Graduation Report

Agata Mintus, 4745523

Building sustainable Martian Habitat

Figure 1: Curiosity's view of Martian soil and boulders after crossing the "Dingo Gap" sand dune, Source: NASA/JPL-Caltech/MSSS

PERSONAL INFORMATION

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STUDIO/TOPIC

NAME:	Sustainable Design Graduation Studio - Material Science & Structural Design
THEME:	Experimental research on sustainable production and fabrication of novel material
TUTORS:	Dr.ir. F.A. Veer (Main Design mentor) Dr. O. Copuroglu (Material Science mentor) Dr.D.P. Peck (Sustainable Development mentor)

GRADUATION PROJECT

TOPIC:	Building Sustainable Martian Habitat
RESEARCH TITLE:	Sustainable design of habitat on Mars with in situ resources and energy efficient in situ fabrication process.
KEYWORDS:	Mars | in-situ resources | ISRU fabrication | sustainability | habitat | regolith | energy efficiency

CHOICE OF STUDIO:

The main reason for choosing this graduation studio, is due to my interest towards, hands-on approach and structural design. During my studies I was developing my skills and knowledge in achieving sustainability in structural design optimization and manufacturing methods. Also, my passion for space architecture pushed me in direction of experimental research which is possible to perform in this studio.

ACCREDITATION TiSD:

The graduation project is realize under Technology in Sustainable Development graduation programme (TiSD). The core issue of the research is to design a building material from local resources and propose sustainable production process as well as an efficient construction method. Although the context of the project is extreme and unusual, the potential application on Earth and contribution to Sustainable Development could be significant. The fact, that the research will be focused on local materials and energy efficient fabrication, can bring beneficial knowledge and solution for ecological and economic issues on our planet. The results of the research could be later translated and adapted to terrestrial conditions.

Content

1.Introduction

This is a report for master thesis project at Building Technology master programme, titled "Building Sustainable Martian Habitat". This document presents graduation plan and preliminary report including explanation of the topic, problem statement, research methodology and goals of the project. The study is supported by literature review and investigation.

The research background knowledge regarding sustainability on Mars and some other data will be based on the thesis project written by Layla van Ellen "Building on Mars", 2018.

1.1. Context

Since 20th century humans have been investigating the universe beyond Earth orbit. For last decades, space agencies were proving, that our civilization is capable of achieving dreams and goals, which at the beginning were just sci-fi stories. The space exploration and colonization planning became part of our culture and everybody is certain, that it will be part of our everyday life in the future. The reasons, why we want to go beyond our planet, referred first to ambition and curiosity but recently people started to see potential politic and economic benefits. These factors drives us towards new space race and more complex missions (Owens & Singh, 2017). Just in 2018, the amount of new discoveries and achievements is enormous, ranging from launching new rocket system – Falcon Heavy designed by SpaceX, which can revolutionize future missions, to sending advanced lander to Mars – InSight, which will for the first time analyse subterranean conditions and environment.

*Figure 2: **Left** - Falcon Heavy launch, 6th February, NASA's Kennedy Space Centre, Source: Walter Scriptunas II / Spaceflight Now, **Right** – InSight lander on Mars, Source: NASA/JPL-Caltech*

Current plans regarding human space exploration are focused on deep space missions. Among these plans is Mars - a destination, which could help us find unknown answers about Earth and develop technologies regarding space colonization. After landing on Moon, space agencies are building enthusiasm to visit new planetary object's surface (Croucher, 2006). Buzz Aldrin, Apollo program astronaut says:

> "Humans need to explore, push beyond current limits just like we did years ago. Apollo was the story of people at their best, working together for a common goal. We started with a dream, and we can do these kinds of things again. I know it. I'm living proof that it can be done."

The new destination brings new challenges and requirements (Larson & Pranke, 2000). The most important aspect of manned mission to Mars is developing space settlement technologies. In the book "Human spaceflight: mission analysis and design", authors write, that future landing missions would require surface modules for extended surface stay for humans, which later could be developed into long-term human presence on the planet. The book also mentions, that the ideal design of building space architecture on the surface of other planet is fully automated and independent of Earth. **Figure 3** presents two concepts for automated construction on the surface of Moon.

*Figure 3: **Left** - A Contour Crafting robot prints a road in front of a hangar for a lunar lander, Source: Behnaz Farahi/NASA, **Right** – 3D printing concept for lunar based using in situ resources, Source: Foster + Partners*

Space architecture is an interdisciplinary specialization which integrates technical fields like aerospace engineering, architecture, human factors and medicine, as well as more humanistic specializations like psychology and art. This broad topic is still an emerging idea, because of the diversity of aspects and challenges regarding implementing and testing concepts in outer space. (Häuplik-Meusburger & Bannova, 2016) This research is focused on building technology aspects of the space architecture, including building material production, construction method and structure design of Martian habitat, which needs to meet habitation requirements.

Habitability in space context can be understood according to Dr. Häuplik-Meusburger "*as the measure of how well the (built) environment supports human health, safety and well-being to enable productive and reliable mission operation and success.*" In this report, the focus is oriented towards creating structure which could be part of the habitat protecting potential crew from some basic hazardous Martian conditions, like micrometeoroids and radiation.

In near future, the deep space exploration and the dream to step on the surface of other planet will be achievable. Space agencies present each year, more detailed and reasonable plans for these missions. The vision of space colonization is not a science fiction idea anymore, but became part of the space program.

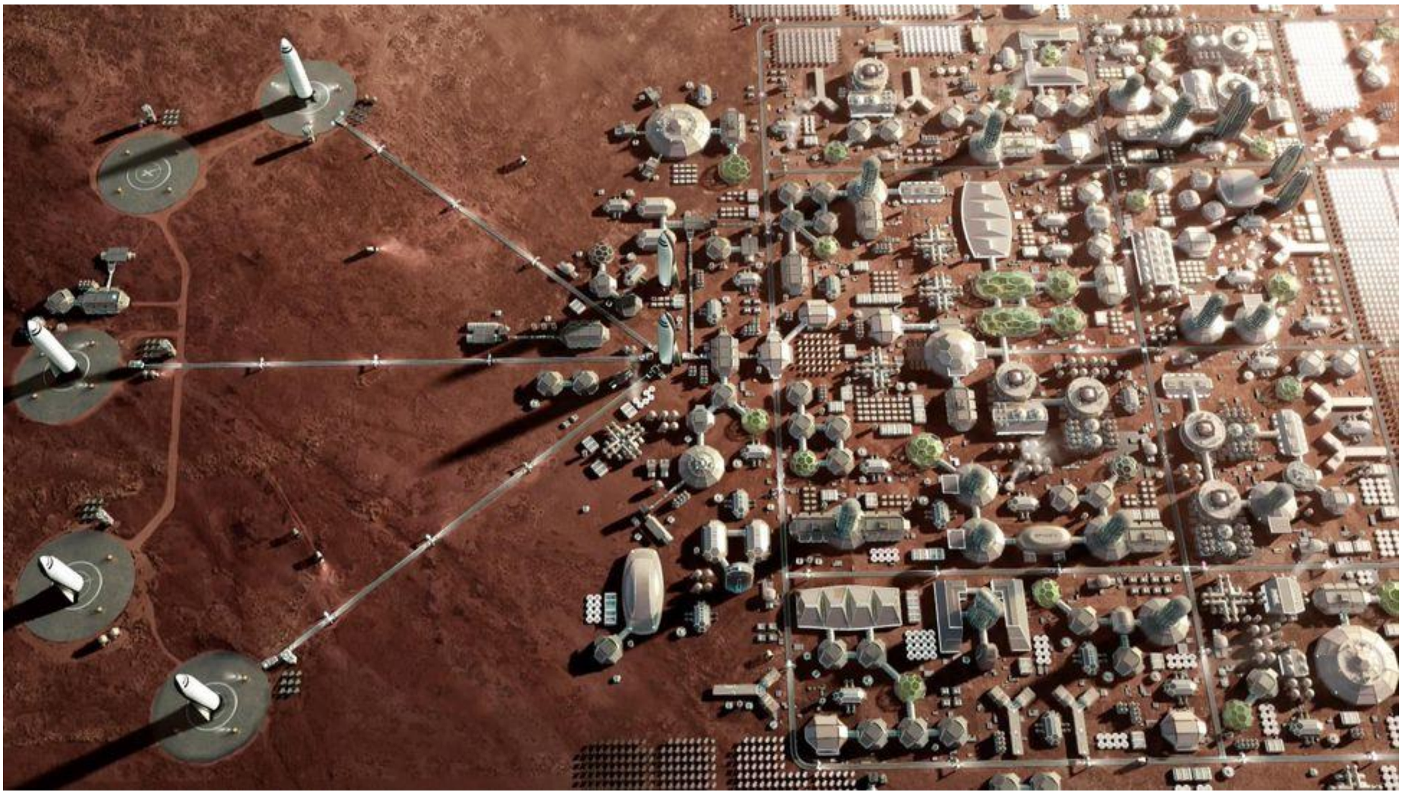

Figure 4: SpaceX render illustrating plans for colonizing Mars, Source: SpaceX

1.2. Problem statement

Emerging Process

The emerging process of space exploration and colonization planning is directing our focus on Mars and Moon for next few years. (Giancarlo Genta, 2017)The need of architects and building engineers is increasing and the research on possible material production and building construction is required. Currently, government space agencies like NASA and ESA, as well as private companies are conducting studies on building extra-terrestrial habitats for first deep space manned space missions, which are planned for years 2025 – 2035. (Lim, Prabhu, Anand, & Taylor, 2017)

Martian Conditions

First manned missions to Mars would be unpredictable, as the data about the Red planet, that we have, might be incomplete. The effect of long-term isolation or Martian unfamiliar, hazardous conditions' impact on human is also unexplored. Therefore, first building structures on Mars would need to be reliable and advanced, but also achievable in terms of technology and time. The building possibilities are limited by Martian conditions.

Mars has a very hostile environment conditions, which impose strict requirements for habitation design and production processes. The crucial issues determining the limits and possibilities is the distance and transportation system which would deliver potential equipment, material and energy source. Due to these limitations there is an emerging concept for in-situ resources utilization (ISRU) as the source for building materials, energy, fuel or life support systems.

The available resources for building material on Mars are: regolith (in form of soil and dust), rock, ice -dry ice (carbon dioxide solid phase) or water. In this research the main focus will be on exploring Martian regolith – its availability, properties, processability. The reason for this choice is the fact that soils is most abundant resource on the planet and relatively broader data is gained about it compared to other materials mentioned earlier.

Potential Application

Curiosity and interest in understanding the universe beyond our planet had driven humans towards many scientific discoveries and technological innovations. In the future, it will indicate our civilizational progress. Since 20th century, along with space missions, humans created many technologies, some of which found an application here on Earth, in our everyday life. The innovations concern often self-sufficient technologies and new materials like commonly used memory foam and space blankets or materials for more technological purpose like high-performance lightweight materials for aerospace engineering and deployable structures. (Schober, 2018) These discoveries and the results of this research can also find application in building industry.

Recent Focus

Ongoing researches regarding Martian regolith as a building material and its production processes are oriented towards advanced technologies and exploring the possibilities and limits of the material. Often, the studies don't integrate sustainable approach into the process, which can lead to inefficient energy and material usage. The advanced technologies and concepts could be more suitable for later phases of Mars colonization, where manufacture and industry is already present on the planet. The focus of this research is building habitat for first manned missions. It means that the planet is still not fully explored and the energy as well as technology is limited due to the transportation conditions.

1.3. Objectives

General objective

The general objective of this thesis is to explore and study the possibilities for building habitat on Mars with in-situ resources (mainly regolith) and sustainable production process and construction.

Sub-objectives

The sub-objective will be:

- Specify and investigate the aspects and parameters determining sustainability regarding building material production process and construction method on Mars
- Specify technology readiness level of the production process and construction method

Final result

The final product of the research will be novel building material and its production process. Additionally the structure and construction method will be designed and optimized in terms of material and energy usage.

1.4. Research Questions & sub questions

Main research question:

How to sustainably construct a habitat on Mars with in situ resources and energy efficient in situ fabrication process?

Sub research questions:

The secondary questions would help determine program of requirements for each part of the research (material, production process, building component, structure) and find the most suitable option for each.

- What are the material requirements and which in situ materials are suitable for that?
- What are the available in situ production processes in terms of energy efficiency and sustainability ?
- What is the relation between production process and physical properties of the building material and how the fabrication could be optimized to reach low energy needs and sufficient physical properties?
- What is the influence of Mars conditions on production process and product properties?
- What are the requirements for building component, structure and construction and which products/ technologies and building forms meet these requirements?
- What is the sustainable construction method for designed building material and structure?

1.5. Methodology & Research Design

Approach & Methodology

Project is developed using three research methods: literature study, an experimental research and a research by design. **Figure 5** presents schematic relation between these parts, which are explained later.

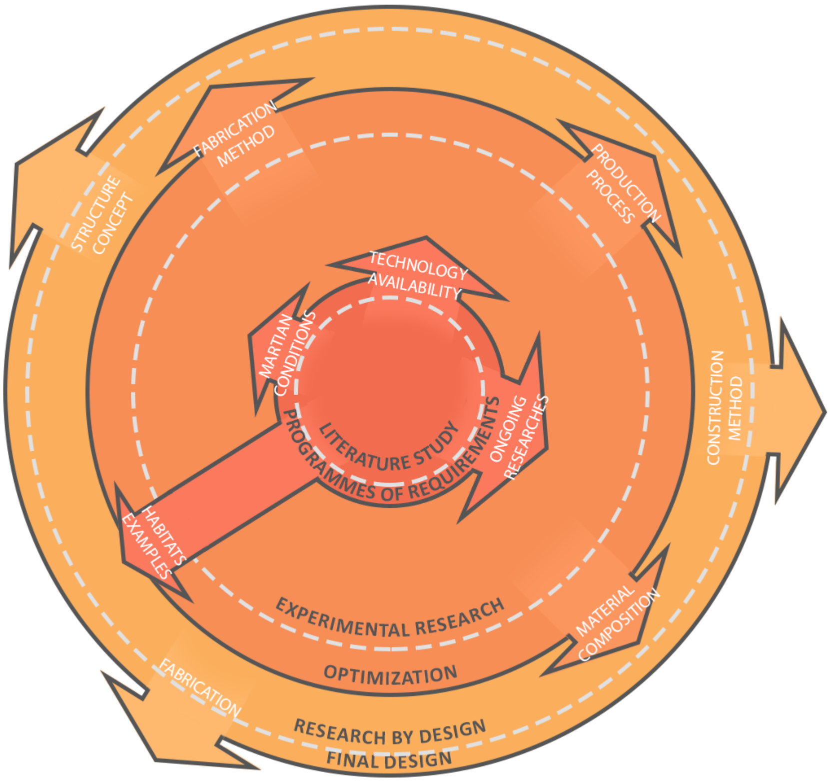

Figure 5: Research methods plan and relation

Literature study

The first one - literature study focuses on determining Martian conditions and programmes of requirements for three aspects of the project: material, production process and structure. Each part will be later developed and tested with physical experiments and computational simulations. As the topic of this research is still emerging idea, the available literature are mostly academic and scientific reports published in magazines or at conferences related to space engineering. The general knowledge about missions plans was investigated by following space agencies programmes like NASA, ESA or SpaceX. Conditions on Mars were gathered using scientific data collected during several missions to Mars. The Literature review is summarized to conclude the approach and design the research. The most important topics investigated are:

a. Martian conditions
b. Habitats examples
c. Technology and equipment availability
d. Ongoing researches study and their comparison
e. Programmes of requirements

Experimental research:

The second part of the research is experimental and is based on the knowledge gained during the first phase. The experiments concern mainly preparing material composition and testing production methods. The experiments will focus on determining best processes and required factors like temperature, time, equipment. Next step would be minimizing energy usage during this process with preserving desired product properties. The experimental topics are listed below:

a) Mixture/ Material preparation and experimentation
b) Production Process preparation and experimentation
c) Relation between production process and properties analysis
d) Production process optimization
e) Fabrication method

Computational modelling, physical models and simulations – research by design:

The third part would be mostly computational including modelling and simulations. The structure and construction method will be designed for building component, which was the final product of experimental part. These two elements will be optimized to minimize energy and material usage.

a) Fabrication, assembly design
b) Habitat's structure concept
c) Construction method design
d) Habitat design

Research Design

The experimental and computational part of the thesis is divided into three phases: material composition, production & fabrication and construction method. **Figure 6** illustrates ideal plan and relation between these phases.

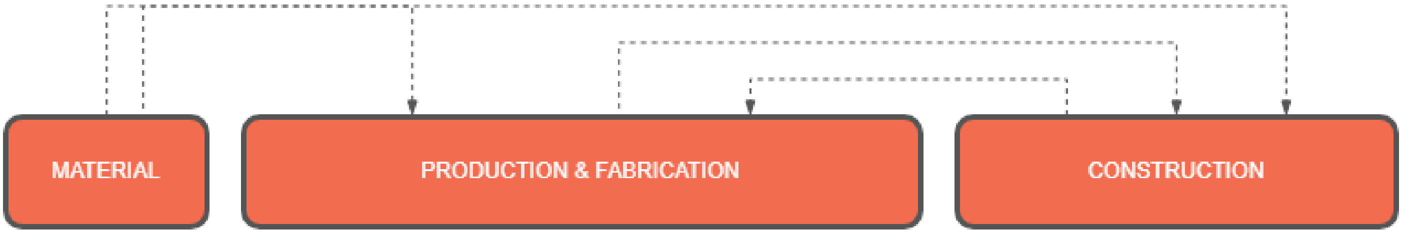

Figure 6: Research design plan + result

First part – **Material Composition**, is performed in research lab using experimenting and modelling techniques. The material composition is analysed in terms of production possibilities and binding method. Preliminary production techniques are performed to analyse the structure.

Production & Fabrication part is divided into two phases, depended on each other. The production phase is an optimization phase, where the product properties, energy usage and simplifying approach are the key factors. The fabrication part is focused on designing and testing the building component. The testing is performed in both research lab and mechanical behaviour lab. Then, the conclusions in terms of relation between production process and building material properties is inferred to achieve final building component.

The third phase – **Construction Method** is performed mostly using computational modelling and simulation. The choice of method is based on previous research phases' results and conclusions. The simulations are used to determine achievability (equipment, time, technology) and structural possibilities of the building component.

All three phases are explained in **Figure 7**.

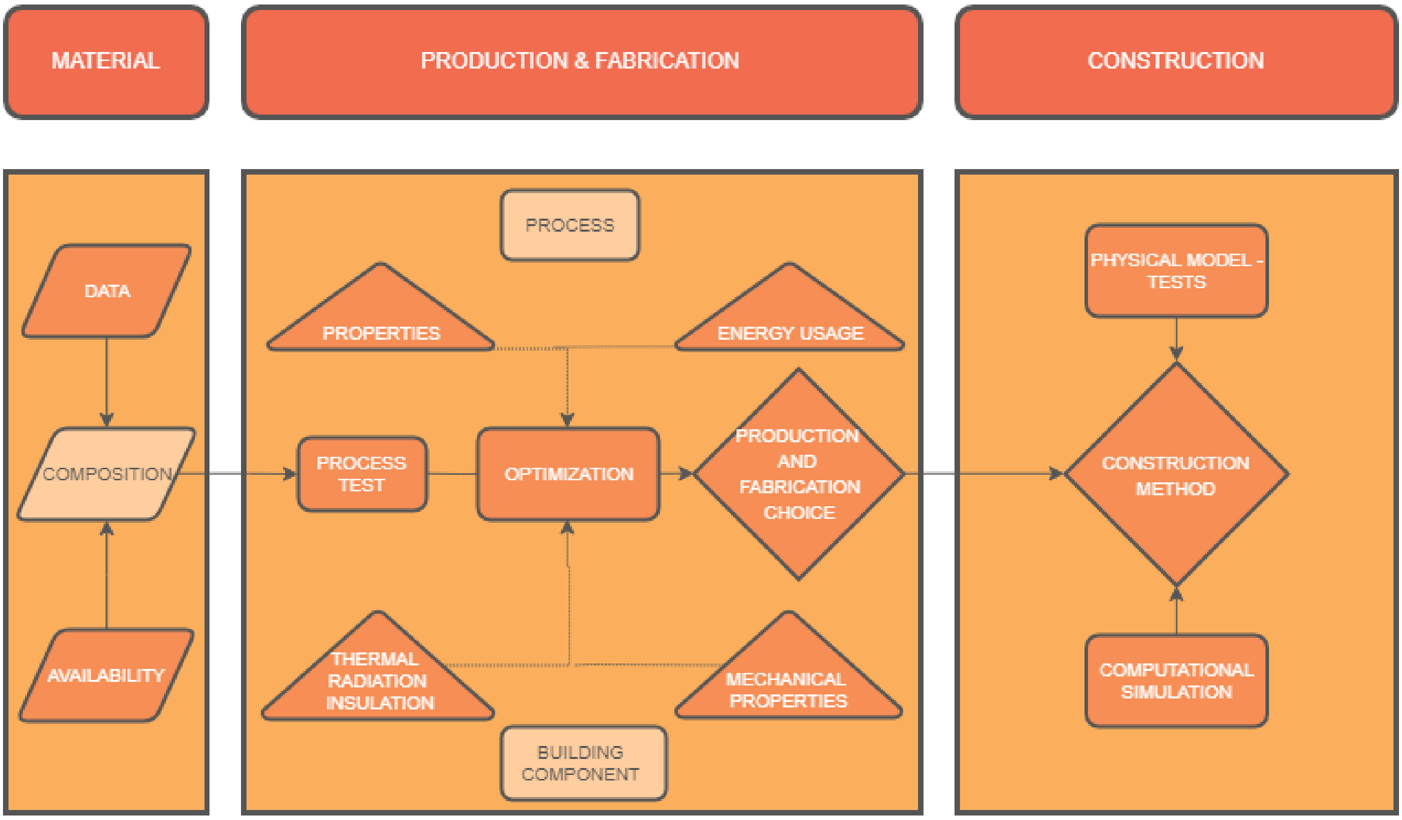

Figure 7: Experimental and computational part including three phases

1.6. Time planning

			P1								P2						
Phase	**Activity**	Oct. - Nov. 29th - 2nd	Nov. 5th - 9th	Nov. 12th - 16th	Nov. 19th - 23rd	Nov. 26th - 30th	Dec. 3rd - 7th	Dec. 10th - 14th	Dec. 17th - 21st	Dec. - Jan. 24th - 4th	Jan. 7th - 11th	Jan. 14th - 18th	Jan. 21st - 25th	Jan. - Feb. 28th - 1st	Feb. 4th - 8th	Feb. 11th - 15th	Feb. 18th - 22nd
Background Research	Literature Study	■	■	■	■	■	■										
	Analysis & Conclusions					■	■	■	■								
	Determination of Program of Requirements							■	■		■						
Experimental research on material	Design simulant's composition											■	■	■			
	Production Processes Testing													■		■	■
	Conclusions															■	■
Experimental research on production process and fabrication	Production Process Optimization																
	Testing (physical and computational simulation)																
	Conclusions																
Research by design and testing	Design of a structure and construction method																
	scale mockup + testing																
	Conclusions																
Research by design	Design of a habitat																
	Computational simulation and modeling																
	Conclusions																
Products	presentation																
	report																
	Conclusions																

											P4								P5
Phase	**Activity**	Feb. - Mar. 25th - 1st	Mar. 4th - 8th	Mar. 11th - 15th	Mar. 18th - 22nd	Mar. 25th - 29th	Apr. 1st - 5th	Apr. 8th - 12th	Apr. 15th - 19th	Apr. 22nd - 26th	May 29th - 3rd	May 6th - 10th	May 13th - 17th	May 20th - 24th	May 27th - 31st	June 3rd - 7th	June 10th - 14th	June 17th - 21st	June 24th - 28th
Background Research	Literature Study																		
	Analysis & Conclusions																		
	Determination of Program of Requirements																		
Experimental research on material	Design simulant's composition																		
	Production Processes Testing																		
	Conclusions	▨																	
Experimental research on production process and fabrication	Production Process Optimization		▨	▨	▨														
	Testing (physical and computational simulation)			▨	▨	▨													
	Conclusions					▨	▨												
Research by design and testing	Design of a structure and construction method						▨	▨	▨	▨									
	scale mockup + testing								▨	▨	▨								
	Conclusions									▨	▨	▨							
Research by design	Design of a habitat												▨	▨	▨				
	simulation and modeling													▨	▨				
	Conclusions													▨	▨	▨			
Products	presentation															▨	▨		
	report															▨	▨		
	Conclusions																	▨	

1.7. Relevance

This research provides a new perspective on planetary space architecture and sustainability. The extreme location and conditions require thinking out of the box and solving challenging issues. These solutions can be significant in building technology industry, both on Earth and in outer space, considering local resources sustainable approach. Terrestrial relevance could concern development of production and fabrication of natural building materials in terms of energy and material usage.

Whereas the outer space building industry could gain potential solution or useful data for sustainable and self-sufficient constructing method. Current approach for colonizing or exploring other planets is focused on maintaining the unknown environment ideally intact. Therefore, research on local and energy efficient building technique could offer an important knowledge. Moreover this approach has also economical relevance as the costs for payloads and follow-up missions could be greatly reduced.

1.8. References

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1.9. Literature review

1.9.1. Mars

General information

This chapter will explain general information about Mars, which will be relevant to the research and further decision making. The Martian conditions will determine programme of requirements for each aspect of the thesis. In the book about Martian surface and atmosphere (Fran Bagenal, David Jewitt, Carl Murray & Ralph Lorenz, Francis Nimmo, 2008), authors create an introduction and perfect background information required for this research.

Mars is the fourth planet from the Sun. The average distance from Earth is 54.6 million kilometres. The day is slightly longer than the terrestrial one and is called "sol". The Martian year is equal to 687 Earth days or 669 sols. The size and mass of Mars is smaller and is presented in the **Table 1** with other basic properties.

Table 1: Basic properties of Martian climate and physical parameters compared to Earth

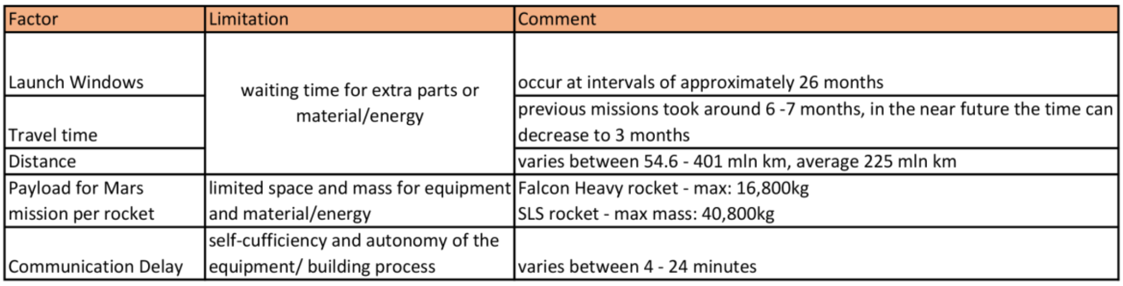
Parameter	Mars	Earth
Radius (equator)	3,396 km	6,371 km
Mass	6,42 x 10 ^{23}	5,97 x 10 ^{24}
Day	24 hours 40 minutes	23 hours 56 minutes
Pressure	0,4 – 0,87 kPa	101,325 kPa
Gavity	3,71 m/s^2	9,8 m/s^2
Surface Temperature (average)	-46°C	-14°C
Surface Temperature (range)	-143°C - 35°C	-80°C - 60°C
Moons	Phobos and Deimos	Moon

Mars as the exploration destination, as mentioned in the Introduction chapter is a realistic plan. Future manned missions to Mars has been planned since 1950's. Current mission models like Zubrin's *Mars Direct*, Aldrin's *Mission to Mars*, NASA's *Journey to Mars* and *SpaceX's Mars Colonization* (Jordan, 2017) are the base approaches, which would be considered as the models for ideal mission's requirements. Most of these mission designs are focused on in situ resources utilization (ISRU). It means, that Mars' local resources should be used as building material, energy source or material for life support systems to decrease payload mass and volume launched from Earth. First manned missions are planned for 600 days - 3 years (surface stay) and 2 - 6 people crew. The missions are planned for years 2025-2035, therefore the technology used for the missions should be already under development and possible to achieve until that time.

As mentioned in the introduction chapter, the transportation is complex and problematic, which makes it essential condition for Martian architecture. **Table 2** presents the overall list of limitations related to these factors. The table was based on most advanced possible equipment and technology available today (Loff, 2018), (SpaceX, 2018), (Harbaugh, 2018). The overall requirements for the mission concluded from the table are:

- Limited and energy efficient equipment used for production process and construction
- Building material resources limited only to in-situ
- Required energy should be limited and if possible renewable
- Production and construction process should be autonomous

Table 2: Mars mission limitations in terms of transportation



Factor	Limitation	Comment
Launch Windows	waiting time for extra parts or material/energy	occur at intervals of approximately 26 months
Travel time		previous missions took around 6 -7 months, in the near future the time can decrease to 3 months
Distance		varies between 54.6 - 401 mln km, average 225 mln km
Payload for Mars mission per rocket	limited space and mass for equipment and material/energy	Falcon Heavy rocket - max: 16,800kg SLS rocket - max mass: 40,800kg
Communication Delay	self-cufficiency and autonomy of the equipment/ building process	varies between 4 - 24 minutes

Mars conditions and hazards

Mars has no magnetic field, although fossil magnetic field was observed on the surface. The field is not generated continuously, it's rather in form of stripes. These remains of previously existing magnetic field have huge influence on upper atmosphere – ionosphere, changing its density. This could affect communication systems between Mars and Earth and on the planet itself. Unfortunately no rover or lander had investigated stronger fields. (Dubinin, Fraenz, Andrews, & Morgan, 2016) The **Figure 8** illustrates the crustal magnetism which disappears in northern hemisphere and in volcanic areas.

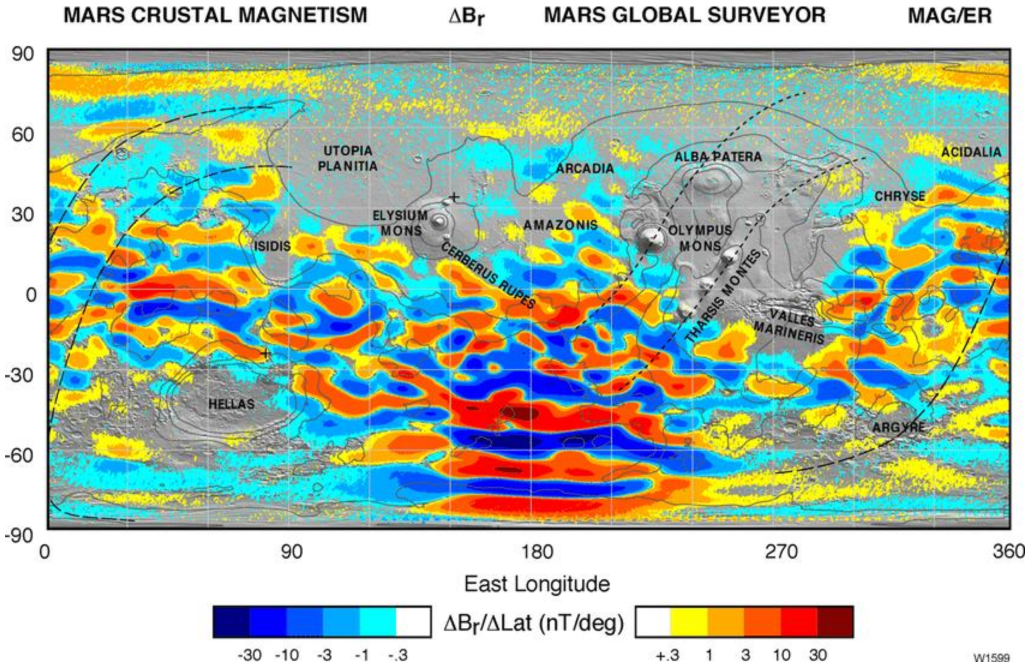


Figure 8: Mars Crustal Magnetic field, MGS Mission, Source: NASA

The lack of magnetic field has an impact on some climate conditions essential for building habitat. Dr Fabio De Blasio, in the book Mysteries of Mars explains atmospheric conditions on Mars and their influance on climate (De Blasio, 2018). The lack of magnetic field results in thin atmosphere and low ground pressure of about 600 Pa. However, the atmosphere is able to keep dust particles suspended by the Martian wind. The composition of atmosphere is presented in the **Table 3** below. Carbon dioxide is the most abundant component, which is responsible for absorption of infrared radiation. Due to this process, the temperature decreases constantly up to 100 km. The temperature can differ significantly, with the average range -143°C - 35°C. The contrast between day and night can reach up to 100°C. Usually the wind is weak, but sometimes a sandstorm occurs, which can last even few months. The strongest storms occur at the perihelion period, when the southern hemisphere surface receives maximum thermal energy from the Sun. During this phenomena, the potential solar energy, which could be used as source of renewable energy for building process is limited. Another effects of Martian wind are dust devils occurring in the afternoon preferably in the south hemisphere. They peak up the dust cover leaving dark path behind. The mentioned phenomena caused by wind are showed in the **Figure 9** .

Table 3: Composition of the Martian atmosphere (by volume), Source:(Fran Bagenal, David Jewitt, Carl Murray & Ralph Lorenz, Francis Nimmo, 2008)

element	name	%
CO_2	Carbon dioxide	95,32
N_2	Nitrogen	2,7
Ar	Argon	1,6
O_2	Oxygen	0,13
CO	Carbon monoxide	0,08
H_2O	Water	210ppm
NO	Nitrogen oxide	100ppm
Ne	Neon	2,5 ppm
HDO	Hydrogen-deuterium-oxygen (semi heavy water)	0,85 ppm
Kr	Krypton	0,3 ppm
Xe	Xenon	0,08 ppm

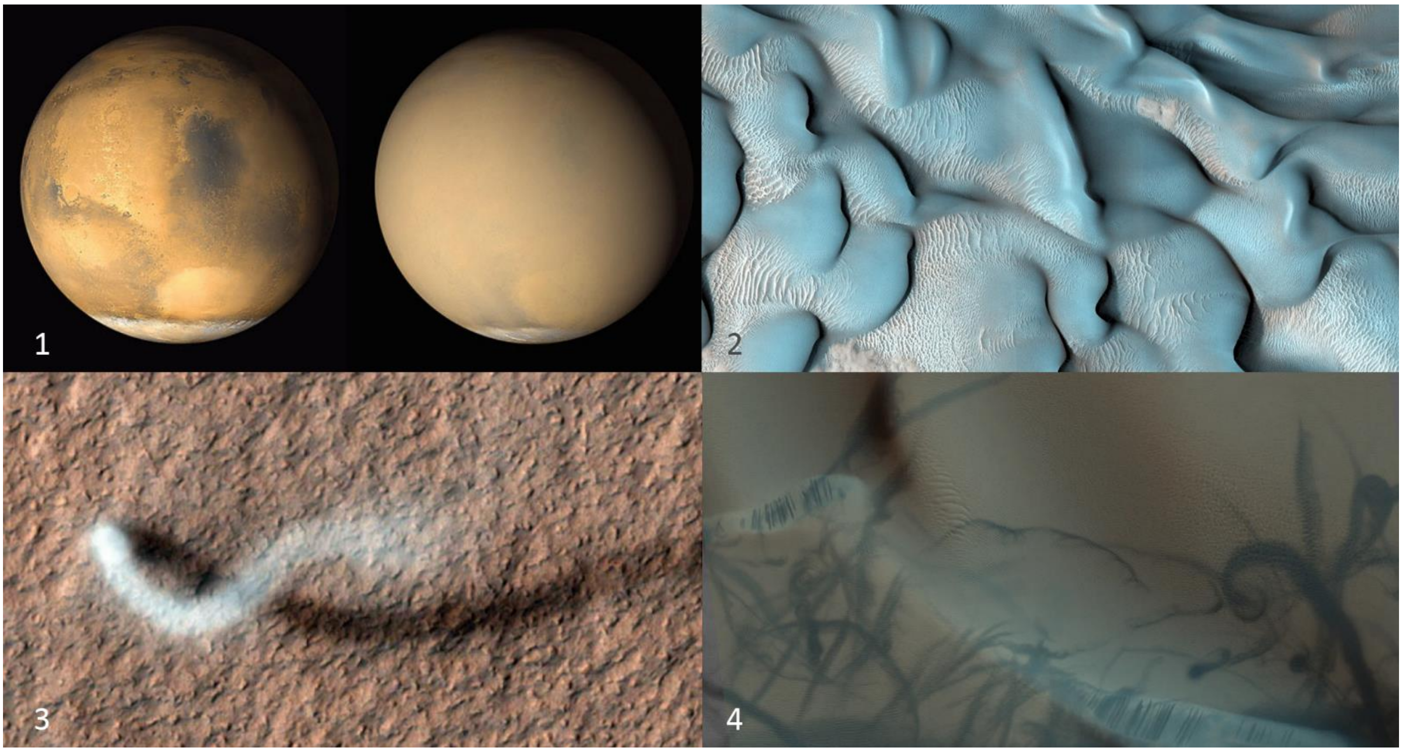


Figure 9: 1 - Comparison of images of the tranquil Mars and Mars covered with dust storm, Source: NASA, 2- sand dunes on Mars, Source: HiRise University of Arizona, 3- example of a dust devil with a base 30m long, Source: HiRise, University of Arizona, 4- Effect of dust devils, dark paths, Source: HiRise, University of Arizona.

Another issue related to thin atmosphere and lack of magnetic field is cosmic radiation. While for the building itself and production process, radiation has slight impact, then for manned crew it is a lethal factor. The radiation environment on Mars has two components: a continuous flux of Galactic Cosmic Rays (GCRs) and transient but intense fluxes of solar energetic particles (SEP).(Parnell, Watts, Jr., & Armstrong, 1998) The compared values of radiation dose rates in different locations and situations is showed in the **Figure 10**. For 500 days on Mars (which is less than the shortest planned mission) the value is located near 300 millisieverts (mSv), while the permissible amount, according to NASA is 1000 mSv for an astronaut in a lifetime. This value is associated with a 5% increase in fatal cancer development risk. This research is aiming to design a structure that could be treated as a habitat or part of the shelter. Therefore the insulation against the radiation is required for the habitat.

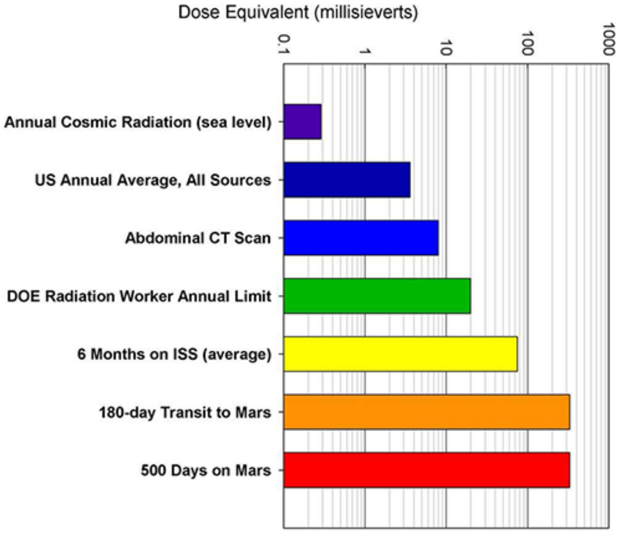


Figure 10: Radiation dose rates. Data for Mars collected by Curiosity mission. Note the scale is drawn in logarithmic increments. Source:(Bennett, 2015)

The surface of Mars is also exposed to micrometeorite strikes, because many of these don't melt during the atmospheric entry. According to Dr. Robert Dycus, the average velocity of micrometeorite hitting the surface can be 7,0±0,2 km/s. (Dycus, 1969) This phenomena requires the structure to be resistant to direct and dynamic impacts.

There is no evidence of plate tectonics, therefore mars quake can be neglected as a factor affecting a built structure and as a hazardous parameter. Moreover, the other consequence is the conservation of old traces of geological activities like impact craters, which are the source of regolith. The preserved geological forms and structures have been investigated by orbit fly-by and landing missions. The data gained by infrared spectroscopic measurements and X-ray diffraction analysis allows to determine the composition of Martian surface.

Topography of Mars is diverse, but easy to distinguish in terms of highlands and lowlands. This division is visible at the **Figure 11** , which represents map of altimetric data made by Mars Global Surveyor (MGS) spacecraft. The legend explaining the colours is below the map. From the image it is evident, that the northern hemisphere has an altitude below datum and is relatively more smooth (less craters and disturbance) compared to the other half. The southern hemisphere is higher and contains more craters and mountains. This division of the planet is called the Martian dichotomy. On the same image there are selected names of regions and structures important for this research.

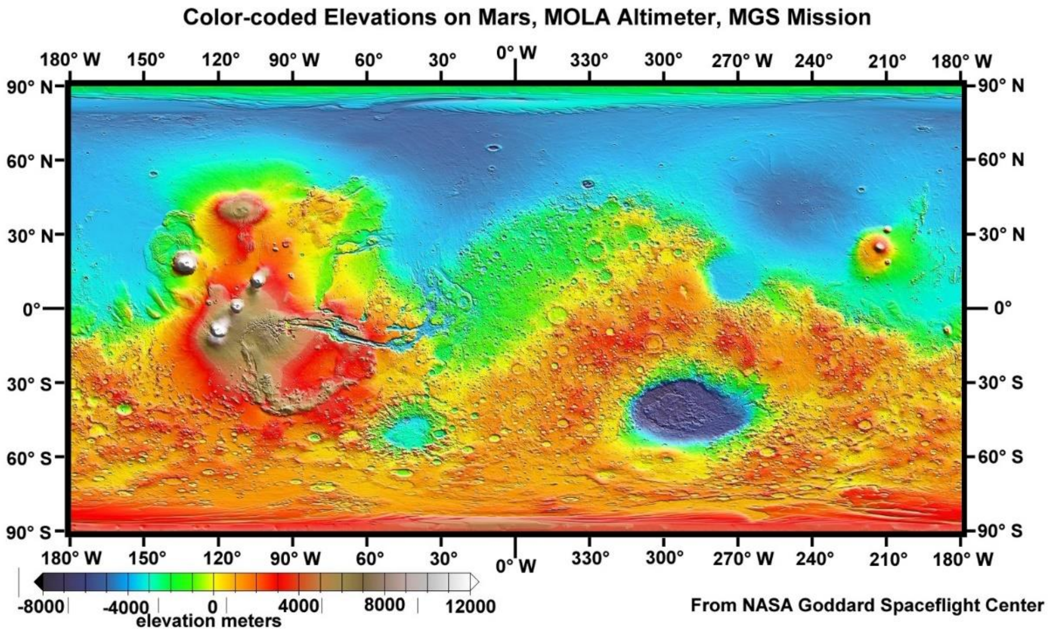
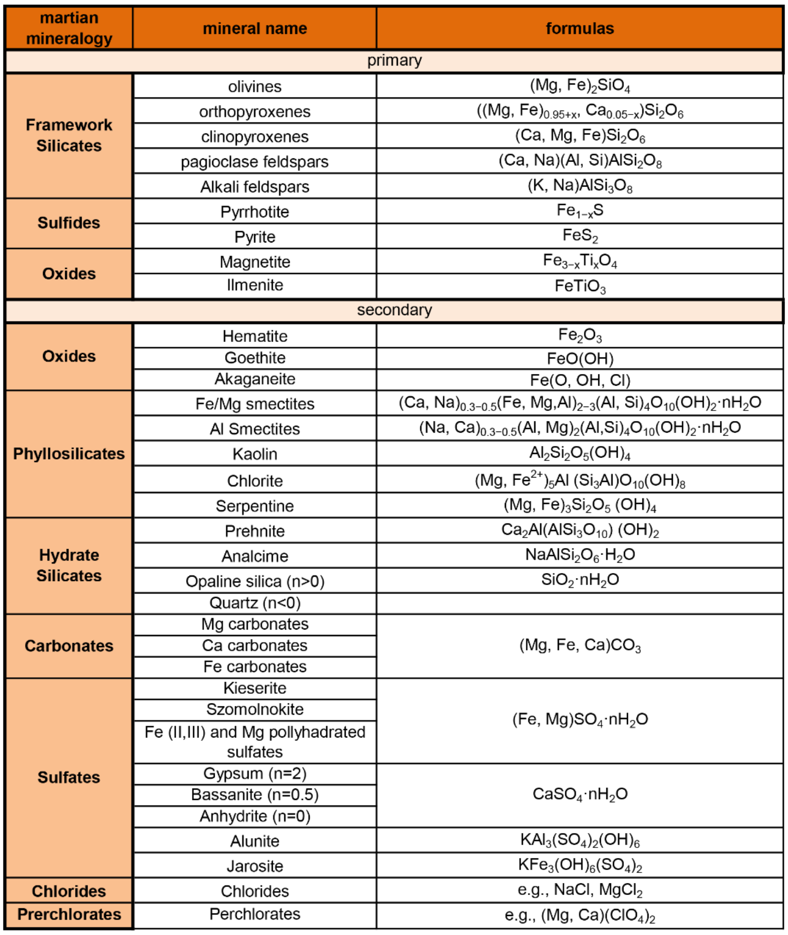


Figure 11: Color-coded elevations on Mars, MOLA Altimeter, MGS mission, Source: NASA Goddard Spaceflight Centre

Mineralogy and regolith

In the article, *Mineralogy of the Martian surface*, authors collected data about minerals detected on Mars from different missions (Ehlmann & Edwards, 2014). **Table 4** presents discovered minerals on Mars, which could be the source of building material – regolith. Later, after choosing the material composition and production process, the excavation method will be determined.

Table 4: Mineral composition of Martian surface



martian mineralogy	mineral name	formulas
primary		
Framework Silicates	olivines	$(Mg, Fe)_2SiO_4$
	orthopyroxenes	$((Mg, Fe)_{0.95+x}, Ca_{0.05-x})Si_2O_6$
	clinopyroxenes	$(Ca, Mg, Fe)Si_2O_6$
	pagioclase feldspars	$(Ca, Na)(Al, Si)AlSi_2O_8$
	Alkali feldspars	$(K, Na)AlSi_3O_8$
Sulfides	Pyrrhotite	$Fe_{1-x}S$
	Pyrite	FeS_2
Oxides	Magnetite	$Fe_{3-x}Ti_xO_4$
	Ilmenite	$FeTiO_3$
secondary		
Oxides	Hematite	Fe_2O_3
	Goethite	$FeO(OH)$
	Akaganeite	$Fe(O, OH, Cl)$
Phyllosilicates	Fe/Mg smectites	$(Ca, Na)_{0.3-0.5}(Fe, Mg,Al)_{2-3}(Al, Si)_4O_{10}(OH)_2 \cdot nH_2O$
	Al Smectites	$(Na, Ca)_{0.3-0.5}(Al, Mg)_2(Al,Si)_4O_{10}(OH)_2 \cdot nH_2O$
	Kaolin	$Al_2Si_2O_5(OH)_4$
	Chlorite	$(Mg, Fe^{2+})_5Al (Si_3Al)O_{10}(OH)_8$
	Serpentine	$(Mg, Fe)_3Si_2O_5 (OH)_4$
Hydrate Silicates	Prehnite	$Ca_2Al(AlSi_3O_{10}) (OH)_2$
	Analcime	$NaAlSi_2O_6 \cdot H_2O$
	Opaline silica (n>0)	$SiO_2 \cdot nH_2O$
	Quartz (n<0)	
Carbonates	Mg carbonates	$(Mg, Fe, Ca)CO_3$
	Ca carbonates	
	Fe carbonates	
Sulfates	Kieserite	$(Fe, Mg)SO_4 \cdot nH_2O$
	Szomolnokite	
	Fe (II,III) and Mg pollyhadrated sulfates	
	Gypsum (n=2)	$CaSO_4 \cdot nH_2O$
	Bassanite (n=0.5)	
	Anhydrite (n=0)	
	Alunite	$KAl_3(SO_4)_2(OH)_6$
	Jarosite	$KFe_3(OH)_6(SO_4)_2$
Chlorides	Chlorides	e.g., $NaCl$, $MgCl_2$
Prerchlorates	Perchlorates	e.g., $(Mg, Ca)(ClO_4)_2$

As mentioned earlier, the regolith is a secondary product of impacts. The ejected material can be distributed up to many kilometres around the crater. It can later consolidate as sedimentary rocks with addition of ice and as a fine powder, free to wander around the surface. Due to the absence of water the fine grained surface layer is easy to be carried and transported by wind flows. Small particles can travel incessantly leading to homogenous composition of the dust on the entire planet. This makes the excavation of the material easier and the resources availability more broad. Moreover, the fact that the composition of dust is homogenous makes it a better building material as the production process and building technologies could be similar in more than one region. Average soil and dust composition is presented in **Table 5**.

Table 5: Average soil and dust composition, Source:(Morris, 2017)

compound	name	Average Mars Dust wt%	Average Mars Soil wt%
SiO_2	silicone dioxide	44,84 ± 0,52	46,52 ± 0,57
FeO	iron oxide	7,28 ± 0,70	12,18 ± 0,57
Al_2O_3	aluminium oxide	9,32 ± 0,18	10,46 ± 0,71
MgO	magnesium oxide	7,89 ± 0,32	8,93 ± 0,45
CaO	calcium oxide	6,34 ± 0,20	6,27 ±0,23
SO_3	sulphur trioxide	4,90 ± 0,74	4,90 ± 0,74
Fe_2O_3	ferric oxide	10,42 ± 0,11	4,20 ± 0,54
Na_2O	sodium oxide	2,56 ± 0,33	3,02 ± 0,37
TiO_2	titanium dioxide	0,92 ± 0,08	0,87 ± 0,15
P_2O_5	phosphorus pentoxide	0,92 ± 0,09	0,83 ± 0,23
Cl	chlorine	0,83 ± 0,05	0,61 ± 0,08
K_2O	potassium oxide	0,48 ± 0,07	0,41 ± 0,03
Cr_2O_3	chromium(III) oxide	0,32 ± 0,04	0,36 ± 0,08
MnO	manganese (II) oxide	0,33 ± 0,02	0,33 ± 0,02
µg/g			
Ni	Nickel	552 ± 85	544 ± 159
Zn	Zinc	404 ± 32	204 ± 71
Br	Bromine	28 ± 22	49 ± 12

Regions abundant in fine grains contain dunes. **Figure 13** presents the map of dust regions on the surface of Mars. As visible in the image, dust is more available in the north hemisphere. Due to the localization of material, more detailed data about the composition will be gathered based on surface missions close to the regions rich in dust. The rovers and landers are showed in the same Figure. The most promising data can be gained from the latest missions as they are better equipped and the analysing technology was improved compared to previous ones. Therefore, the data about composition of dust gained by Curiosity and Spirit rovers was chosen to be investigated.

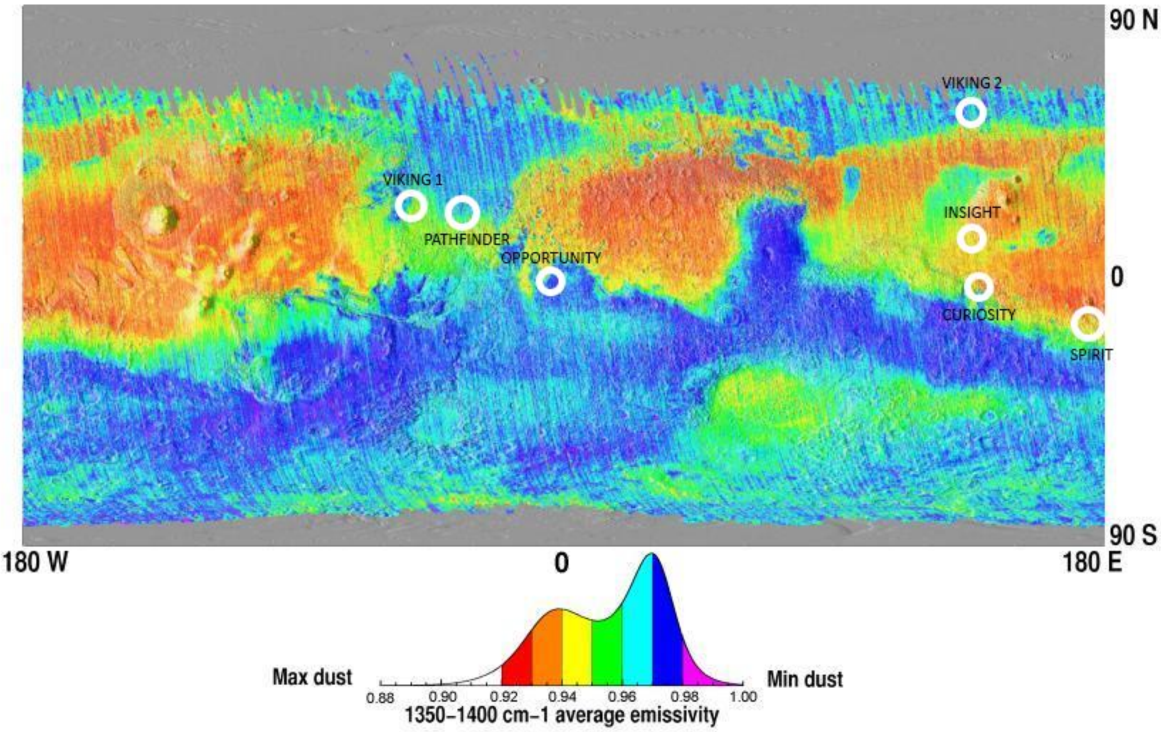


Figure 12: Dust cover map of Mars, Source: Mars Global Data Sets

Martian regolith can be subdivided by grade scale of particles. **Table 6** presents the comparison and sizes of different particles, which occur as a loose material on the surface. The size of the surface material depends on the geological processes present in region. This data would be relevant for the experimental part of the research, when the building material would be processed. The size of particles required for processes will differ based on the chosen production. For example, for the concrete-like products ideal would be three different grains, but for melting process the smaller the particle the faster and more efficient the process proceeds.

Table 6: Grade scale for small particles

Diameter (mm)	Particle
<0,004	Clay
0,004 – 0,00625	Silt
0,00625 – 0,125	Very fine sand
0,125 – 0,25	Fine sand
0,25 -0,5	Medium sand
0,5 – 1,0	Coarse sand
1,0 – 2,0	Very coarse sand
2,0 – 4,0	Granule
4,0 – 64	Pebble
64 - 256	Cobble

Curiosity data

The mineralogy of Martian dust and soil is gathered by the CheMin X-ray diffraction instrument onboard Curiosity rover. This equipment analysed surface soil in Gale Crater, a dust deposit – Rocknest and an aeolian dune – Bagnold. According to Prof. Ming (Ming & Morris, 2017) dust from Rocknest has the most similar to global composition. **Table** presents the quantitative mineralogy of the Rocknest windblown deposit. The amorphous component includes npOx phases, S- Cl- bearing volatile phases (sulphides, sulfates) and Ca-sulfate and hematite.

Mineral	Wt.%
Feldspar	26
Olivine	13
Pyroxene	20
Magnetite	2
Hematite	1
Anhydrite	1
Quartz	1
Ilmenite	1
X-ray Amorphous	35

Ice and Water

The water on Mars was discovered only in solid and volatile form. At Martian low pressure the sublimation occurs, where the solid phase is directly transformed to a gaseous state, skipping the liquid one. This effect can have an impact on a production process of the building component. Moreover, the water, even in form of ice is precious as fundamental element for life support systems for crew. Ideal for the space architecture would be to avoid the need of using water for production process. **Figure 14** presents the map of surface water detected on Martian surface. The Martian regolith likely contains mixture of soil particles and ice, therefore final composition of the material used for building habitat might include small amount of water.

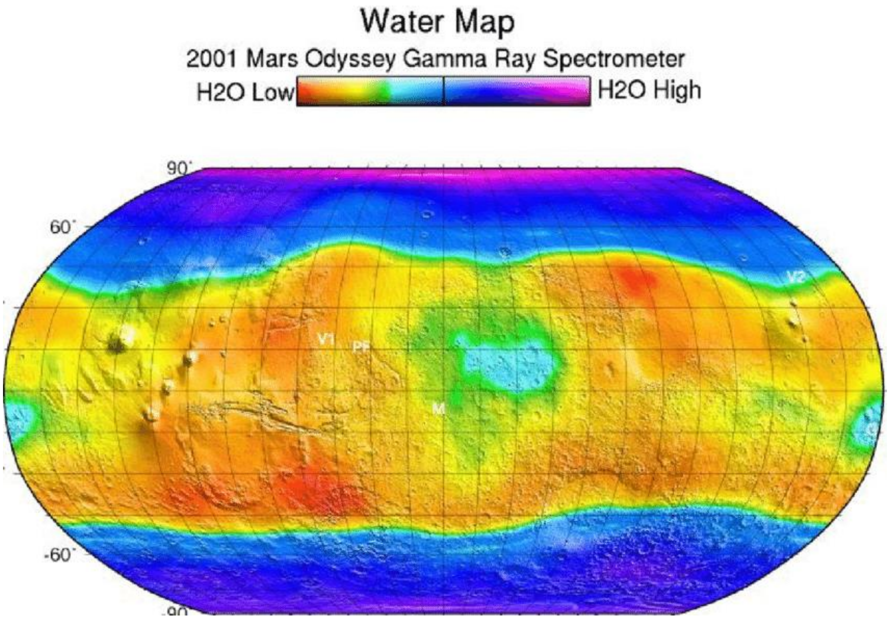


Figure 13: Map of water detected on Martian surface, Source: Jonathan D. A. Clarke.

Habitat, Martian architecture

Habitation design requirements for human missions mostly regard safety and wellbeing of the crew. The ones important for this research were collected from the book “Space Architecture – Education for Architects and Engineers”. (Häuplik-Meusburger & Bannova, 2016) Due to hazardous conditions on the surface of Mars, the interior of the habitat should support the isolated habitable environment and the building systems should be self-sufficient and sustainable. The factors regarding the indoor climate are atmosphere, temperature, humidity, pressure and light. However these conditions are significant for habitable space, for purpose of this research they are considered as secondary. This decision was made, because the factors of indoor climate are solved mostly by life-support systems and installations. As this thesis is focusing on production of the building material and construction method the most important requirements concerns safety against the hazards like micrometeoroids, outdoor temperature and cosmic radiation.

REFERENCE PROJECTS

Projects from 3D printed Habitat Challenge Phase 1 - the Design Competition, required teams to submit architectural renderings and was completed in 2015.

1. ICE House

Although this project uses different resource material than regolith I decided to keep it as a reference regarding the space design. This project in a concept of a Martian habitat proposed by winning team formed by SEArch (Space Exploration Architecture) and Clouds AO (Clouds Architecture Office). The group designed a 3D printed structure made of Ice. Despite the fact, that this material brings precious light inside the habitat, it has an important advantage in the fact that water is better as radiation insulation than regolith. Another potentially good part of the design is the idea of creating gradient transition between safe interior and hazardous outdoor environment.

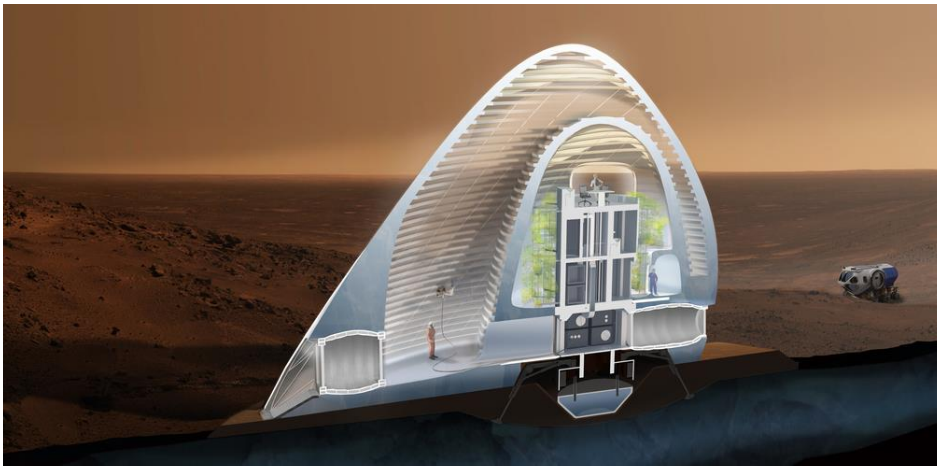
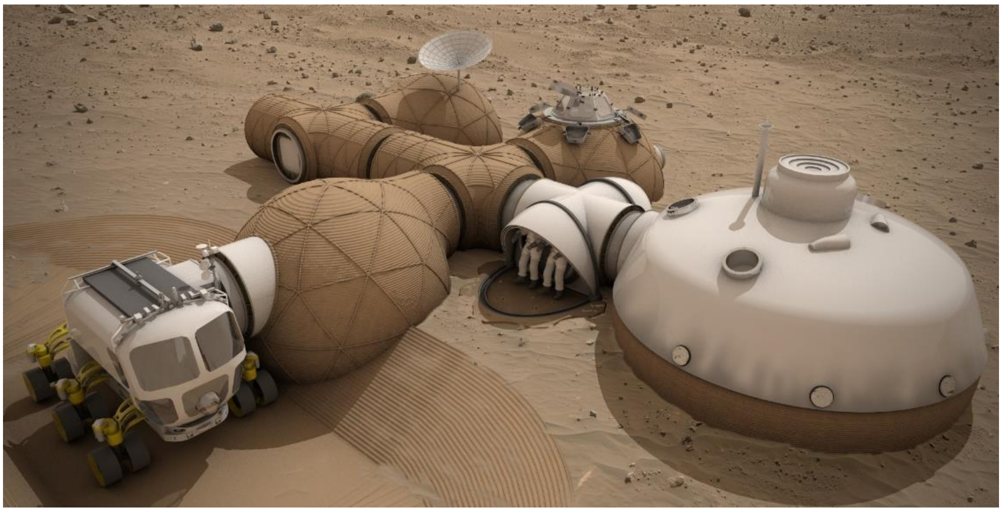


Figure 14: Section of the ICE HABITAT, Source: (SEArch+ & CloudsAO, 2015)

The core of the habitat is a vertically oriented lander which contains all the mechanical services and life supports systems. Two layers of the ice structure visible in the **Figure 16** create intermediate zones acting as thermal and radiation insulation. This allows a crew to exit the main habitat without an EVA (extravehicular activity) suit. The middle space – between the lander and first layer of ice is pressurized at the same level as the interior of the hab. It is allowed by a ETFE membrane stretched on the surface of ice structure. In the production process, team uses the physics of phase change of water.

2. LavaHive project



This is a project designed by European Space Agency's European Astronaut Centre and LIQUIFER Systems Group, which won the 3rd place in the NASA 3D Printed Habitat Challenge. It's a modular habitat using novel construction method – lava casting. According to authors: "*A linear configuration of modules was decided to be the safest, most effective, and most flexible option when considering this larger scale structure. Extending the configuration in the future is foreseen for including additional docking ports or other working areas.*"

The building process is performed by 2 rovers – one to sinter, second to melt regolith. The core of the habitat is inflatable and the 3D printed structure is layered on its surface. The inside of the regolith structure is covered with epoxy which will seal the habitat. The potential of this design is the incorporation of components that are part of a spacecraft, which would bring rovers and landers to Mars. The reuse of these elements can be advantage regarding the sustainable design.

Projects from 3D Printed Habitat Challenge Phase 3 - the On-Site Habitat Competition, challenges competitors to fabricate sub-scale habitats, and has five levels of competition – three construction levels and two virtual levels. For the virtual levels, teams must use Building Information Modeling software to design a habitat that combines allowances for both the structure and systems it must contain. The construction levels challenge the teams to autonomously 3D-print elements of the habitat, culminating with a one-third-scale printed habitat for the final level.

1. **SEArch+/Apis Cor's project – Mars X House**

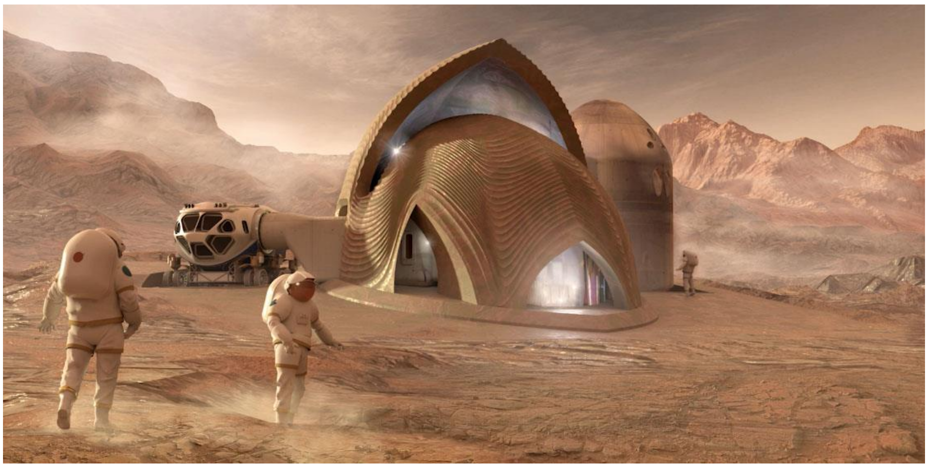
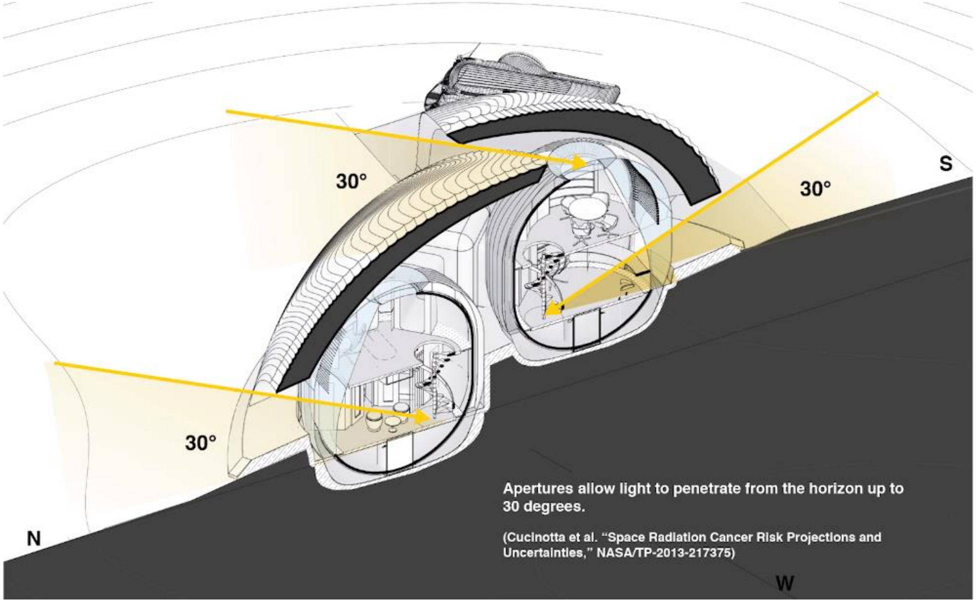


Figure 15: Mars X House visualization, Source: (SEArch+ & Cor, 2018)

This project is another interesting design of the habitat, where the team tried to combine two Martian resources – ice and regolith. A valuable research on radiation protection as a factor for structure design might be an important information for this research. According to authors, "*the density of Martian atmosphere along the horizon allows solar transmission up to 30° above the horizon*". The design takes into account the orientation and location (northern hemisphere) of the habitat. The opening in the shell structure made of regolith are oriented towards north and let a diffused light to the interior up a 30° angle.



Apertures allow light to penetrate from the horizon up to 30 degrees.

(Cucinotta et al. "Space Radiation Cancer Risk Projections and Uncertainties," NASA/TP-2013-217375)

Figure 16: Scheme section of the design explaining the implementation of radiation shielding research to the design, Source:(SEArch+ & Cor, 2018)

2. **Team Zopherus – Rogers, Arkansas**

Modular design, where the lander is the equipment and printing place at the same time. The lander creates a printing chamber sealed to the ground and creates hexagonal structures in its pressurized interior space.

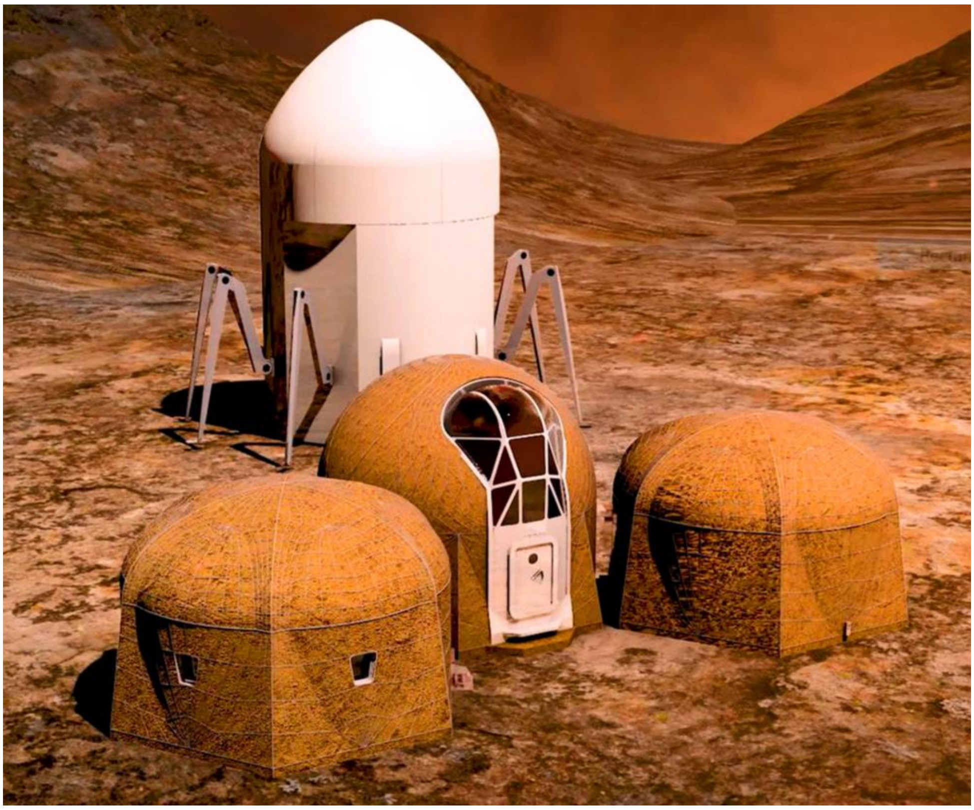


Figure 17: Zopherus habitat concept visualization presenting three 3d printed modules and the spider-lander, Source: NASA

Programme of requirements

The previous part of this chapter presented the conditions regarding Martian climate and mission. Below will be presented programme of requirements ensuing from these conditions. Based on these requirements the ongoing researches were chosen to study and compare – see next chapter.

Material requirements:

- Available on the surface – preferably entire planet
- Easy excavation and collecting process
- Preferably ready for usage after collecting – no extra processes required

Mixture and production requirements:

- Minimize water consumption – ideal water-less production
- Be adjustable to slightly different compositions of regolith
- Easy and fast to prepare
- Minimal amount of processing and energy to produce from in-situ resources
- Minimum resources required from Earth
- Limited volume, mass and complexity of equipment required from Earth

Building product/structure requirements:

- Withstand extreme temperature differences
- Withstand damage due to radiation or micrometeorites
- Not flammable, not decompose
- Easy to maintain, repair, safe
- Preferably last longer than one mission (1-3 years)
- Possible to construct volumes and dimensions required for habitable space
- Thermal and radiation insulation

2.9.2. Ongoing researches

General overview and conditions

The researches relevant to this graduation project will be presented here as a literature review of scientific reports and concepts for building on Mars. The requirements determining importance of a research, based on which the papers were chosen, are water-less production process and regolith/dust as the building material. These concepts were later compared to each other regarding energy consumption and complexity (equipment) of the process, product mechanical (or other if performed) properties, production duration and potential of the idea.

Production processes available on Mars concern three stages: extraction, material preparation/selection and final production process. This chapter is focused on final production processes, while the first two stages will be determined and investigated after choosing the last one.

The most important aspect of the production is how to bind dry and loose material into building component. The melting point of regolith is about 1100°C, which require too much energy. Therefore one solution is to find an element that could behave as binder connecting regolith together.

Production methods

The available, water-less binding processes on Mars can include two most basic methods: compression or sintering/melting. The first one might be performed using quasi-static or impact compaction and had been investigated both as the main production method and the additional treatment. The binding based on thermal treatment can be used in two techniques: sintering (high-power laser, solar concentration, microwave sintering, radiant heating) and melting. Sintering is energy demanding and might be problematic in low pressure.

Compaction and cementation

Despite the fact that common cementation is performed in a presence and addition of water, there are few examples of binding aggregates and small particles using melted materials. In the next sub-chapter there will be two researches using this method of production process.

Microwave melting / sintering

Existing researches using this technology were working on pure regolith, without any additives. This method can lead to volumetric heating due to microwaves. A problematic aspect is a temperature gradient, where an interior of a sample has higher temperature than its surface. Another possible option is heating the surface – microwave sintering, but the volumetric heating can be used to fabricate larger samples.

Solar / Laser sintering/melting

Solar concentration method could be energy efficient option for sintering compared to laser technology. Electric power is more reliable, but the total energy required for building habitat would be enormous due to small volume of material possible to thermally treated at a time. Solar concentration could have better depth of penetration, but the extra complexity of the equipment and the maintenance or positioning could be a big issue.

Chosen researches using water-less binding

Martian concrete (Wan, Wendner, & Cusatis, 2016)

PRODUCTION DESCRIPTION:	Production of martian concrete is based on using molten sulphur powder as a binder. Sulphur concrete is manufactured on Earth by hot-mixing sulphur and aggregate (in this case martian regolith). For the research, different ratios of sulphur and regolith are mixed at temperature of 120°C. After reaching the required conditions, the material is cooled down at room temperature (20°C) in formworks.
MATERIAL, MIXTURE:	aggregate - martian regolith (simulant JSC Mars-1A)

binder - sulfur powder (best mixture ratio 1-1)

MECHANICAL TESTS:

The test we performed after 24 hours of cooling down of the samples. The tests included unconfined compression, notched and unnotched three-bending (TBP) and splitting. The TBP tests were made using beams with the dimensions of formwork, while for the other tests cubes of 25,4mm edge size were used.

PRODUCT PROPERTIES:

max compressive strength – 50 MPa

COMMENTS:

During the research, different proportions of mixture composition and various aggregate sizes were prepared and tested. During curing of samples, high stress and cavities induced by shrinkage of sulphur occurred. The issue decreased when the size of the aggregate was reduced. Interesting approach of recasting and reusing the tested material resulted in increase of the strength of the final product. Additional pressure applied while placing the material in formwork also facilitated material strength. Moreover, some unidentified chemical reactions between sulphur and metal elements in regolith could cause the strength improvement. However this was just a hypothesis.

The potential of the production is promising although the energy consumption could be still investigated. The other issue is the fact, that sulphur is not heat resistant and its smell is unpleasant.

Atomic bond between iron oxide and oxyhydroxide particles (Chow, Chen, Zhong, & Qiao, 2017)

PRODUCTION DESCRIPTION:

The steps in production process are listed below:

- Sieve separation – subjected 500ml batches to temperature of 105°C for 24 hours (to remove any water from the material), then mechanical sieve separated simulant into bin sizes
- Size fractionation
- Thermal treatment – simulants transferred in crucibles, protected with aluminium foils, drying at 600°C for 12 hours, cooled down at ambient t (to remove water to <5wt%, because most martian soil contains <5wt%, to remove carbon)
- Compression in uniaxial mode between flat pistons
  - 6 configurations: two rates of loading (quasi-static – mm/min, impact – m/s) and three lateral boundary conditions (rigid – steel wall, free, flexible – elastomeric wall)
  - Quasi-static compaction:
    - Rigid boundary condition
    - Free boundary condition
    - Flexible boundary conditions
  - Impact Compaction:
    - Free boundary condition
    - Flexible boundary condition

MATERIAL, MIXTURE:

martian regolith simulant – JSC Mars-1A, (important content of nanoparticulate iron oxides and oxyhydroxides)

MECHANICAL TESTS:

The test we performed after 24 hours of cooling down of the samples. The tests included unconfined compression, notched and unnotched three-bending (TBP) and splitting. The TBP tests were made using beams with the dimensions of formwork, while for the other tests cubes of 25,4mm edge size were used.

PRODUCT PROPERTIES:

Results:

- Quasi-static compaction
  - Rigid boundary condition: average flexural strength: 10MPa
  - Free boundary condition: average flexural strength: 27MPa
  - Flexible boundary condition: average flexural strength: 25MPa
- Impact compaction:
  - Rigid boundary condition: average flexural strength: 13MPa

- Free boundary condition: average flexural strength: 40MPa
- Flexible boundary condition: average flexural strength: 50MPa

COMMENTS:

Following comments could be highlighted:

- compatible with additive manufacturing
- Process might be adapted to other Martian minerals (clays and evaporite salts)
- Both compaction processes are compatible with additive manufacturing
- For habitat building application this process would require addition of binding into the process
- For the Quasi-static compaction:
    - flexural strength insensitive to the particle size (particle size range: $20\mu m$ - $100\mu m$), strength remains similar, may be associated with the high compressive pressure (peak),
    - Quasi-static compaction in flexible boundary conditions resulted in best relation between peak compression and product's flexural strength
    - When amount of basalt increased – strength decreased
    - Hypothesis of mechanical interlocking particles
    - Goethite plausible constituent of npOx
- For the Impact compaction:
    - size of the particles influence the strength – may be related to effects of inertia and npOx availability, larger particles fall into less-than-optimal arrangements, because rotational inertia depends on the size of particles, larger particles have larger solid volume-to-area ratio, so less npOx I available to bond particles.
    - strength determined by impact energy (no matter if adjusted with hammer mass or impact velocity)
    - nitrogen permeability is on the order of $\sim 10^{-16} m^2$ – similar density to rocks
    - particle motion localized
    - critical to allow rotation and transverse motion of particles to maximize effective contact area and promote bond formation, but excessive motion may lead to defects

<u>Phosphate-based binder</u> (Buchner, Pawelke, Schlauf, Reissner, & Makaya, 2018)

PRODUCTION DESCRIPTION:

First approach: dry binder (phosphorous) was mixed with martian regolith. The mixture was placed and pressed into 50 x 4mm wide bar moulds.

Second approach : water was added to the binder

MATERIAL, MIXTURE:

martian regolith + phosphorus pentoxide (P_2O_5 or P_4O_{10})

MECHANICAL TESTS:

Compression tests – Zwick Z050 testing machine with traversal speed 0,5 mm/min. Rectangular samples, cross sectional area: 60,7-100,6mm^2 , 2,85-3,41mm height

Bending tests - Zwick Z050 testing machine with traversal speed 2 mm/min. Samples irregular, shaped as thin strips with rectangular cross-section 7,1-9,46 mm width and 2,55-3,56 mm thickness.

PRODUCT:

max compressive strength – 10-20MPa

COMMENTS:

Problems with solidification of the first approach with dry binder (maybe because of no liquid-binder), absence of protons which promote chemical binding reaction. Moreover, the time between fabrication and testing was too long – 2 months. The thermal treatment instead of addition of water could be problematic, as at the melting point, if heated up rapidly, can sublimate.

Synthesis with polyethylene (PE) (Sen, Carranza, & Pillay, 2010)

PRODUCTION DESCRIPTION: PE was mixed with martian regolith and heated up to 140°C in a stainless steel mold cavity (to ensure complete melting of the PE). Pressure of 240MPa was applied.

MATERIAL, MIXTURE: martian regolith + polyethylene (PE) produced from martian atmosphere

MECHANICAL TESTS: Compression testing – unconstrained compression tests performed on cylindrical samples 1,27cm in diameter and 2,54 cm in length. Loading rate was set to 1mm/min

Micrometeoroid ballistic testing – two stage micro light gas gun used, impact velocity of 7km/s, samples 3,81 x 3,81 x 2,54 cm^3

Radiation testing - samples 3,81 x 3,81 x 2,54 cm^3

Flexural testing – Instron T60 test frame at a crosshead rate of 1mm/min

PRODUCT PROPERTIES: 20 wt% PE – 41.1MPa,

COMMENTS: The research is focused on radiation shielding as the main purpose of the structure. With 20wt% addition of PE, the radiation protection was strengthened by 12%. The synthesis of polyethylene from Martian atmosphere is a complex process which requires extra energy and equipment.

3D Microwave Print Head (Barmatz, Steinfeld, Anderson, & Winterhalter, 2014)

PRODUCTION DESCRIPTION: 3D printing of regolith using microwave volumetric heating. Collected powder regolith is placed in a feedstock hopper and moved to emitter chamber by compression auger. Inside the chamber the material is melted by microwaves and ejected through a nozzle. A 200-Watt TWT microwave amplifier was used to heat up the samples (up to 600 - 700°C) in a quartz holder. The samples heated up to more than 700°C surface temperature – they were completely melted.

MATERIAL, MIXTURE: Martian regolith

MECHANICAL TESTS:

PRODUCT PROPERTIES:

COMMENTS: The samples heated up to 500-600°C surface temperature had powdery outer surface, sintered outer rind and melted interior. It means the products had gradient properties.

Powder Bed Fusion (PBF) (Goulas, Harris, & Friel, 2016)

PRODUCTION DESCRIPTION: Martian regolith had to be screened and crushed before the production process. Manufacturing was conducted using commercial equipment like selective laser melting machine (SLM) producing laser radiation of 1.06-1.09 μm wavelength, while requiring 50W power. Thickness of powder layer could range between 150-300 μm.

MATERIAL, MIXTURE: Martian regolith, 70 μm to 350 μm

MECHANICAL TESTS: - Microscopic analysis of surface morphology, internal porosity and material microstructure

- Vickers micro-indentation method to measure the hardness of samples, values were measured in 12 different locations of a sample to investigate differences in properties in one sample

- Thermal analysis using Thermo-Gravimetric Analysis in order to determine presence of volatile compounds.

	- Change in crystallinity or presence of amorphous content in processed samples determined using X-ray Diffraction
PRODUCT PROPERTIES:	- 710 ± 30 HV Vickers hardness
COMMENTS:	Due to small thickness of powder layer the production time might be an issue.

Energy

Energy used for production process on Mars should be efficient and ideally renewable. The possible sources of renewable energy are the Sun and wind. If required, importation of nuclear reactors is also possible. Although the fact, that the payload is very limited, the volume of reactor should be small.

The available energy sources for Mars missions were compared by Simon D. Fraser in a chapter of a book about Prospective Energy and Material Resources on Mars. (Soediono, 2009) In the Automation and Robotics for Human Mars Exploration (AROMA) study made by ESA, the output power requirement for investigated systems ranges between few watts up to tens of kilowatts. Due to the climate conditions on Martian surface, thin atmosphere, there is a broad range of options for power generation. According to the author, the energy generated on the surface on Mars can be achieved by following options:

Table 7: Power generation options on the surface of Mars highlighted options are the most likely pathways according to the author, Source: "Mars: Prospective Energy and Material Resources" (Soediono, 2009)

power generation options	technologies e.g.
Alternative power generation options	geothermal energy, solar power satellites/beamed power from space
Landed energy resources	primary batteries, fuels or feedstock species, nuclear energy resources
Solar-energy-to-electric conversion	photovoltaic, solar dynamic power systems
Landed non-nuclear energy resources	primary batteries, readily-fuelled fuel cells or heat engines
Landed nuclear energy resources	radioisotope generators, fission reactors with static or dynamic conversion systems
ISRU process	utilisation of in-situ resources for propellant and/or oxidant production
Fuels/oxidants	hydrogen/oxygen, methane/oxygen, carbon monoxide/oxygen, methanol/oxygen

The most likely available options are surface solar energy utilisation and landed energy resources, where the best one would be nuclear power.

Solar energy

This renewable source of energy is one of the most obvious choice. However, the limitations due to climate conditions are an issue when we consider a high performance application such as complex production process. These limitations are mostly related to atmosphere impurity caused by floating dust. As mentioned earlier, potential dust storms, could decrease the energy output to minimal or none for weeks or months. Therefore, even if the solar energy would be considered the main option for power supply, there should be an alternative source, which would be independent from environmental conditions. The possible solar energy utilisation technologies are photovoltaic, photothermal and solar dynamic systems. They depends on solar irradiance, which can be divided into direct, diffused and global solar radiation.

The equipment for direct solar irradiance collection requires expensive and complex tracking mechanism to orient the receiving surface always perpendicular to the Sun's rays. The global solar irradiance is collected by flat plate collectors with one rotation axes continuously adjusted or adjusted from time to time. According to prof. Viorel Badescu, on Martian surface, the solar global irradiance could range between 400 W/m^2 at the noon of a clear summer day to 80 W/m^2 at midday during winter dust storm. (Badescu, 1998)

The InSight lander equipped in solar panels produced 4588 watt-hours during first sol (two solar panels, about 2,2m each in diameter). (Brown & Wendel, 2018) ***"On a clear day two panels will provide 600 to 700 watts of power – enough electricity to run a household blender"*** say the panels' designers.

Landed energy resources

Among the available landing resources is nuclear power. A developed technology commonly used in space exploration is Radioisotope Thermoelectric Generator (RTG), which is currently working on Mars in Curiosity rover. This power system produce electricity from the natural decay of plutonium-238 dioxide, transforms into uranium 234 and which generates heat. Curiosity rover's record for power output is **2806 watt-hours per one sol**. It is equipped with about 5kg nuclear power. In the future there is a plan for developing the technology by creating e-MMRTG (Enhanced Multi-Mission Radioisotope Thermoelectric Generator.

Another system under development is Kilopower Reactor Using Stirling Technology (KRUSTY), which is one of NASA solutions for generating power for Mars colonization. (Hall, 2017) According to the team the system is available to produce **1-10kW** of electricity. The expected mass for the 10kW output is 226kg.

In the same chapter, the author Simon D. Fraser compared these two options: solar and nuclear resources, in the **Table 8** below. Although it's clear from the table, that the nuclear power has more potential, the plans for future missions assume, that there would be at least two sources of energy. Solar energy advantage is related to its sustainable aspects, while future nuclear systems can produce much more energy.

Issue	Surface solar energy utilisation (PV, dynamic system)	Landing nuclear resources
specific energy with respect to the Earth launch mass	very high	very high
system lifetime	very long, but depends on maintenance	very long
continuous power output	not available, intermittent storage system necessary	available
reliably	very high, but depends on installation, location and operation	very high
maintenance	required	not required with RTG
operation in harsh environmental conditions	problematic	no problem
output power predictability	limited	very high
dependence on orientation	limited	no problem
cost	lower	high development
portability	lower	higher (compact) (diameter-64cm x height-66cm)

Table 8: Surface solar energy utilization versus nuclear power generation, Source: "Mars: Prospective Energy and Material Resources" (Soediono, 2009)

Experiments and Tests

Density/Weight

Equipment: Balance

Sieving

Mechanical tests

Equipment: Tensile and compression benches

Properties to test: Compressive strength

Samples to test: 50x50x50mm cubes

Thermal

– how the material insulates (temperature: -120°C - 20°C)

Radiation – protection against solar irradiation and galactic cosmic rays

Micrometeoroid ballistic test

Equipment: Impact gun

Properties to test: Impact resistance

Samples to test: 50x50x50mm cubes

Permeation tests – penetration of a permeate (gas, liquid, vapor) through a solid.

Other

If possible, the production process could be performed in simulated martian conditions (temperature – low values, pressure – low values, humidity - none).

Autoclave - a pressure chamber used to carry out industrial processes requiring elevated temperature and pressure different from ambient air pressure.