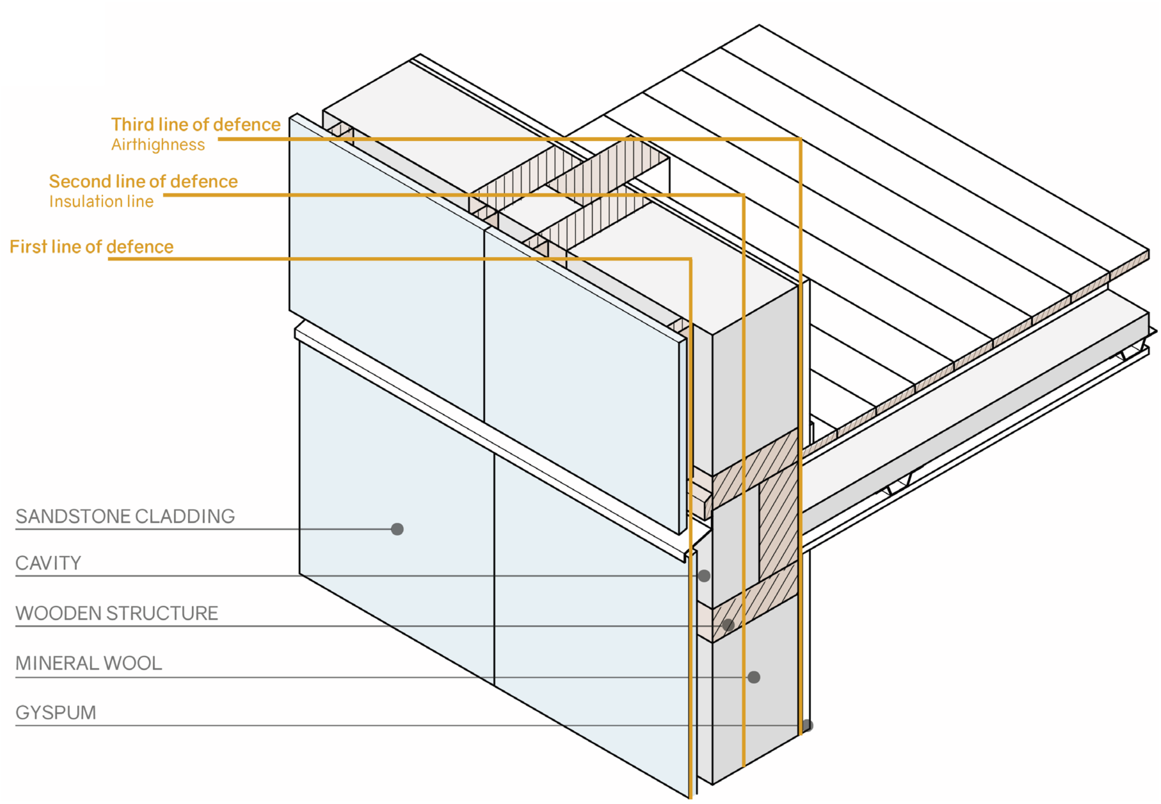


Figure 94. Standard Dutch cavity wall with the different line of defence.

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25. Processing of the ice for the Ice Hab

25.1 Mining

The steps taken to mine the ice are crucial for the habitat design. The amount of ice needed for the two habitat modules is calculated based on the optimum structural shape as well as the wall thickness needed for radiation protection. The mass for both walls for both modules is estimated at 48000 kg. As the ice sublimates and redundancy is vital, as safe value of 75 mt of ice is chosen. The weight of that ice is adjusted to the Martian gravity of 3,711 m/s^2 which means that the total weight of the ice that should be mined is 278325 N.

The robots used for mining are RASSORs. RASSORs are excavating robots developed by NASA for mining regolith and ice on Mars, especially designed to deal with the low pressure and gravity of Mars (Mueller, Cox, Smith, Schuler & Nick, 2015). The properties of the RASSORs are leading for the building time and power need calculations.

RASSOR PROPERTIES	UNIT	VALUE
TRANSPORT SPEED	cm/sec	20
	m/sec	0.2
WEIGHT	kg	45
HEIGHT	cm	76
MAX. PAYLOAD	kg	18
MINING TIME FOR 1 PAYLOAD	min	10
BATTERY (2X)	V	12
	AH lithium	19
DRAW DRIVING	A	3-5
DRAW RAISING	A	8-10
DRAW MINING	A	2

Table 46. Properties of the RASSOR. Based on information from (Mueller, et. al., 2015).

Figure 95. RASSOR prototypes. The size and principle of the excavations units are shown (Mueller, et. al., 2015).

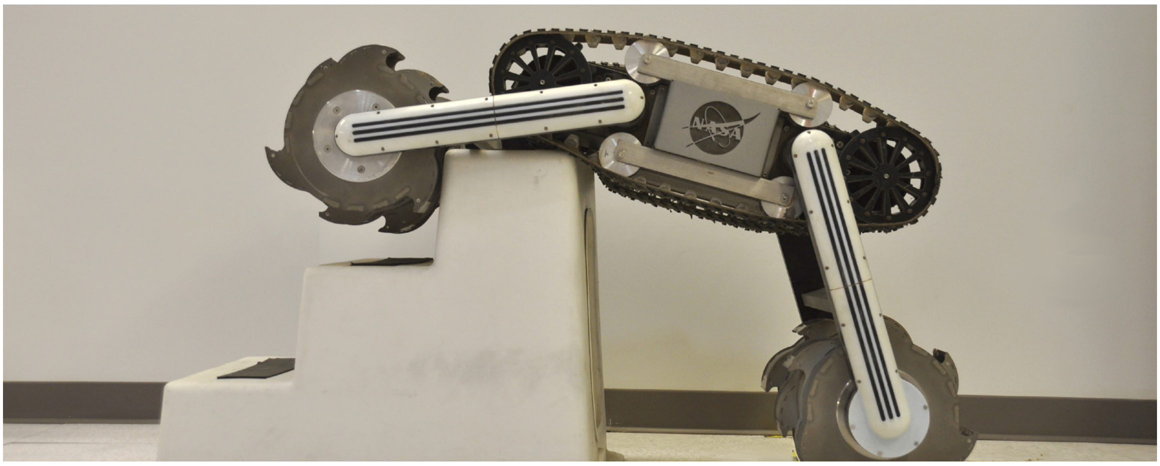


Figure 96. RASSOR 1 prototype. The flexibility and ability to climb is shown (Mueller, et. al., 2015).

25.2 Validation

This heading is a validation of the design through manual calculations regarding the energy needed to build the habitat. The energy requirement for the Martian habitat states that a maximum amount of 40 kW/h should be used to build the habitat.

As stated in the process chapter, the building time and power needed for the ice structure of the habitat depend on the overall design of the habitat itself. This heading deals with the validation for this specific design where the criteria for the building time and power are verified. These two aspects are related as the longer the building time, the less power is needed and vice versa.

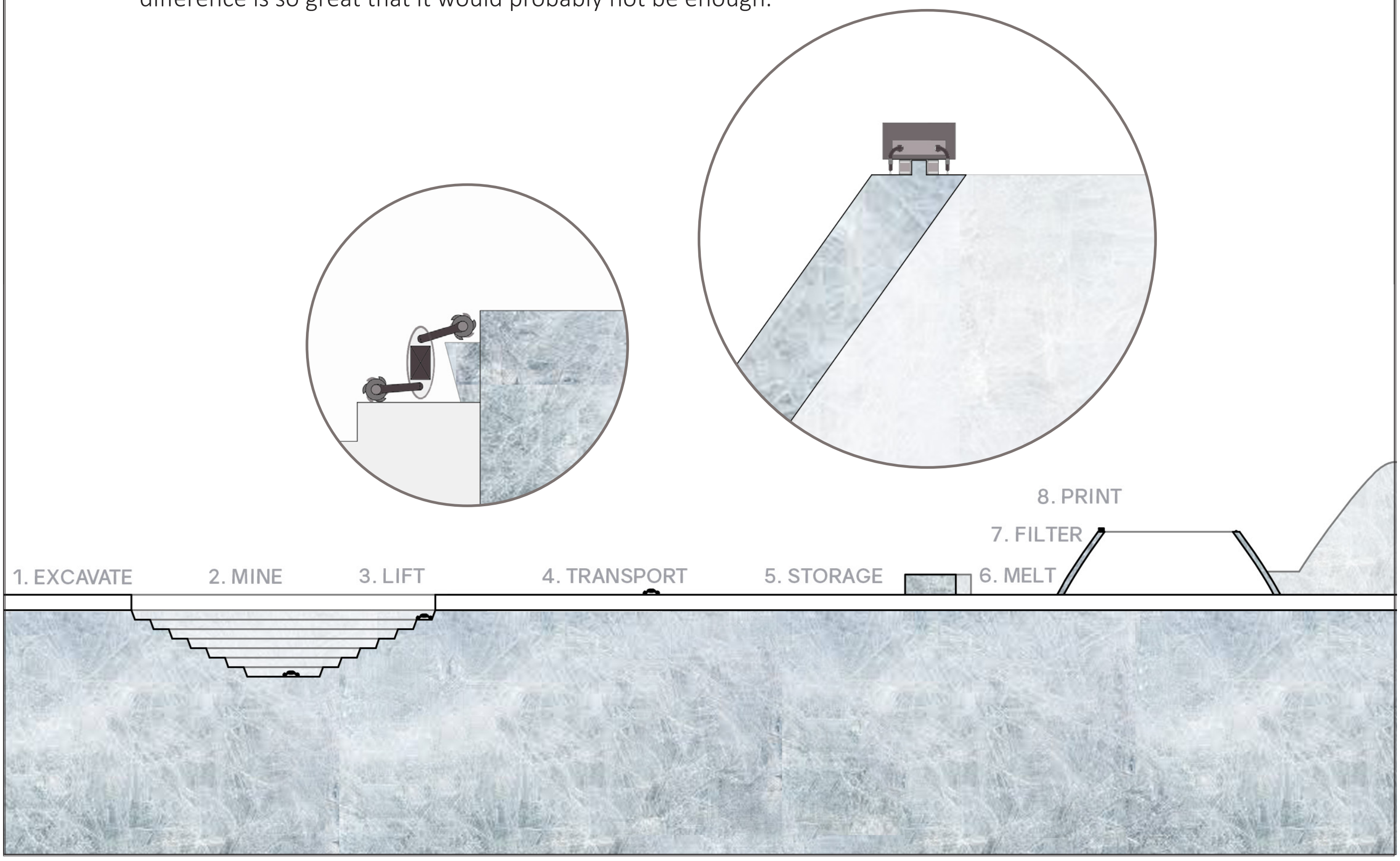
First, the different processing steps for the ice are isolated from mining to building itself. Eight steps are identified:

1. **Excavation** of the regolith
2. **Mining** of the ice
3. **Lifting** the ice onto the surface
4. **Transport** from the mining location to the storage
5. **Storage** of the ice
6. **Melting** of the ice
7. **Filtering** of the impurities
8. **Printing** of he structure

Each step has different power and time demands but two clusters can be created regarding building time: the first cluster is from step 1 (Excavate) to 5 (Storage) and the second from step 6 (Melt) to 8 (Print). The first cluster takes approximatively 6 months and the second 8 months, these values are based on the building timeline.

Calculations are made based on literature for the properties of the RASSORs and the sublimation and freezing rate of the ice at Jezero crater and can be found in table 47.

The total power needed for the whole building of the ice structure would be approximatively 21 GW for the whole building phase spanning 14 months (10220 hours). Therefore, the total power needed would average around 2060 kW/h. This is far above the requirement of 40 kW/h. Therefore, the power requirements are not met. The power required per hour could be decreased by increasing the building time, however, the difference is so great that it would probably not be enough.



	PROCESS	UNIT	VALUE
1. EXCAVATE	thickness	m	1
> REGOLITH	volume	m3	20.16
	draw mining	A	2
	power to excavate	W	24
	time available for activity	h	10
	Excavate	**kW/h**	**0.024**
2. MINE	ice	mt	75
OPEN-PIT MINING	penetration rate	mm/h	400 - 500
	sublimation rate	mm/h	0.08
	draw mining	A	2
	mining rate	mt/h	0.017361111
		kg/h	17.36111111
	power to mine	W	24
	time available for activity	h	490.5555556
	Mine	**kW/h**	**0.000489241**
3. LIFT	payloads	-	4166.666667
	power draw/payload	W	120
	power to lift	W	500000
		kW	500
	time available for activity	h	1666.666667
	Lift	**kW/h**	**0.3**
4. TRANSPORT	distance	m	70
	time to make distance	s	350
		min	5.833333333
	total distance	m	583333.3333
	Power to drive	W	60
	time available for activity	s	29166.66667
		h	486.1111111
	Transport	**kW/h**	**0.001234286**
5. STORAGE	lift height	m	2
	Energy to lift	KJ	
	Power to lift	W	500000
	time available for activity	h	1666.666667
	Storage	**kW/h**	**3**
6. MELT	heat of fusion water	kJ/kg	333.55
	specific heat brine	W/mK	3.04390244
	mass ice to melt	kg	75000
	Energy to melt	KJ	25016250
	Power to melt	kWh	90058500000
	Power to melt	kW	20846875
	time available for activity	h	1680
	Melt	**kW/h**	**12408.85417**
7. FILTER	pressure needed	kPa	30
		Pa = N/m2	30000
	Area of filter	m2	2
	length from storage to habitat	m	16
	Force	N	15
	Energy	J = Nm	240
	power to filter	kWh	864000000
		kW	200000
	time available for activity	h	480
	Filter	**kW/h**	**416.6666667**
8. PRINT	freezing time	s	471
	temperature day	°C	-30
	estimated Volume	L	0.0044
	estimated Volume	mt	0.000004048
	Estimated layers	-	18527667.98
	Estimated time	s	8726531621
	Estimated time	days	101001.54
	Estimated time	months	3320.6
	Amount of robots needed	-	415.075
	power to lift and drive	W	180
	time available for activity	h	4080
	Print	**kW/h**	**0.000441176**
TOTAL	**Power total**	W	21047875288
		kW	21047875.29

Table 47. Calculations of the power need and building time of the ice wall. These calculations do not take into account the power and time needed to assemble the core capsule of the habitat.

25.3 Improvements

The result of the energy calculations indicates that the energy consumption for the processing of the ice will vastly exceed the requirements. The melting step is, by far, the greatest energy consumer followed by the act of lifting. The other steps are quite negligible regarding energy consumption.

A possible improvement would be to fully use the phase change properties of the ice/water by changing the pressure instead of the temperature. Indeed, the latest usually requires more energy. As Martian pressure is near the triple point of H_2O, a change of 100-700 Pa would already induce a phase change from ice to gas. This step is easy to achieve when the ice is stored (step 5) as the containers would be pressurized anyway to prevent losses of H_2O.

Using reduced pressure to sublimate ice is often used on Earth in different industries (food processing, pharmaceuticals, restoration of historical documents, etc.) in a process called freeze drying. Freeze drying is used to separate water from a substance to dehydrate the substance. It is a three stage process where the product is first frozen below its triple point then dried twice. To dry the frozen product the first time, a partial vacuum is created with a pressure of a few millibars (0,01 Pa) and a small amount of heat is applied. During the second drying stage, the product is exposed to higher temperatures going up to 0°C and lower pressure to sublimate the unfrozen water molecules (Roy & Pikal, 1989). On Mars, possibly the radiating heat from the sun as well as a low pressurized environment could be used to sublimated the ice into gas.

There is, however, a temperature limit situated around -50 °C for the phase change as can be seen on the phase diagram of water in figure 97.

On top of using less energy to phase change the ice, gas is lighter. Therefore the energy required to lift the gas would decrease compared to the lifting of the ice.

This preliminary idea could help reduce the energy consumption for the building of the habitat. However, this improvement requires more research which does not fit within the timespan of this research.

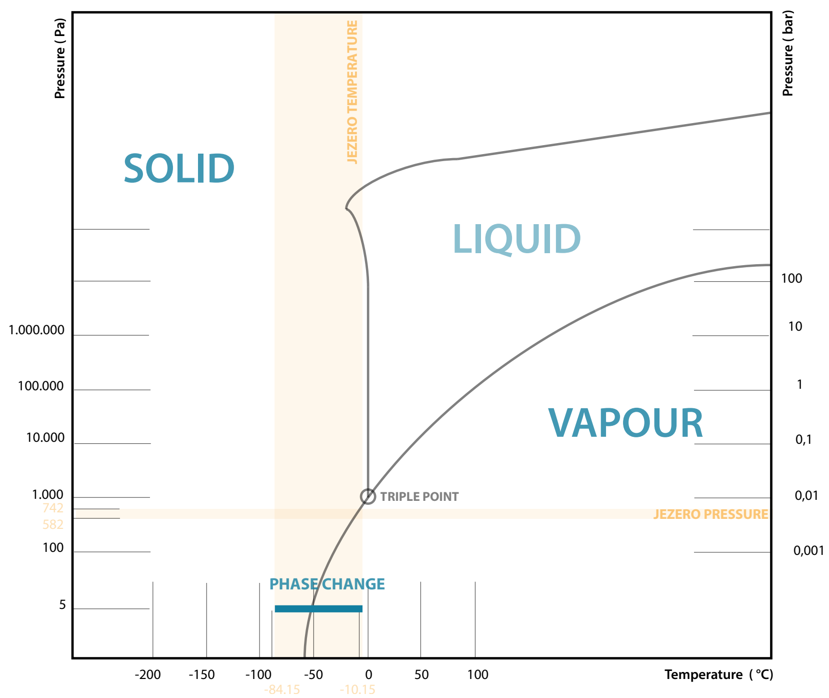


Figure 97. Phase change diagram for H_2O. The pressure at which a phase change occurs within the temperature range of Jezero crater is highlighted in blue.

26. Conclusion

This resulting design is assessed with the previously set programme of requirements.

	THEME	NUMBER	CRITERIA	COMPLIES
1.0	**Landing site**	1.1	Safe distance from pre-deployed structures	Y
		1.2	Relatively smooth and flat terrain	Y
		1.3	Close proximity to POI	Y
		1.4	Ease of transportation to and from landing site	Y
		1.5	Constant temperature through day and night	N
		1.6	H_2O present near the landing site	Y
2.0	**Structural systems**	2.1	Moderate temperatures are provided for the crew inside the habitat (short sleeve environment)	Y
		2.2	Materials are selected in on low outgassing	Y
		2.3	Technical systems have minimal noise and vibration influence	Y
		2.4	Materials and structure are to be fire and smoke proof	Y
		2.5	Redundancy	Y
		2.6	Minimal structural openings	Y
		2.7	Radiation shielding following ALARA	Y
		2.8	Resistance against meteoroids following ALARA	Y
		2.9	Resistance against perchlorates following ALARA	Y
		2.10	Mass: 130 mT	Y
		2.11	Volume: max diameter: 10m and max height: 31m	Y
3.0	**Typology**	3.1	Pressure ports with dust control	Y
		3.2	EVA airlocks	Y
		3.3	Gravity orientation	Y
		3.4	Energy harvesting near or within the habitat	Y
		3.5	Possible expansion	Y
		3.6	Habitat for 6 crew members	Y
4.0	**Sustainability**	4.1	use of ISRU	Y
		4.2	Class IV technology	Y
		4.3	low impact on Mars upon departure (waste)	Y
		4.4	Re-use of organic matters	Y
5.0	**Life support**	5.1	Physical/chemical systems to provide O2	Y
		5.2	Extraction system for H2O	Y
		5.3	Greenhouse	Y
6.0	**Psychological**	6.1	visual contact with exterior environment	Y
		6.2	Flexible plan, furniture, lighting, temperature	Y
		6.3	Separating work and leisure, private and public	Y
		6.4	Private crew quarters for each member	Y

	THEME	NUMBER	CRITERIA	COMPLIES
7.0	**Assessment**	7.1	TRL 1	Y
		7.2	TRL 2	Y
		7.3	TRL 3	Y
		7.4	TRL 4	-
		7.5	TRL 5	-
		7.6	TRL 6	-
		7.7	TRL 7	-
		7.8	TRL 8	-
		7.9	TRL 9	-
8.0	**Material**	8.1	ISRU at least 70%	Y
		8.2	recyclables	Y
		8.3	thickness of at least 325 mm of H_2O	Y
9.0	**Process**	9.1	semi-autonomous	Y
		9.2	lightweight machinery	Y
		9.3	min. amount of machines needed > machinery is multipurpose	Y
		9.4	time: should not exceed 17 months	Y
		9.5	power: max 40 kW	N

Y=yes
N=no

Table 48. Assessment of the design with the programme of requirements.

Overall, the habitat design complies well with the requirements, however two aspects do not comply. The manual calculations indicate that the power needed to mine the ice and build the habitat, greatly exceeds the maximum amount of 40 kW/h. Therefore many more solar panels or an extra fission power unit would be necessary. A possible improvement would be to use the phase change properties of H_2O by decreasing the pressure and only slightly increasing the temperature to allow the ice to sublimates. This could decrease the energy needs for the building of the habitat, especially as the gas is lighter than water.

The location does not comply to requirement 1.5 "constant day and night temperature". On hindsight, no location on the surface of Mars complies with this criterium. Jezero crater, however is situated close to the equator, therefore the temperatures are quite constant throughout the year which is not the case for the whole planet.

Another aspect which can't be read from the table is the TRL which differs for each design elements, but is at least a level 3 for each element.

Bibliography – PART F

Mueller, R.P., Cox, R.E., Ebert, T., Smith, J.D., Schuler, J.M., & Nick, A.J. (2015). *Regolith Advanced Surface Systems Operations Robot (RASSOR)*. NASA Kennedy Space Center. FL United States.

Roy, M.L. & Pikal, M.J. (1989). Process Control in Freeze Drying: Determination of the End Point of Sublimation Drying by an Electronic Moisture sensor. *PDA J Pharm Sci Techno March April* 1989 43:60-66.

PART G

CONCLUSIONS

27. Conclusions

This research aimed to answer the research question:

Which **in situ materials** and **forming techniques** are suitable to create an outer shell for a **sustainable habitat** on Mars which protects the crew from **the harsh Martian environment?**

First, sustainability on Mars is defined. Sustainable building on Mars means being as much independent from Earth as possible in order to achieve complete redundancy. This can be directly linked to the habitation classes set by Cohen in 1991 ranging from class I to class V with class V being completely independent from Earth. However, the technology to achieve a class V habitat is not ready yet and firstly a class IV habitat should be tested in situ to assess it. The proposal of this research is to use both class III and class IV elements in order to have redundancy (class III) but also to test out class IV technologies for the follow up missions needing new habitats. Therefore the sustainability criteria are still in development and will be part of the many experiments carried out by the crew on Mars.

Secondly, a new material and forming technique has been found. After an extensive analysis, ice is found to be the most promising building element for a habitat which protects the crew from the harsh Martian environment. This conclusion is also reached by other parties like Clouds AO and NASA. However, the material ice itself is weak and a reinforcement is needed. Studies focus on using regolith as reinforcement, however this is time and power extensive and has not met promising results yet. This research sheds a light on the use of sodium chloride as reinforcement through experiments. This material changes the properties of the ice to comply with the set requirements. The results for all perfomed tests were the same: the addition of sand or plastic did not upgrade the building properties of the ice. However, adding salt does improve the building properties. The outcome of the experiments indicates that up to 15 ppt of NaCl increases the compressive strength from an average of 1 MPa to 4 MPa. A higher percentage of sodium chloride does not influence the compressive strength. The experiments also indicated that the colder the testing environment (up to-70°C), the higher the compressive strength of the NaCl ice is. The warmer the environment (up to +25°C), the more ductile the NaCl ice behaves. Moreover, adding salt is much simpler than using regolith as well as cheaper and faster. This is because sodium chloride is already present in the Martian ice, the harvesting process would be to maintain the salt in the ice when filtering it. Although the experiments performed gave interesting results, more are needed to completely evaluate these findings.

Thirdly, a forming technique has been found to create a dome out of that ice, made of water and salt. The filling of ETFE pockets is relatively advanced in the design; however the printing of a dome without any support is still in an experimental stage. Therefore a structural optimization was designed using the Vault plugging for the Rhinoceros modelling software. Another experiment also was carried out where a manually activated linear frame "printed" ice at -30 °C. The results indicate that ice will freeze at a rapid rate of less then 10 min per 0,8 mm. Another extraordinary finding is that the ice printed layer by layer reinforces the overall structure. Moreover, ice thus printed has the ability to repair the ice structure along the way. This is due to the water filling cracks that may have formed and then expanding upon freezing. However, this part needs much more research to determine how the ice freezes, attaches to itself, and finally sublimates in a Martian envrionment.

Finally, a habitat is made to assess the criteria and the newly found material and processing technique. Overall, the habitat complies well with the requirements. However, it fails on the power requirement as, especially the melting phase exceeds greatly the energy limit.

This research answered the question by discovering a new material, sodium chloride ice, and a specific technique to process the ice via additive manufacturing. Further research is needed to determine the viability of those results, nevertheless, the results look promising.

28. Further research

Further research is needed on the topic of building on Mars. As most experiments were time and equipment restrained, the values found are non-conclusive and further experiments should be done before using the values as empirical data. Especially the processing of the ice and the way the constructed ice will behave under Martian conditions, requires more study, as the equipment available could only recreate a simplified analogue.

First of all, the exact composition of the sodium chloride ice should be further investigated as only few specimens were tested with few variables. The specimens were taken out of the freezing environment before testing, hence we found that the time they were kept at ambient temperature was critical. Therefore, the specimens could not be properly measured and weighed to determine the density. This should be done in further experiments within a freezing environment. Moreover, the different percentages of sodium chloride should be tested again in compression as well as in a three point bending test. The values found should then be plotted against the percentage of sodium chloride present in the underground ice of Mars at Jezero crater, at the moment, this data is not known.

Secondly, the process of building with the ice through additive manufacturing can be further investigated. First of all, a prototype RFP machine needs to be built to be able to mount or climb the ice structure on a large scale using a robotic arm. The design would be based on the Cobra 600 RFP prototype developed by P. Sijpkes at McGill University. This device probably won't work by only printing ice as the water will drip along the sides of the previously printed structure. Some kind of mold will be necessary to restrain the water from flowing along the sides of the print. It will however allow for repairs and this ability should not be restrained too much.

Furthermore, the energy needed to melt, filter, transport and print the ice should be further analyzed. At the moment, the first manual calculations indicate that the energy demand will greatly exceed the supply available on Mars. A concept worth developing is to combine as effectively as possible all the steps needed to transform the ice to an ice structure. Maybe allowing the ice to sublimate instead of melting it would be more energy efficient. However, the time needed to sublimate the ice would probably be a lot longer than the time to melt it. Changing the pressure rather than the temperature may also be a viable option to further investigate.

Finally, an analysis on the lifespan of the habitat should be made. As redundancy is vital on Mars, different scenarios should be investigated and possible solutions for problems can be developed. A few possible scenarios are f.g. potential seismic events, the influence of dust storms on the structure and power of the solar panels, the failure of a machine or step, the influence of the environment on the ice (pressure, temperature and gravity). These scenario's could occur at any given time during the mining of the ice, construction and deployment of the habitat as well as during the stay of the crew.

PART H

APPENDICES

Appendix A – Climatology

The graphs generated with the Mars Climate Database v5.2 used to define the climate of Mars in general and at the Jezero crater in particular.

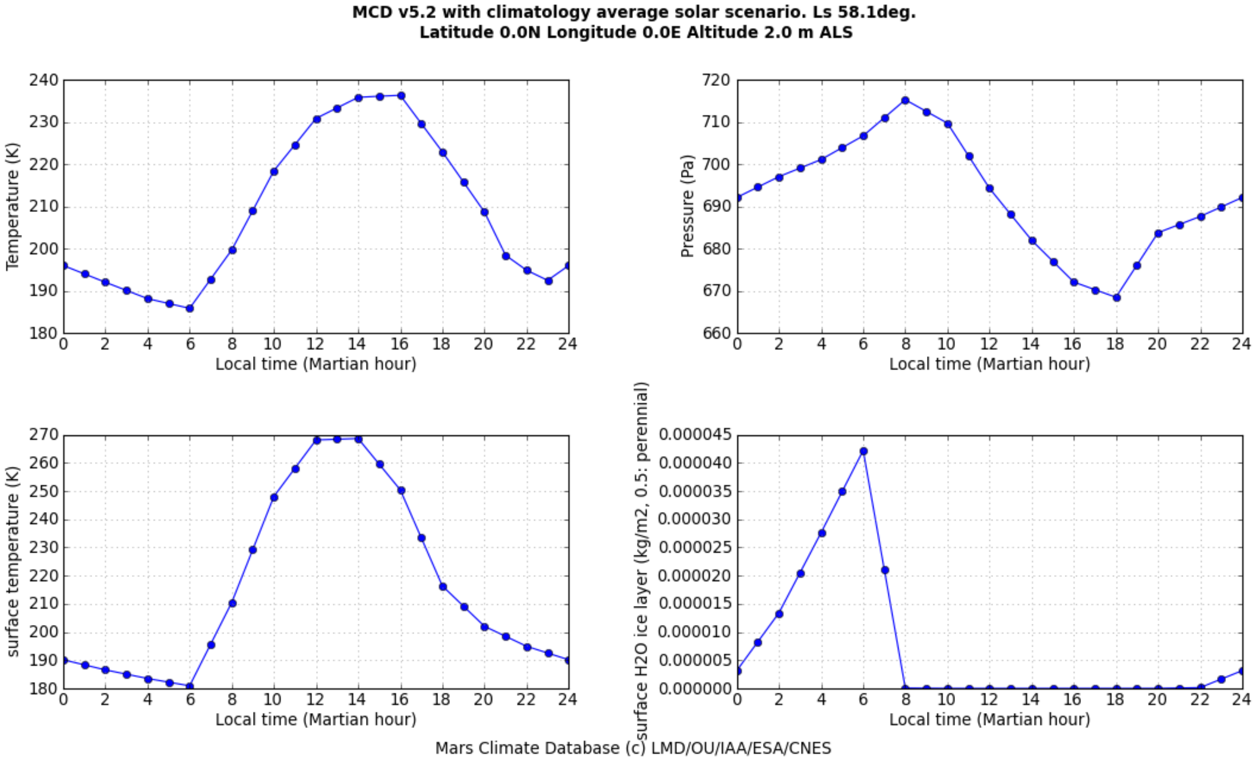


Figure F1. Climate at Mars equator. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

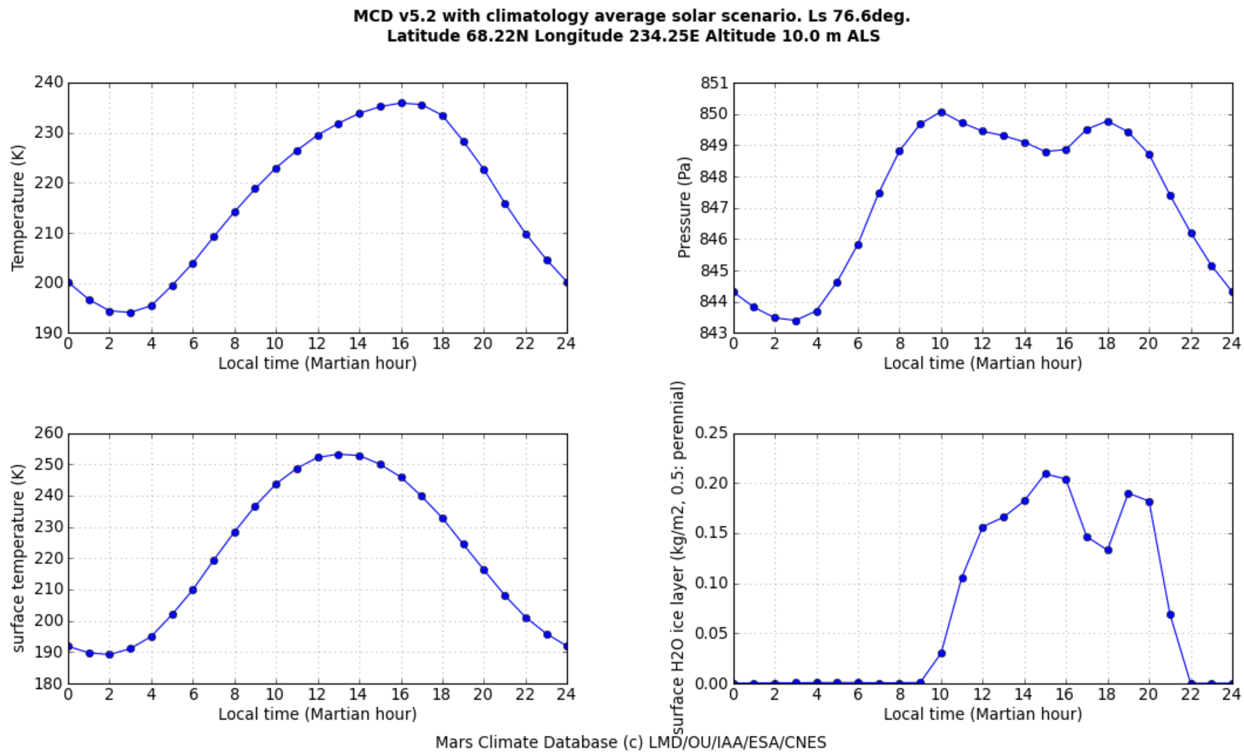


Figure F2. Climate at Mars Phoenix Lander site. The air temperature and surface temperature are given in Kelvin (0 K = -273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

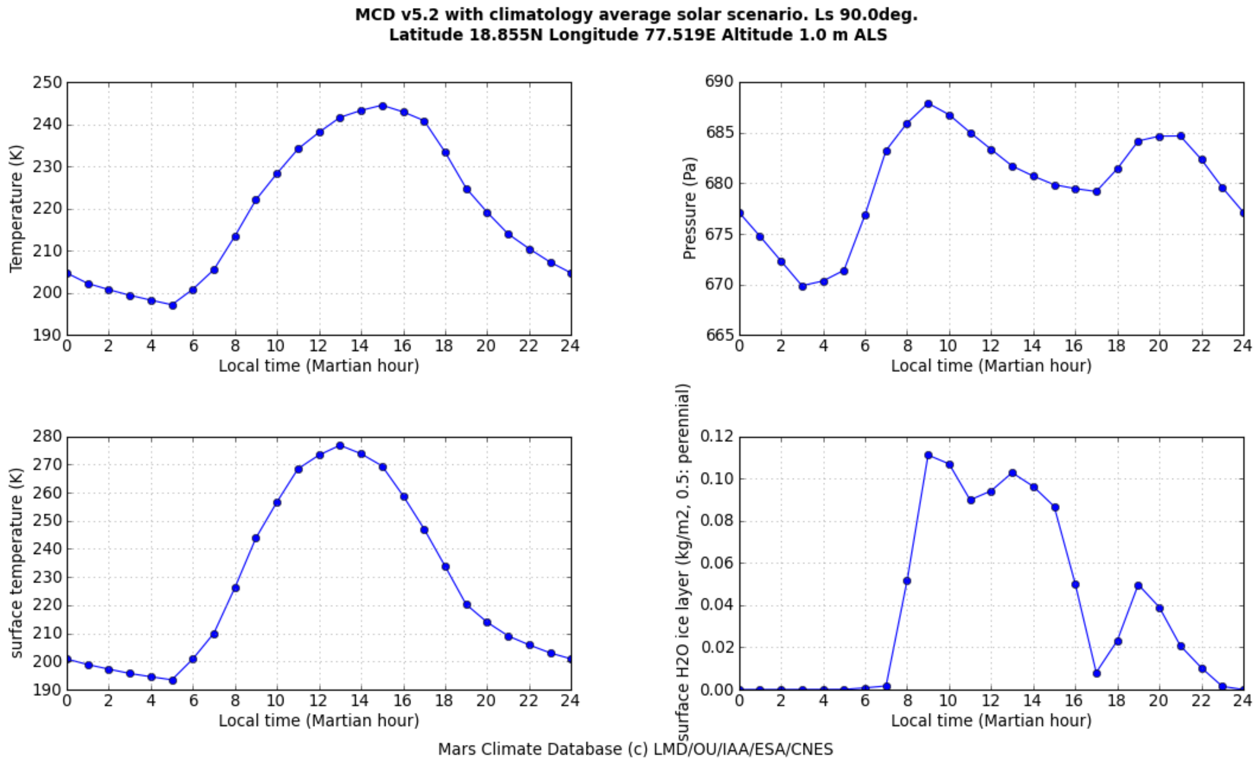


Figure F3. Climate at Jezero Crater on the summer solstice. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H_2O ice on the surface in kg/m2.

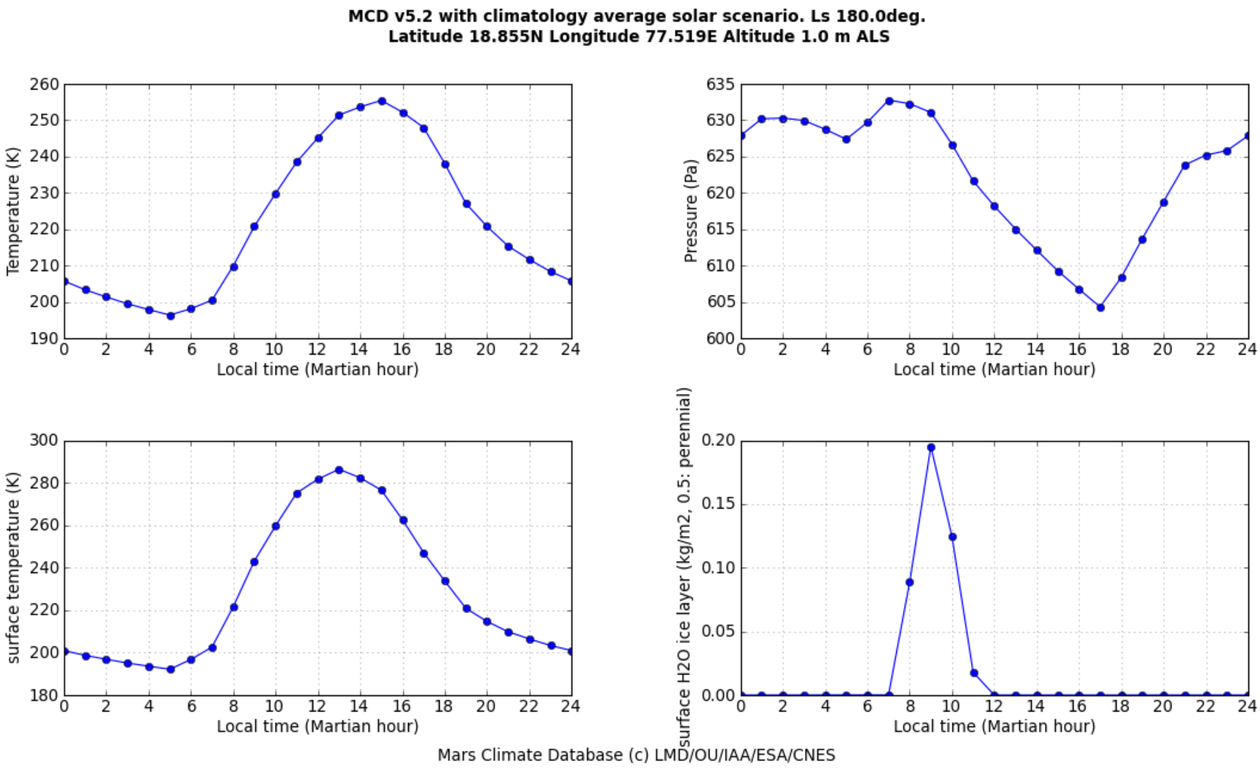


Figure F4. Climate at Jezero Crater on the winter solstice. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H_2O ice on the surface in kg/m2.

Appendix A – Climatology

The graphs generated with the Mars Climate Database v5.2 used to define the climate of Mars in general and at the Jezero crater in particular.

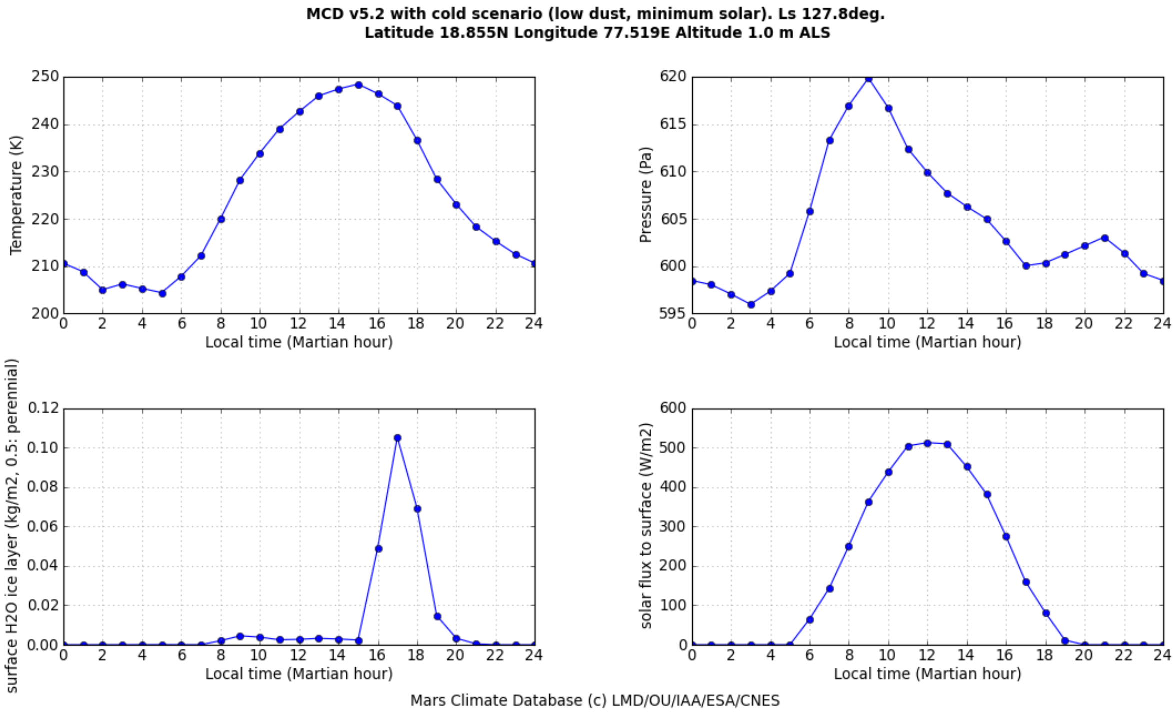


Figure F5. Climate at Jezero crater with a cold average weather (minimum solar flux) for the first landing option at Ls= 127.8. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

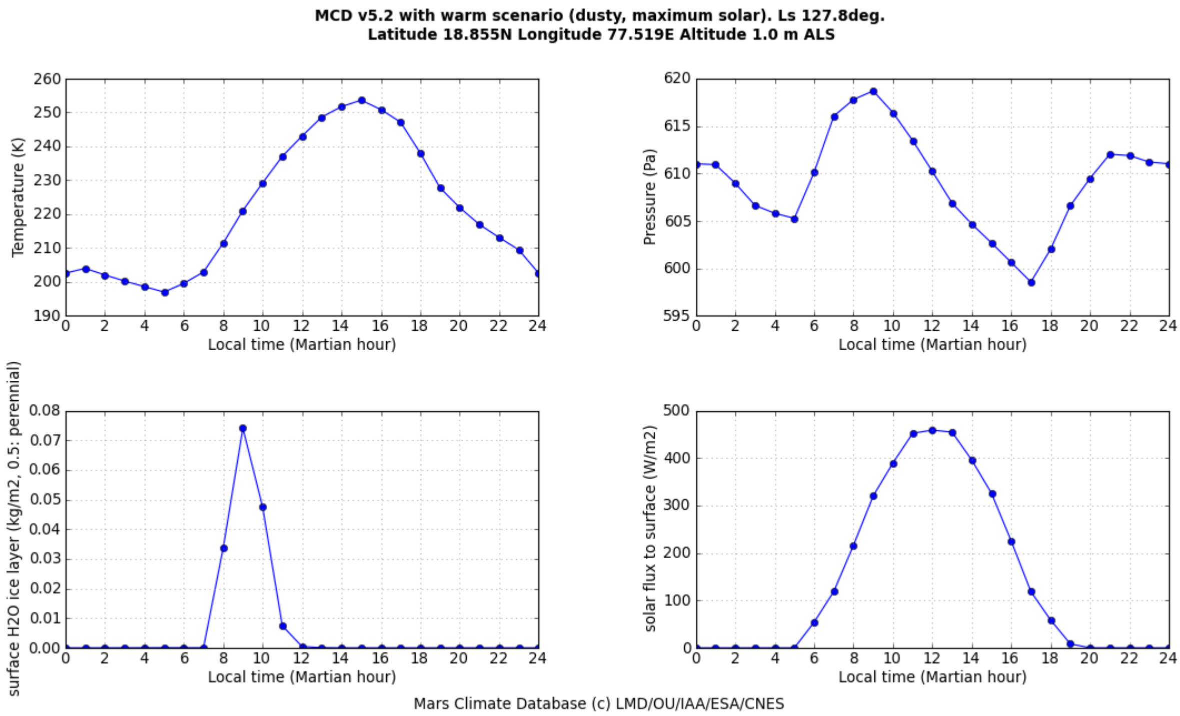


Figure F6. Climate at Jezero crater with a warm average weather (maximum solar flux) for the first landing option at Ls= 127.8. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

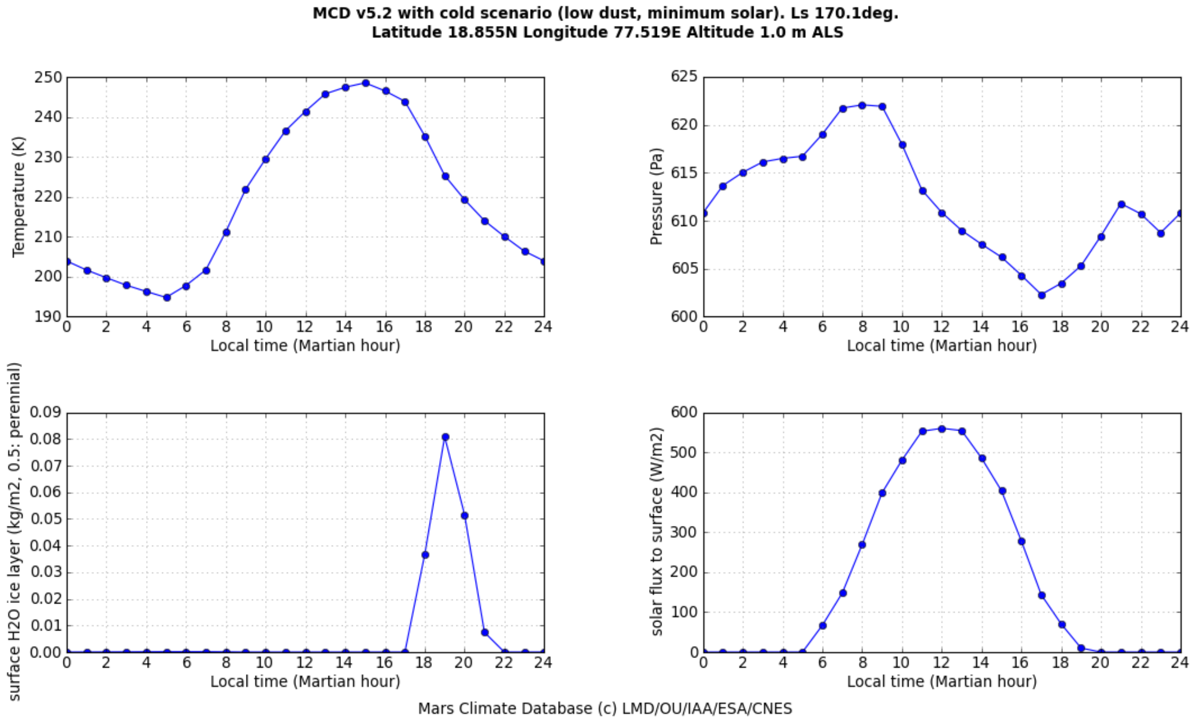


Figure F7. Climate at Jezero crater with a cold average weather (minimum solar flux) for the second landing option at Ls= 170.1. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

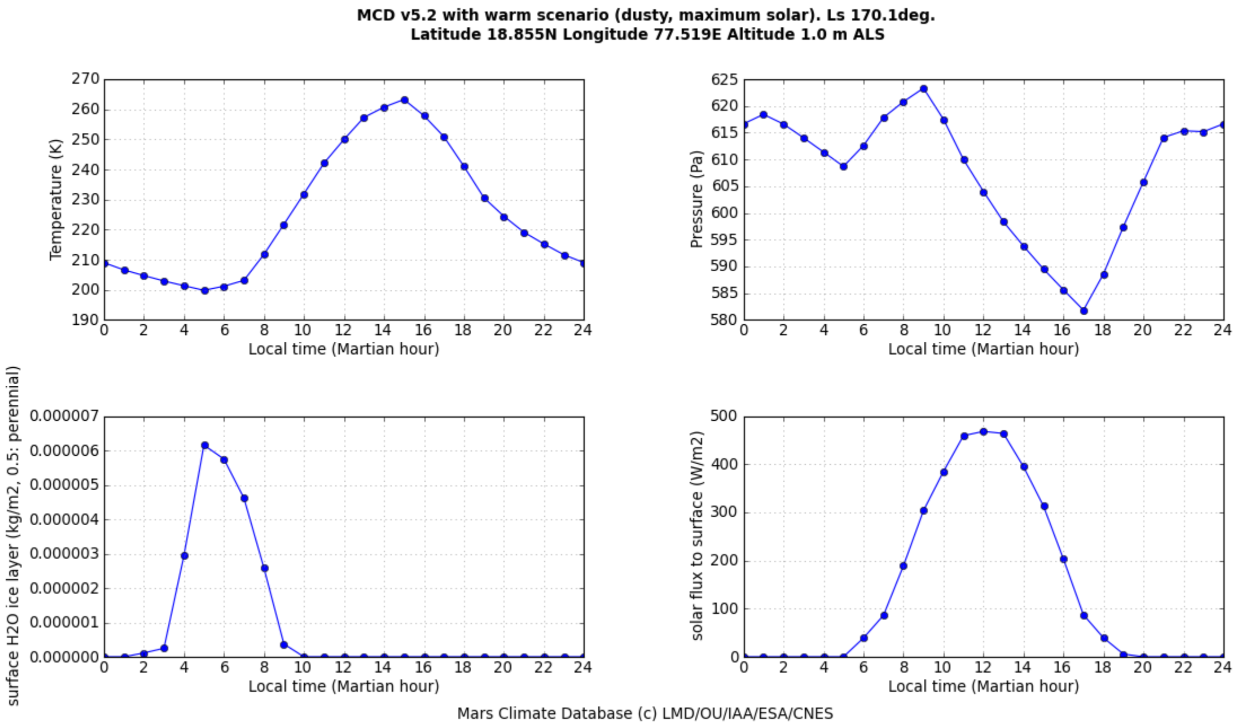


Figure F8. Climate at Jezero crater with a warm average weather (maximum solar flux) for the second landing option at Ls= 170.1. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

Appendix A – Climatology

The graphs generated with the Mars Climate Database v5.2 used to define the climate of Mars in general and at the Jezero crater in particular.

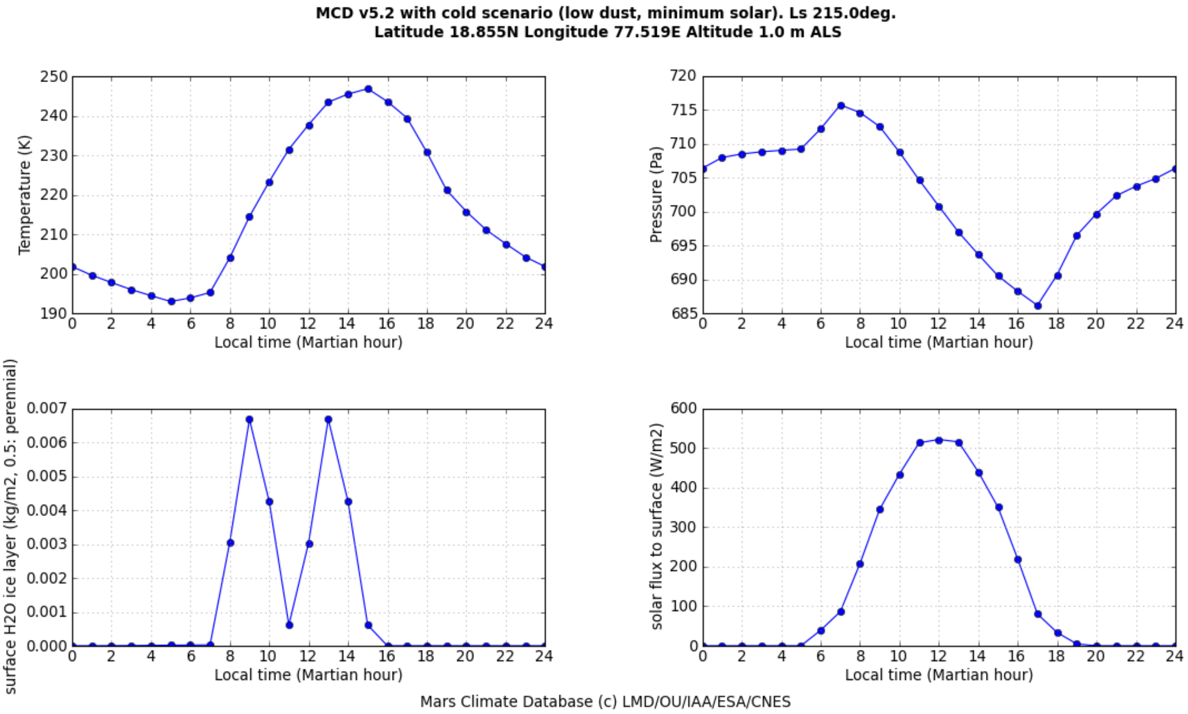


Figure F9. Climate at Jezero crater with a cold average weather (minimum solar flux) for the third landing option at Ls= 215. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

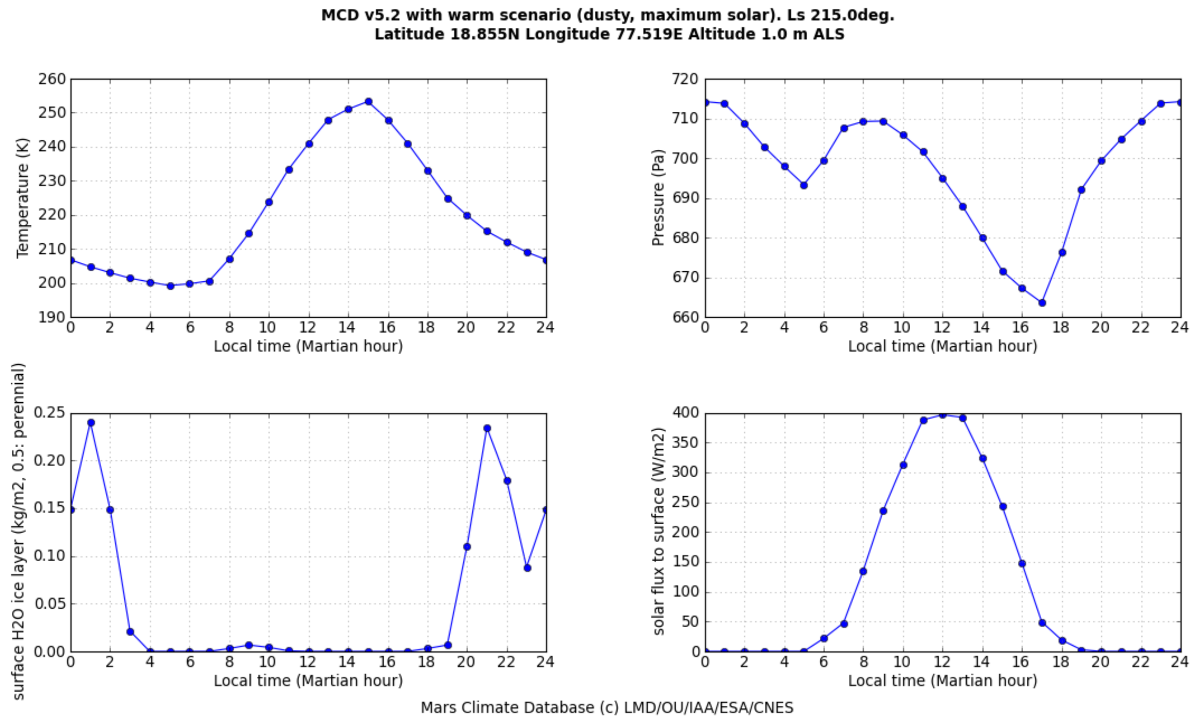


Figure F10. Climate at Jezero crater with a warm average weather (maximum solar flux) for the third landing option at Ls= 215. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

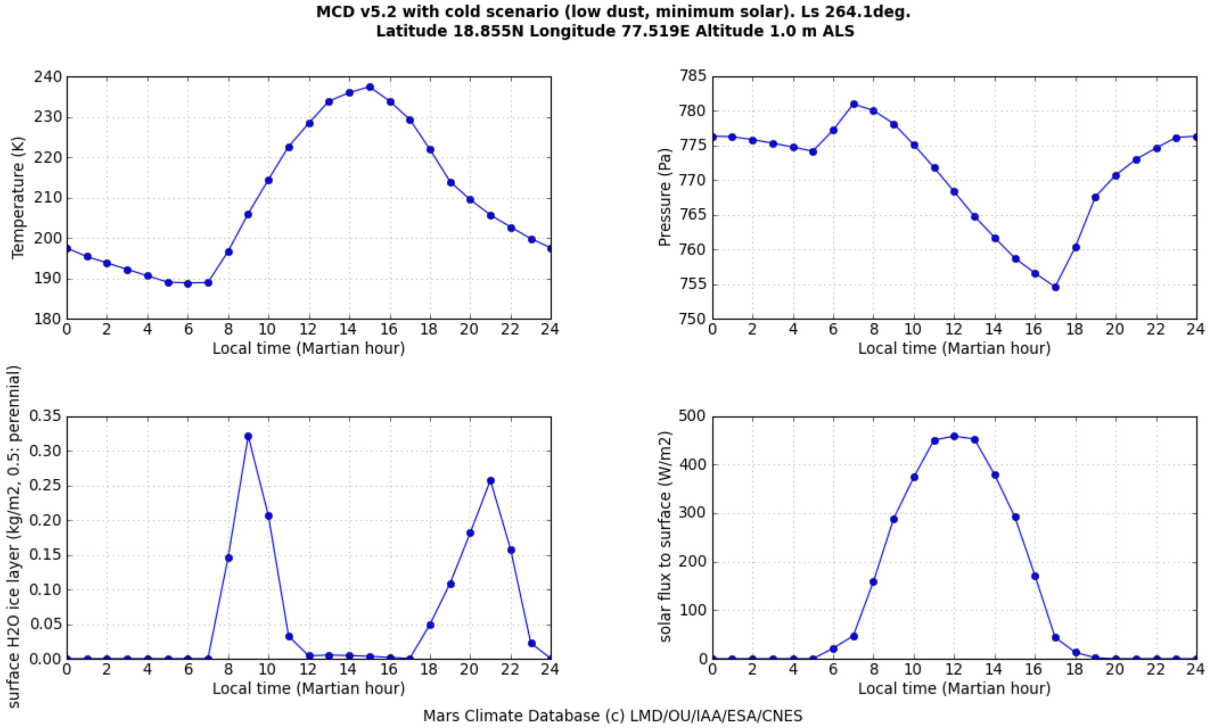


Figure F11. Climate at Jezero crater with a cold average weather (minimum solar flux) for the fourth landing option at Ls= 264.1. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

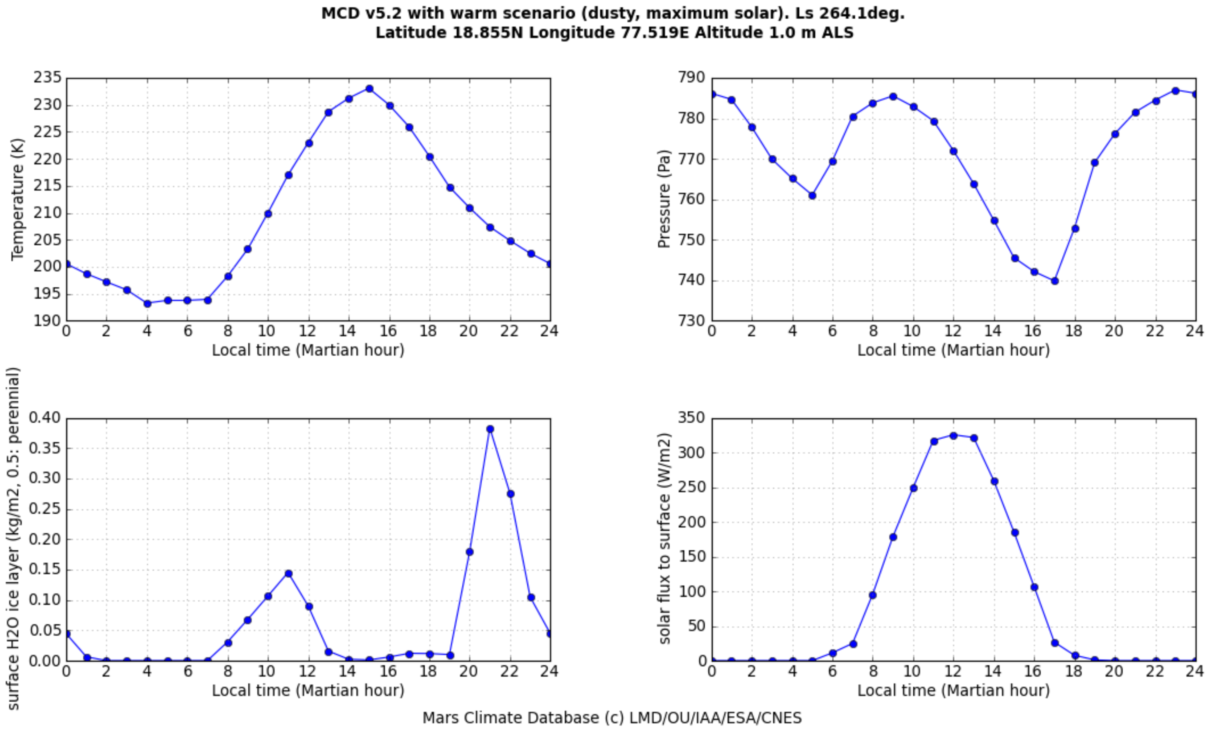


Figure F12. Climate at Jezero crater with a warm average weather (maximum solar flux) for the second landing option at Ls= 264.1. The air temperature and surface temperature are given in Kelvin (0 K =-273,15 °C), the pressure in Pascal (Pa) and the presence of H2O ice on the surface in kg/m2.

Appendix B – Complete Programme of Requirement

The complete programme of requirement for a sustainable habitat on Mars as derived from the different literature findings.

	THEMES	NUMBER	CRITERIA
1.0	**Landing site**	1.1	Safe distance from pre-deployed structures
		1.2	Relatively smooth and flat terrain
		1.3	Close proximity to POI
		1.4	Ease of transportation to and from landing site
		1.5	Constant temperature through day and night
		1.6	H_2O present near the landing site
2.0	**Structural systems**	2.1	Moderate temperatures are provided for the crew inside the habitat (short sleeve environment)
		2.2	Materials are selected in on low outgassing
		2.3	Technical systems have minimal noise and vibration influence
		2.4	Materials and structure are to be fire and smoke proof
		2.5	Redundancy
		2.6	Minimal structural openings
		2.7	Radiation shielding following ALARA
		2.8	Resistance against meteoroids following ALARA
		2.9	Resistance against perchlorates following ALARA
		2.10	Mass: 130 mT
		2.11	Volume: max diameter: 10m and max height: 31m
3.0	**Typology**	3.1	Pressure ports with dust control
		3.2	EVA airlocks
		3.3	Gravity orientation
		3.4	Energy harvesting near or within the habitat
		3.5	Possible expansion
		3.6	Habitat for 6 crew members
4.0	**Sustainability**	4.1	use of ISRU
		4.2	Class IV technology
		4.3	low impact on Mars upon departure (waste)
		4.4	Re-use of organic matters
5.0	**Life support**	5.1	Physical/chemical systems to provide O2
		5.2	Extraction system for H2O
		5.3	Greenhouse
6.0	**Psychological**	6.1	visual contact with exterior environment
		6.2	Flexible plan, furniture, lighting, temperature
		6.3	Separating work and leisure, private and public
		6.4	Private crew quarters for each member
7.0	**Assessment**	7.1	TRL 1
		7.2	TRL 2
		7.3	TRL 3
		7.4	TRL 4
		7.5	TRL 5
		7.6	TRL 6
		7.7	TRL 7

	THEMES	NUMBER	CRITERIA
		7.8	TRL 8
		7.9	TRL 9
8.0	**Material**	8.1	ISRU at least 70%
		8.2	recyclables
		8.3	thickness of at least 325 mm of H_2O
9.0	**Process**	9.1	semi-autonomous
		9.2	lightweight machinery
		9.3	min. amount of machines needed > machinery is multipurpose
		9.4	time: should not exceed 17 months
		9.5	power: max 40 kW
10.0	**Assessment**	10.1	Mixing test of a brick
		10.2	Melting test of a brick
		10.3	Drop test of a brick
		10.5	Compression test (ASTM C39) of a cylinder (diam: 150 - height: 300mm) min. load failure at 450 kgf = 44 MPa
		10.6	Compression test (ASTM C78) of a beam (100x200mm 650mm) min. load failure at 750 kgf = 73 MPa
		10.7	Compression test (ASTM C78) of a dome min. load failure at 625 kgf = 61 MPa
		10.8	Flexural strength (tpb test)of a beam (100x200mm 650mm)
		10.7	Compression test (ASTM C78) of a dome min. load failure at 625 kgf = 61 MPa
		10.8	Flexural strength (tpb test)of a beam (100x200mm 650mm)

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Table F1. Complete table of requirements put together through literature findings.

Appendix C – Material – Literature study

This research is strongly influenced by the research made by Janssen and Houben (2013) on testing ice and pykrete for building purposes. Their testing matrix for 100% ice cylinders are found below.

General information					
Mixture Number	3	3	3	3	3
Specimen Number	Ac	Bc	Cc	Dc	Ec
Reinforcement type	n/a	n/a	n/a	n/a	n/a
Percentage reinforcement by dry weight dry (%)	0	0	0	0	0
Water/snow ratio	1/0	1/0	1/0	1/0	1/0
Beam / Cylinder	Cylinder	Cylinder	Cylinder	Cylinder	Cylinder
Creating specimens					
Date	21-5-2013	21-5-2013	21-5-2013	21-5-2013	21-5-2013
Time first layer	14:00	14:00	14:00	14:00	14:00
Time last layer	n/a	n/a	n/a	n/a	n/a
Number of layers	1	1	1	1	1
Layer thickness (cm)	15,00	15,00	15,00	15,00	15,00
Production time (hours)	0,5	0,5	0,5	0,5	0,5
Demoulding					
Date	23-5-2013	23-5-2013	23-5-2013	23-5-2013	23-5-2013
Time	10:00	10:00	10:00	10:00	10:00
Mould number	n/a	n/a	n/a	n/a	n/a
Place in mould	n/a	n/a	n/a	n/a	n/a
Hours between last layer and demoulding	44	44	44	44	44
Dimensions after demoulding – Length (mm)	n/a	n/a	n/a	n/a	n/a
Dimensions after demoulding – Width or Ø (mm)	95	95	95	95	95
Dimensions after demoulding – Heigth (mm)	150	150	150	150	150
Weight (kg)	0,975	0,975	0,995	0,975	0,975
Density (kg/m^3)	917,48	917,48	936,30	917,48	917,48
Average Density (kg/m^3)			921,24		
Testing					
Date	31-5-2013	31-5-2013	31-5-2013	31-5-2013	31-5-2013
Time	09:33	09:40	09:45	09:50	09:55
Hours between demoulding and testing	191 11/20	191 2/3	191 3/4	191 5/6	191 11/12
Hours between last layer and testing, total time (hours)	235 5/9	235 2/3	235 3/4	235 5/6	236
Load cell (5/80kN)	80	80	80	80	80
Calibration factor (kg/V)	4919,4423	4919,4423	4919,4423	4919,4423	4919,4423
Start value (V)	-0,011	-0,011	-0,011	-0,010	-0,010
End value (V)	0,2810	0,3700	0,5760	0,4080	0,6430
End - start value (V)	0,292	0,381	0,587	0,418	0,653
Not meassured extra weight (kg)	6,105	6,105	6,105	6,105	6,105
Ultimate strength (kg)	1442,5822	1880,4125	2893,8176	2062,4319	3218,5008
Ultimate strength (N)	14146,8983	18440,5474	28378,6567	20225,5476	31562,7111
Flexural/ Compressive strength testing	Compressive strength	Compressive strength	Compressive strength	Compressive strength	Compressive strength
Strength (N/mm^2)	1,9958	2,6016	4,0036	2,8534	4,4528
Average strength (N/mm^2)			3,1815		
Positive error value			1,2714		
Negative error value			1,1856		
Remarks					

Table F2. Ice testing matrix (Janssen & Houben, 2013).

Appendix D – Experiment A – Specimen data

Date	Test type	Test nr	Picture nr	Movie nr	Matrice		Reinforcement		Mould	Temperature	Time
					Material	Percentage	Material	Percentage	[-]	[°C]	[h]
04/09/2017	zero measurement	A0.001	5682 - 5687 - 5692 t/m 56	-	Tapwater	100	-	-	M001	-20	16
04/09/2017		A0.002	5685 - 5688 t/m 5691 - 56	-	H2O purified	100	-	-	M001	-20	16
08/09/2017	Plastic	A0.003	5704 t/m 5711	5712	H2O purified	100	-	-	M002	-20	36
08/09/2017		A0.004	5702 - 5703 - 5715 t/m 57	5722	H2O purified	355 mL	Plastic PP & HDPE	1 tablespoon	M002	-20	36
08/09/2017		A0.005	5700 t/m 5702 - 5725 t/m	5732	H2O purified	355 mL	NaCl Plastic PP& HDPE	+/- 10 gr - 2 teaspoons 1 tablespoon	M002	-20	36
12/09/2017: freezing 13/09/2017: drop test	Sand	A0.006	5740 t/m 5753 - 5765 t/m	5774	H2O purified	355 mL	Sand	1 tablespoon	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.007	5740 t/m 5747 - 5754 t/m	5778	H2O purified	355 mL	Sand NaCl	1 tablespoon +/- 5 gr - 1 teaspoon	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.008	5740 t/m 5747 - 5760 t/m	5782	H2O purified	355 mL	Sand	2 tablespoons	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.009	5740 t/m 5747 - 5787 t/m	5808	H2O purified	355 mL	Sand NaCl	2 tablespoons +/- 5 gr - 1 teaspoon	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.010	5740 t/m 5747 - 5792 t/m	5812	H2O purified	355 mL	Sand	5 tablespoons	M002	-20	20
12/09/2017: freezing 13/09/2017: drop test		A0.011	5740 t/m 5747 - 5797 t/m	5818	H2O purified	355 mL	Sand NaCl	5 tablespoons +/- 5 gr - 1 teaspoon	M002	-20	20

Test type	Test nr	Ice formation	Strength test	
		[visual]	[test type]	[observations]
zero measurement	A0.001	air bubbles present no big difference between tapwater and purified water		
	A0.002	air bubbles present / t is too short: not frozen in the middle		
Plastic	A0.003	cracks through the structure	Drop test (height: +/- 1m40 - Outside temeprature: 13°C)	strong structure only a small corner broke off
	A0.004	plastic is divided on top and bottom of the ice, cracks are present	Drop test (height: +/- 1m40 - Outside temeprature: 13°C)	structure cracks easily in the ,iddle and the ice is more cracked then before
	A0.005	plastic is mostly on top (floats) of the ice, structure is more granular which melt quickly in contact with outside temperature and hand, ice is a lot colder (-18,3°C)	Drop test (height: +/- 1m40 - Outside temeprature: 13°C)	structure is strong, onlu a small corner broke off
Sand	A0.006	Sand doesn't mix and sinks to the bottom althought stirring every 30min, the sand froze quicker	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	
	A0.007	Granular structure, sand mixes better but still concentrates at the bottom, don't know if the sand froze quickier than brine, concentrated brine is found on top of the ice	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	stronger than 0.006, 0.008, 0.010, broke after being dropped from a higher (approx 20 cm)
	A0.008	Sand doesn't mix and sinks to the bottom althought stirring every 30min, the sand froze quicker, takes longer than 0.007	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	
	A0.009	Granular structure, sand mixes better but still concentrates at the bottom, don't know if the sand froze quickier than brine, concentrated brine is found on top of the ice	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	stronger than 0.006, 0.008, 0.010, only small corner broke off, sand is more brittle than ice
	A0.010	Sand doesn't mix and sinks to the bottom althought stirring every 30min, the sand froze quicker	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	
	A0.011	Granular structure, sand mixes better but still concentrates at the bottom, don't know if the sand froze quickier than brine, structure isn't full, there is an air bubble near the top on the side	Drop test (height: +/- 1m40 - Outside temeprature: 17°C)	stronger than 0.006, 0.008, 0.0010, broke after being dropped from a higher (approx 20 cm), structure is more brittle than 0.007 and 0.009

Appendix D – Experiment B – Specimen data

Date	Test type	Test nr	Matrice		Reinforcement			Mould	Temperature	Temp. process	Time
			Material	Quantity	Material	Quantity	ppt	[-]	[°C]	[-]	[h]
15/09/2017	zero measurement	B0.001	Tapwater	0,65L	-	-	-	M003	-70	-2°C/min	24
15/09/2017		B0.002	Tapwater	0,65 L	Table salt	+/- 5 gr	7,7	M003	-70	-2°C/min	24
15/09/2017	zero measurement	B0.003	Tapwater	0,65L	-	-	-	M003	-70	from + 22°C to -35°C	22
15/09/2017		B0.004	Tapwater	0,65L	Table salt	+/- 5 gr	7,7	M003	-70	from + 22°C to -35°C	22
18/09/2017: freezing 19/09/2017: compression		B0.005	Demiwater	0,70L	NaCl	1 gr	1,43	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.006	Demiwater	0,70L	NaCl	1 gr	1,43	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.007	Demiwater	0,70L	NaCl	2 gr	2,86	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.008	Demiwater	0,70L	NaCl	2 gr	2,86	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.009	Demiwater	0,70L	NaCl	4 gr	5,72	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.010	Demiwater	0,70L	NaCl	4 gr	5,72	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.011	Demiwater	0,70L	NaCl	10 gr	14,3	M003	-70	-2°C/min	24
18/09/2017: freezing 19/09/2017: compression		B0.012	Demiwater	0,70L	NaCl	10 gr	14,3	M003	-70	-2°C/min	24

Test type	Test nr	Ice formation	Strength test	
		[visual]	[test type]	[observations]
zero measurement	B0.001	After 33,5min, ice starts to form on top, after 38min ice starts to form at botom. After 1h47, sample seems completely ice. After 2h20 sample begins to crack within its structure. After 3h54, crack is through the structure and air is found in between the two pieces. The resulting ice has beautiful crystals on top and cracked structure in sharp cracks with an Y and X shape.	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melt a little quicker than salty ice (about 15min) after about 5,5 hours with an eight-shape
	B0.002	After 40 min, ice crystals form on the border of the mould. After 1h47 the sample seems completely ice. The resulting ice is more dense (whiter and softer to the touch) then B0.001 and B0.003 and has nerves like cracks however no sharp elongated cracks.	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melts after 6 hours in a solid cylindrical form
zero measurement	B0.003	After 45min, ice froms on top. After 1h, the sample is almost completely ice, after 2h it is. After 3h, the sample is cracking in sharp Y shape. The resulting ice has a cracked structure in sharp cracks with an Y and X shape.	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melt a little quicker than salty ice (about 15min) after about 5,5 hours with an eight-shape
	B0.004	After 2h, the sample seems ice. The structure has almost no cracks and is dense like B0.002	Melt test at + 25°C - sun is shining on the samples behing a glass window therefore radiant heat is a big factor	melts after 6 hours in a solid cylindrical form
	B0.005	Structure has lots of cracks and is translucent. Taking the sample out of the mould is difficult and the ice cracks when the temperature difference is too high (like putting it in a bucket of water). Sanding is a good solution to flatten the top of the structure. However due to the water on the sanding paper, it becomes slippery and this sample fell on the floor and shattered.	-	-
	B0.006	Structure has lots of cracks and is translucent. Taking the sample out of the mould is difficult and the ice cracks when the temperature difference is too high (like putting it in a bucket of water). Sanding is a good solution to flatten the top of the structure, however the structure isn't completlly rhigh angled.	Compression test at room temperature @ 3me	First test: machine was set too fast (100mm/min instead of 1mm/min) thus the sample cracked immediately.
	B0.007	Cracks as well but less translucent. The bottom is white (due to salt?) with air bubbles.	Compression test at room temperature @ 3me	
	B0.008	2 larges cracks	Compression test at room temperature @ 3me	No chuncks fell off. The structure is cracked but the cracked piece are melted together and strongly attached to each other.
	B0.009	No cracks, white translucent	Compression test at room temperature @ 3me	
	B0.010	No crcaks, white translucent, bottom is whiter with air bubbles, the sample was quite melted before the test started.	Compression test at room temperature @ 3me	The test was stopped by hand before 80% was achieved.
	B0.011	No cracks, white translucent, bottom is whiter with air bubbles	Compression test at room temperature @ 3me	
	B0.012	No cracks, white translucent, bottom is whiter with air bubbles	Compression test at room temperature @ 3me	

Appendix D – Experiment B – Test B01 results

Customer			
Job no.			
Test standard	Compression		
Type and designation			
Material	Ice		
Specimen removal			
Specimen type			
Pre-treatment			
Tester			
Note			
Machine data	Speed start	10	mm/min
	path	none	
	Pre-load	10	N
	Speed pre-load	5	mm/min
	Test speed	1	mm/min
	Force shutdown	80	%

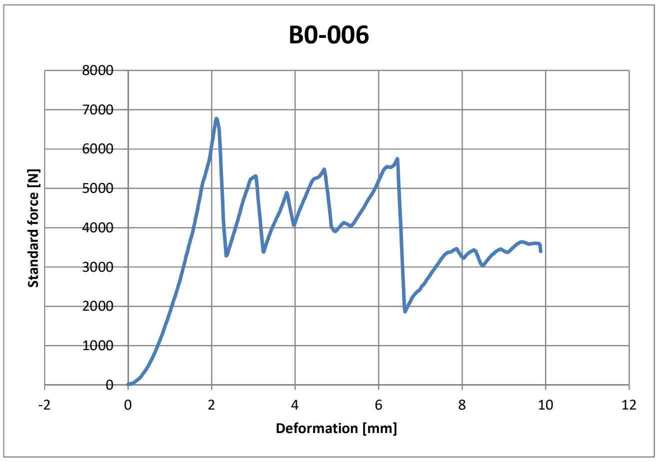
Compression testing machine parameters experiment B.

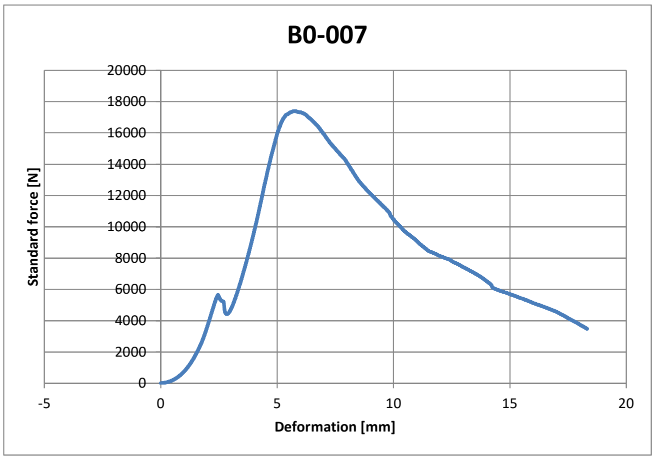
	E_{mod}	F at 0.2% plastic de	F_{max}	dL at F_{max}	F_{Break}	dL at break	d_0	S_0
	GPa	N	N	mm	N	mm	mm	mm²
B0-006			6778.413	2.113839	3395.711	9.88046	85	5674.502
B0-007			17398.55	5.77072	3478.573	18.31565	85	5674.502
B0-008			15847.53	4.153584	3169.073	10.65334	85	5674.502
B0-009			15673.58	6.606108	3133.863	19.46256	85	5674.502
B0-010			16194.63	4.054775			85	5674.502
B0-011			16001.06	9.777625			85	5674.502
B0-012			17135.48	6.464743	3426.142	26.89482	85	5674.502

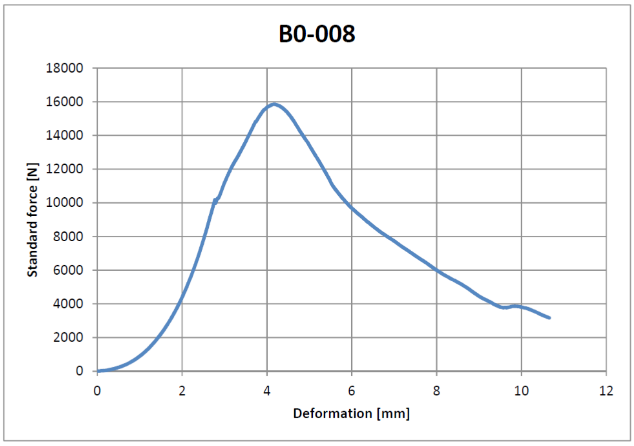
Results compression test experiment B.

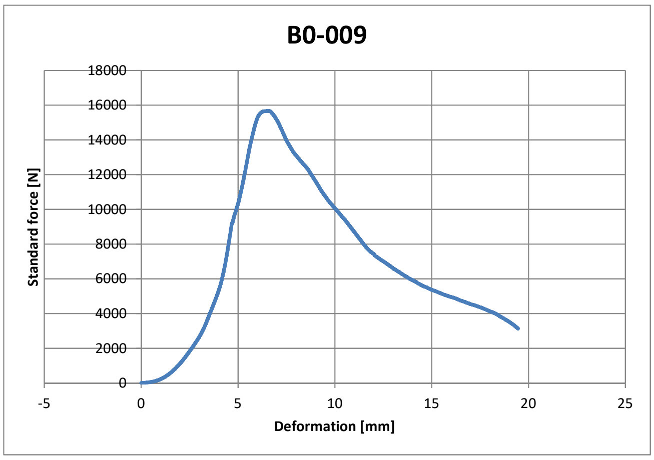
	Specimen	F_{max}	dL at F_{max}	F_{Break}	dL at break	d_0	S_0	Compressive strength	Tensile strength
	–	N	mm	N	mm	mm	mm²	Mpa	Mpa
Ice	B0-006	6778.413	2.113839	3395.711	9.88046	85	5674.502	1.194538905	nk
	B0-007	17398.55	5.77072	3478.573	18.31565	85	5674.502	3.06609382	nk
	B0-008	15847.53	4.153584	3169.073	10.65334	85	5674.502	2.792760694	nk
	B0-009	15673.58	6.606108	3133.863	19.46256	85	5674.502	2.762107018	nk
	B0-010	16194.63	4.054775			85	5674.502	2.853929679	nk
	B0-011	16001.06	9.777625			85	5674.502	2.819816862	nk
	B0-012	17135.48	6.464743	3426.142	26.89482	85	5674.502	3.019733747	nk
Brick (hard)								80	2.8
Brick (light)								7	0.28
Granite								130	4.8
Cement								24 - 27	1,9 - 3
Concrete								14 - 50	1 - 3
Glass								1.1e3 - 1.6e3	45 - 155
Toughened glass									
Aluminium								280 - 325	290 - 365
Plywood								8 - 25	10 - 44
Polyethylene (PE)								19.7 - 31.9	20.7 - 44.8
Flexible polymer foam (LD)								0.02 - 0.3	0.24 - 2.35

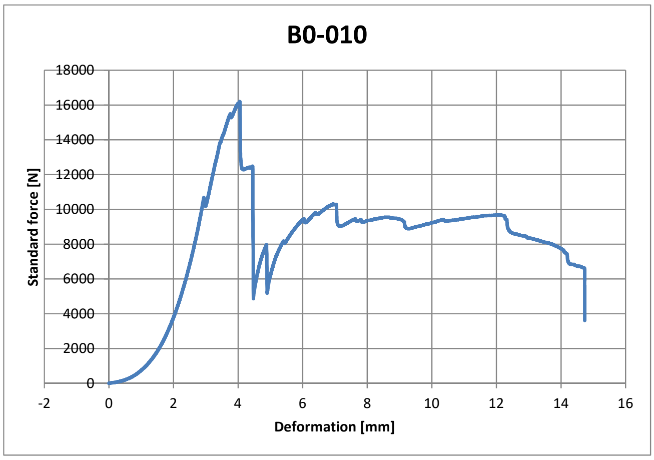
Results compression test experiment B compared to other building materials.

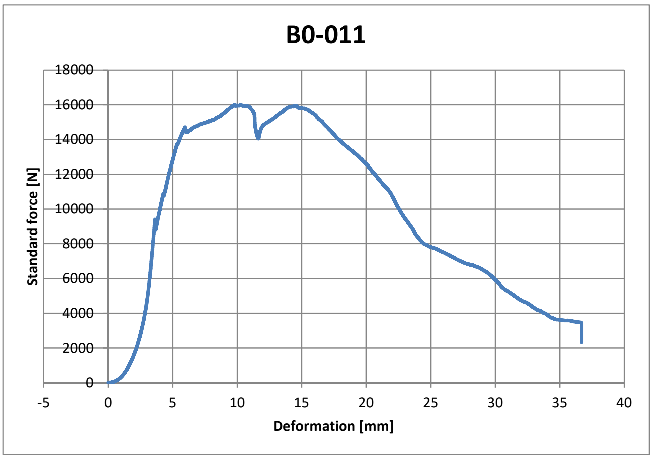


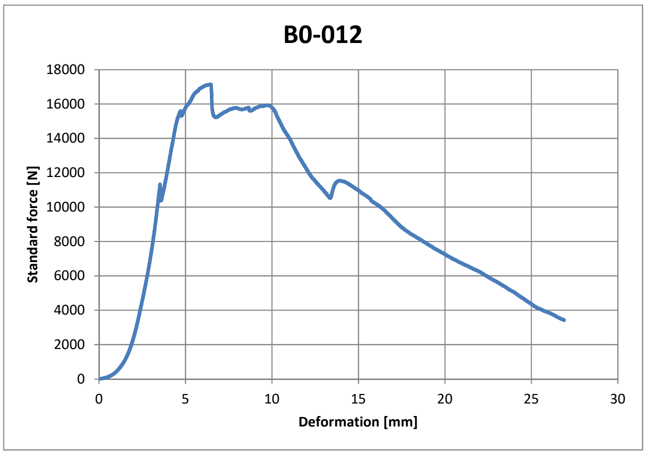












Graphical results of the compression tests.

Appendix D – Experiment C – Specimen data

Date	Test nr	mould label	Matrice		Reinforcement			Mould	Temperature	Temp. process	Time
			Material	Quantity	Material	Quantity [gr]	ppt	[-]	[°C]	[-]	[h]
freezing: 31/10/2017 - testing: 01/10/2017	C0.001	B0.005	Demi water	0,8 L	-	-	-	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2018	C0.002	B0.006	Demi water	0,8 L	-	-	-	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2019	C0.003	B0.007	Demi water	0,8 L	-	-	-	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2020	C0.004	B0.008	Demi water	0,8 L	NaCl	8	10	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2021	C0.005	B0.009	Demi water	0,8 L	NaCl	8	10	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2022	C0.006	B0.010	Demi water	0,8 L	NaCl	8	10	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2023	C0.007	B0.011	Demi water	0,8 L	NaCl	12	15	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2024	C0.008	B0.012	Demi water	0,8 L	NaCl	12	15	M003	-70	-2°C/min	23,5
freezing: 31/10/2017 - testing: 01/10/2025	C0.009	none	Demi water	0,8 L	NaCl	12	15	M003	-70	-2°C/min	23,5

Test nr	Ice formation	Strength test	
	[visual]	[test type]	[observations]
C0.001	lots of cracks form after taking it out of the coolbox but first nice longitudinal bubble formation (crystals?) - ice is clear	compression at -70°C (1mm/min)	broke in the short direction in lots of little pieces
C0.002	lots of cracks (really clear) form after taking it out of the coolbox but first nice longitudinal bubble formation (crystals?) - ice is clear	compression at -70°C (1mm/min)	a corner broke off with different little pieces
C0.003	lots of cracks (lots of small ones) form after taking it out of the coolbox but first nice longitudinal bubble formation (crystals?) - ice is clear	compression at -70°C (1mm/min)	Specimen broke upon demoulding, therefore not tested.
C0.004	ice is white - one or two vertical cracks	compression at -70°C (1mm/min)	corner broke off in one piece
C0.005	ice is white - one nerve like vertical crack	compression at -70°C (1mm/min)	smooth cut in the middle in longitudinal direction with small pieces in the cut
C0.006	ice is white - one nerve like vertical crack	compression at -50°C (1mm/min)	Liquid N2 tank went empty - smooth cut in the middle in longitudinal direction - one half broke into many pieces when deposing it in the box
C0.007	ice is white - one small crack formation (Y)	compression at -20°C (1mm/min)	smooth cut in the middle in longitudinal direction - keeps its original shape
C0.008	ice is white - no visible cracks	compression at -20°C (1mm/min)	smooth cut in the middle in longitudinal direction with little broke off pieces
C0.009	ice is white - no visible cracks	compression at -20°C (1mm/min)	smooth 2 cuts in the middle in longitudinal direction - keeps its original shape

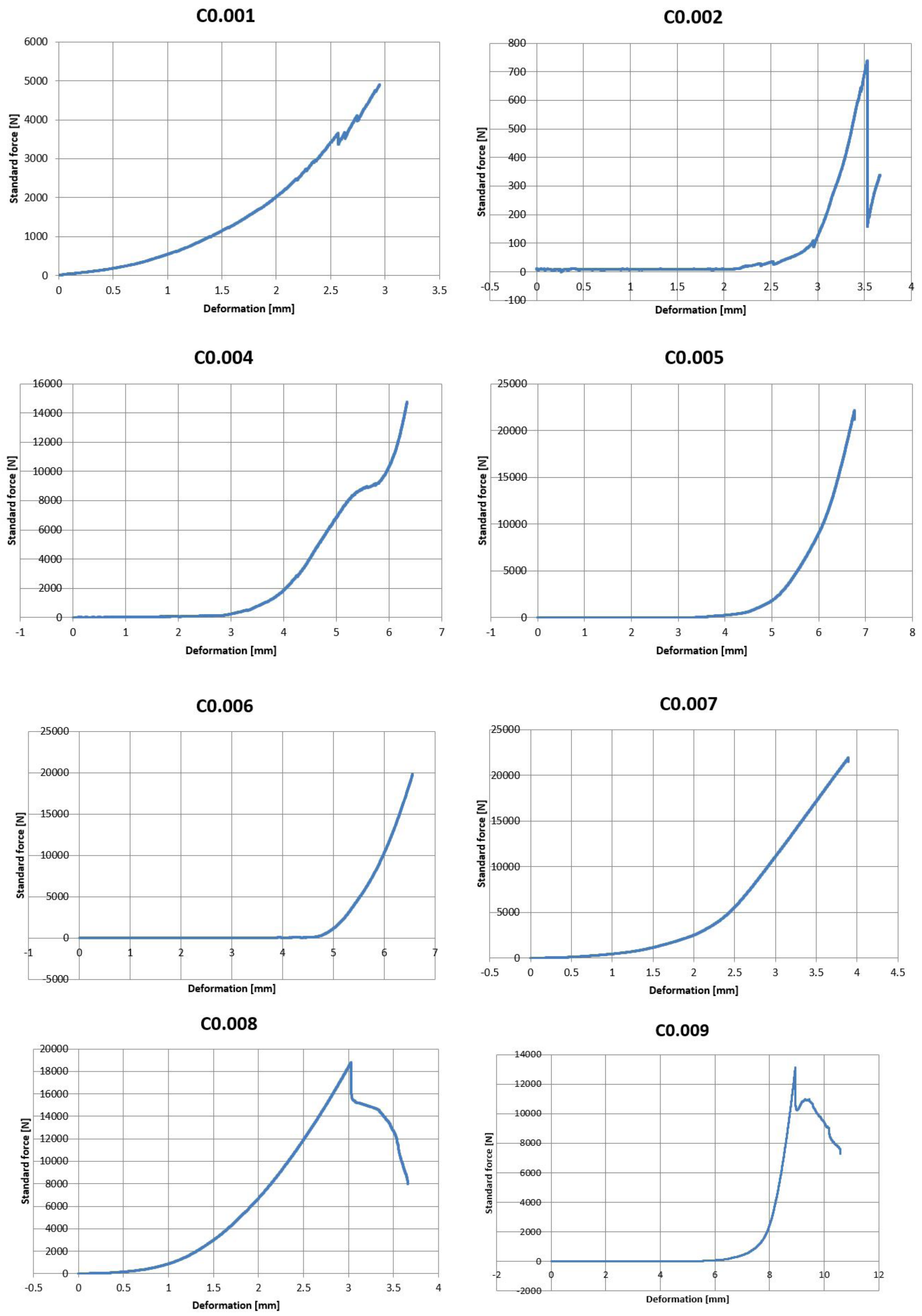
Appendix D – Experiment C – Test C02 results

Customer			
Job no.			
Test standard	Compression		
Type and designation			
Material	Ice		
Specimen removal			
Specimen type			
Pre-treatment			
Tester			
Note			
Machine data	Speed start	10	mm/min
	path	none	
	Pre-load	10	N
	Speed pre-load	5	mm/min
	Test speed	1	mm/min
	Force shutdown	80	%

Compression testing machine parameters experiment C.

	F_{max} N	dL at F_{max} mm	F_{Break} N	dL at break mm	a_0 mm	b_0 mm	S_0 mm²	S_0 mm²	Pressure Mpa
C0.001	4894.765	2.948334	4893.729	2.948665	100	100	10000	5200	0.941301
C0.002	738.8736	3.528872	335.6396	3.664473	100	100	10000	5200	0.142091
C0.004	14774.86	6.343115	14774.86	6.343115	100	100	10000	5200	2.841319
C0.005	22171.65	6.763497	21175.65	6.763683	100	100	10000	5200	4.263778
C0.006	19834.32	6.560014	19834.32	6.560014	100	100	10000	5200	3.814292
C0.007	21910.94	3.896068	21468.94	3.896234	100	100	10000	5200	4.213643
C0.008	18826.46	3.029797	7980.002	3.655502	100	100	10000	5200	3.620474
C0.009	13157.66	8.945711	7302.341	10.59237	100	100	10000	5200	2.53032

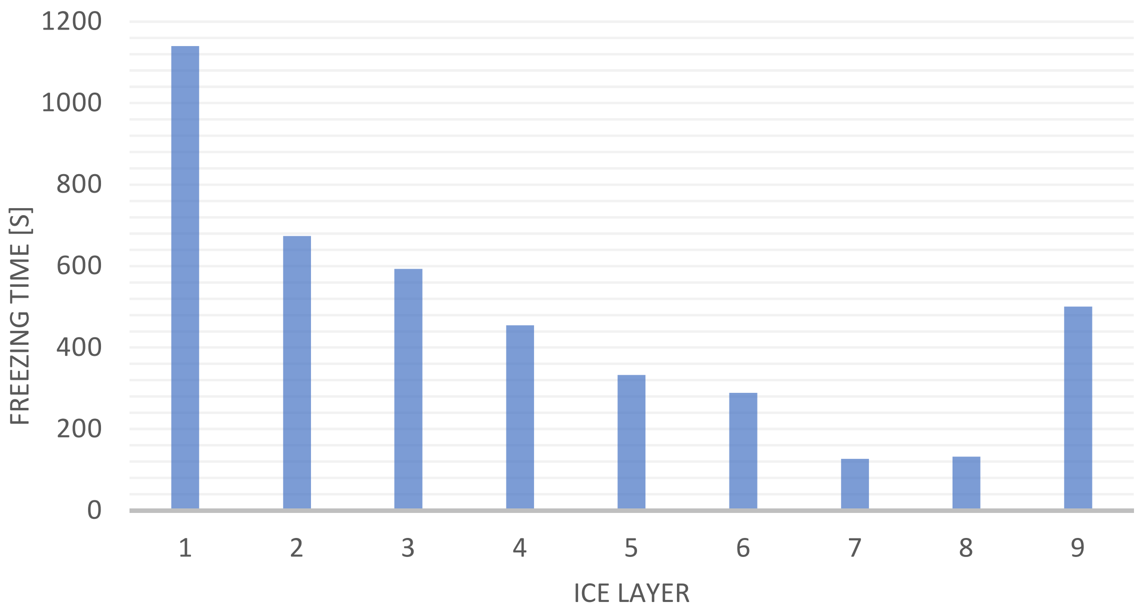
Results compression test experiment C.



Graphical results of the compression tests.

Appendix D – Experiment D – Test Data and results

Date	Layer	Ice type	freezing time	Temperature	Observations
10/01/2018	-	-	sec	°C	-
@EWI				- 30.00	**Freezer set for 20 min at temperature**
	1	Tapwater	300	- 9.00	side is freezing
			420	- 13.30	small droplets frozen
			660	- 27.00	middle sized droplets frozen
			1140	- 31.00	large droplets (ϕ= 1,5-2cm) are frozen thus all water
	2	Tapwater	66	- 14.00	No more droplets but line is forming
			92	- 20.00	small droplets frozen
			151	- 27.00	crust forms on the line
			375	- 28.00	middle sized droplets frozen
			674	- 30.00	all the droplets and line is frozen
	3	Tapwater	30	- 15.00	Line is froming again but flows down the side of the previous layer
			186	- 30.00	crust forms on the line
			593	- 30.00	all the droplets and line is frozen
	4	Tapwater	39	- 16.40	-
			455	- 30.00	the line is frozen and detaches itself from the plastic plate (on the sides)
	5	Tapwater	35	- 18.30	The additional water creates a crack on the previously made ice structure
			333	- 30.00	the line is frozen and detaches itself from the plastic plate (on the sides)
	6	Tapwater	41	- 16.80	-
			289	- 30.00	the line is frozen
	7	Tapwater	127	- 28.00	the line is frozen
	8	Tapwater	45	- 18.00	crust forms
			181	not recorded	the line is frozen
	9	Tapwater	38	- 18.40	Large crack forms when new layer is printed
			501	- 30.00	the line is frozen
10/01/2018		14:51		- 70.00	**Freezer is set to -70°C overnight**
11/01/2018		14:18	41580	- 70.00	the large crack is gone overnight, the ice is less translucent



Results from Experiment D. The bar graph shows that the more layers are applied, the faster the ice frezzes. One of the resaons for that may be the underlaying cold ice layer.

Appendix E – Volume estimations for a Martian habitat

This is a summary of the different volume and area required for a Martian habitat made by Adams in 1999 (Hauplik-Meusburger and Bannova, 2016). This table is used as guideline for the Ice Hab design made in part F.

Function	Notes	Dimensions in cm (in.)	Minimum volume
Translation	Translation path between activity stations	H: 215 [84″] W: 825 cm [32″]	
Translation (vertical)	Stairs for surface habitats Storey H: 215 cm [7 ft] Step L × H: 28 × 19 cm Landing 85 cm	W: 85 [33″] L: 308 [121″] H: 420 [165″]	14 m³ [494.4 f³]
Dining	Accommodates crew of 6 Width/Crew member: 70 cm [28″]	H: >215 [84″] L: 300 [118″] W: 254 [100″]	for a crew of 6: 16.4 m³ [579.1 f³]
Sleeping Partial G and Full G	Volume orientation must be horizontal to the local vertical Human envelope W: 85 cm [33″] D: 85 cm [33″] Exclusive of access area	H: 85 [33″] L: 215 [84″] W: 85 [33″]	1.55 m³ [54.4 f³]
Crew quarter Micro-G	Sleeping + stowage + dressing + personal work Critical dimensions of the workstation are combined with those of sleep	H: 215 [84″] L: 105 [41″] W: 105 [41″]	2.37 m³ [83.6 ft³]
Crew quarter Planetary surface habitat	Sleep position should be perpendicular to the vertical (or, horizontal)	H: 215 [84″] W: 215 [84″] D: 105 [41″]	4.85 m³ [171.2 ft³]
Changing clothes	Volume provided should allow free movement of the entire body	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.19 m³ [77.3 ft³]
Personal Hygiene Micro-G	Good habitability may be defined by the space required to perform the activities of cleaning the whole body in privacy	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.19 m³ [77.3 ft³]
Personal Hygiene Partial G surface habitat		H: 215 [84″] L: 101 [39″] W: 202 [80″]	4.38 m³ [154.6 ft³]
Waste management Toilet partial G		H: 201 [79″] W: 90 [35″] D: 105 [41″]	1.9 m³ [67.0 ft³]
Waste management Toilet Micro-G	Requirements for personal hygiene station might be added to waste management		4.09 m³ [144.4 ft³]
Food Preparation Micro-G	Galley equipment placed close together for ease of restraint Envelope in each direction ~101 cm [40″]	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.17 m³ [76.6 ft³]
Food Preparation Partial G and full G	Double-loaded if optimized Min. preparation galley L: 2 m	H: 215 [84″] W: 100 [39″] L: 240 [94″]	5 m³ [176.5 ft³]

(continued)

Volume study made by Adams in 1999 (Hauplik-Meusburger and Bannova, 2016).

Function	Notes	Dimensions in cm (in.)	Minimum volume
Exercise	For a crew of 4–6 Treadmill H: 245 cm [96″] L: 150 cm [60″] Cycle ergometer W: 101–150 cm [40–60″] L: 150 cm [60″]	W: 251 [99″] L: 150 [59″] H: 245 [96″]	9.22 m^3 [325.6 ft^3]
Personal workstation	Dimensions for a personal workstation should be taken around the user up to the face of the computer monitor	H: 205 [80″] W: 101 [40″] At elbows D: 90 [35″]	1.86 m^3 [65.5 ft^3]
Inventory management	A double-loaded stowage area will have a depth of 60 cm + 85 cm + 60 cm For proper inventory management and access to all stowed items, a basic translation path of 85 cm [32″] must be kept clear between every two stowage banks Each bank of stowage, if optimized for accessibility, has a maximum depth of 60 cm [24″]	H: 215 [84″] L: 300 [118″] D: 205 [80″]	13.2 m^3 [466.1 ft^3]
Trash management	Trash center H: 215 cm [84″] L: 120cm [47″] D: 90 cm [36″] Minimum initial allocation of volume for a crew of 6+ accessible space added	H: 215 [84″] L: 120 [47″] W: 172 [67″]	4.44 m^3 [156.7 ft^3]

Volume study made by Adams in 1999 (Hauplik-Meusburger and Bannova, 2016).

Appendix F – Reflection

This is the compulsory thesis reflection which was handed in at the P4.

Reflection paper

This is a reflection on the graduation project:
Building on Mars. A *Research on In Situ Research Utilisation (ISRU) for a sustainable habitat which protects the crew on a Martian surface mission against the harsh environment.*

Relationship between research and design

The research question this thesis aims to answers is:
Which **in situ materials** and **forming techniques** are suitable to create an outer shell for a **sustainable habitat** on Mars which protects the crew from **the harsh Martian environment?**

The answer to this question is focussed on research in the field of material science (in situ materials) and on process technology (forming techniques), and is divided into different steps. The first step is a literature study on the subject of traveling to space, mission design, architecture in space, sustainability in space and an analysis of the design location: Jezero crater, Mars. This literature study forms the base to generate a programme of requirements for a sustainable habitat on Mars. This programme of requirements is leading for the following research and design as most currently available technologies are not complying to the high requirements. Therefore the programme of requirements is divided into three topics: material, process and structural design and further research is done. The research is done in a methodological way, starting with a literature study specific on the subject to identify the missing gaps. Then an experimental approach is used to create more empirical values. For example, ice composites were made as no current material complied to the high set of requirements. The composites were tested on mixing, melting and compressive strength to try to achieve a material which complies to the requirements. This led to the conclusion that adding sodium chloride (NaCl) to purified water adds strength, redundancy, still lets light through and is 100% ISRU, therefore meeting all the requirement regarding building materials.

When the three topics specific requirements are met, a design for a habitat is made to test the new technologies.
Hence research and design are closely related in this graduation thesis in an iterative process. For example, a research is done on material requirements, then a new ice composite is designed based on this literature study. To verify that the design of the material complies to the requirements, research in the form of experiments is made. Although both aspects are in constant iteration, this thesis has a clear focus on research and the design of the habitat is considered as another test for the research done rather than as the end goal.

Relationship between the theme of the graduation lab and the subject/case study

Within the Building Technology (BT) master track, every student graduates within the same studio: sustainable graduation studio. Throughout the whole master, sustainability has played an important role during design and research projects. This thesis has a clear focus on sustainability as it is part of the TISD (Technology in Sustainable Design) annotation. Sustainability is already a broad and controversial topic in the building environment here on Earth but building a sustainable habitat on Mars is even more vague. Therefore, the first sustainable aim of this project is to define sustainability on Mars. The term sustainability and the need for ecological measures on Earth became an urgency mainly due to climate change.

As Mars does not have a population yet and it is thus not currently experiencing climate change. As a matter of fact, the Red Planet was hotter and wetter some 3,6 gigayears (Gyr) ago and has therefore already experienced "climate change". It is therefore nonsense to apply sustainable principles used on Earth to counteract climate change to design a sustainable habitat on Mars. The core concept behind sustainability is "to be able to sustain". This concept is closely linked to the concept of redundancy which are both essential if a crew is sent to Mars. This crew will have to survive the harsh Martian environment having only 22 min delay communications with Earth and a possibility for a voyage every 26 months at best. This distance between Earth and the Martian surface is why redundancy and sustainability are not only important but are crucial for the crew's survival and the completion of the mission.

Following this logic, to be able to sustain would mean being as much independent from Earth as possible, therefore allowing problems and potentials to be handled in situ without any time delay. Hence being sustainable on Mars means being independent from Earth and its resources. This concept of sustainability on Mars is translated into concrete design requirements.

The use of ISRU for the design of a habitat can be divided in five classes with class V indicating a complete independency from Earth. The analysed precedent designs are all categorized as class III habitats: an ISRU derived structure with integrated Earth components. Each of these classes can be compared to the technology readiness level (TRL), with the lower the class the higher the TRL. Therefore, as those two aspects need to be taken into account, the requirements set for this research is to have a habitat in between class III and IV, meaning that a class III habitat is designed with some class IV technologies which are tested in situ. This enables the class IV technology to have a higher TRL for the next Martian surface habitat as more missions will probably be sent after the first one. Combining technologies from both classes allow redundancy and possible sustainable expansion of the habitat following the principles set by Häuplik-Meusburger and Bannova (2016).

Relationship between the methodology of Building Technology & the chosen method

Within the master building technology, every project is a constant iteration between the design chairs: façade design, structural design, climate design and computational design. All of these disciplines are used to answer a technological challenge within the built environment. Although this method often leads to innovative ideas, I do think that the building industry often stays within known paths on specific aspects. Hence, I choose a new challenge which can't be answered using only the design chairs from the BT master track. When building a habitat on Mars, mission design is a huge design driver and therefore the complex matters of space travel, EDL, space architecture, etc. have to be understood in order to respond with an adequate habitat design.
Hence this thesis is based on knowledge from the other fields of aerospace engineering, material sciences and civil engineering and is then combined with my own knowledge within the build environment. This multi-disciplinary aspect influenced the design and design decisions, making this graduation project quite different from other projects within the BT master track. Outside the learning environment of the University, projects are often an iteration between different disciplines. Therefore, I think the methodology chosen for this project taught me valuable concepts which can be used in the future.

Relationship between the project and the broader social context

Societal relevance
This graduation research offers a new perspective for architects and building engineers on outer space architecture and sustainability. Usually sustainability is about preserving our planet because we live on it. As asteroids and other planets aren't inhabited by humans (yet), sustainability isn't believed to be an important factor when designing structures. However, as humans are starting to colonize space, maintaining and sustaining the resources as well as the current situation becomes more important. Especially as space isn't owned by a specific party (e.g. a state, a company, etc.) it is important to maintain this environment for everyone interested in space exploration. Moreover, just like Earth is our only Earth, the solar system is our only solar system. Building for a sustainable long term habitat has also economical relevance as the costs will greatly be reduced for follow-up missions.

Scientific relevance
The information gathered in this research can help design a new habitat for manned missions to Mars for interested parties. As some large space agencies (e.g. NASA, SpaceX) are planning to send manned missions onto Mars, the success of the mission depends on the wellbeing of the crew and on whether they survive the trip and stay on the planet. As outer space architecture isn't fully developed yet, every piece of information on how a habitat can be built will help protect the manned mission's crew.

● (green) **Full utilization in relevant environment** ● **Sufficient risk reduction in relevant environment** ⊙ **Initial feasibility validation/partial validation**	Earth	ISS/Low-Earth Orbit	Lunar Vicinity (Earth-Moon Lagrange Point (EML), Moon Orbit)	Moon Surface	Mars Vicinity	Mars Surface (Robotic Mission)
Beyond Low-Earth Orbit Crew Transportation			●	●	● (green)	
Heavy Lift Launch			⊙	●	● (green)	
Reduced Supply Chain		⊙	●	●	● (green)	
Autonomous Crew Operations	⊙	⊙	●	●	● (green)	
Deep Space Staging Operations			● (green)		● (green)	
Mars Ascent	⊙			⊙		⊙
Space Radiation Protection/Shielding		⊙	●	●	● (green)	
Life Support & Habitation Systems		●	●	●	● (green)	
Entry, Descent, & Landing Systems	⊙			⊙		●
Surface Power and Energy Management	⊙			● (green)		● (green)
Surface Mobility	⊙			●		●
Human Robotic Integration	⊙	●	● (green)	● (green)	● (green)	● (green)
Mars In-Situ Resource Utilization	⊙			⊙		●
Long Duration Human Health	⊙	●	●	●	●	
Deep Space Operation Techniques	⊙	⊙	●		● (green)	

Note: This table assumes critical capabilities will be provided by multiple agencies.

Figure 1. Risks of space exploration (ISECG, 2013, p. 21).

Relevance at TU Delft Building Technology

This research takes into account the research of two other TU Delft Building Technology students: Nihat Mert Ögüt and Carlijn van der Werf who both started their graduation project in November 2016 on building on Mars focussing on radiation shielding and on the program of requirements, respectively. This research is focussing on a different aspect (ISRU materials and process with regard to sustainability) of the overall task which is: building on Mars. In a way this research is complementary to the two other master theses.

Ethical aspects

Building on Mars, or even sending humans to Mars, is a complex issue especially combined with sustainability concepts. As one of the reasons to go to Mars is mining, some people think we shouldn't go. Their main argument is that we create problems on our own planet (climate change, material scarcity, water scarcity, etc.) and therefore shouldn't go and create problems to another planet like Mars. Especially because mining Mars would possibly mean to completely "destroy" the planet to satisfy the needs of humans. This thinking leans towards finding a solution within our planet as we are the ones who created the problem.
On the other hand, people think that we past the point where a solution can be provided within Earth and that mining other planets would help our planet as this planet is the only friendly environment to humans. Their main argument is thus that it is better to destroy another less habitable planet than our planet Earth.
Both arguments are for sustainability and show how broad and open to interpretation the term sustainability is. This ethical question is at the core of my thesis on whether we should or shouldn't send humans to Mars.

Sources:

Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: designing and planning beyond earth*. Cham: Springer.

ISECG, (2013). The global Exploration Roadmap. *National Aeronautics and Space Administration*. Washington.