BUILDING ON MARS

AN EVOLVABLE DESIGN STRATEGY FOR THE ARCHITECTURAL ENGINEER

Carlijn van der Werf

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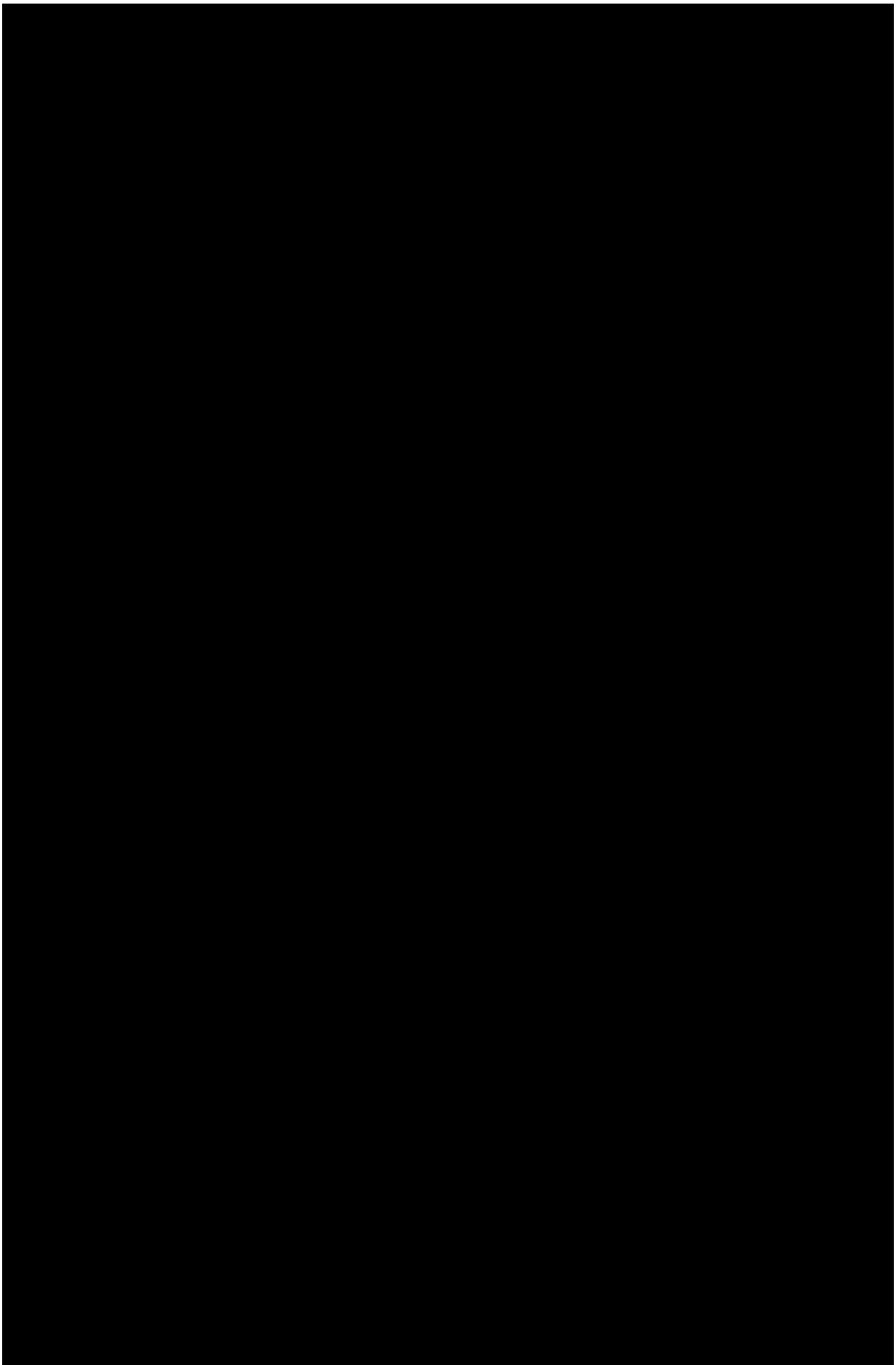


PREFACE

In the past decade, I witnessed the development and increased global awareness for many crises in the world: the financial crisis, the refugee crisis and perhaps the most important of all, the climate crisis. After choosing to take up the challenge on engaging in further specialisation in sustainable design, I decided in 2014 to go for the master track in Building Technology, which focussed on sustainable building development. In the master track a heavy emphasis was put on managing and optimising the use of Earth's resources.

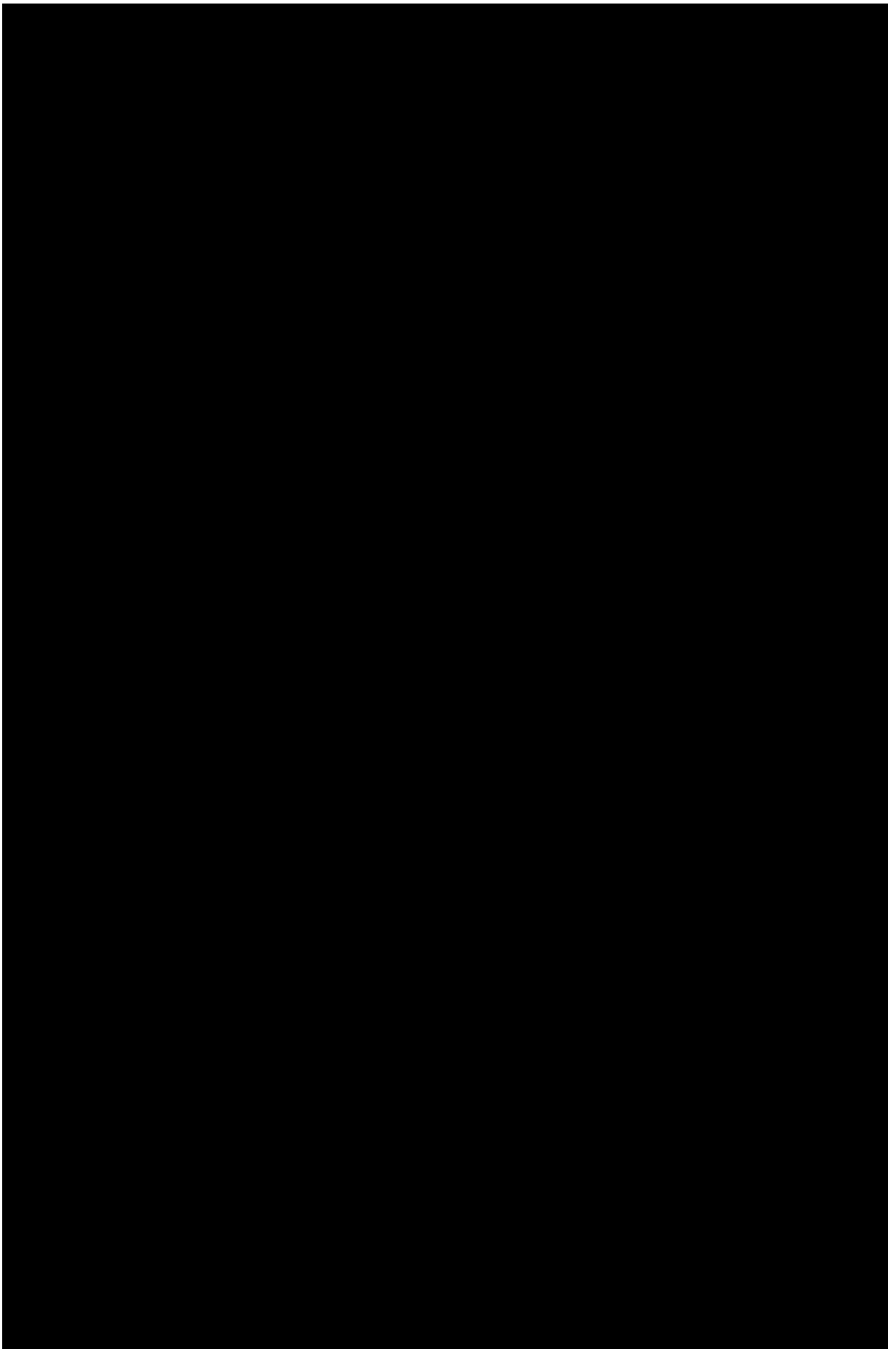
For my graduation research, I decided not to fixate on the problems we've created in the past and present, but to focus on hopeful future solutions and ideas that ignite motivation and excitement. An inspiring vision is likely to result in a more effective and successful journey towards the end goal. I'm convinced that exploration induces innovation and generates new perspectives on these problems. This is why I chose to design for Mars.

First of all, I want to thank Nihat Mert Ogut for his thoughts and ideas on the topic. Also thanks to Ulrich Knaack and Michela Turrin for providing guidance and support, and making it possible to graduate on a topic that was not within the curriculum for Building Technology. And many thanks to Kevin Cowan, who was an important mentor from the aerospace discipline, and with whom I could engage over aerospace developments and always motivated me to pursue.

In addition, I would like to thank Angelo Vermeulen, Layla van Ellen, Tristan Bassingthwaigthe, Sandra Hauplik-Meusburger and Olga Bannova for their incredible support and constructive feedback that brought me new, uplifting perspectives. And last, but certainly not least, I want to thank my friends, family and colleagues for their continuous help and support, with a special thanks to Thomas for always being there for me.

As a final note, I wish to thank Wubbo Ockels, the late dutch astronaut. He was the first to help me in applying my professional background and knowledge in practice by offering me an internship in helping Suze Gehem to establish a new organization, under the name De Groene Grachten. His drive for sustainability, after seeing Earth from space, inspired me to cross the set boundaries and taught me that goals can also be achieved in a less conventional way.

In memory of Wubbo J. Ockels (1946 - 2014)



ABSTRACT

Humans are going to Mars and the plan is to achieve this within the next couple of decades. In the past century many mission architectures have been developed by various space agencies. In all these architectures the habitat is considered a sub-system in the overall mission's system architecture. In current mission engineering, the crew's psychology is barely considered in the design of the mission. In space mission system design, one refers to Human Factors Engineering or Human Systems Integration. NASA did acknowledge the need of designing for habitability. (Connors et al., 1985). However, a method to address or assess this has not been found.

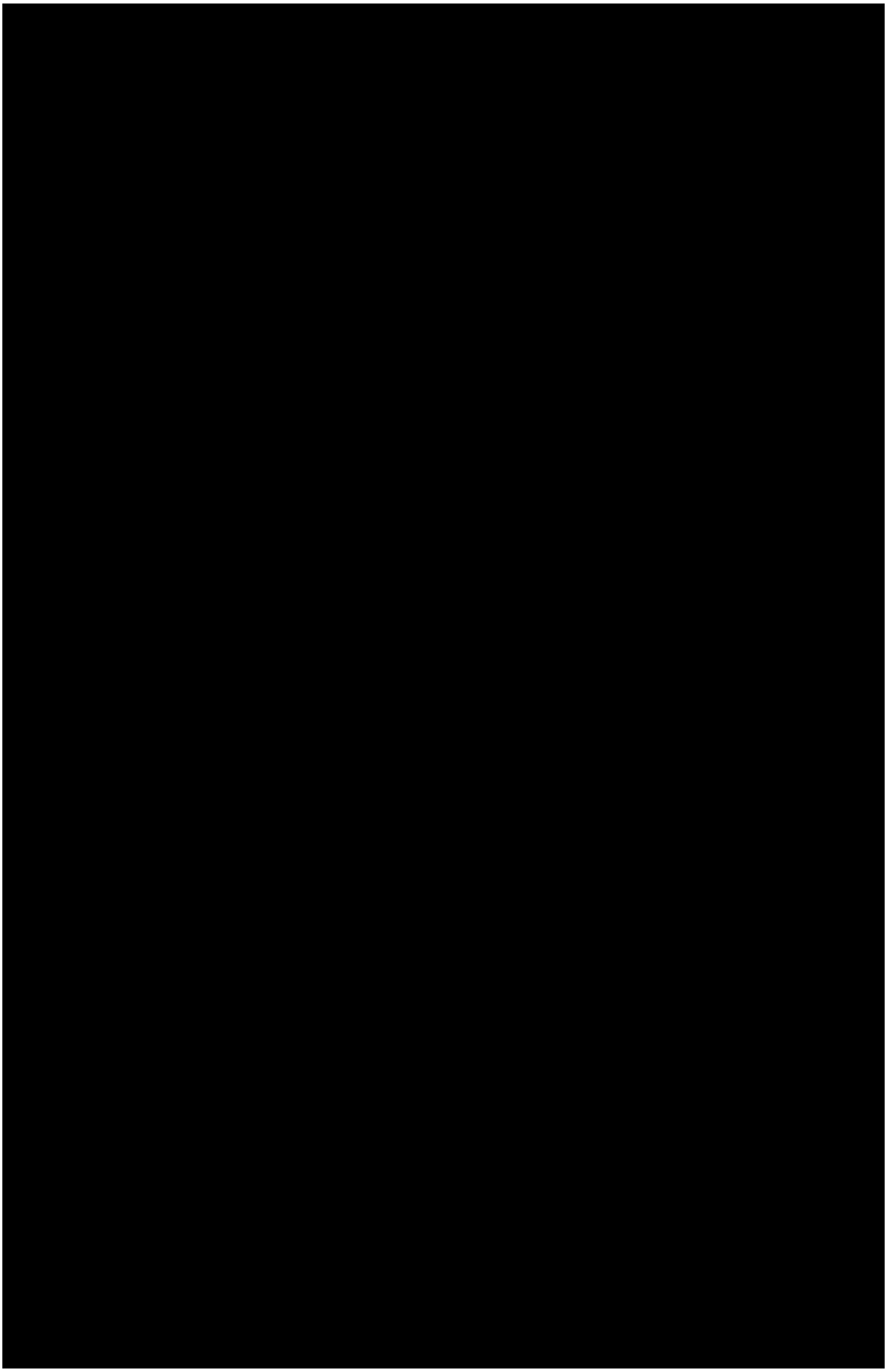
The International Space Exploration and Coordination Group (ISECG) has summarized in their Global Exploration Roadmap (GER, 2013) that the risks concerning Behavioral Health and Performance are still too high for a human exploration mission to Mars. Research in space psychology shows that a long duration isolation mission to Mars will be a next level challenge, as there will be no evacuation or break-out possibility in case of emergency. It is thought that designing for habitability in the architectural design of the habitat is likely to decrease stresses on the crew and will therefore improve the crew's performance.

This research explains that the architect has to synthesize quantitative constraints, concerning the constructability of the habitat as a sub-system, and qualitative requirements, related to the habitability of the architectural program organization, into one integrated design. For extreme circumstances, such as a mission to Mars, it was found that the mission architecture forms the baseline for the design parameters that the architect has to consider. The mission architecture, or concept of operations, will result in several baseline assumptions such as mission objectives, duration, crew characterization, location, logistics and functional activities. Based on these assumptions the criteria for constructability of the surface habitat can be quantified. In addition, the characteristics of the crew and their psychological and physical needs can be defined. These requirements will then form the driving parameters for the space architect's design of the surface habitat.

During habitat development a continuous design iteration will be necessary between the architect and mission engineers as well as space psychology experts. The architect will develop the habitat's configuration of system elements and organization of functional activities. In turn, the other experts will evaluate the proposal based on the constructability and habitability of the habitat system, therefore qualifying the design in terms of its feasibility.

Some preliminary criteria for the design evaluation of the surface habitat have been defined. The criteria related to constructability enhold, but are not limited to, fitting the budgets of mass, power, volume and the schedule as well as having the chosen sub-systems to meet the required Technology Readiness Levels and the building construction to meet the requirements for technical performance based on characteristics of the chosen location. The criteria related to habitability enhold, but are not limited to, meeting the physiological needs and safety measures for psychological well-being, facilitating privacy, engagement opportunities and autonomy in organizing the physical and psychological perception of the environment as well as a creating a positive perception of the enclosed space.

Finally, a design exercise was conducted to test application of the design parameters based on the formulated quantitative constraints and qualitative criteria. The result of the preliminary design revealed insight in the complexity of the design task at hand and the need for a continuous interdisciplinary design iteration between experts from both mission engineering and space psychology. These iterations will be of vital importance in order to come to a final habitat design which will be feasible in terms of constructability and habitability and add to achieving mission success. The defined framework will form a starting point for shaping this design process, thus resulting in an evolvable design strategy.



CONTENTS

ACRONYMS

3DP	3D-printed
A	Area
AU	Astronomical Unit; exact value 149,597,871 kilometers
bar	Unit for atmospheric pressure; equal to 100.000 Pa
BEAM	Bigelow Expandable Activity Module
C_D	Drag coefficient
CL	Cargo Lander
DRA 5.0	Design Reference Architecture 5.0
ECLSS/ ECLiSS	Environmental Control and Life Support System
EDL	Entry Descent and Landing
EMC	Evolvable Mars Campaign
ESA	European Space Agency
EUE	Extreme and Unusual Environments
EVA	Extra Vehicular Activity
EZ	Exploration Zone
FPU	Fission Power Unit
G	Gravitational force; 9,81 m/s^2
GCR	Galactic Cosmic Rays
gray	Unit for radiation
HAB	Habitat
HI-SEAS	Hawaiian Institute for Space Exploration Analog and Simulation
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HIDH	Human Integration Design Handbook (NASA)
HLS2	Human Landingsite Selection workshop 2
HRL	Habitation Readiness Level (Appendix B)
ICE	Isolated and Confined Environments
IMLEO	Injected Mass into Low Earth Orbit
ISECG	International Space Exploration and Coordination Group
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JPL	Jet Propulsion Laboratory (NASA)
JTM	Journey To Mars report (NASA)
LEO	Low Earth Orbit
LOX	Liquid Oxigen fuel
m	Mass
M-SIS	Man Systems Integration Standard (NASA)
MAV	Mars Ascent Vehicle
MCD	Mars Climate Database
MER	Mars Exploration Rover(s)
MMOD	Micro-Meteoroid and Orbital Debris

MSL	Mars Science Laboratory
mSv	milliSievert (see Sv)
mt	metric tonnes; 1000 kg
MTV	Mars Transfer Vehicle
N	Newton; equals m/s^2
NASA	National Aeronautics and Space Administration
p	pressure
Pa	Pascal; unit to measure pressure, equals N/m^2
ROI	Region Of Interest
S-HAB	Surface Habitat
SEP	Solar Electric Propulsion
SEV	Space Exploration Vehicle
SICSA	Sasakawa International Center for Space Architecture
SLS	Space Launch System
SMAD	Space Mission Analysis and Design
sol	a martian day; equals roughly 24 hours and 38 minutes on Earth
SPE	Solar Particle Event
Sv	Sievert; unit to measure radiation levels with a safety factor related to the human physiology included
T	temperature
TEI	Trans Earth Injection; stage during a mission where a vehicle is inserted on a direct transfer trajectory from Mars to Earth
TMI	Trans Mars Injection; stage during a mission where a vehicle is inserted on a direct transfer trajectory from Earth to Mars
TRL	Technology Readiness Level (See Appendix B)
β	ballistic coefficient
ΔV	delta velocity

01

INTRODUCTION

In 1492, roughly 500 years ago, Columbus came to the New World.
In 1911, roughly 100 years ago, Roald Amundsen reached the South Pole.
In 1969, roughly 50 years ago, the first man landed on the moon.

So when are humans going to Mars?

After more than half a century of Mars' exploration with orbiters, landers and rovers, the urge has risen to bring humans. A manned mission to Mars will be an expensive international entreprise with many involved stakeholders and interests. It is important to understand why exactly humans should land on Mars and how they plan on getting there.

This chapter will give a brief introduction on the scope and problems that rise from the perspective of habitat design development for a human mission to Mars. In the second and third paragraph the objective, approach and structure of the research will be defined.

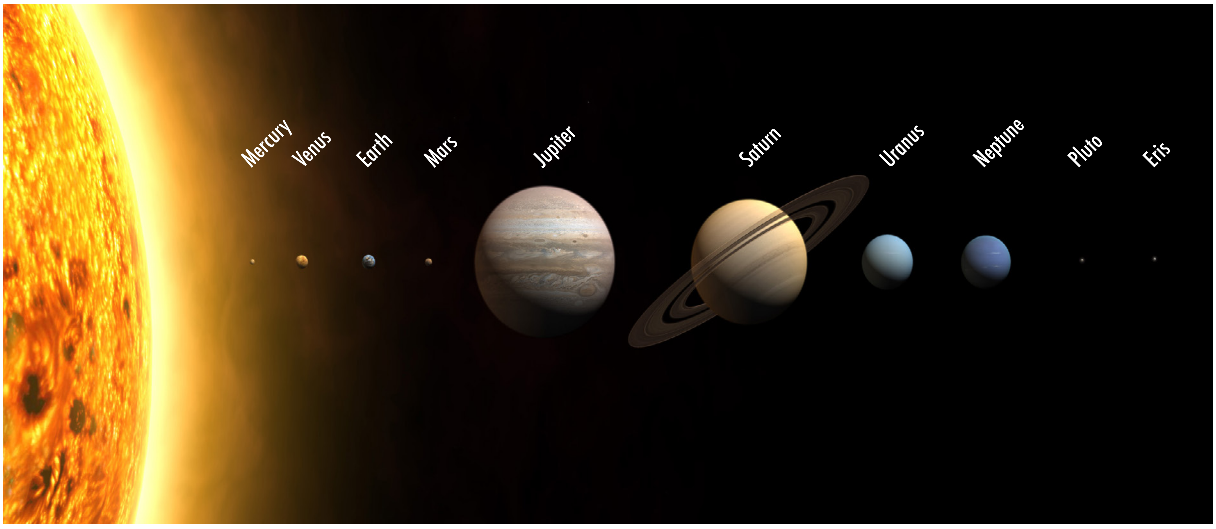


Figure 1.1.1. : The Solar System

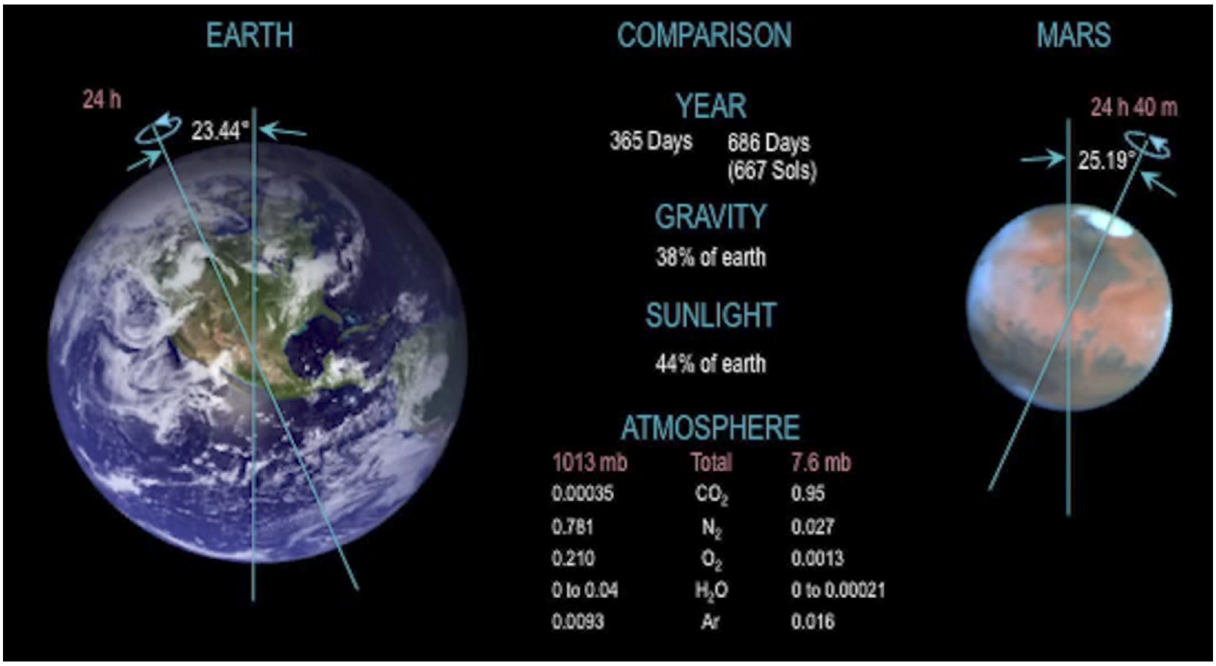


Figure 1.1.2. : Comparison of Earth and Mars

1.1 DESTINATION MARS

1.1.1. WHY GO TO MARS?

From various perspectives, various arguments can be formulated to design a human mission to Mars. Zubrin (2015) summarizes three major comprehensive reasons to go to Mars: for the science, the challenge and the future. The science on Mars will tell us more about our understanding of Life in our universe. Mars is considered the sister planet of Earth within our solar system. It is the only other planet that falls in the habitable zone around our sun. Science on the martian surface has proven that there used to be an enormous amount of liquid water on the surface for at least one billion years, which is about five times the amount of time that was needed for life to develop on Earth. Research can proof if our basic scientific assumptions about life in our universe adds up or if this should be altered. (Zubrin, 2015)

The challenge is thought to be of an unquantifiable value. When Apollo reached the Moon, there was a brief moment where mankind thought anything could be possible. Reaching beyond Earth is what unites societies and especially, motivates the youth across the planet. The intellectual capital that will grow from this entreprise is thought “to dwarf” the cost of the mission itself. It serves an inspiring goal in this time of many global crises. (Zubrin, 2015)

The final reason, for our future, relates to how we want to be remembered through history. This is what drives many leaders. An example is Elon Musk, who is working on an optimistic future and on making humankind a multiplanetary species. We want to be remembered by what we did for the advancement of our future civilization. (Zubrin, 2015)

Exploration pushes to go beyond the boundaries of our knowledge and therefore induces technological innovation on it’s way. Research that followed from exploration of the South Pole has taught us many great things. An important finding is data on the scarcity and value of the circumstances on planet Earth, resulting in the discovery and definition of Climate Change.

1.1.2. CURRENT PLANS

In a global effort for faster advancement in Space Exploration the ISECG published the Global Exploration Roadmap (GER) in 2013. The ISECG Mission Scenario, presented in the GER, defines a clear stepwise evolution of human exploration capabilities to advance human exploration of the Moon and a near-Earth asteroid, with Mars as the ultimate goal. The approach is based on activities that the involved space agencies are already undertaking or have planned to undertake. The major reason that a human mission to Mars is continuously postponed is because the known risks are still too high. (ISECG, 2013)

In spring 2015, the Planetary Society held a workshop in Washington D.C. that evaluated the current efforts and strategies towards a manned mission to Mars. The result of the conference was summarised in the report “Humans Orbiting Mars” (Hubbard et al., 2015). The conclusion of the workshop was that NASA would have to remain leading in their role in deploying a suitable strategy in collaboration with other space agencies, industries and governmental or non-governmental organizations.

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 1.1.1. : Comparison of mission aspects and design considerations for different mission durations and destinations. (Hauplik-Meusburger et al., 2016)

To achieve this, NASA published their Journey to Mars strategy (JTM) under the name the Evolvable Mars Campagn (EMC) in October 2015. The document sets out their intended strategy, with room for developmental changes. One of the formulated decisions in the JTM is that NASA's has intended to define the intial deep-space habitation capabilities and to design Mars surface habitats. (NASA, 2015)

Selected Critical Time Frames and Decisions		
DECISIONS MADE & IMPLEMENTATION UNDERWAY	DECISIONS FOR THE NEXT FEW YEARS, IN WORK NOW	DECISIONS UNDER STUDY NOW TO BE MADE IN THE NEXT DECADE
• Extend ISS operations to at least 2024 • Pursue an evolvable SLS via Exploration Upper Stage before advanced solid rocket boosters • Select an ARM baseline mission to return an asteroidal boulder to lunar orbit for subsequent crew rendezvous • Predeploy cargo and infrastructure through split missions	• Develop an exploration EVA suit for use on Orion missions • Define initial deep-space habitation capability • Select in-space transportation systems • Identify future Mars robotic precursor missions beyond Mars 2020 • Further define potential future exploration missions in cislunar space	• Select initial human missions beyond the Proving Ground • Identify the role of ISRU in the overall logistics strategy • Design Mars surface habitats • Develop Mars surface power generation

Tabel 1.1.2. : Selected Critical Time Frames and Decision (NASA, 2015)

1.1.3. SURFACE HABITAT DESIGN

To start with designing habitats for Mars a 3D-printed habitat design challenge was organised in 2015 by NASA in collaboration with Berkeley University and America Makes (3DP hab, 2015). The competition led to some initial concept designs for martian surface habitats. Several lessons can be drawn from the designs, but still the question rises whether these designs will meet all the necessary requirements. As long as there is no clear mission defined it is hard to define the leading parameters for the brief.

This is where Space Architecture comes in. The Space Architect is positioned between the architect and the engineer, trained to balance qualitative and quantitative requirements for space design. (Hauplik-Meusburger et al., 2016) Space architecture is concerned with designing habitability for missions to orbit, Moon, Mars and beyond.

Yet, it is a relatively new discipline officially developed as an education in 2003 (Duerk, 2004). Due to it's recent establishment, it is not widely known to be a certified profession. Space Architecture is currently taught at ten universities around the world. (Hauplik-Meusburger et al., 2016) Clear manuals on Space Archicture barely exist. A profound knowledge of both architectural design and space mission design is required. (Bannova et al., 2011)

MAIN RESEARCH QUESTION:

What aspects are to be considered when developing a habitat for the first human settlement on Mars?

Several sub-questions:

What are the conditions on Mars?
- what are the differences compared to Earth?
- what are major issues concerning habitat design?

What will the mission look like?
- what will be the mission objective?
- what is the schedule?
- what are logistical constraints to consider?

What team will go and what will they need?
- what is the crew size?
- what are the psychological needs?
- what architectural means can be applied in addressing these needs?

What habitat will they need and how should it be build?
- what is the brief for programmatic functions?
- what is the site?
- what does the habitat system look like?

1.2 RESEARCH AND OBJECTIVE

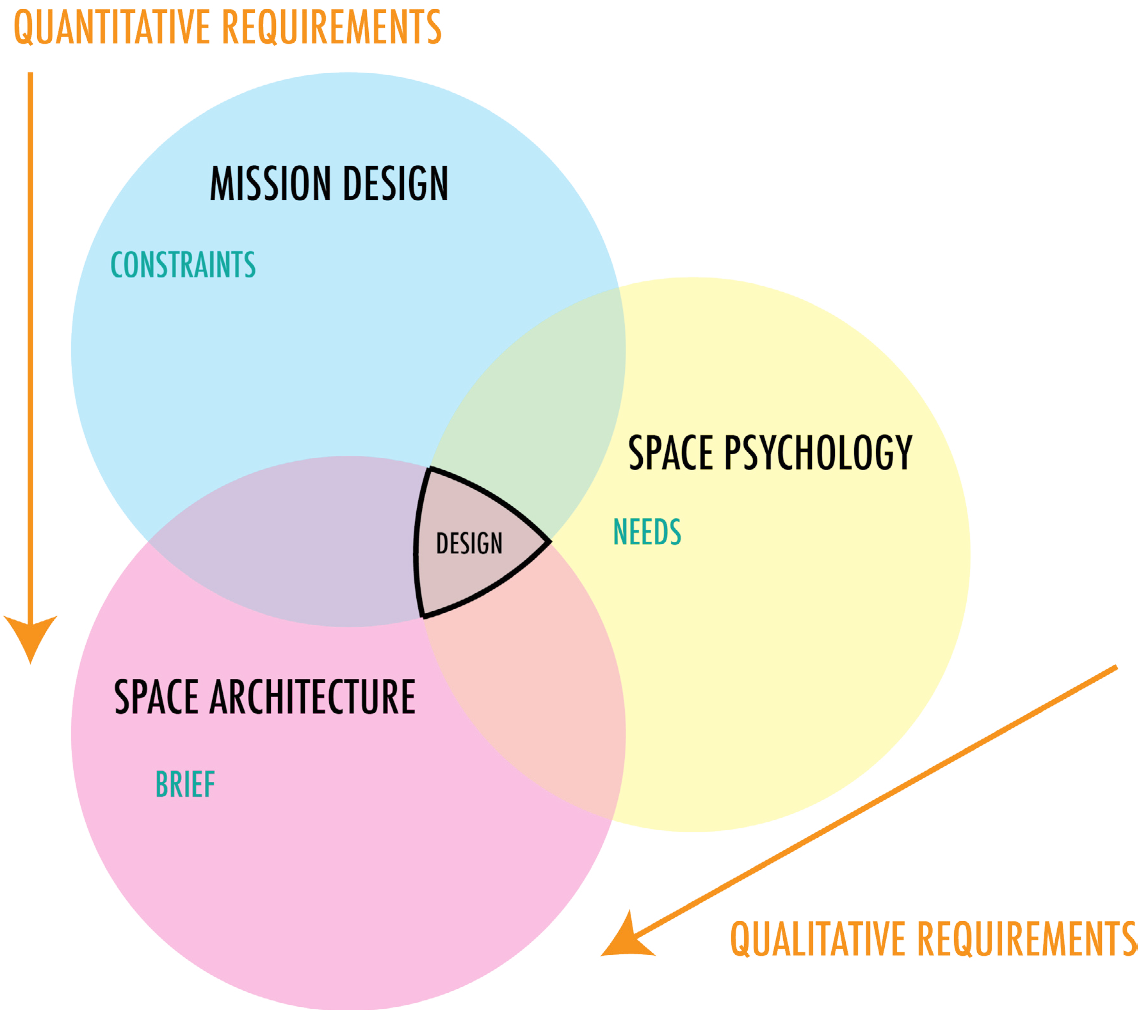
1.2.1. RELEVANCE

Space is a hostile and inhabitable environment and doesn't have a forgiving nature. A space exploration mission calls for extremely rigourous planning, with many built-in failure-safety scenarios in order to achieve mission success. Designing for space enforces an efficient, effective and flexible approach for product development. Past exploration missions have led to radical technical innovations beneficial for earth application, such as development of the solar panel. Research in the field of extreme, deep-space architecture, can advance innovative development for new building systems, advancing current knowledge about Building Technology and Architectural Engineering.

1.2.2. OBJECTIVE

The objective of this research is to come up with a strategy to develop a habitat for Mars. The architectural engineer is trained in balancing quantity and quality to serve the design goal. In order to check if the suggested approach works, it ought to be tested with a design. The desired outcome is to develop a list of requirements for martian architecture and highlighted problem areas in the habitat system. These challenges can stimulate further research in the field of Building Technology, with the ultimate goal of a faster advancement in martian surface habitat development and mission succes.

To narrow the domain of research, several boundaries and assumptions are defined. The focus is put on developing a suitable habitat for the first human settlement on Mars. Planning for this mission assumes immediate development and application of state of the art technologies. Future technological developments are likely to have a major impact on the design outcome. These alterations have to be taken into account for future value of the research outcome.


QUANTITATIVE REQUIREMENTS
MISSION DESIGN
CONSTRAINTS
SPACE PSYCHOLOGY
NEEDS
DESIGN
SPACE ARCHITECTURE
BRIEF
QUALITATIVE REQUIREMENTS

1.3 METHODOLOGY

1.3.1. APPROACH

Before starting with research into mission design and space architecture, the conditions and characteristics of Mars will be studied and explained. The first chapter of the thesis, will form a brief introduction to Planet Mars.

In order to come up with a realisation strategy for a martian surface habitat, it is necessary to define the mission context as a baseline. Understanding the keydrivers and decision parameters in Mission Design for a manned mission to Mars, is critical in habitat development as the technical constraints form an integral part of the mission's system architecture.

Apart from these technical constraints, the qualitative needs for the crew are to be identified as important architectural design parameters. Space Psychology plays a leading role. Research in this field has generated leading insights in the crew's composition and psychological processes that occur during a mission.

In addition, a lot can be learned from former Space Architecture research and the designs. Findings from design analysis, will contribute to building a comprehensive brief as a baseline for the assignment. The brief will serve as a checklist in the first stages of development to check to what extend the habitat intends to add value and to identify points for improvement.

The outcome of this research will be a strategy to approach a problem of this size in these extreme circumstances where the stakes are high. Also a design will be developed intended to get a first grasp on the size of the challenge in meeting the formulated list of requirements. The list can serve as a starting point for defining the parameters in the equation to guarantee mission success. These parameters can then be updated according to developments in other areas of the mission's system architecture.

Information is gathered based on literature research and interviews with various experts. The chapter on Mission Design has been peer reviewed by Kevin Cowan, professor in Space Systems Engineering at the faculty of Aerospace Engineering from Delft University of Technology. Peers from the field of Space Architecture are Tristan Bassingthwaighte, Olga Bannova and Sandra Hauplik-Meusburger. (See Appendix A)

1.3.2. THESIS STRUCTURE

The research is set up according to three leading disciplines: Mission Design, Space Psychology and Space Architecture. The history, progress and most recent findings will be explained and evaluated. Findings from this research will add up to a conceptual brief that enholds, but is not limited to, some first basic requirements. As a result, overlapping design drivers for a human mission to Mars will be identified and used for the baseline habitat's system architecture. A sketch design will be made and weighed against the criteria. Conclusions are drawn in the final chapter, followed by recommendations for future research.

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02

PLANET MARS

Mars is the fourth planet from the Sun and the second smallest planet in the Solar System. Named after the Roman god of war, it is often described as the “Red Planet”. The iron oxide prevalent on its surface gives it a reddish appearance.

Many similarities can be found between Earth and Mars. However, Mars does offer very different climatic conditions. This chapter will give a brief overview about Mars as a planet and the local conditions relevant for human habitat design. First, Mars as a planet within our solar system will be discussed. This will be followed by an elaboration on current findings of the known conditions on the martian surface.

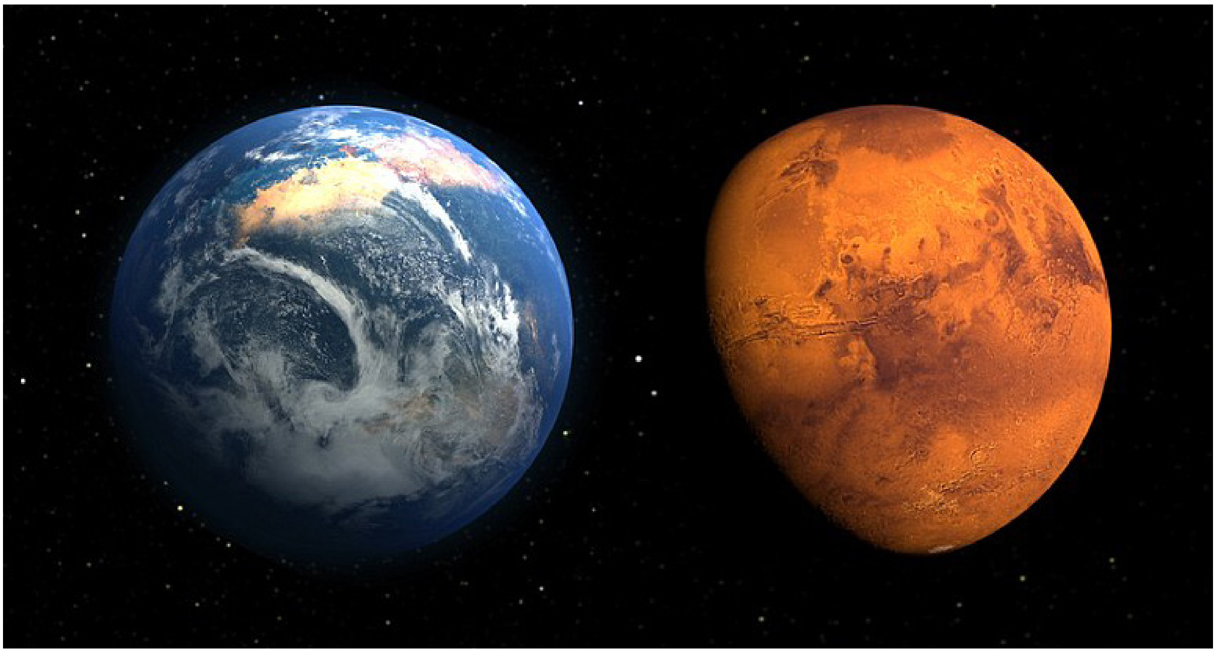


Figure 2.1.1 : The sister planets Earth and Mars

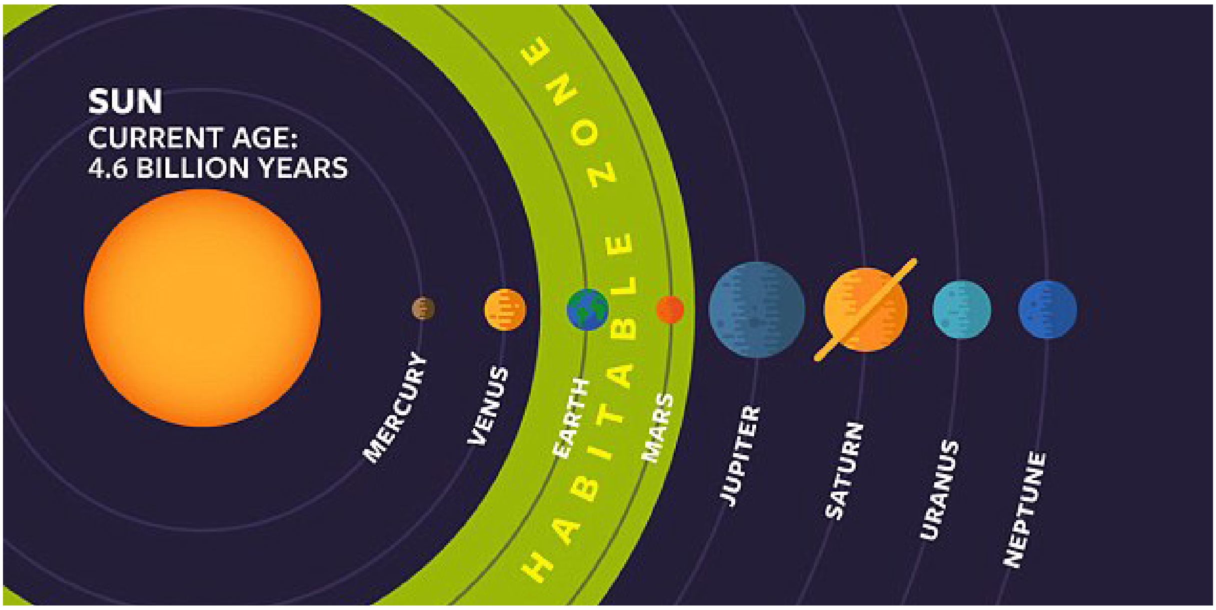


Figure 2.1.2 : Earth and Mars fall in the habitable zone around the sun (Cornell University, 2017)

2.1 PLANET

2.1.1. A SISTER PLANET

Mars is a terrestrial planet with a thin atmosphere, having surface features reminiscent both of the impact craters of the Moon and the volcanoes, valleys, deserts, and polar ice caps of Earth. The rotational period and seasonal cycles of Mars are likewise similar to those of Earth, as is the tilt, which results in seasons. Mars is the site of Olympus Mons, the second highest known mountain within the Solar System (the tallest on a planet), and of Valles Marineris, one of the largest canyons. The smooth Borealis basin in the northern hemisphere covers 40% of the planet and may be a giant impact feature. Mars has two known moons, Phobos and Deimos, which are small and irregularly shaped.

2.1.2. DISTANCES

Mars can easily be seen from Earth with the naked eye, as can its reddish coloring. Its apparent magnitude reaches –3.0, which is surpassed only by Jupiter, Venus, the Moon, and the Sun. Optical ground-based telescopes are typically limited to resolving features about 300 km across, when Earth and Mars are closest, because of Earth’s atmosphere.
Due to the different orbits, the distances between both planets vary. Every 26 months, the planets are closest and a launch window opens for spacecrafts to travel there on the shortest possible trajectory. Travel trajectories are important to consider, as they require energy mass that has to be carried into space.

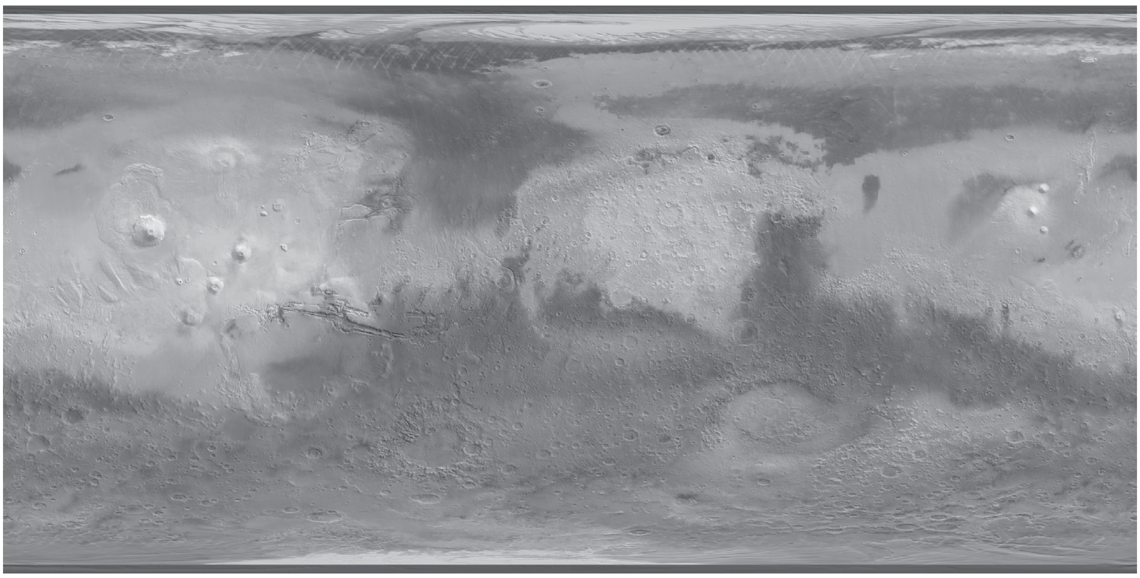


Figure 2.1.3 : Map of Mars showing the albedos (contrasts) on the surface

	Mars	Earth	Venus
Mass (10^{24} kg)	0.64185	5.9736	4.8675
Volume (10^{10} km^3)	16.318	108.321	92.843
Equatorial radius (km)	3,396.2	6,378.1	6,051.8
Polar radius (km)	3,376.2	6,356.8	6,051.8
Ellipticity (flattening)	0.00648	0.00335	0
Topographic range (km)	30	20	15
Mean density (kg/m^3)	3,933	5,515	5,243
Surface gravity (m/s^2)	3.71	9.81	8.87
Surface acceleration (m/s^2)	3.69	9.78	8.87
Escape velocity (km/s)	5.03	11.19	10.36
Solar irradiance (W/m^2)	589.2	1367.6	2613.9
Orbit semimajor axis (10^6 km)	227.92	149.60	108.208
Sidereal orbital period (days)	686.980	365.256	224.701
Perihelion (10^6 km)	206.62	147.09	107.477
Aphelion (10^6 km)	249.23	152.10	108.939
Synodic period (days)	779.94	—	583.92
Mean orbital velocity (km/s)	24.13	29.78	35.02
Max. orbital velocity (km/s)	26.50	30.29	35.26
Min. orbital velocity (km/s)	21.97	29.29	34.79
Orbit inclination (°)	1.850	0.000	3.39
Long, of ascending node (°)	49.579	—	76.678
Orbit eccentricity	0.0935	0.0167	0.0067
Longitude of perihelion (°)	336.04	114.27	55.186
Sidereal rotation period (hrs)	24.6229	23.9345	−5,832.60
Length of day (hrs)	24.6597	24.0000	2,802
Obliquity (°)	25.19	23.45	177.36
Min. dist. from Earth (10^6 km/light minutes)	55.73/3.1	—	38.2/2.12
Max. dist. from Earth (10^6 km/light minutes)	401.322/22.3	—	261.0/14.5

Table 2.1.1 : The main features of Mars compared to those of Earth and Venus. (Genta, 2017)

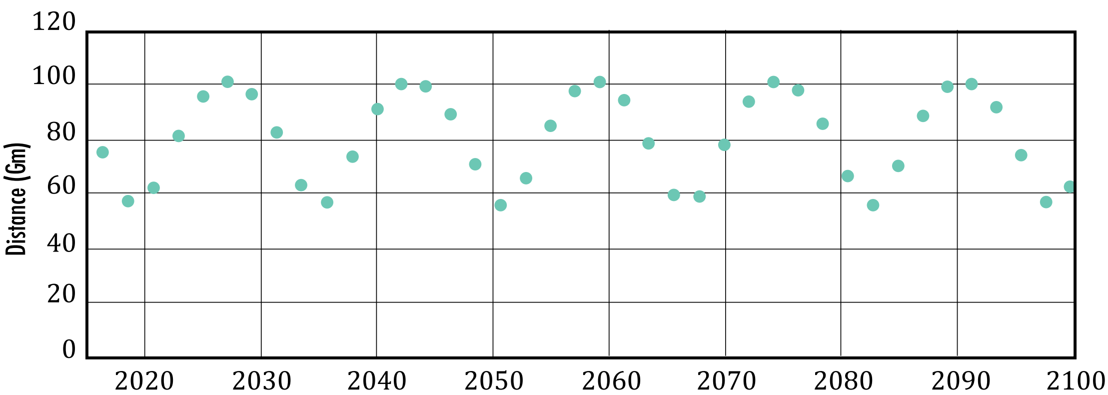
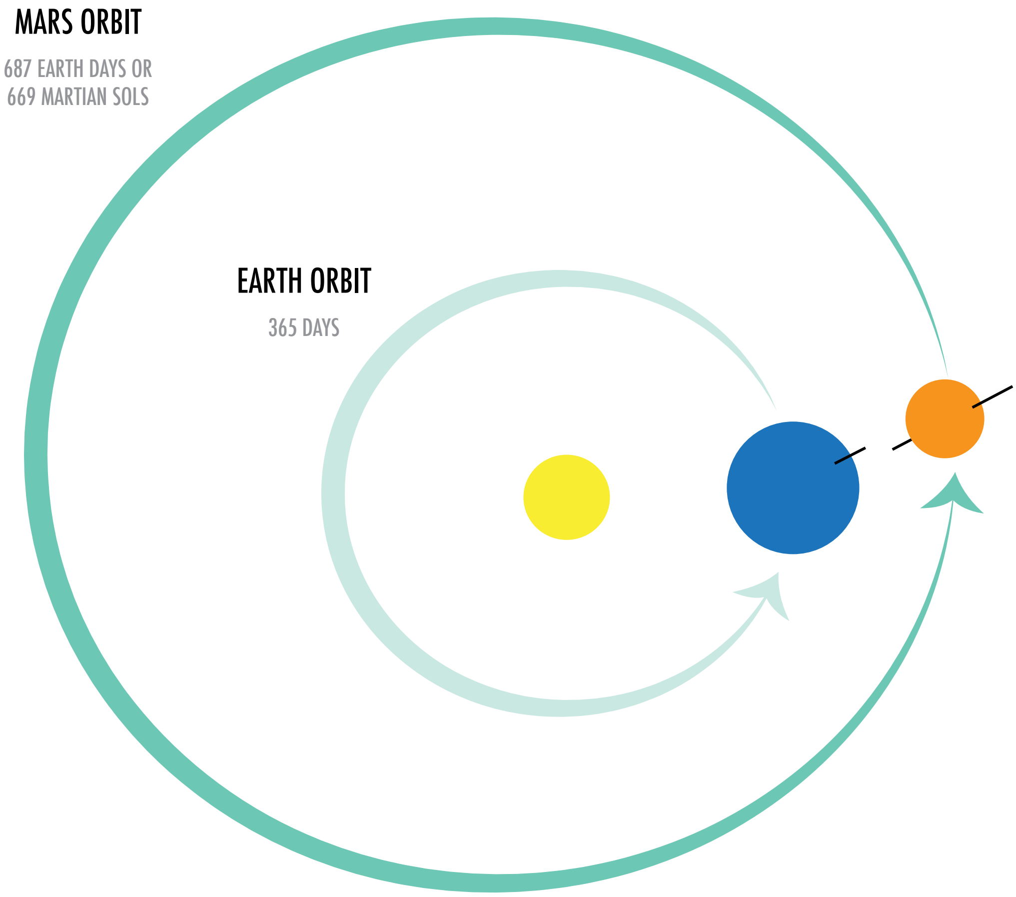


Figure 2.1.4 : Distances between Earth and Mars, expressed in Gigameters (Genta, 2017)



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

Table 2.1.2. : Distances between Earth and Mars (Genta, 2017)

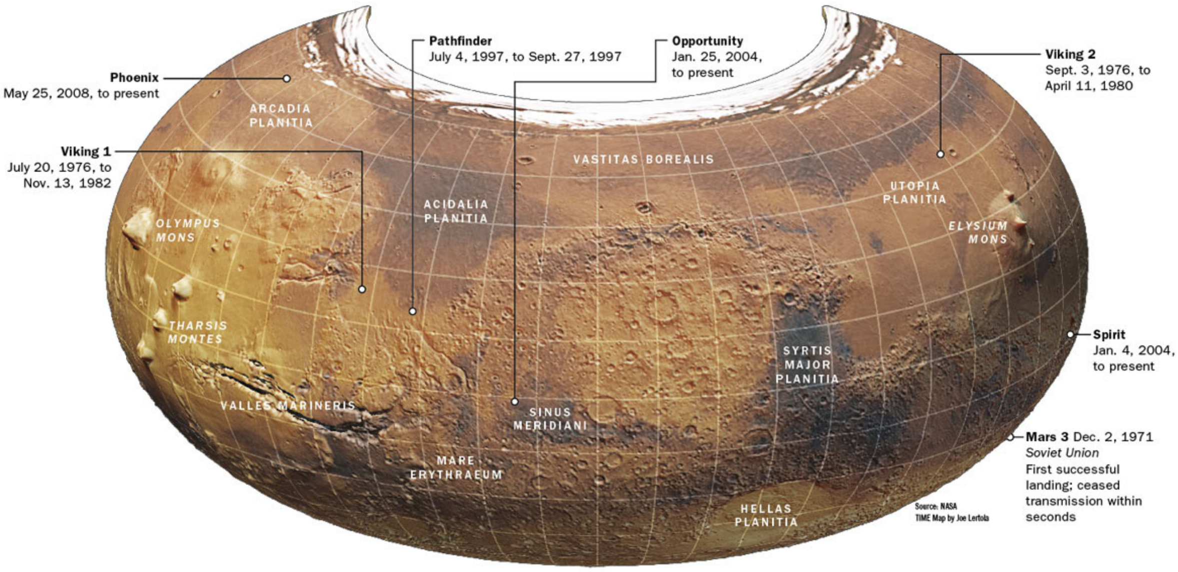


Figure 2.2.1 : Planet Mars with indicated locations of past landed missions (Courtesy of NASA)

Figure 2.2.2 : The martian surface, photographed by the Mars Pathfinder in 1997. The Sojourner, in the right half of the image, was the first robotic rover on Mars. (Courtesy of NASA)

2.2 SURFACE CONDITIONS

2.2.1. PAST MISSIONS

Mars is currently host to five functioning spacecraft: three in orbit – the Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter; and two on the surface – Mars Exploration Rover (MER-B) Opportunity and the Mars Science Laboratory Curiosity. Defunct spacecraft on the surface include MER-A Spirit and several other inert landers and rovers such as the Phoenix lander, which completed its mission in 2008. Observations by the Mars Reconnaissance Orbiter have revealed possible flowing water during the warmest months on Mars. Many missions have failed, but the rate of succes is definitely increasing.

2.2.2. MAGNETIC FIELDS

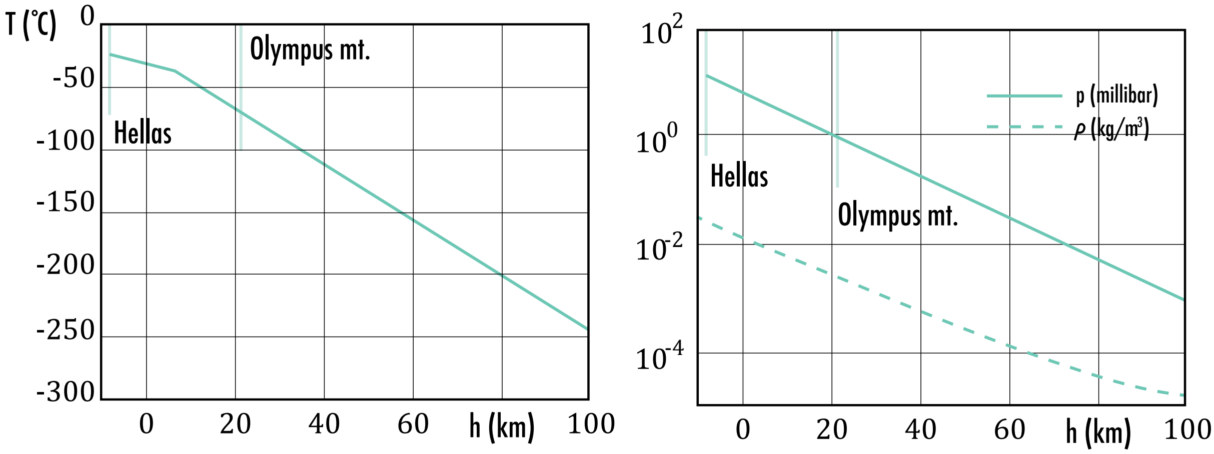
Mars lost its planetary magnetic field about 4 billion years ago, so there is almost no magnetosphere. As a result, the atmosphere offers very little protection from the ultraviolet portion of sunlight, and only limited protection from cosmic rays. Heavy Galactic Cosmic Rays (GCR) particles impinging on the iron oxide in the Martian rocks release high energy alpha particles that are not stopped by the thin atmosphere. Hence from the point of view of radiation, even though the atmosphere scatters light and the environment looks more like Earth than the Moon, Mars is only a slightly better place to be than the Moon. Radiation levels at the surface would be somewhat lower than in space, and might vary significantly at different locations depending on altitude and local magnetic fields.

2.2.3. ATMOSPHERE

The Martian atmosphere is very thin. The surface pressure is less than 1 percent of that at sealevel on Earth (it roughly equals atmospheric pressure on Earth at an altitude of 35km) and varies significantly with altitude and latitude, ranging from a minimum of about 0.3 millibar on Olympus Mons to over 11.6 millibars in the depths of Hellas Planitia. The mean surface pressure is 6.36 millibars and varies with seasons from 4.0 to 8.7 millibars (Earth is 1000millibar or 1 bar). The density of the atmosphere is also strongly affected by the temperature. Its average value on the ground is about 0.020 kg/m3. This variability poses a challenge in planning the entry of a probe into the atmosphere.

Table A and B on the right, give an approximation of temperature and pressure as functions of altitude, relative to the arbitrary zero referred to above. These values, which are just averages in time and space, have been obtained from the mathematical model supplied by NASA. The model is questionable since the bi-linear dependence of temperature would be lower than absolute zero at a certain given altitude.

The composition by volume of the atmosphere is reported in the table below. Although it is present only in trace amounts, methane is concentrated in several places during the northern summer. Since methane is broken down by ultraviolet radiation, for it to be present at all there must be a mechanism which produces it. Possible explanations include volcanism, cometary impacts, and the presence of methanogenic microbial life. The mean molecular weight of the atmosphere is 43.34 g/mole.


T (°C)
0
-50
-100
-150
-200
-250
-300
Olympus mt.
Hellas
0
20
40
60
h (km)
100
10^2
10^0
10^{-2}
10^{-4}
p (millibar)
ρ (kg/m³)
Hellas
Olympus mt.
0
20
40
60
h (km)
100

2.2.4. WIND

The fine dust in the atmosphere gives the sky a tawny color when viewed from the ground. The two Viking landers of 1976 reported wind speeds of 2-7 m/s in the summer, 5-10 m/s in the autumn, and occasionally gusts of 17-30 m/s during dust storms. Although the wind speeds are high, the aerodynamic forces are weak due to the low atmospheric density. Vehicles and structures on the surface will not be mechanically stressed by even the strongest winds.

2.2.5. TEMPERATURES

The average temperature on the surface is -63 'C but there are pronounced diurnal and annual variations. At the Viking 1 site variations occurred in the range of -89C and -31C during a sol. Larger variations were recorded over a Martian year, ranging from -120C to -14C. Summer temperatures as high as 20-30C above freezing have been recorded in the southern hemisphere.

2.2.6. DUST

Winds carry large amounts of dust that is rich in iron oxide, with particles even smaller than about 1.5 micrometer diameter; even finer than the lunar dust. The very fine dust will pose a danger to machinery and human beings, so provisions to prevent it from entering any part of a habitat must be taken.

The experience of the Apollo missions showed that measures must be taken to prevent lunar dust from being breathed in, but Mars dust is potentially even more dangerous. Like lunar dust, it was produced by aeons of rock-shattering meteorite impacts, but Mars has an atmosphere and the resulting weathering processes have smoothed the dust grains, making them less sharp than those of lunar dust. However, one thing the grains have in common is that they will likely carry sufficient static electrical charge to stick to space suits, habitats, and vehicles. It will therefore be essential to remove dust from space suits in order to deny its entry to habitable spaces where it could block ari filters and contaminate food. This discipline will be particularly strict during long stays on the planet.

The average composition of Mars' atmosphere.

Gas	%
Carbon dioxide	95.97
Argon	1.93
Nitrogen	1.89
Oxygen	0.146
Carbon monoxide	0.0557

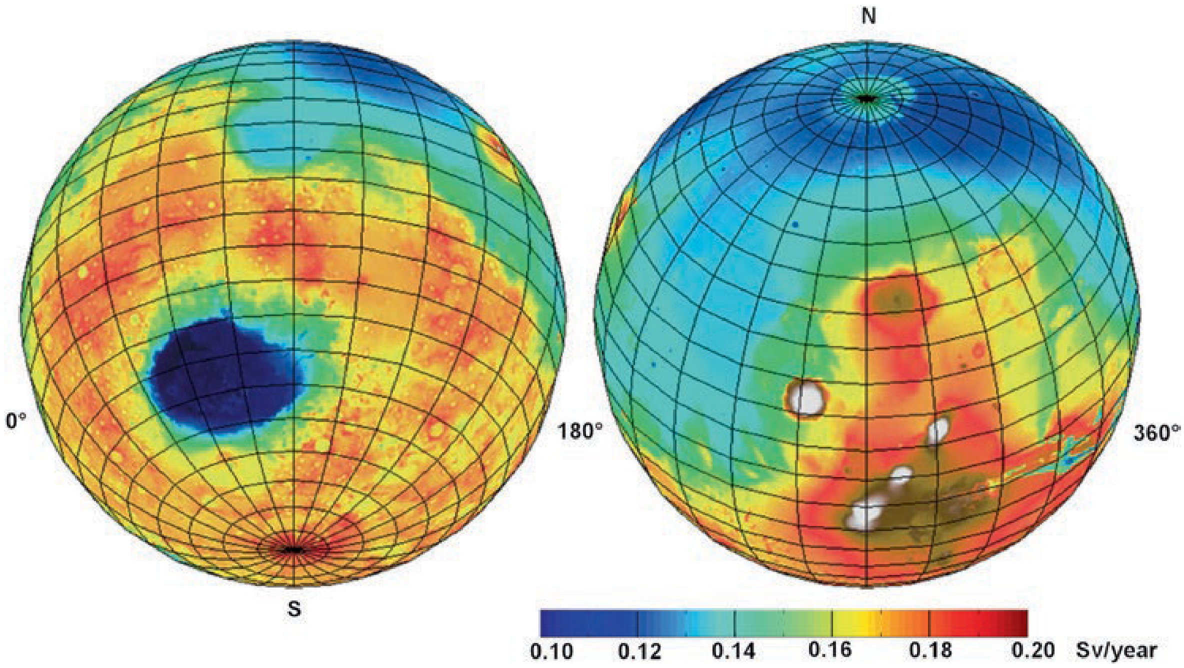
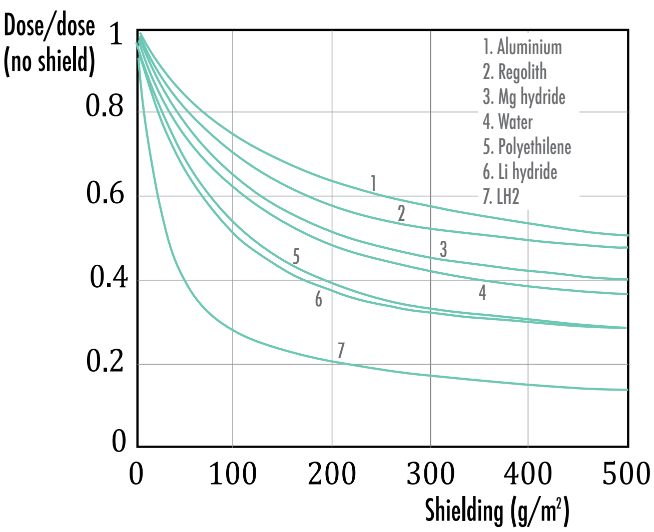
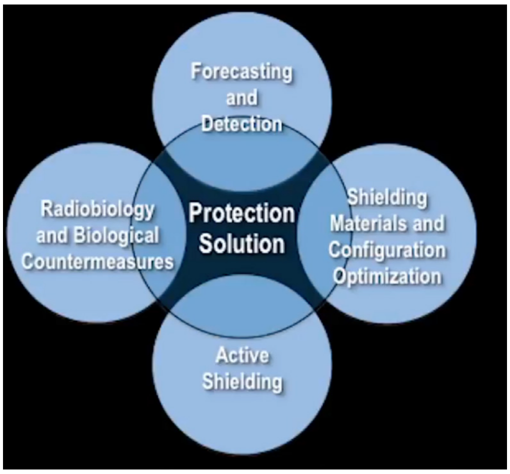


Figure 4.6 Effective radiation dose rate (in Sv/year) on the Mars surface. Map obtained from cosmic radiation data by the Mars radiation environment experiment (MARIE), on board NASA's Mars 2001 Odyssey spacecraft. The surface radiation was obtained using Mars altimetry data from the MOLA instrument aboard Mars Global Surveyor. (NASA/JPL/JSC image)





2.3 RADIATION AND SHIELDING

2.3.1. SPACE RADIATION

In space travel radiation is a one of the major hazards for human health. Three different kinds of radiation occur in space travel. First, when humans leave Earth, they will have to travel through radiation that's captured in the Von Allen belt. However, this radiation is not directly relevant for surface habitat design. The other two types of space radiation both occur on the martian surface. These are Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE). GCR is always present in space and comes from exploding stars from anywhere in the galaxy. SPE occurs from explotions on the sun, also known as solar storms. Research has found that GCR levels are lower when SPE's occur and vice versa. (Durante, 2011)

2.3.2. DESIGNING FOR RADIATION

There are several strategies to protect astronauts against high radiation doses. Four protection solutions are defined: Radiobiology and Biological Countermeasures; Forecasting and Detection; Shielding Materials and Configuration Optimization and Active Shielding. The last one is a relatively new solution. A technology for active shielding is to create a magnetic shield, which requires a lot of energy. The first two fall under the primary responsibility of the mission command and ground control centre. Communications and datahandling during the mission is therefore key.

Passive screening is a common measure and is quite effective for many Earth applications. In many Earth applications ionizing radiations are electromagnetic (e.g. x rays and gamma rays) and the best screening is supplied by heavy metals such as lead or tungsten. A completely different situation is posed by particle radiations like GCR or SPE. In this case screening is best achieved using light elements. Hydrogen is the best. Next best are materials that contain a large amount of hydrogen, for example hydrogenated polyethylene or water or, even if it is less efficient, magnesium hybride. Some boron compounds, materials containing silicon (such as regolith) or, amongst the metals, magnesium or aluminum are also good. However, passive shielding againts particles has an intrinsic problem, in that the particles of GCR or SPE will strike the atoms within the shield and produce secondary particles (or in general secondary radiation) that may be as dangerous, or possibly even more dangerous than the original radiation. Hence a fairly thick shield will be required in order to stop both primary and secondary radiation.

The decrease of the absorbed dose as a function of the thickness of the shield is plotted in the graph on the right for different shield materials. The thickness is expressed in terms of mass per unit area, expressed in kg/m2. By dividing this value with the density of the material in kg/m3 the shield thickness in meters is directly obtained.

The habitat should at any rate be protected by regolith, either because it is built inside a cave or lava tube, because regolith is spread on top of the structure, or because it is built from regolith. Regolith is worse than hydrogenated material (see Fig. 4.3b) but is abundant and increasing the mass of the habitat is not a major issue. The lower gravity will reduce the structural load placed on a habitat compared to a similar structure on Earth. About 1.5m of regolith will be needed to reduce the radiation level inside the habitat to below 50mSv per year in the worst conditions.

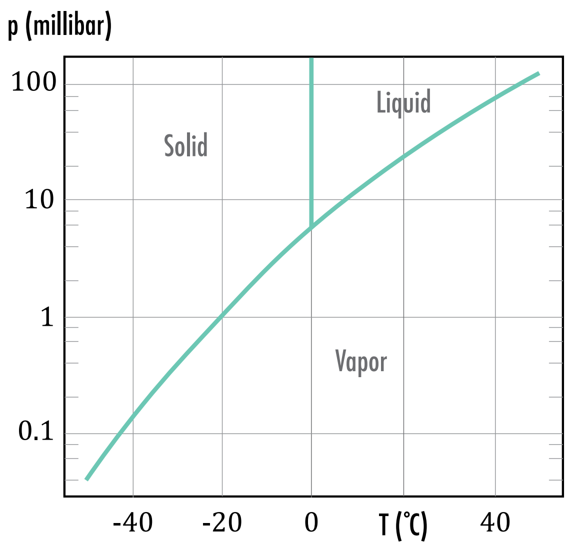
2.4 WATER

2.4.1. IS THERE LIQUID WATER ON MARS?

Until the first successful Mars flyby in 1965 by Mariner 4, many speculated about the presence of liquid water on the planet's surface. This was based on observed periodic variations in light and dark patches, particularly in the polar latitudes, which appeared to be seas and continents; long, dark striations were interpreted by some as irrigation channels for liquid water. These straight line features were later explained as optical illusions, though geological evidence gathered by unmanned missions suggest that Mars once had large-scale water coverage on its surface. In 2005, radar data revealed the presence of large quantities of water ice at the poles and at mid-latitudes. The Mars rover Spirit sampled chemical compounds containing water molecules in March 2007. The Phoenix lander directly sampled water ice in shallow Martian soil on July 31, 2008.

As can be seen from the phase diagram of water in the table on the next page, it cannot exist in the liquid state on the surface of Mars at the temperatures and pressures mentioned above because the triple point of water occurs at 0 C and 6.12 millibars.

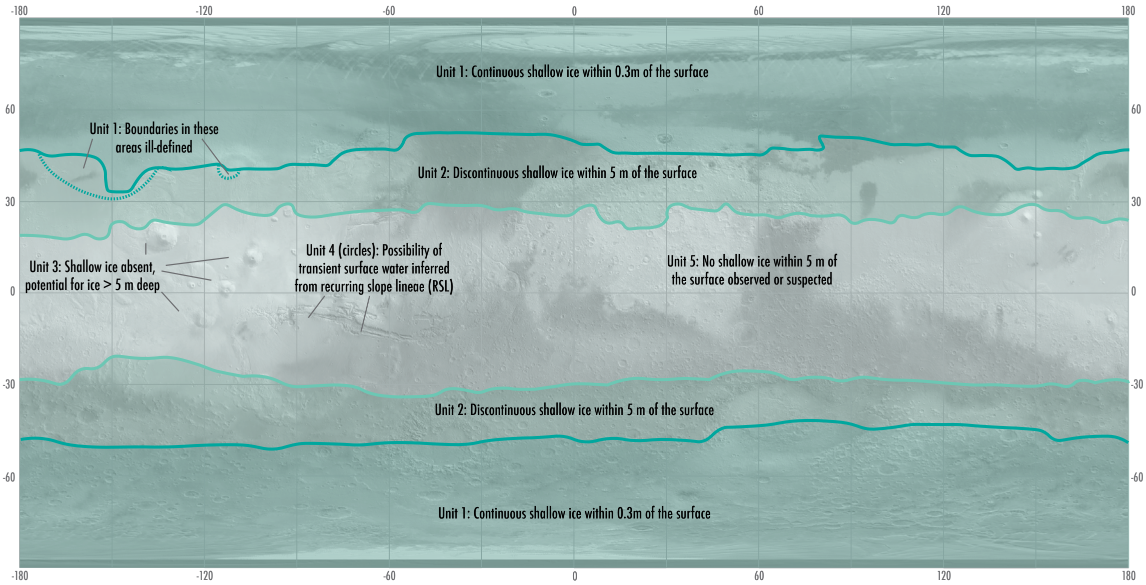
Surface water ice can be seen on the north polar ice cap. It also lies beneath the cap of carbon dioxide ice at the south pole. The presence of subsurface ice has been established by the data collecte by several robotic probes indicating large quantities of hydrogen. (Feldman, 2004) The total quantity of subsurface ice likely exceeds five million cubic kilometers, sufficient to cover the entire planet to a depth of 35m. More is likely to exist at greater depths. Even larger quantities of water should be stored in hydrated minerals; althought the amount is unknown, some results from the data obtained by the Opportunity rover at Meridiani Planum suggest the sulfate deposits there could contain as much as 22 percent water by weight.

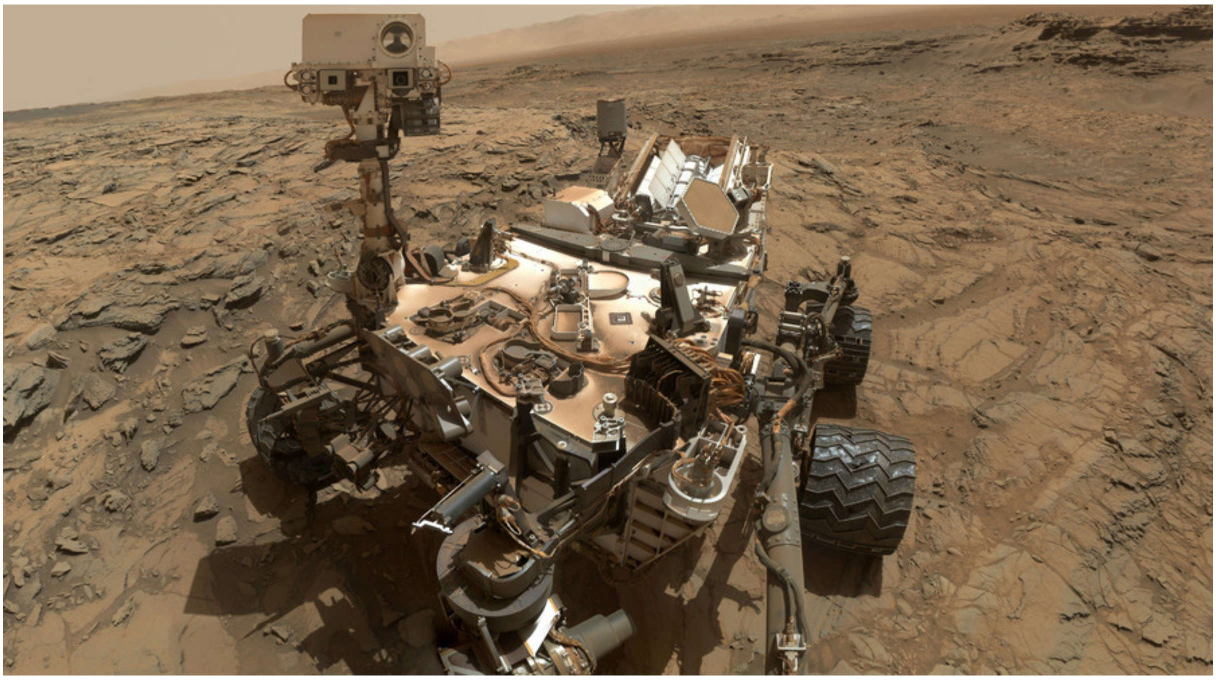


2.4.2. CHALLENGES AND OPPORTUNITIES

The question is not whether there is water on Mars, it is a matter of where the water is located and how difficult it will be to extract. Water is arguably the currency of space, and prospecting for water will be one of the most important tasks assigned to early missions. Whilst it is possible to produce propellants on Mars just from atmospheric carbon dioxide, it will be much easier to do this if local water is available; therfore the presence of ice at a depth shallow enough for it to be readily extracted will be important in selecting a landing site. At present, the search for water is performed from orbit using neutron spectrometers and gamma ray spectrometers that can detect the presence of hydrogen in the uppermost layers of the regolith. This hydrogen is believed to be incorporated into the molecular structure of ice, and from measurements of the amount of hydrogen it is possible to obtain the concentrations of water ice in the top meter of the Martian surface.

Liquid water may occur transiently on the Martian surface today, but only under certain conditions. In 2011, NASA announced seasonal changes which occur on steep slopes below rocky outcrops near crater rims in the southern hemisphere, suggesting they were caused by salty water (brines) flowing downslope and then evaporating. Actually, although liquid water cannot exist on the surface, a brin can survive briefly because it has a lower freezing point. For example, perchlorate salts would reduce the freezing point of water from 0C to -70C. Changes on the surface were observed in several places with ice subliming and forming water that flowed and evaporated. And snow was seen to fall from cirrus clouds, hence at least some clouds are composed by water-ice rather than carbon dioxide ice.





2.5 LANDING SITE

2.5.1. CONSIDERATIONS FOR LANDING SITE

In order to make landing and living on Mars easier, a landing site should be:

- A flat place with few large boulders, so that it is not difficult to find a landing place and to travel using rovers.

- Located at low altitude in order to allow a lander additional time to lose speed in the descent, and the greater atmospheric density at low level offers also protection from cosmic radiation.

- At low latitude in order to simplify landing and ascending. In addition an equatorial site will not suffer such cold winters.

- At high latitude, where water ice is readily available if ISRU and ISPP involving the use of water is predicted.

- A place where it is unlikely there is life, in order to minimize contamination issues. However, in seeking life the opposite could be argued.

- A place from which interesting places can be reached, either using crewed rovers or automatic ones. However, it should be noted that automatic rovers might be landed in interesting places without the need of traveling there overland.

More on this will be discussed in the following chapter.

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03

MISSION DESIGN

Many reasons can be found for humans to go to Mars. Some say it is essential to explore space in order to learn more about our life on earth. Others belief we should start looking for new resources as we're depleting our own planet. Musk is advocating for humans to become an interplanetary species. And some are driven with the thought that exploration is in our DNA. The drive to cross new boundaries brings hope and excitement for human life in our universe.

Over the course of the past century, a plurality of proposals for a mission to Mars were developed by various actors in the field of space exploration. However, there is still no definitive answer to how we shall explore Mars, despite decades of comparative analyses. In this chapter the mission constraints will be defined as a baseline architecture for this research via characterization of the Mission Architecture. The objective of the research in this chapter is to find an overlapping design driver for the habitat design, related to both Mission Design and Space Psychology.

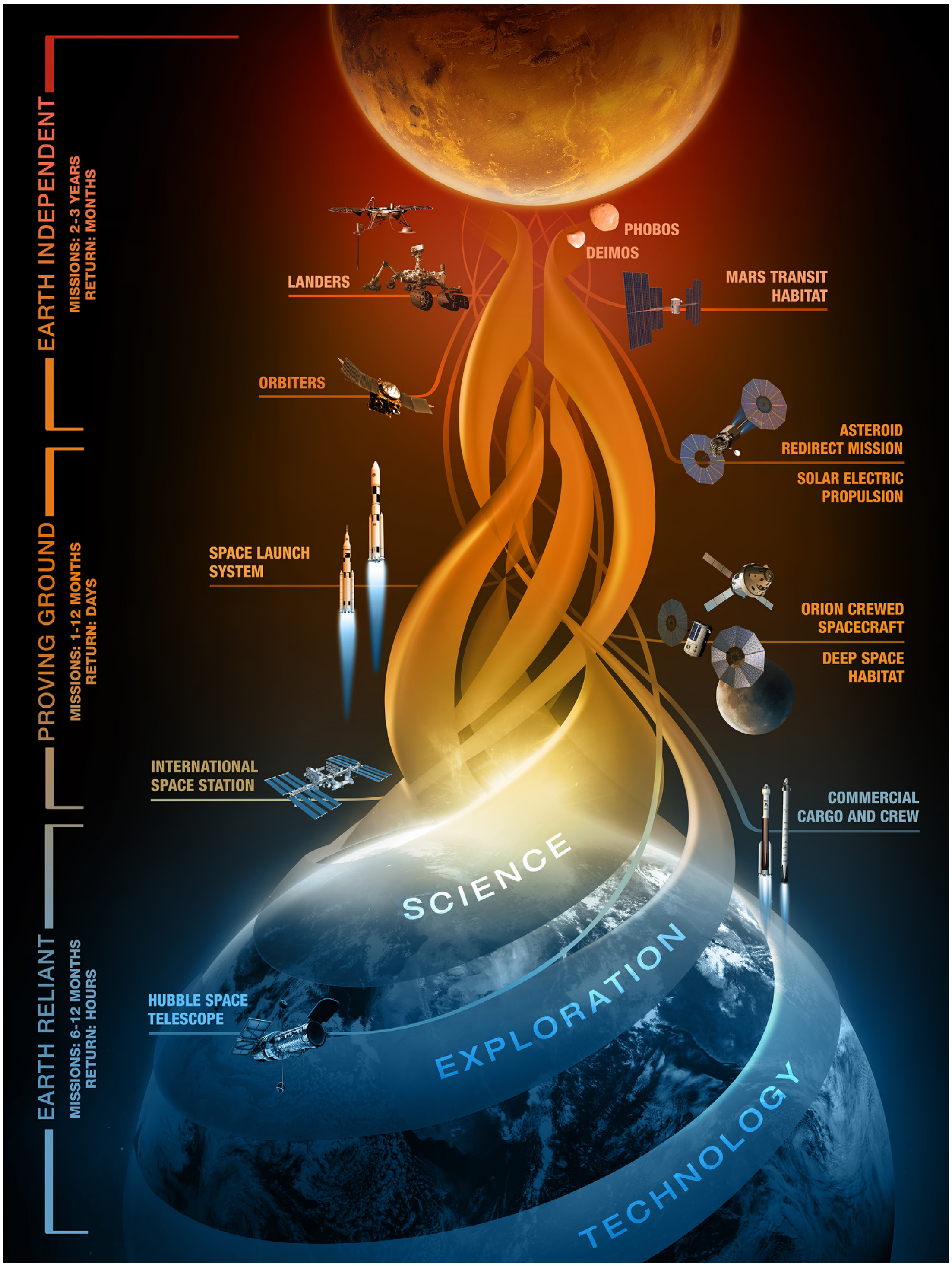


Figure 3.1.1. : Visual representation of NASA's Evolvable Mars Campaign: Journey to Mars. (NASA, 2015)

3.1 MISSION ARCHITECTURES

3.1.1. BRIEF HISTORY

Werner von Braun was the first person to make a detailed technical study of a Mars mission in 1952 (Wikipedia, 2016). After the first proposal, many others have followed. In the majority of proposals by many space organizations, NASA has played a leading role in providing intelligence on the topic, being an expert in manned mission design for space exploration.

In 1989, NASA presented a study of a project for human lunar- and Mars exploration. The report, called the 90-day study, proposed a long-term plan consisting of all necessary steps that would have to be undertaken before being able to send astronauts to Mars. This report was widely criticized as too elaborate and the plan it proposed as too expensive. As a consequence, all funding for human exploration beyond Earth orbit was canceled by US Congress. (Wikipedia, 2016)

As a result of the 90-day study, private intiatives for human missions to Mars started to pop up from everywhere. Zubrin was the first to criticize NASA’s study and replied with his own mission design, in collaboration with Baker, called Mars Direct. Later, based on Zubrin’s critique NASA undertook a new effort on developing a human mission to Mars and developed the “*Human Exploration of Mars: a Design Reference Architecture*” (DRA 5.0) as a mission baseline architecture. NASA developed the DRA over the course of many years. The first DRA was published in 2005 and was updated every two to three years. The latest version is the DRA 5.0, published in 2009. (Drake et al., 2009)

Many other initiatives with various mission proposals have followed since from various agencies and studygroups. The new proposals all advocate a minimised mission architecture. The mission designs range from manned flyby’s to 30-day stay and return missions, 500-day stay and return missions, up to one-way missions to Mars, banning the need for humans to return and to start with building a colonization on Mars.

3.1.2. TODAY’S PLANS

With the objective to coordinate the efforts for faster advancement in space exploration, the International Space Exploration Coordination Group (ISECG) was established in 2007. The group connects 14 space agencies in a global effort to exchange information for strengthening both individual exploration programmes as well as the collective effort. (ISECG, 2016)

In 2013, the ISECG published their latest version of The Global Exploration Roadmap (GER). The ISECG Mission Scenario, presented in the GER, defines a clear stepwise evolution of human exploration capabilities to advance human exploration of the Moon and a near-Earth asteroid, with Mars as the ultimate goal. The approach is based on activities that the involved space agencies are already undertaking or have planned to undertake. (GER, 2013)

In spring 2015, the Planetary Society held a workshop in Washington D.C. that evaluated the current efforts and strategies towards a manned mission to Mars. The result of the conference was summarised in the report “Humans Orbiting Mars” (HOM, 2015). In the report the study done by JPL was cited as recommendation for NASA. NASA’s Jet Propulsion Laboratory (JPL) had just published a study named “A Minimal Architecture for Human Journeys to Mars”. The study group from JPL pursued a minimal architecture by embracing existing programs and limiting new hardware development, thus avoiding a common source of budget overruns and schedule delays. The JPL study was done as an input to the overall NASA planning process. (Price et al., 2015)

The conclusion of the workshop was that NASA would have to remain leading in their role in deploying a suitable strategy in collaboration with other space agencies, industries and governmental or non-governmental organizations. To achieve this, NASA published their Journey to Mars strategy (JTM) in October 2015. The document sets out their intended strategy, with room for developmental changes. The baseline architecture remained the DRA 5.0, which had been published in 2009. However, the JTM does not express the intention to land humans on Mars, but to bring them to Mars Orbit by 2033. (JTM, 2015)

3.1.3. WHAT NOW?

Initial steps have been defined to prepare for future Mars missions, which also enable discovery along the way. However, despite all the reports and joint efforts, there is still no definitive plan for a human mission to Mars, nor a combined focus (Rapp, 2007, p.417). Since there is no recent mission baseline, assumptions about the mission circumstances will have to be made as a starting point to formulate the baseline for the habitat design. In the following chapter, the process of mission design will be explained and applied to further evaluate NASA’s formulated baseline assumptions of the DRA 5.0.

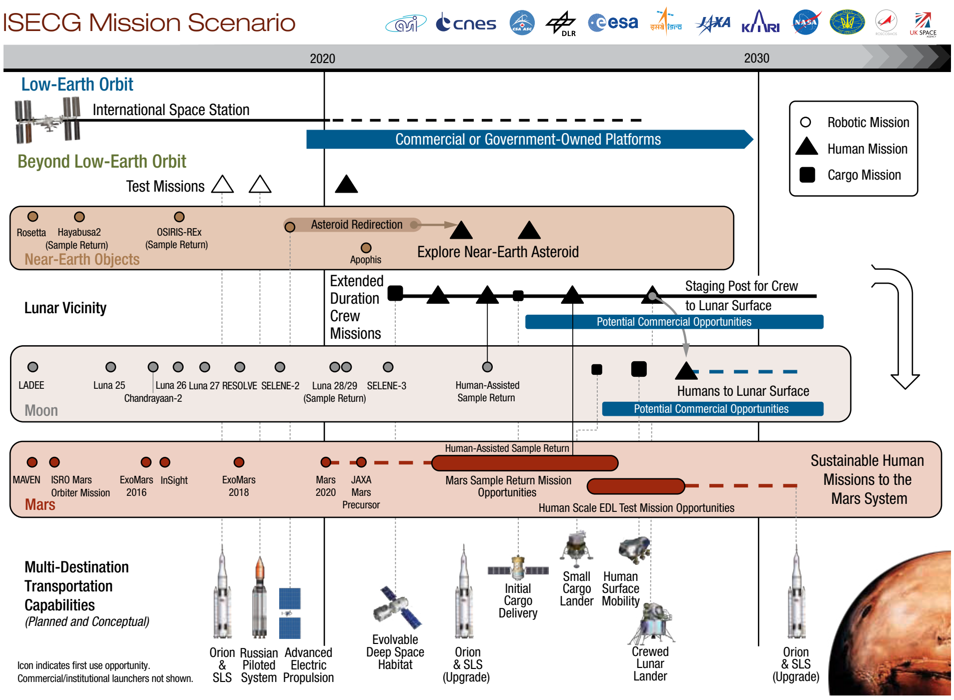


Figure 3.1.2. : ISECG Mission Scenario presented in the Global Exploration Roadmap (ISECG, 2013)

3.2 SPACE MISSION DESIGN

3.2.1. PROCESS OF SPACE MISSION DESIGN AND ANALYSIS

The book *Space Mission Analyis and Design* (SMAD) (Wertz, 2005) is a course manual on mission design for space systems. SMAD suggests several sequential steps for the process. It starts with defining the objective of the mission. Apart from the objective, there are certain factors that influence the decision making within the process of mission design. These decision parameters often relate to drivers such as cost, risk, schedule and performance.

The sequential steps for Mission Design are given as follows (Wertz, 2005; p2):

> Define Objectives
Step 1. define broad objectives and constraints
Step 2. estimate preliminary quantitative needs, requirements and contraints

> Characterize the Mission
Step 3. identifying alternative mission concepts (data delivery, tasking, scheduling, timeline)
Step 4. identifying alternative mission architectures
Step 5. identify system drivers
Step 6. characterizing mission architecture

> Evaluate the Mission
Step 7. identify critical requirements
Step 8. evaluate mission utility
Step 9. define mission concept (baseline)

> Define Requirements
Step 10. define system requirements
Step 11. allocate requirements to system elements

Throughout this chapter, the definition of the mission baseline will touch upon the first nine steps of the SMAD sequential steps. The context of the mission will only be studied and defined to a certain extent, because the focus of this graduation research is on design of the surface habitat. The desired outcome is to point out key parameters that characterize the mission and help the architectural engineer.

3.2.2. OBJECTIVES AND GOALS

The first step in analyzing and designing a space mission is to define mission objectives: the broad goals which the system must achieve to be productive. In the mission design for space systems, the client that purchases the system, plays a leading rol in defining the mission objectives. During the process of mission development, these objectives an be updated and altered when necessary. There is a general differentiation between primary and secondary objectives. In this case, the primary objective of this mission design would be for humans to live on Mars, be it for a yet to be defined period of time. However, the mission goals can be much more broadly defined than having the mission to serve a single purpose.

Häuplik-Meusburger and Bannova state (2016, p. 55):

> *"Mission goals and objectives spread much further than the destination of a space journey – they begin on Earth and come back to it in many aspects, including planning for future missions, future developments on Earth, and potential benefits that may not be very obvious at the beginning."*

For this reason, it helps to think of all stakeholders when defining the secondary objectives. Generally, in space mission design the client is the leading stakeholder. Since there is no defined client, the interests of the International Space Exploration Coordination Group (ISECG) have been studied. The Global Exploration Roadmap (GER), published in 2013 by the ISECG, formulates eight common goals for space exploration.:

1. Develop Exploration Technologies and Capabilities
2. Engage the Public in Exploration
3. Enhance Earth Safety
4. Extend Human Presence
5. Perform Science to Enable Human Exploration
6. Perform Space, Earth, and Applied Science
7. Search for Life
8. Stimulate Economic Expansion

With these acknowledged common goals, it is easier to define the mission objectives. The secondary objectives specify what fundamental characteristics make the space mission desirable. Studies within the aerospace industry often emphasize the quantifiable benefits that can form the outcome. Examples are the profitability of space exploration, for example via exploitation or scientific research.

As Häuplik-Meusburger et al. (2016) mentioned, sometimes these beneficial outcomes are hard to define in advance. Through space exploration many technologies were developed that stimulated economic expansion, for example the development of solar panels. This resulted in an entire new market and industry. Another example that is hard to quantify, is the impact that exploration would have via inspiring the public. For this reason, it is generally thought that a human mission to Mars should also serve the public interest in an inspiring way.

To maintain focus on this research' objective, the secondary objectives for this mission design have to fall in line with research in Architectural Engineering and Building Technology. With the primary objective to realise the first human settlement on the Red Planet, secondary objectives from the perspective of the architectural engineer will both be quantitative and qualitative.

The main secondary quantitative objective is to develop a feasible construction methodology for a martian surface habitat. This objective calls for specific needs, requirements and constraints. The qualitative objective relates to the habitability of this habitat. Habitability calls for totally different needs, requirements and constraints. Each of these objectives with their requirements will be defined in the following chapters.

3.2.3. RISK AS A DRIVER

Before we can get to further characterization of the mission, SMAD suggests to identify system drivers, defined as (Wertz, 2005: p. 37):

> *"System drivers are the principal mission parameters or characteristics which influence performance, cost, risk or schedule and which the user or designer can control."*

Exploration missions beyond Low Earth Orbit (LEO) bring significant health risks. Key research areas, where solutions are needed to reduce risk during human missions to an acceptable level, have been summarised in the GER (Table 3.2.1.). The table reflects past demonstrations of agencies in the maturity of a technology, capability or operation to enable a human mission to the Martian surface and the respective risk reduction.

🟢 **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			●	●	🟢	
Heavy Lift Launch			⊙	●	🟢	
Reduced Supply Chain		⊙	●	●	🟢	
Autonomous Crew Operations	⊙	⊙	●	●	🟢	
Deep Space Staging Operations			🟢		🟢	
Mars Ascent	⊙			⊙		⊙
Space Radiation Protection/Shielding		⊙	●	●	🟢	
Life Support & Habitation Systems		●	●	●	🟢	
Entry, Descent, & Landing Systems	⊙			⊙		●
Surface Power and Energy Management	⊙			🟢		🟢
Surface Mobility	⊙			●		●
Human Robotic Integration	⊙	●	🟢	🟢	🟢	🟢
Mars In-Situ Resource Utilization	⊙			⊙		●
Long Duration Human Health	⊙	●	●	●	●	
Deep Space Operation Techniques	⊙	⊙	●		🟢	

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

Table 3.2.1. : Past efforts on identified research areas (GER, 2013)

Crew health and performance are primary and critical concerns when planning an exploration mission. NASA comprehensively summarized the human risks in space exploration in three broad categories (Durante, 2011):

1. Physiological problems caused by reduced gravity
2. Psychological and medical problems caused by isolation
3. Acute and late risks caused by exposure to radiation

A lecture series organized by NASA in June 2017, elaborates on all the major challenges that NASA faces for a human mission to Mars. Radiation risks and the technical risks for Entry Descent and Landing were mentioned as the key parameters in their mission design. (NASA EDL, 2017)

The GER also describes the risks for the Mars mission scenario that need to be mitigated in order to meet established human health and performance standards in Table 3.2.2.

The GER suggests that risk is currently the biggest reason why exploration of Mars is still not possible. An emphasis is put on the Behavioral Health & Performance risks for the crew, with radiation defined as the biggest hazard. For this reason, the mission parameters and characteristics will have to influence this risk. The means to mitigate these risks can be highlighted and some can be directly influenced by the architectural designer. All system drivers for this mission architecture will have to mitigate risks for constructability and habitability of the surface habitat.

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

Table 3.2.2.: Identified risks concerning a human mission to Mars (GER, 2013)

3.2.4. CHARACTERIZATION OF THE MISSION ARCHITECTURE

Now that risk is defined as the most important driver, the preliminary mission architecture can be designed as the context for the surface habitat. Characterization of the mission consists of several design decisions. The Concept Characterization Process is given as follows (Wertz, 2005, p. 39):

A define the preliminary mission concept
B define the subject characteristics
C determine the orbit or constellation characteristics
D determine payload size and performance
E select the mission operations approach
F design the spacecraftbus to meet payload, orbit, and communications requirements
G select a launch and orbit transfer system
H determine deployment, logistics and end-of-life strategies
I provide costing support
J document and iterate

The process emphasizes the steps to be taken for planning the engineering and logistics that have to be considered for the design of the habitat system. The following paragraphs will elaborate on the mission trajectory, schedule, technology, payload dimensions and operations approach, relevant to support the design decisions to be made by the architectural engineer.

Crew Health & Performance (CHP) Component	Short Stay (Opposition-class; 22 months total)	Long Stay (Conjunction-class, 30 months total)
Physiological Countermeasures	▪ Extended 0-g transits at limits of human spaceflight experience base ▪ Preferred option only if artificial-gravity is available	▪ 0-g transit phases well within experience base ▪ 3/8-g surface phase outside experience base, will be partially mitigated by Lunar Outpost experience
Human Factors & Habitability	▪ Not preferred option without access to Surface Habitat	▪ Preferred option with access to Surface Habitat
Radiation	▪ Higher risk of carcinogenesis, acute syndromes, central nervous system effects and degenerative effects due to longer transits (solar proton events & galactic cosmic radiation) and close perihelion passage (solar proton event effects) ▪ Option is well outside current permissible exposure limits	▪ Slightly preferred option due to less exposure to free space heavy ion environment ▪ Prolonged exposure to poorly-understood surface mixed-field (neutrons and charged particles) environment ▪ Option is well outside current permissible exposure limits
Behavioral Health & Performance	▪ Preferred option due to shorter overall duration ▪ Possible risk due to higher acute radiation exposure within 0.7 astronomical unit	▪ Increased risk due to longer overall duration
Medical Capabilities	▪ Slightly preferred option due to less duration of risk exposure on surface and total mission	▪ Slightly increased risk due to longer overall duration

Table 3.3.1.: Comparison of mission architectures (DRA 5.0, 2009)

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

Table 3.3.2.: Distances between Earth and Mars (Genta, 2017)

3.3 PLANNING AND SCHEDULE

3.3.1. TRAJECTORY

With radiation defined as the major hazard for human health, the shortest trip should be taken in order to minimise exposure time to space radiation during transfer. Radiation shielding can be more easily achieved on the planet Mars itself (Durante, 2011).

Mars and Earth have different orbits, which means that they have continuously changing distances between one and another. Mars is only closer to Earth every 26 months. Because the windows of opportunity are so limited, they need to be carefully planned to make sure that the appropriate equipment is brought. Efficient planning requires minimising cargo, hence minimising fuel, hence minimising travel distance. In all the different kinds of mission proposals, it can be concluded that the most feasible missions are the designs that achieve a maximised efficiency in cargo. (Landau, 2009)

NASA's Design Reference Architecture 5.0 (DRA, 2009) describes two possible trajectories to get to Mars. Both proposals were compared and assessed on perceived value based on cost, risk and performance. It was concluded that a mission design with a longer surface stay, the Conjunction Class, offered more advantages.

3.3.2. LAUNCH WINDOWS

As mentioned before, due to different orbits the launch opportunities are limited. Genta (2017) gives a list of launch windows for the coming decades. Within this research, the scope is to determine the feasibility for the first settlement. The ambition is to bring people to Mars as soon as possible. The table below shows there are six opportunities within the next decade to sent technology to Mars. This will be the timeframe that has to be considered within the overall mission architecture.

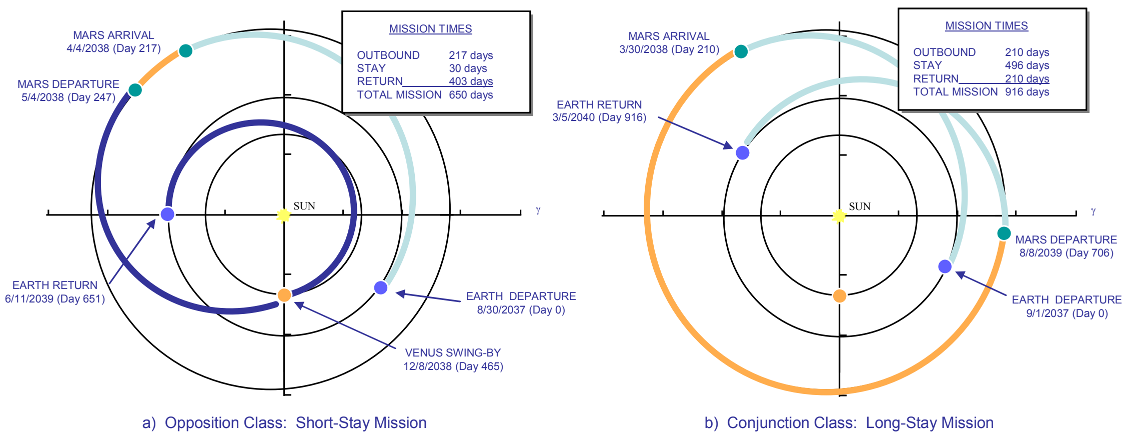


Figure 3.3.1.: Comparison of mission architectures (DRA 5.0, 2009)

3.3.3. TRL AND HRL

To quantify technological risks, NASA defines a Technology Readiness Level (TRL) as a general standard for space systems. The figure below shows the standards that apply to the nine seperate levels. The explanation is stated as (NASA, 2012):

> *"When a technology is at TRL 1, scientific research is beginning and those results are being translated into future research and development. TRL 2 occurs once the basic principles have been studied and practical applications can be applied to those initial findings. TRL 2 technology is very speculative, as there is little to no experimental proof of concept for the technology.*
>
> *When active research and design begin, a technology is elevated to TRL 3. Generally both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept model is constructed.*
>
> *Once the proof-of-concept technology is ready, the technology advances to TRL 4. During TRL 4, multiple component pieces are tested with one another. TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model.*
>
> *TRL 7 technology requires that the working model or prototype be demonstrated in a space environment. TRL 8 technology has been tested and "flight qualified" and it's ready for implementation into an already existing technology or technology system. Once a technology has been "flight proven" during a successful mission, it can be called TRL 9."*

Connolly et al. (2006) have developed a Habitation Readiness Level (HRL) in line with the TRL. More elaboration on the exact conditions and requirements can be found in Appendix B. (Hauplik-Meusburger et al., 2016)

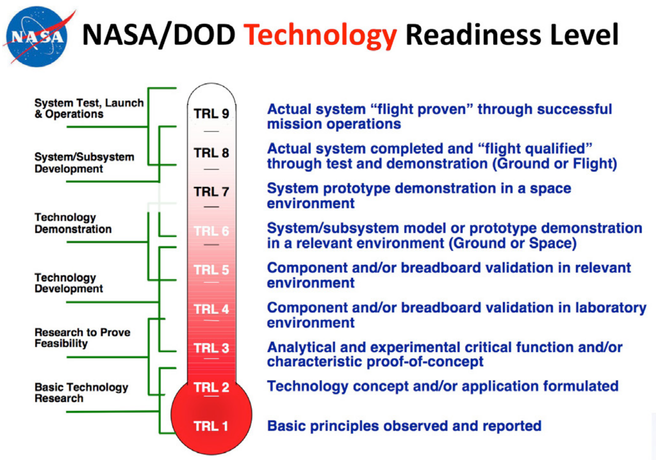


Figure 3.3.2.: NASA's definitions for Technology Readiness Levels

3.3.4. SCHEDULE

In June 2015, NASA's Jet Propulsion Laboratory (JPL) conducted a study named "A Minimal Architecture for Human Journeys to Mars". The study group from JPL pursued a minimal architecture by embracing existing programs and limiting new hardware development, thus avoiding a common source of budget overruns and schedule delays. The JPL study was done as an input to the overall NASA planning process.Later in 2015, NASA announced the Evolvable Mars Campagn (EMC) as a baseline mission architecture that combined the findings from JPL with the earlier developed DRA 5.0.

In the DRA 5.0 the pre-deploy strategy was defined as the preferred option, meaning that the base on Mars is in place and operating, before the crew arrives. It assumes two cargo landers with various mission equipment. The first lander will bring a Mars Ascent Vehicle (MAV), a Space Exploration Vehicle (SEV), the first Fission Power Unit (FPU), two fetch rovers, a drill, an ISRU unit for in-situ propellant production and a science kit. The second lander will carry the surface habitat, a second FPU and a second SEV. Both cargo landers will be launched and landed two years before the crew arrives. Within the period the base will have to be set up and operational. If all systems are tested and checked for approval, then the crew launches and leaves Earth. This mission architecture is defined as the pre-deploy strategy. (DRA 5.0, 2009)

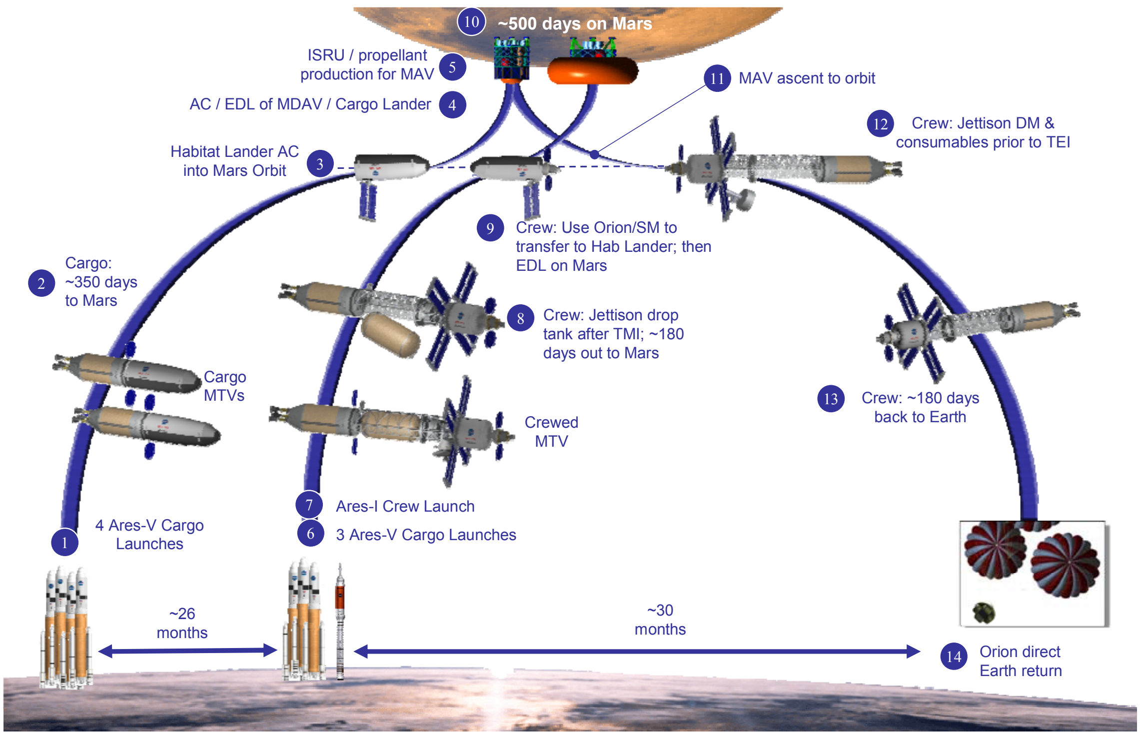


Figure 3.3.3.: Overview of the Design Reference Architecture for a human mission to Mars (DRA 5.0, 2009)

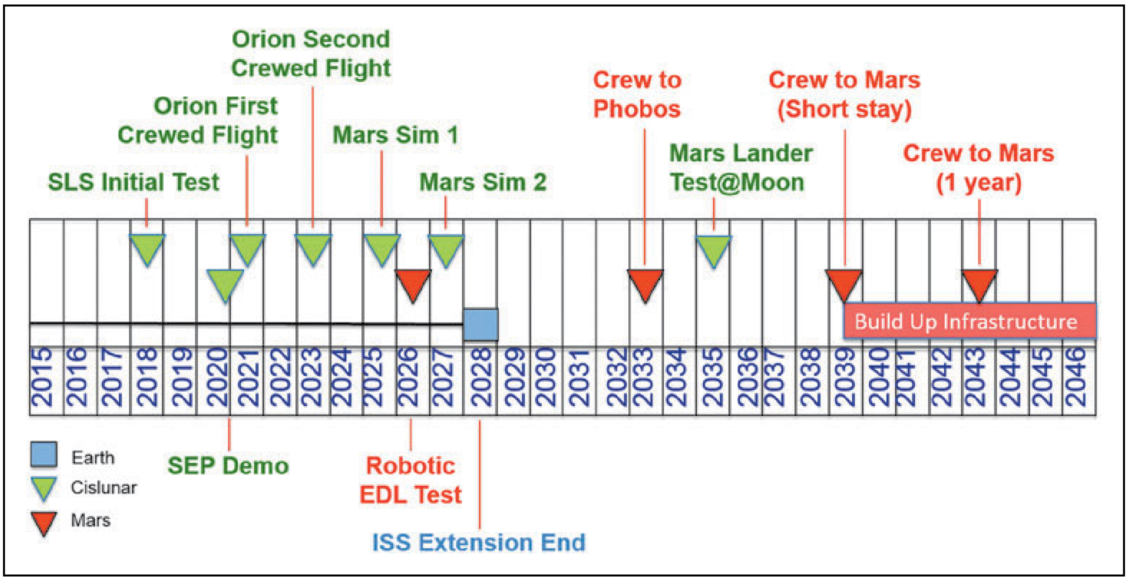


Figure 3.3.4.: Example program timeline for a Mars Mission (JPL, 2015)

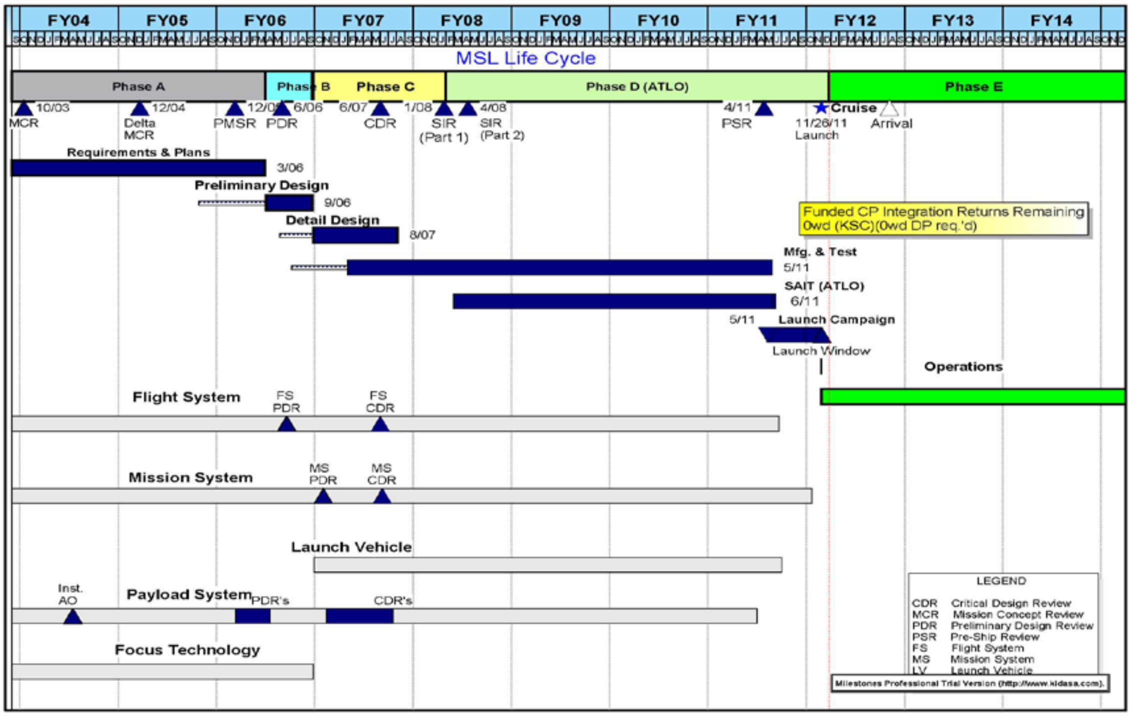


Figure 3.3.5.: Schedule of technology development phases for the MSL-rover Curiosity (Cook, 2012)

The EMC and DRA 5.0 didn't specify a clear timeline for project development to land a human mission to Mars, but the JPL-study did present some sort of a conceptual draft. To get more insight in the complexity of planning a Mars mission a report on the MSL mission that landed the Curiosity-rover in 2012, provided more insight. (Figure 3.3.5.) It showed that a design and product development process of over four years preceded the landing of a single rover.

Considering the TRL and HRL that should be defined before the final product is developed and tested a project timeline could be derived. Several stages for product development are necessary to be completed prior to the mission launch. Habitat development was assumed to start immediately and take up to ten years to achieve all TRL and HRL requirements. Within these ten years an analogue simulation mission is taken in consideration to test the psychological perception of the habitat. This is referred to as habitability and will be further explained in paragraph 4.4.

In short, a conclusion concerning scheduling and timing, the habitat deployment, construction and testing should not exceed a period of 18 months for surface operations. (Figure 3.3.6.)

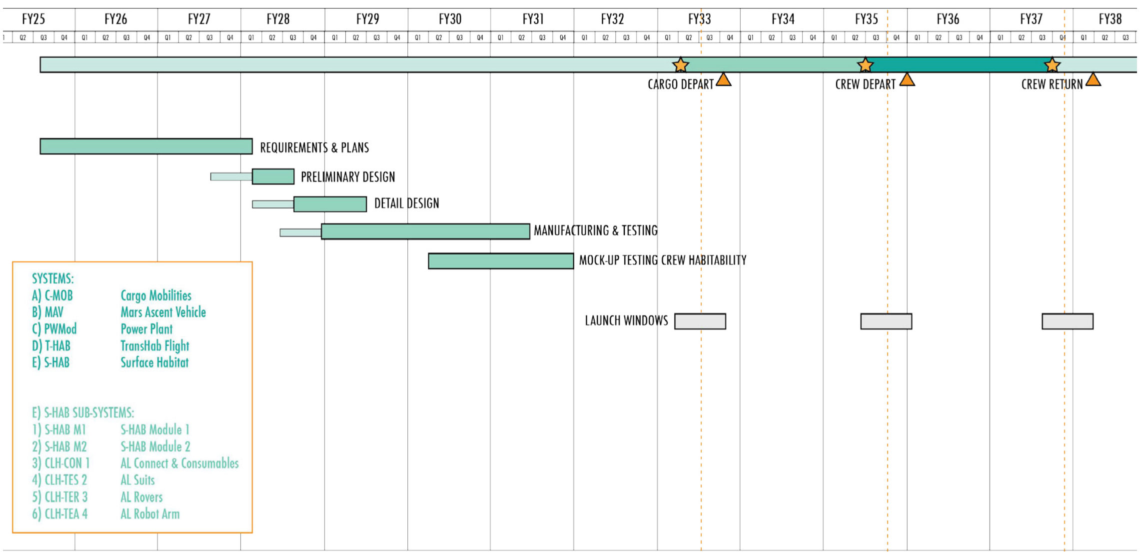


Figure 3.3.6. : Possible schedule concerning habitat system development in relation to mission timeline

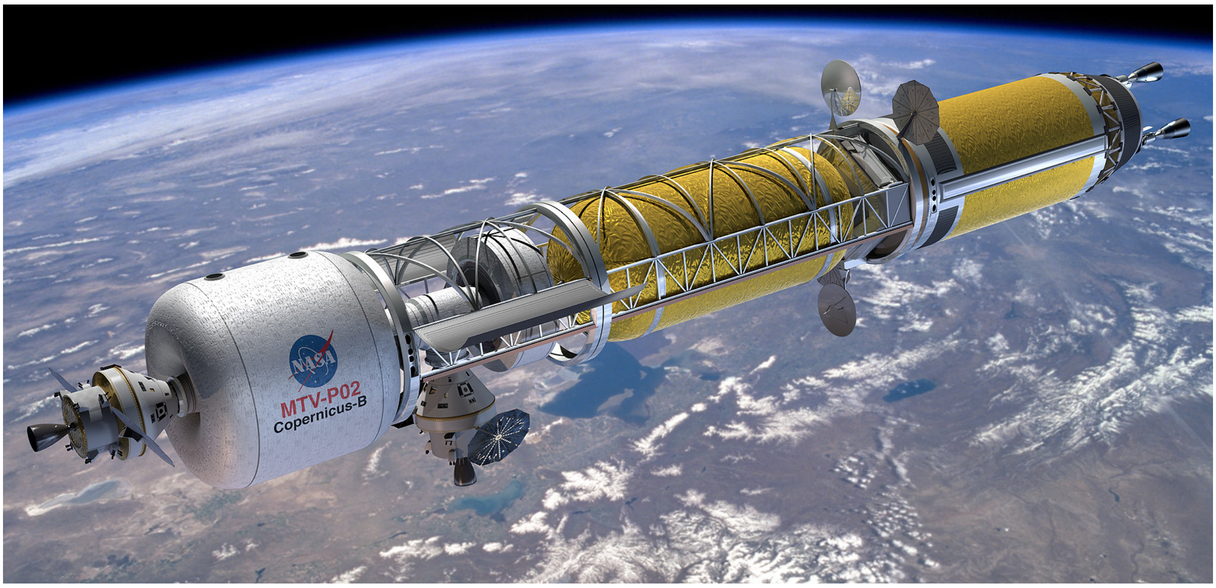


Figure 3.4.1: Visualisation of NASA's DRA 5.0 proposal for the Mars Transfer Vehicle (MTV) (Courtesy of NASA)

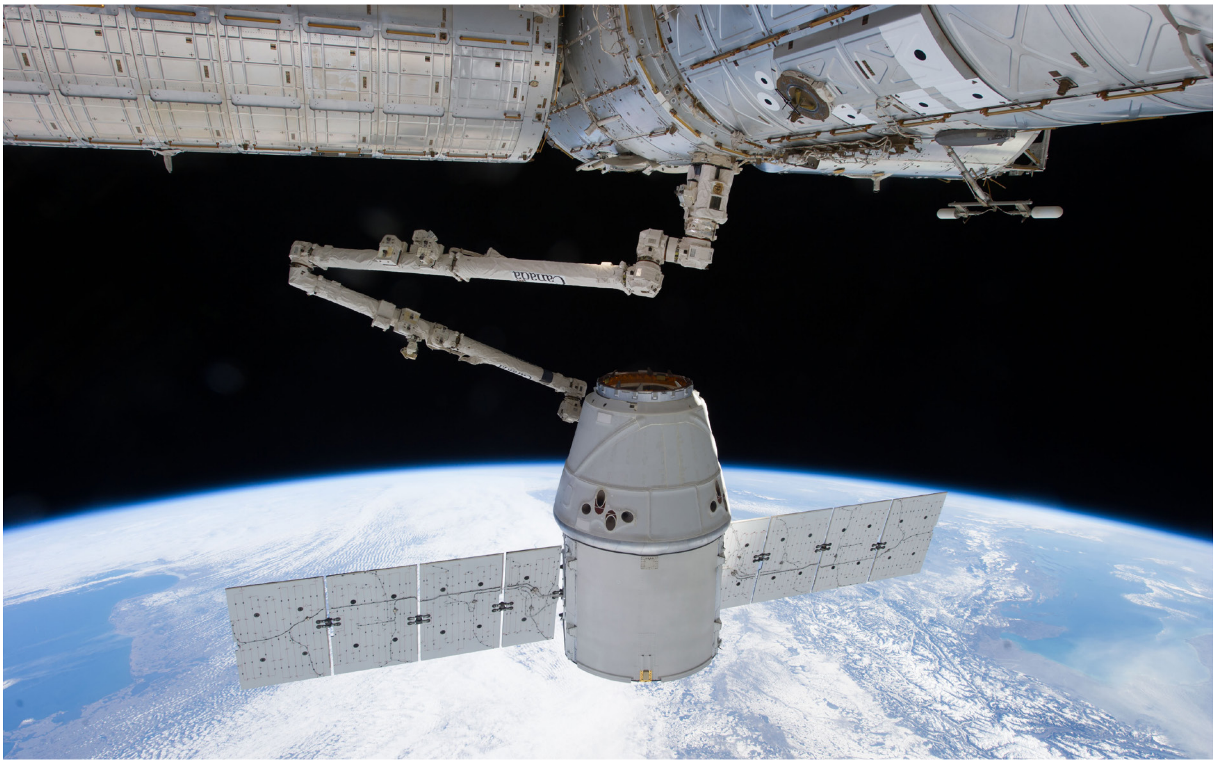


Figure 3.4.2 : SpaceX' Dragon Capsule docking to ISS in May 2016 (Courtesy of NASA)

3.4 TRANSPORT AND LOGISTICS

3.4.1. TRANSPORTATION

JPL (2015) proposes an architecture that relies on the Block II version of the Space Launch System (SLS) heavy-lift rocket, the Orion-crew capsule, 100kWe solar electric propulsion (SEP) tugs, and a long duration crew habitation module that can be reused. Only the habitat module and chemical transfer stages would still have to be newly developed. All other hardware is currently in various stages of development.

In the JTM, the Orion is explained as "a launch, reentry, and in-space crew spacecraft design designed to transport a crew of four to deep space." The Orion will be stationed on top of the Space Launch System (SLS). The initial Block 1 SLS is designed to carry Orion as well as cargo, equipment, and science experiments to staging points in cislunar space. (JTM, 2015)

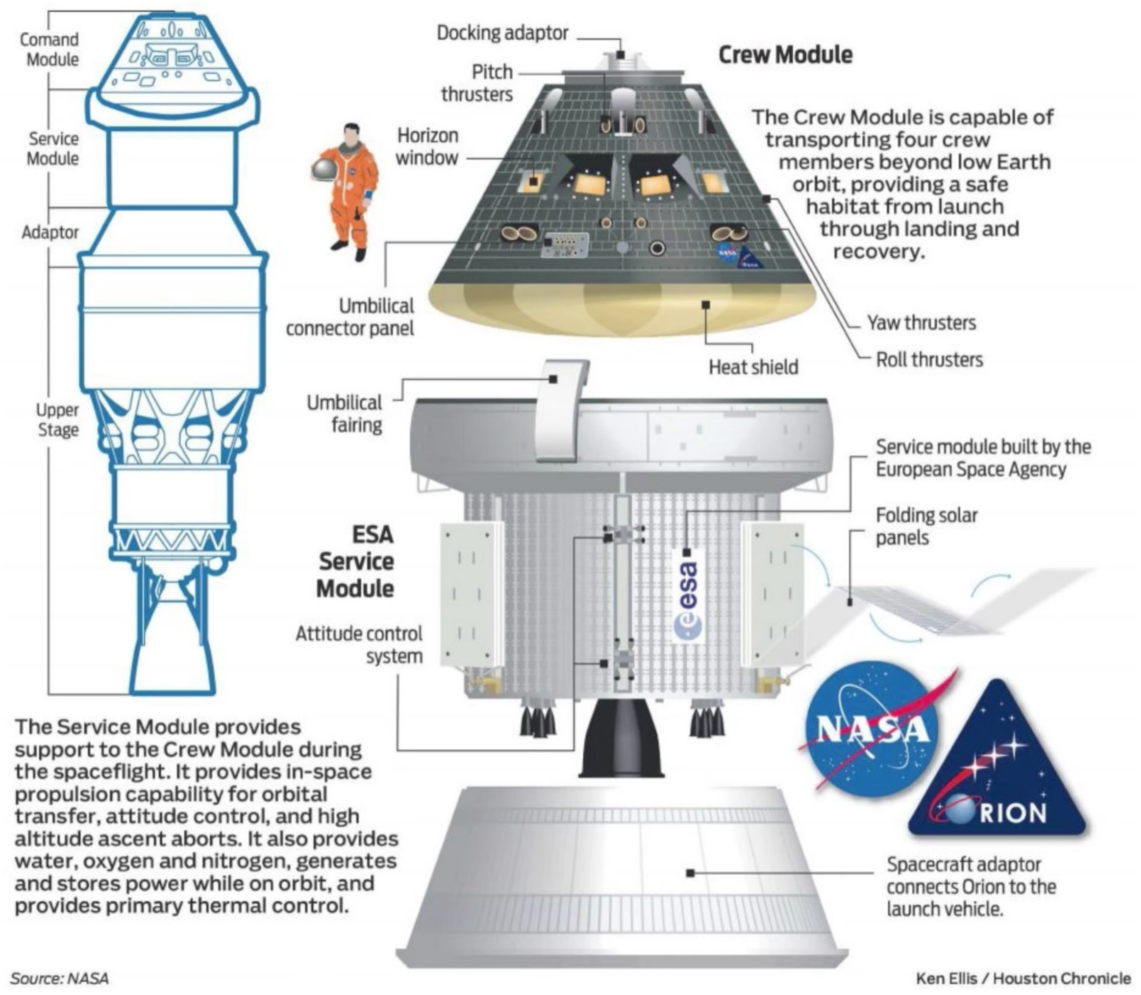


Figure 3.4.3. : Design of the Orion Crew Module

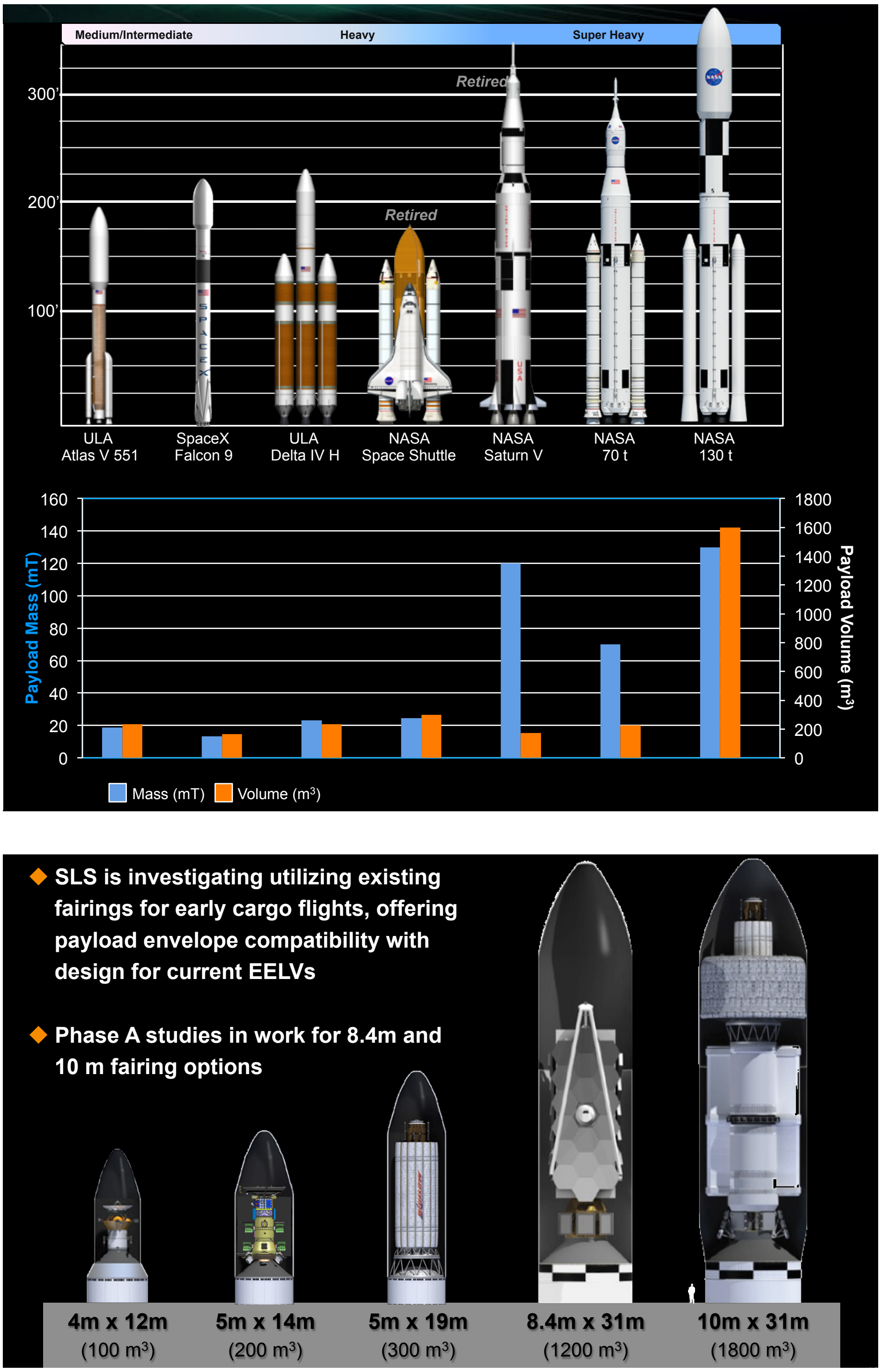


Figure 3.4.4. : Space Launch System capabilities (NASA)

SLS Block 1
Initial Configuration

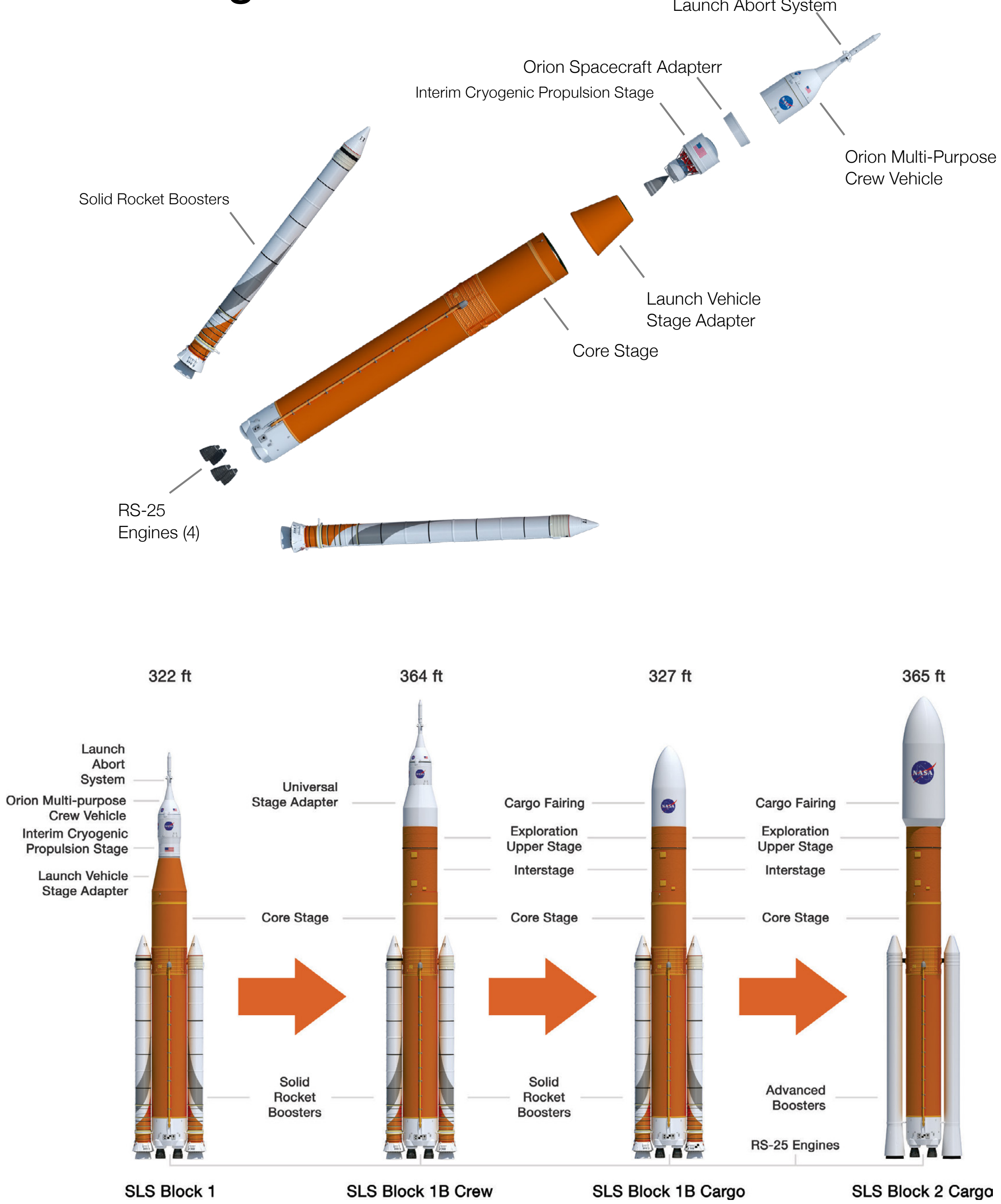


Figure 3.4.5. : Design of the Space Launch System and various scales (NASA)

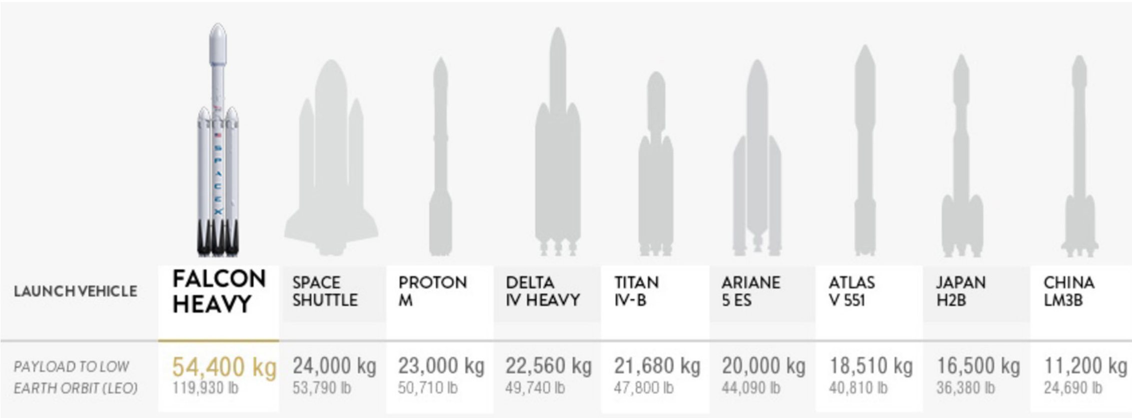


Figure 3.4.6. : Falcon Heavy compared to other space fairing technologies (SpaceX, 2017)

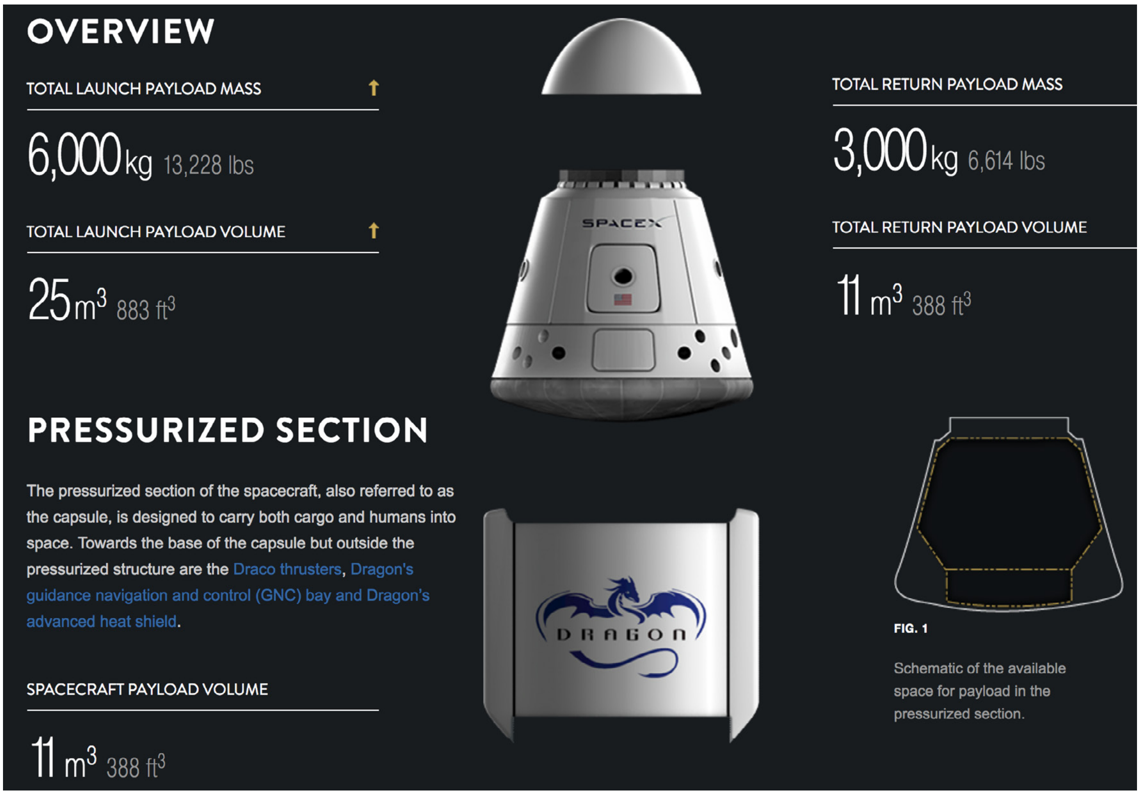


Figure 3.4.7. : Technical Specifications of the Dragon Crew Module (SpaceX, 2017)

Re-usability of the technology is an often repeated theme in mission design. (National Geographic, 2015) SpaceX, a commercial space technology developer, is making progressive steps in spacecraft development. Musk explains that the majority of costs for space exploration lie in the disposal of the rocket boosters when launching a rocket. (Musk, 2016) SpaceX has made it their first and foremost objective to bring humans to Mars, starting with developing reusable transportation technologies. Online the various rocket designs and technical capablities can be found. (SpaceX, 2017) An overview of various alternatives and dimensions are shown in the figure below.

Most mission proposals, focus on a minimal architecture relying on technologies that are ready or under further development. Hopes are set on the Orion and SLS spacecrafts, currently under development by NASA. SpaceX offers great insight in other transportation technologies and their dimensions. These dimensions define the first logistical constraints to be taken in consideration for Martian building construction.

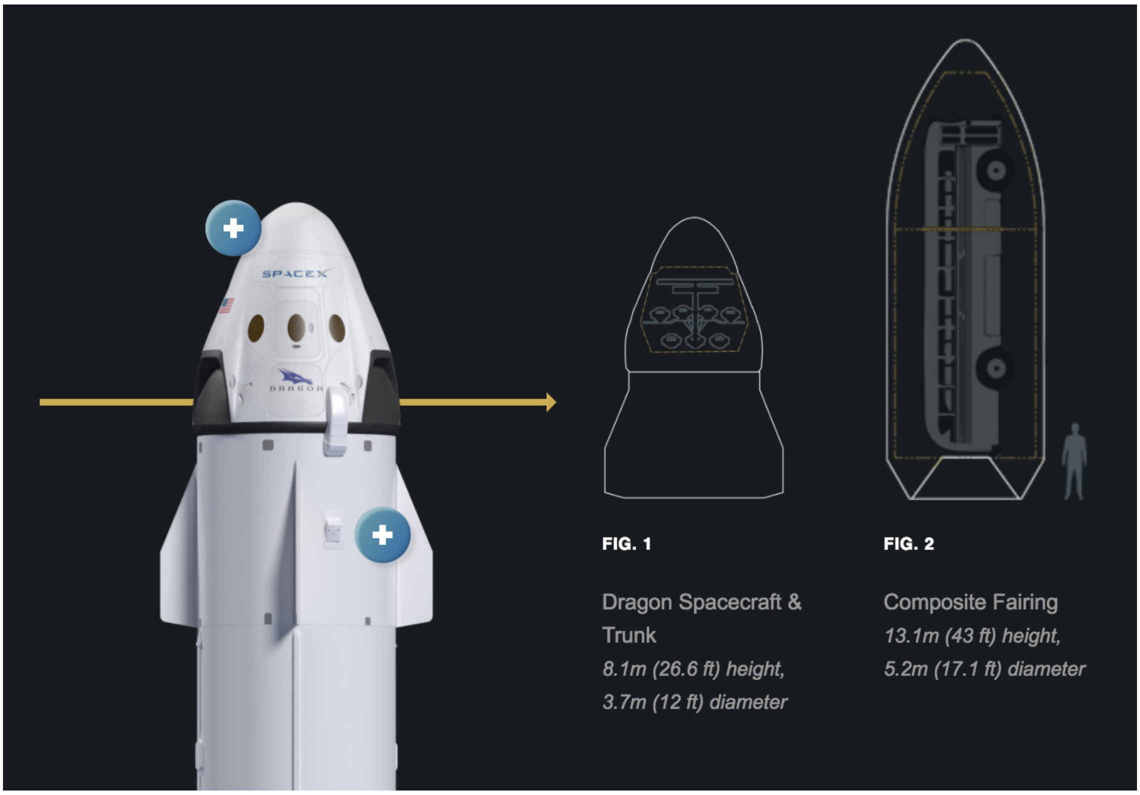


Figure 3.4.8. : Dimensions of modules that can be placed on top of the Falcon (SpaceX, 2017)

Figure 3.4.9 : Atmospheric Entry of MSL-rover Curiosity deceleration with aerobreaking (wikipedia, cc)

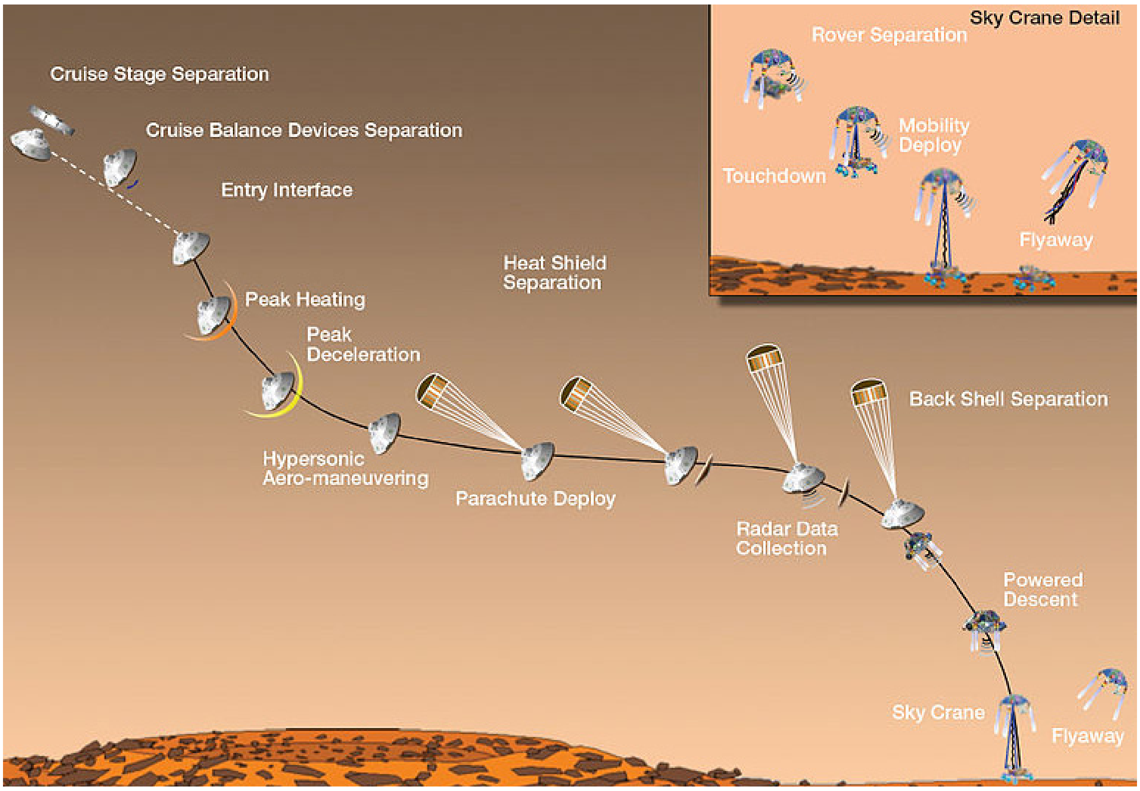


Figure 3.4.10 : Entry Descent and Landing (EDL) sequence of MSL-rover Curiosity (wikipedia, cc)

3.4.2. ENTRY DESCENT AND LANDING

A major technological risk driver in space exploration is the choice of the systems and procedures concerning the Entry, Descent and Landing on Mars (EDL). Up until today, not many missions have had success in landing various technologies on the surface on Mars. Some spacecraft have even missed the planet. However, regarding the recent history the rate of success is increasing. A total of seven landers and rovers have succesfully landed and operated on the surface of Mars. (Wikipedia, 2017)

Missions to the surface of Mars consist of several phases of which the EDL is a critical challenge to overcome. Due to different speeds during this phase, the EDL is generally cut up in three different stages as different speeds require different engineering procedures and solutions. Entry refers to the atmospheric entry of the spacecraft.

To limit the payload mass that has to be carried from Earth, aerobreaking is the generally preferred option to decrease the velocity of the entering object. Aerobraking refers to using the atmospheric density to create a certain drag on the object, so it slows down when entering the atmosphere. A higher surface area of the object is therefore preferred. Think of this as holding an umbrella in front of you when riding a bicycle.

Parameter	Viking	MPF	MER	Phoenix	MSL
Entry Mass (kg)	980	585	836	603	3257
Landed Mass (kg)	612	370	539	364	850
Mobile Mass (kg)	0	11	173	0	850
Aeroshell Diameter (m)	3.5	2.65	2.65	2.65	4.5
Parachute Diameter (m)	16.15	12.4	15.09	11.5	19.7
Mach 24 L/D	0.18	0	0	0	0.24
Landing Site Altitude (km)	-3.5	-1.5	-1.3	-3.5	+1.0

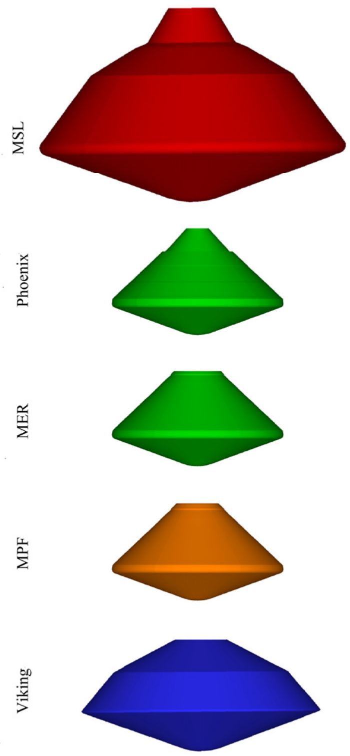


Figure 3.4.11 : Comparison of EDL technical data from all landed missions (Way et al., 2007)

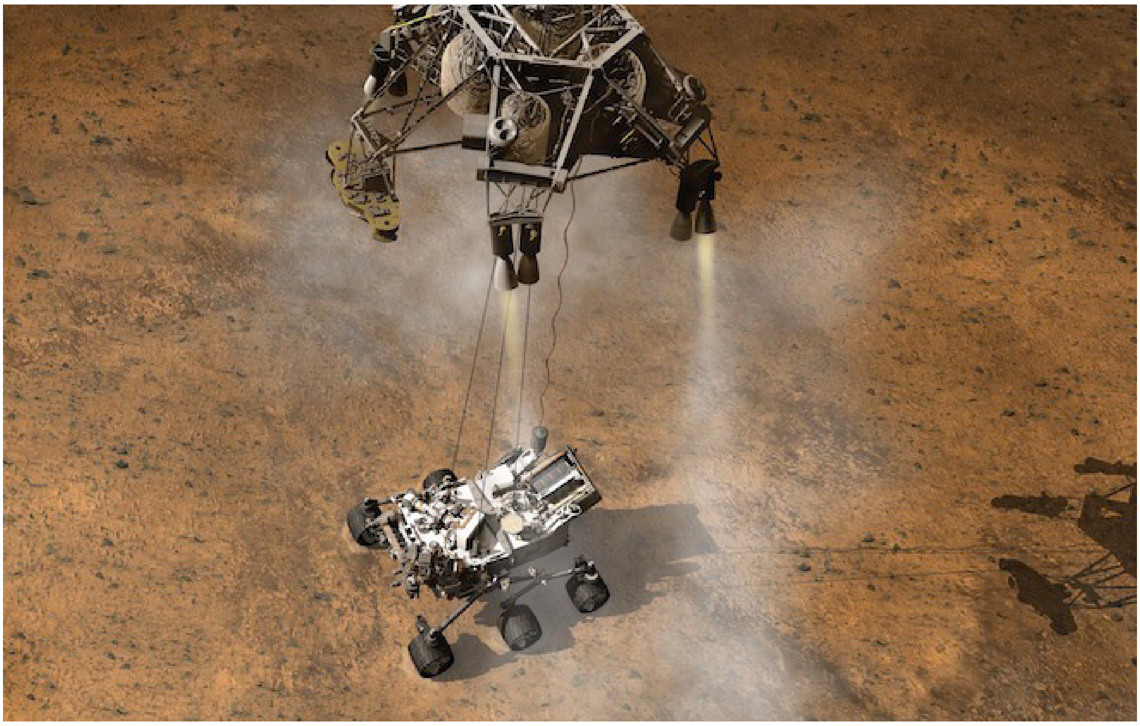


Figure 3.4.12 : Landing of MSL-rover Curiosity with retropropulsion technology (wikipedia, cc)

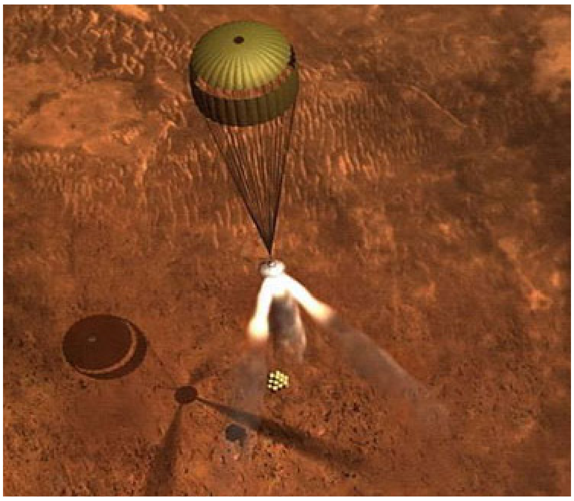


Figure 3.4.13. : Descent of MER-rovers Spirit and Opportunity with parachutes and retropropulsion technology. (Nat Geo Live, 2015)

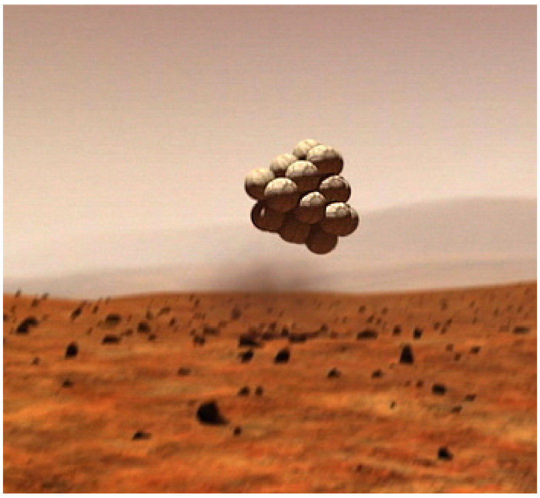


Figure 3.4.14. : Landing of MER-rovers Spirit and Opportunity with inflatable airbags. (Nat Geo Live, 2015)

In the field of aerospace, the increase or decrease in velocity is referred to as the ΔV (delta V). Various stages in the mission sequence have to consider a ΔV-budget. This means that within a stage, the system has to slow down or increase in a certain velocity. With aerobreaking during the Entry-stage, the ballistic coefficient plays a key role. The ballistic coefficient is defined as the ratio of mass over the dragcoefficient times the surface area. Lower ballistic coefficient systems dissipate energy at higher altitudes, increasing the landing sequence time line. (Meginnis et al., 2013) The formula is given as:

$$\beta = \frac{m}{C_D A}$$

After entry, thus after aerobreaking down to a different velocity, the object deploys it’s parachute for further decrease of the downrange velocity. Due to aerobreaking the heatshield is heated up to about 1600 °C. With the parachute deployed, the backshell is dropped to avoid heat transfer into the vehicle. This stage is referred to as the Descent stage within the EDL. (National Geographic, 2015)

In the past, several EDL strategies have been applied for surface missions to Mars. The mass of the cargo that has to be landed on the surface defines the best strategy for EDL. After the backshell drop, several alternatives can be chosen to descend and land the object. Until now, the largest mass that has ever been landed on the surface of Mars was the MSL Curiosity Rover with the total mass of 850 kg. (Figure 3.4.12)

The Mars Exploration Rovers, Spirit and Opportunity, were landed with a different EDL strategy. After the backshell drop, a retropropulsion system was fired to level the object. Then, the cargo was craned outside of the descent stage on an umbilical cord, airbags where inflated and when the height of approximately 40 metres was reached, the wires were cut and the object bounced to the surface. With each bounce, energy was dissipated until it came to a halt. The airbags were deflated and the system unfolded itself. The solar panels on the rover were opened and the rover drove off the lander to explore the surface. (National Geographic, 2015)

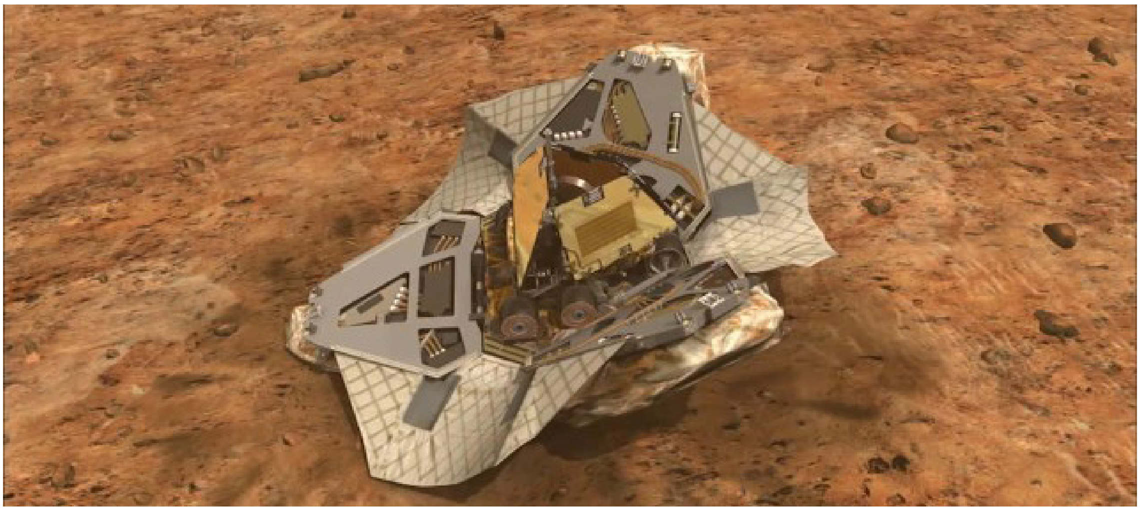


Figure 3.4.15. : Mechanical opening of tetrahedron with deflated airbags. The MER-rover is folded up inside and will deploy its solar arrays and antennas in the next stage of surface operations. (Nat Geo Live, 2015)

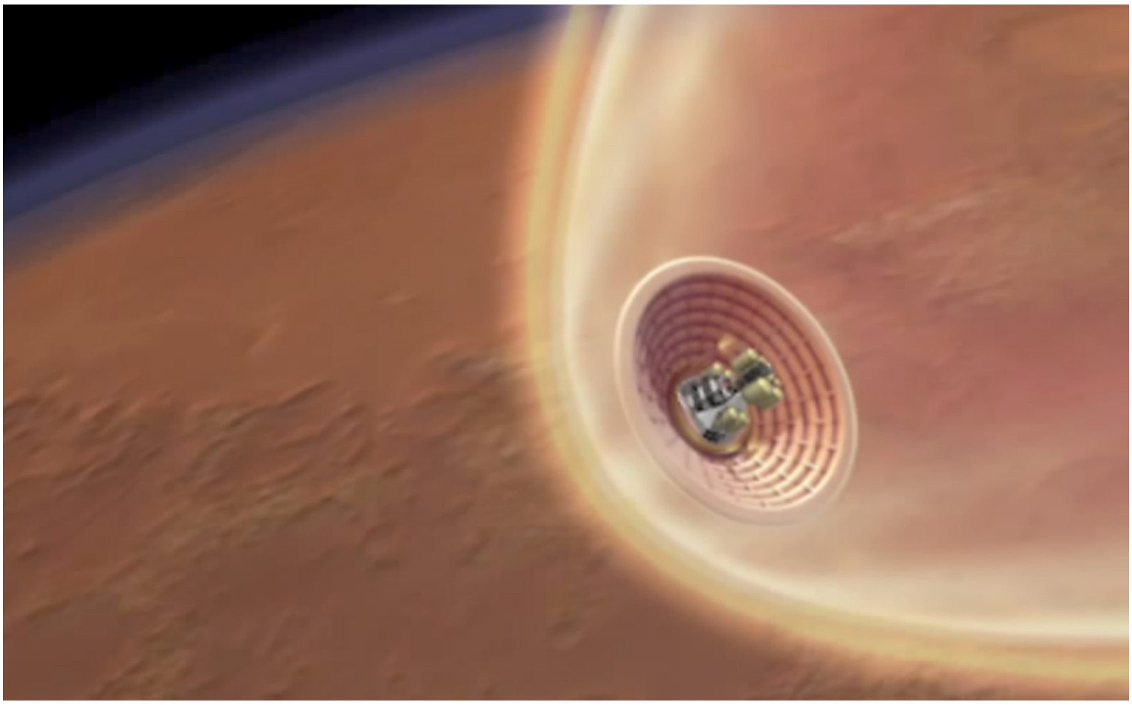


Figure 3.4.16 : Artist impression of atmospherice entry of the HIAD-technology (NASA)

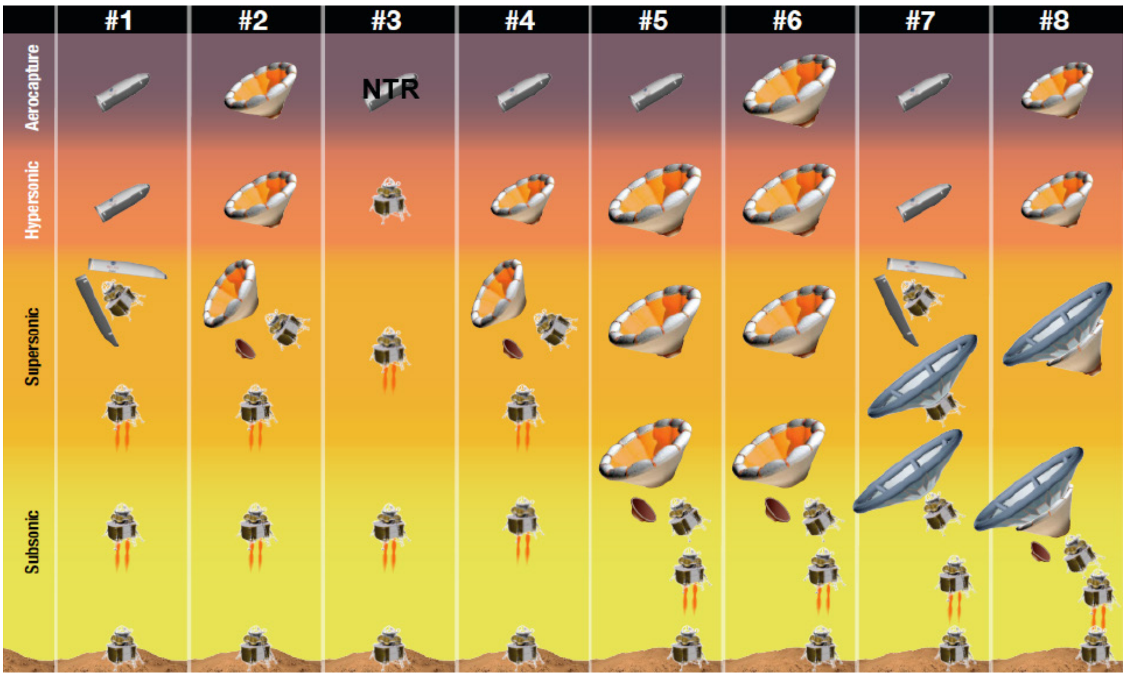


Figure 3.4.16 : Visualisation of the eight different EDL architectures (Dwyer-Ciancolo, 2010)

To land the habitat on Mars, the EDL strategy has to be taken in consideration for the constraints on mass and volume and the sequence of assembly. Limitations on mass and volume of the construction are therefore determining criteria that have to be met for feasibility of the deployment. For larger masses, an EDL sequence such as the ones applied for landing the Mars Exploration Rovers, Spirit and Opportunity, can be considered as it has proven it's succes in a prior mission. However, this strategy does not bring the object to an exact location as it is dependent of the direction in which it bounces. The EDL sequence of Curiosity has shown that it is also possible to navigate the object to an exact location with a correctly sized retropropulsion system.

After publication of DRA 5.0 in 2009, NASA performed a study in 2010 concerning EDL architecture for landing a human mission to Mars. Eight EDL architectures were evaluated on the potential of landing a mass of 40 metric tonnes. The sets of technologies were assessed on their overal performance, risk and feasibility. The second architecture came out as the most feasible and led to development of the Hypersonic Inflatable Aerodynamic Decelerator (HIAD). (Dwyer-Cianciolo et al., 2010)

NASA is currently still testing and developing the technology to get it to an approved EDL. The latest updates tell, that the HIAD is now flight proven on a lower scale model. Therefore it is currently estimated at TRL-6. (NASA EDL, 2017)

After EDL, the surface operations start. Due to the communications delay and black-out periods between Earth and Mars, the operational phase has to be planned thoroughly and not require to many sets of commands from Earth. For this reason the packed configuration of the surface systems is important to consider in the design. It was said that the operational commands to deploy the MER rovers took up to three weeks, before research could start on the surface. Configuration strategies for the HIAD EDL architecture are now under research and development. (NASA EDL, 2017)

	Aerocapture	**Hypersonic**	**Supersonic**	**Subsonic**
Architecture 1	Rigid Mid-L/D AS	Rigid Mid-L/D AS	Propulsion	Propulsion
Architecture 2	Lifting HIAD	Lifting HIAD	Propulsion	Propulsion
Architecture 3	N/A	Propulsion	Propulsion	Propulsion
Architecture 4	Rigid Mid-L/D AS	Lifting HIAD	Propulsion	Propulsion
Architecture 5	Rigid Mid-L/D AS	Lifting HIAD	Same LHIAD	Propulsion
Architecture 6	Lifting HIAD	Lifting HIAD	Same LHIAD	Propulsion
Architecture 7	Rigid Mid-L/D AS	Rigid Mid-L/D AS	Drag SIAD	Propulsion
Architecture 8	Lifting HIAD	Lifting HIAD	LSIAD–Skirt	Propulsion

Table 3.4.1. : Simplified Set of Technologies considered as EDL System Architectures (Dwyer-Ciancolo, 2010)

Figure 3.4.17. : Packed configuration of MER-rovers Spirit and Opportunity (Braun et al.,)

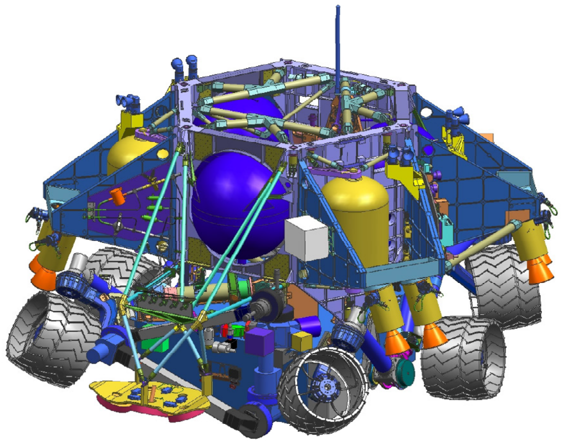


Figure 3.4.18. : Packed configuration of MSL-rover Curiosity (Way et al., 2012)

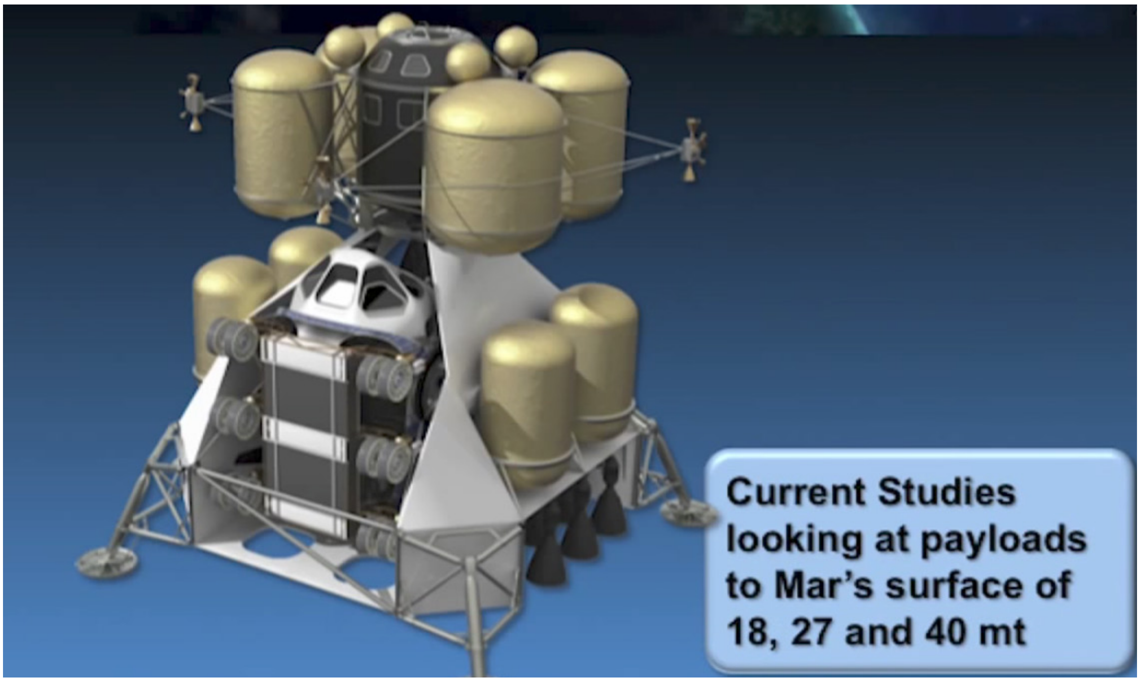


Figure 3.4.19 : Possible configuration of the first cargo lander (NASA EDL, 2017)

3.4.3. MASS REDUCTION

Mass is often referred to as the currency of space missions. The required cargo for the mission defines the injected mass into Low-Earth Orbit (IMLEO). Reducing mass would result in reducing costs, therefore increasing the feasibility of the mission. Landau and Longuski (2009) performed a comparative assessment of human-Mars mission technologies and architectures. Though the mission design space was modeled along two dimensions: trajectory architecture and propulsion system technologies, the paper also addressed the mission sensitivities. The mission sensitivity was examined to crew size, vehicle masses, and crew travel time. The objective was to determine which combinations provide the greatest potential reduction in the Injected Mass to LEO (IMLEO).

It was found that mission designs based on re-usablility of the transferring spacecraft, require the least IMLEO of any other architecture. In other words, the major gain in a mission design is when the descend or ascent of mass, on either Earth or Mars, can be avoided as much as possible. Landau (2009, p.893) states:

> *"... when a new technology or architecture is applied to a given mission, the fundamental benefit is a reduction in mass (provided the crew, payload, vehicles, and mission timeline are held constant)."*

While most proposals from the aerospace industry focus on the mission trajectory to safe on fuel, it is often high lighted that In Situ Resource Utilization (ISRU) would result in mass reduction for propellant loads. The habitat proposals from the aerospace industry do not elaborate on ISRU as an option for habitat construction on the surface. Mostly habitat modules for in space travel are discussed. Research in the field of ISRU habitat construction, thus materialization with indigenous materials, could result in mass reduction for cargo. Adapting generative manufacturing methods for the building industry is a relatively new and unfortunately, a barely utilized concept. (Knaack et al., 2010)

NASA's strategy document Journey to Mars tells that NASA has started with developing and testing habitat systems for Mars on Earth. Tests have been done with inflatable, pressurized cabins on the ISS, developed by the company Bigelow. (BEAM, 2016) The objective is to develop a modular pressurized volume that would enable extended stays by crews of four arriving with Orion. The first inflatable habitat concepts have been developed and tested by NASA in 2001 under the name TransHab. (Kennedy, 2002)

Humans would not be sent to Mars if risks are not defined. For this reason, technologies need to have been tested and validated before a manned mission to Mars would occur. The transportation technologies are well under way. Therefore, the need for development of mission surface stay technologies, such as the surface habitat, is rapidly increasing.

3.4.4. IN-SITU RESOURCE UTILIZATION

In literature it is often assumed that In-Situ Resource Utilization (ISRU) on Mars would bring major cost benefits for mission architectures. The cost to deliver mass to Low Earth Orbit is roughly estimated around 22,000,000 USD per metric ton in 2012 dollars. (Rapp, 2007) This translates to approximately 22,000 EUR in 2016 to launch 1 kilogram of mass into space. However, in literature the performed studies on cost reduction often do need seem to consider the cost of prospecting, developing, testing and implementing ISRU. (Rapp, 2007)

For a long time, research in the field of ISRU has not been prioritised in the aerospace industry. With the NASA decision of 2004–2005 to return humans to the Moon, ISRU received new life and significant new funds began to pour in for ISRU development. (Rapp, 2007) Recent recommendations by NASA for ISRU related research for habitat design suggest to develop a light-weight inflatable habitat with molded-in airlocks and furniture, to explore fabrication at 0,38g, to develop construction methodologies with autonomous robotics and to find solutions for the corrosiveness of Mars dust at interior habitat conditions. Published news on design developments from Foster&Partners, Clouds AO and testing of the BEAM on ISS prove that NASA has already started on this research.

Further research in the area of extracting ice, especially for supporting life, was also recommended by NASA. (Moses et al., 2016) An assessment of Mars ISRU for mining ice was presented by NASA in July 2016. The analysis indicates that use of terrestrial ice excavation techniques to generate a source of liquid water from presumptive Martian glaciers has promise for an operational system on Mars. However, the analytical results still require validation through testing with a functional prototype. (Abbud-Madrid et al., 2016) Recently, NASA has held a new research design competition to develop this prototype and send it to Mars with the next 2020 rover. (NASA RASC-AL, 2017)

The M-WIP study further suggests to first gather as much data as possible with an orbiter, than send a robotic lander to gather even more on site information and test some inital technologies. Finally, the data that is gathered by the rover on site, will serve as input for the architecture of a human mission to Mars. (Abbud-Madrid et al., 2016)

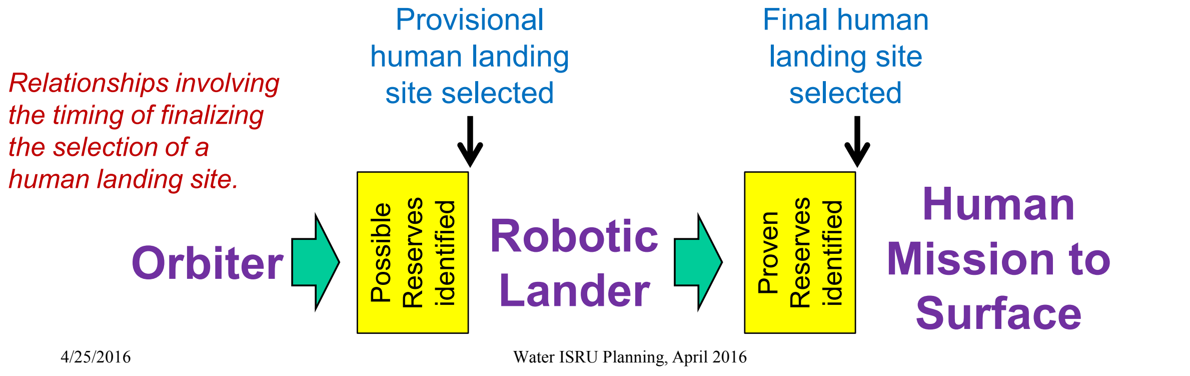


Figure 3.4.20 : An orbiter and lander will serve as precursor missions prior to the human mission (M-WIP, 2016)

3.5 LOCATION

3.5.1. LOCATION SELECTION

To select a suitable exploration zone for Mars several aspects have to be taken in consideration. In October 2015, NASA held a first workshop in which the most promising sites for human exploration on Mars were selected. 178 landing sites were selected and assessed on several values. The paper defines Exploration Zones (EZ) and Regions of Interest (ROI) for scientific research performed by humans. An EZ is a collection of ROIs located within a range of approximately 100 kilometres of a centralized landing site. ROIs are areas relevant for scientific investigation and/or development/ maturation of capabilities and resources necessary for a sustained human presence. The EZ also contains one or more landing sites and a habitation site that will be used by multiple human crews during missions to explore and utilize the ROIs within the EZ. (Bussey, 2016)

Mitigation in radiation exposure and a reduction in mass with ISRU technology increase feasibility for a human mission to Mars. Radiation shielding and ISRU both benefit from use of hydrogen rich materials. It is therefore strongly recommended to search for locations where hydrogen is abundant. (Rapp, 2007) Bussey (2016) suggests that the resource feedstock for water must be of a size that is sufficient to support several needs for a human mission. To meet these needs a quantity of water approaching 20,000 kg must be produced for each crew member. If the raw material is in the form of hydrated minerals, then it must have a potential for a high concentration, which means the hydrogen content in the soil must be greater than 5% by weight. (Bussey, 2015)

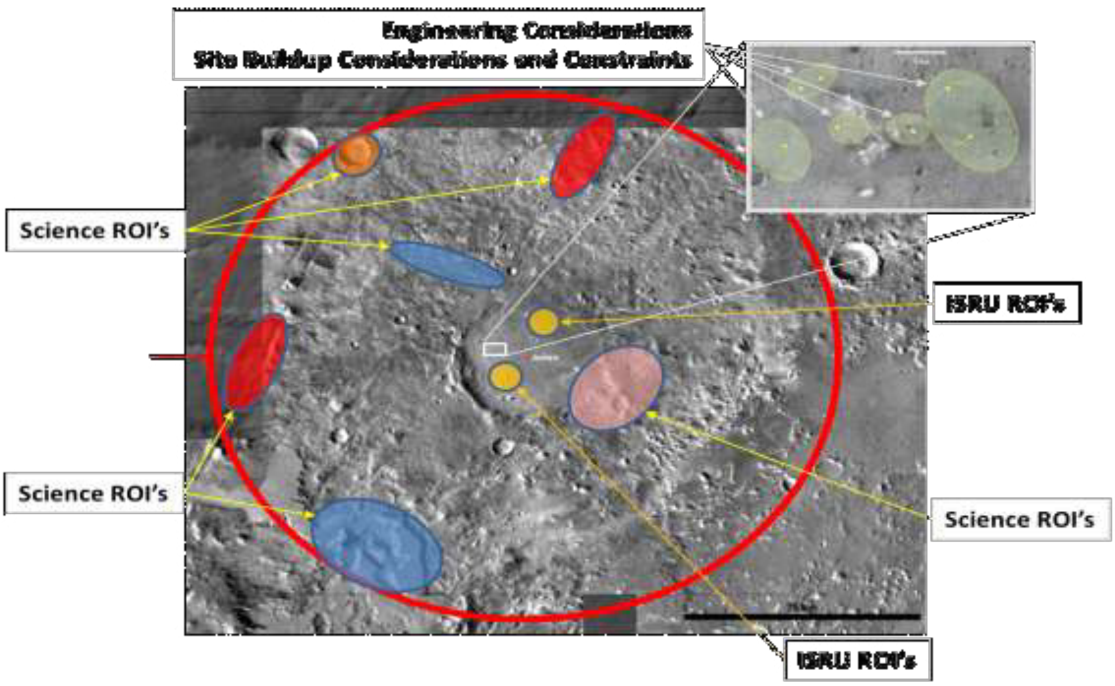


Figure 3.5.1 : Example of an Exploration Zone (EZ) with identified Regions of Interest (ROI's) (Bussey, 2016)

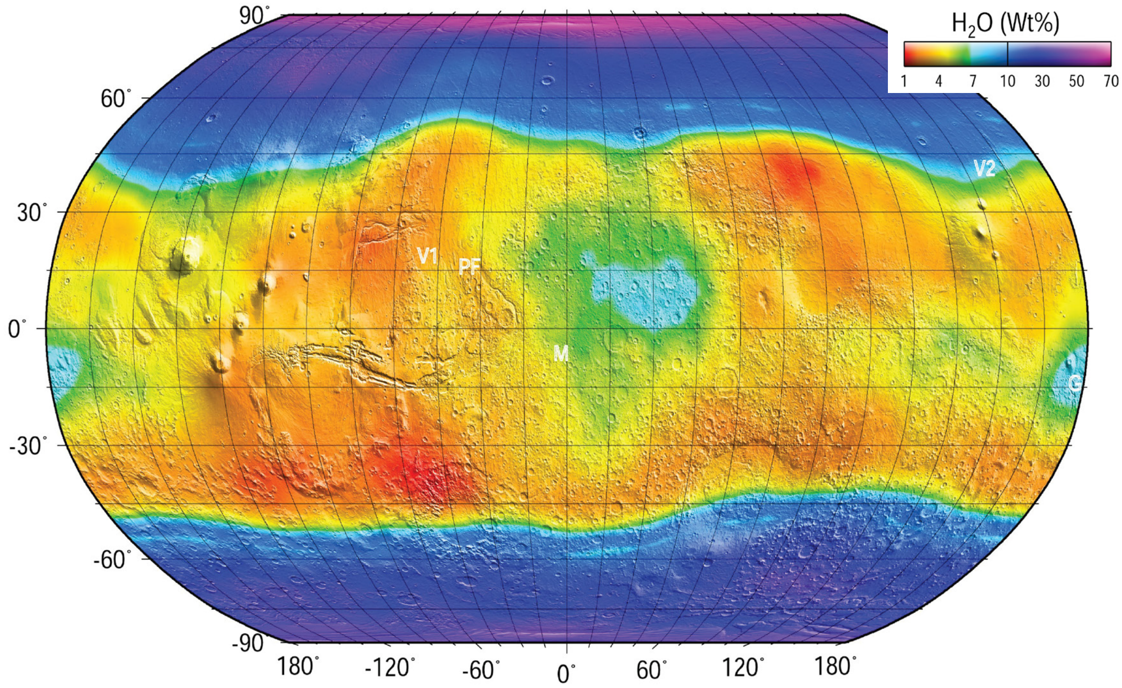


Figure 3.5.2 : Map of Mars' surface with indication of hydrogen rich locations in relation to latitude and longitude. Hydrogen content in the soil should be more than 5% by weight according to Bussey (2016).

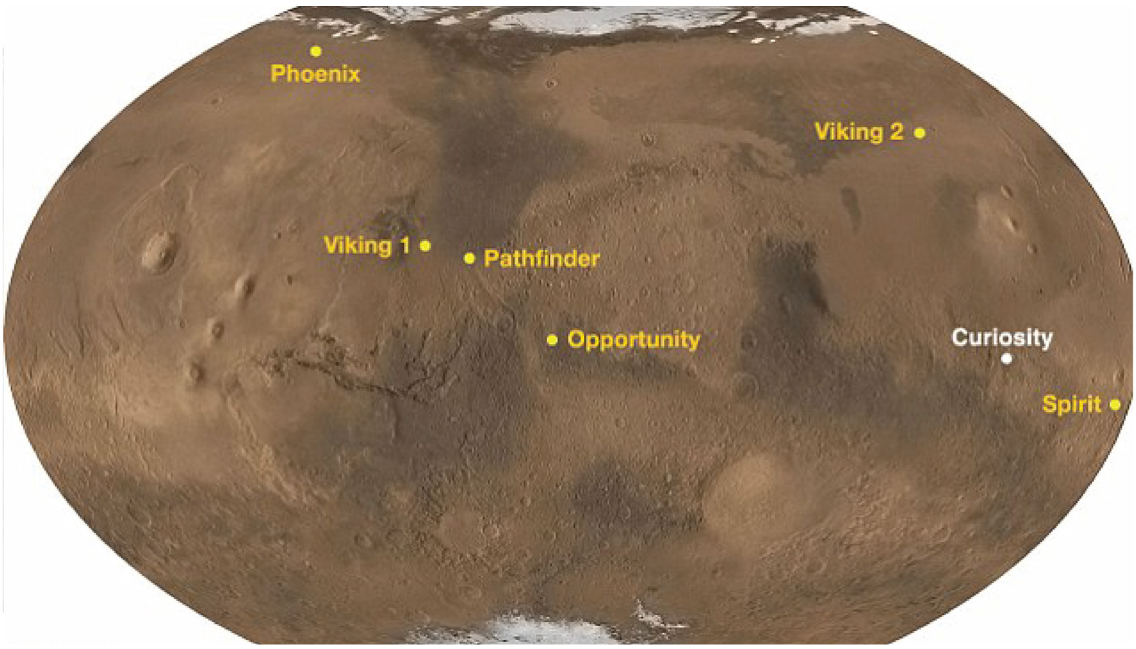


Figure 3.5.3 : Locations of past surface missions on Mars

Also important for location selection is the latitude of the location. A long term surface stay is assumed, which means the crew will be staying during several seasons on Mars. Closer to the equator it would require less propellant to launch a Mars Ascent Vehicle (MAV) back into orbit. However, closer to the equator no ice has been detected in previous studies, apart from a few exceptions. For this reason, the preferred latitudes range from 20 to 50 degrees where a minimal distance to the equator is highly preferable.

A location closer to the equator is also preferred to maximise effective solar irradiation. Solar panels are often considered as a potential power source. Unfortunately solar panels can get covered by dust. Dusty regions on Mars would bring many implications for a mission. Dust storms can lead to obstructed vision and pollution of equipment. The MSL-rover Curiosity has witnessed dust devils on the surface. These wind swirls have proven to be beneficial for cleaning the panels, leading to a longer life expectancy of the rover, as Curiosity is still active today. (National Geographic, 2015)

The Entry, Descent and Landing technology (EDL), to land a vehicle on the surface of Mars, needs further refinement to increase current chances of success. In order to extend landing duration, it is suggested to land the vehicle on a location with an altitude lower than 2 km from the surface. Therefore, the altitude of the site is another important aspect to consider.

Previous rover missions to Mars, have also done location selection studies. Past surface missions are a reliable source for information of the site. A landing site for a rover proves to have been profoundly researched so the rover can drive there, meaning that there is a maximum slope of 10 degrees. Construction of the habitat is also easier to be done on planar sites. Also, a human mission scenario often includes the requirement for surface mobility. (DRA 5.0, 2009)

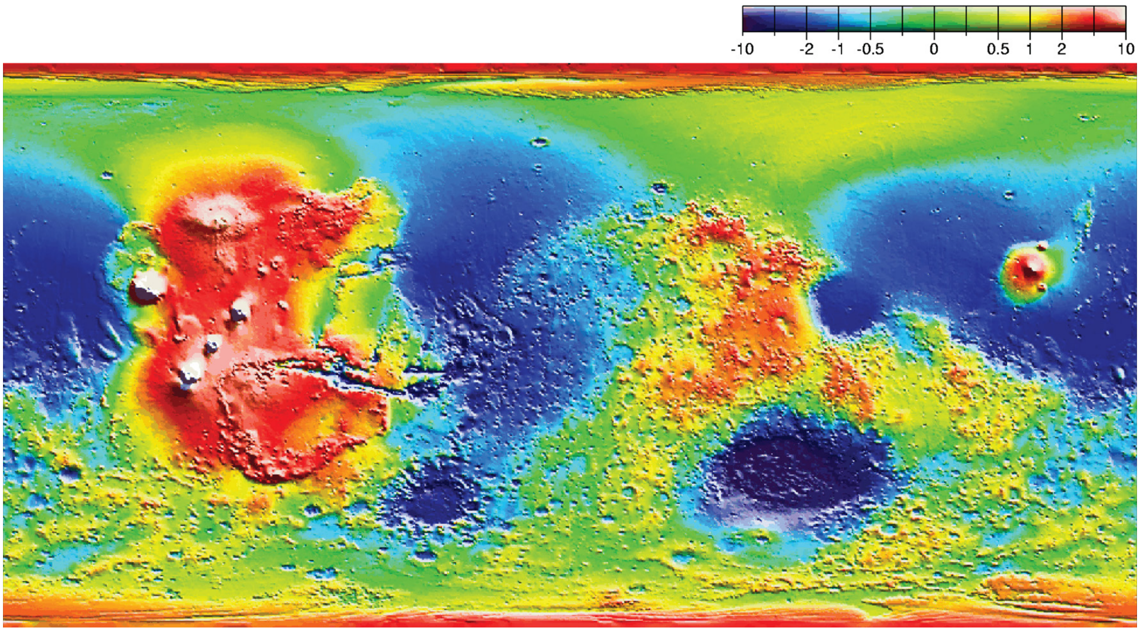


Figure 3.5.4 : Map with altitude variations on Mars in kilometers (km)

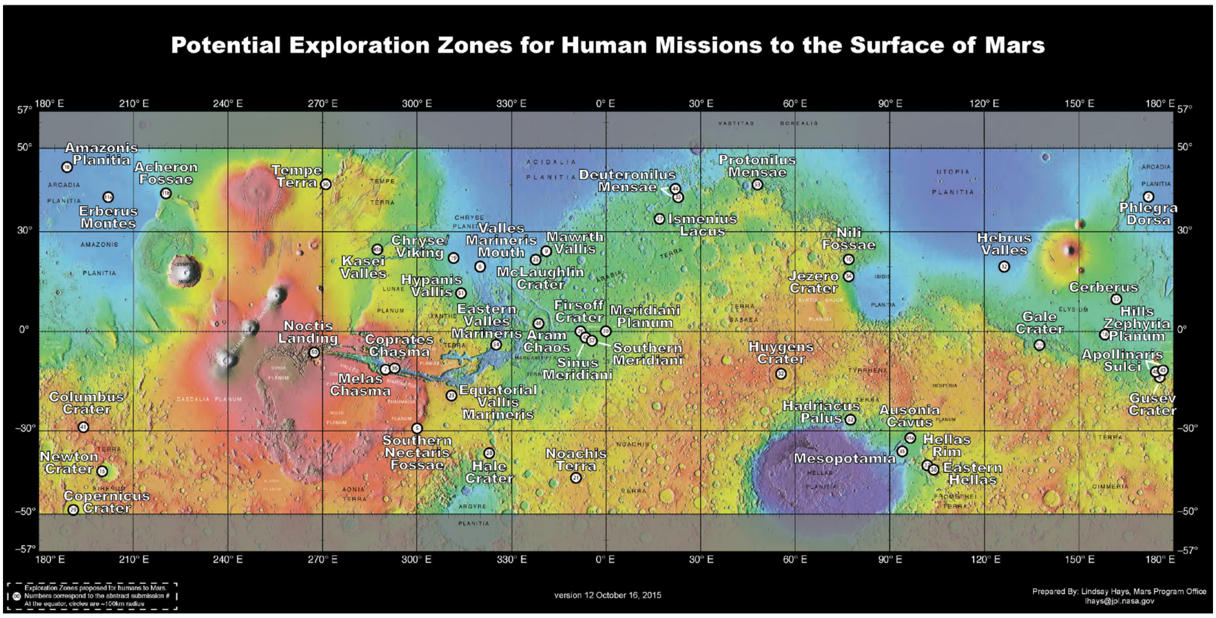


Figure 3.5.5. : Locations that were investigated during the Human Landingsite Selection workshop (HLS2, 2016)

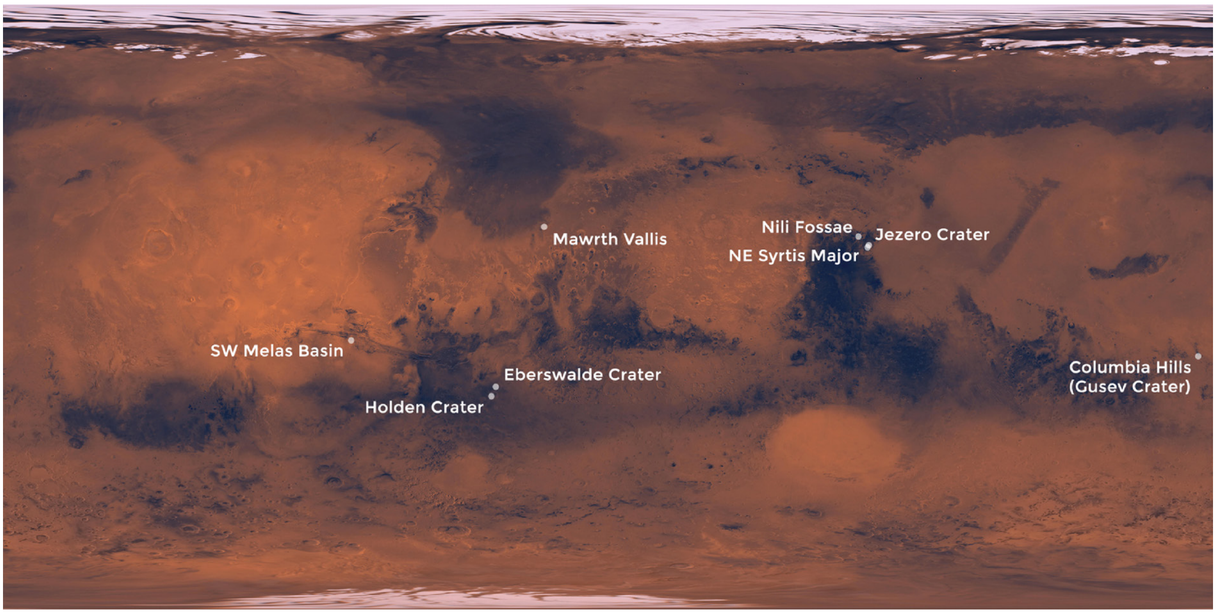


Figure 3.5.6. : Weighed alternatives for the next landing site of the Mars 2020 Rover (NASA)

Currently, both NASA and ESA are planning new rover missions in 2020 under the name Mars2020 and ExoMars. (Wikipedia, 2017) NASA's Mars2020 Rover will also test the feasibility of an intial ISRU-technology called MOXIE. (NASA Mars2020, 2017) MOXIE generates oxygen from carbondioxide and is designed to be scaled up for future human missions. (Hecht et al. 2016) The preferred location for Mars2020 is currently to land in Jezero Crater. When selecting the site of Jezero Crater for Mars2020, all of the criteria mentioned above were also considered by the selecting team. (JPL, 2017) For this reason, Jezero Crater will be the assumed location in this research.

3.5.2. JEZERO CRATER

Jezero Crater is located on the martian coordinates 18.8N77.5E, within the Nili Fossae region. The site offers interesting exploration zones within NASA's strategy to "follow the water". Based on geological evidence, the crater is thought to have been wet twice in the history of the planet. It is roughly 45 km in diameter and is thought to have formed due to impact of a large meteoroid. The site offers many Regions of Interest (ROIs) for exploration. The soil was measured to contain large deposits of Mg-carbonates and other elements relevant for ISRU. (Goudge et al., 2017)

The online Mars Climate Database gives a lot of information on the location. It is found that the surface temperature fluctuates between -85 °C and 0 °C. The surface pressure fluctuates between 708 and 714 Pa. (Mars Climate Database, 2017) It is situated at an elevation of -2.5 km.

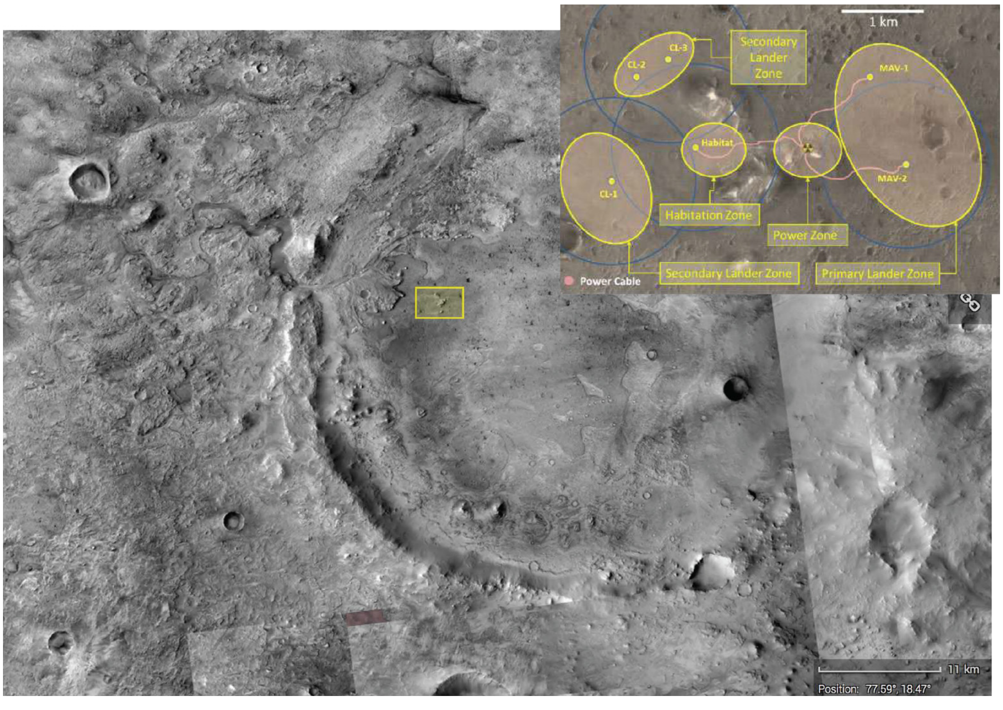


Figure 3.5.7. : Jezero Crater is the selected landing site for the Mars 2020 Rover and also considered as a potential site for a human mission.

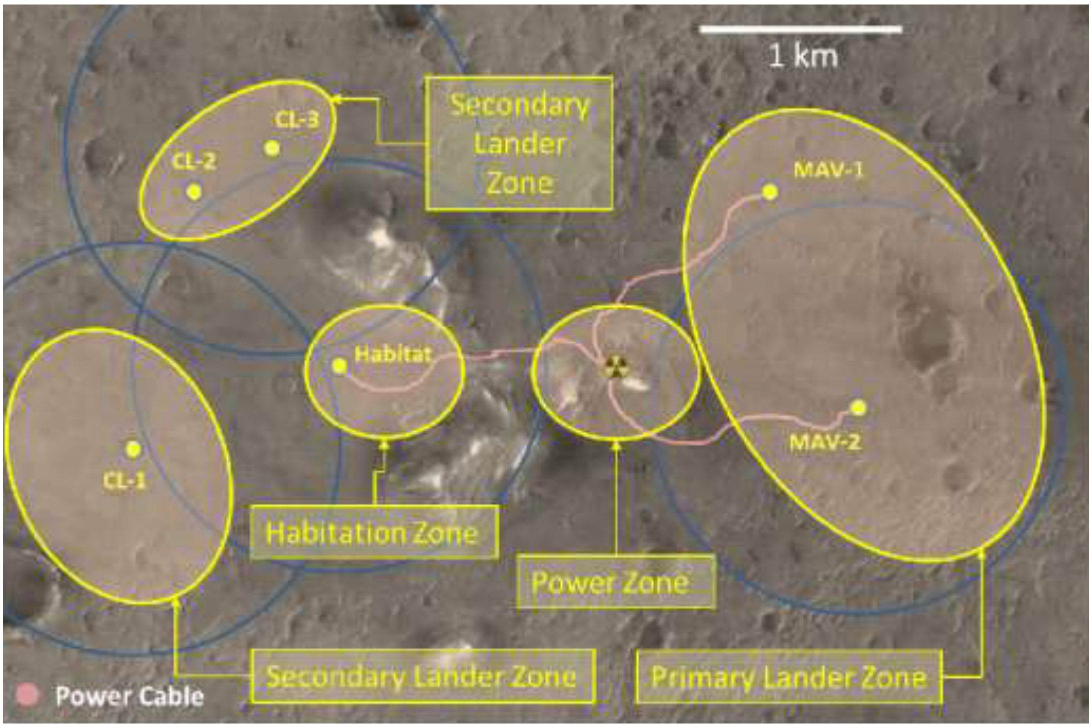


Figure 3.5.8. : Example of a possible site configuration for a human mission to Jezero Crater (Bussey, 2016)

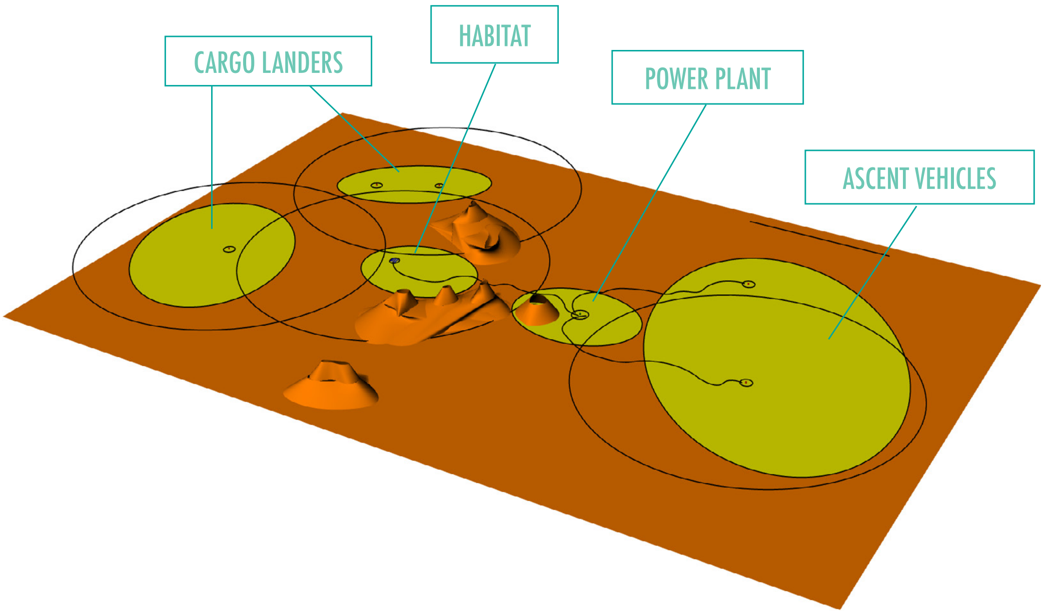


Figure 3.5.9. : 3D visualisation of site configuration for a human mission to Jezero Crater

3.5.3. BASE ELEMENTS

The Human Landing Site selection workshop organized by NASA in 2015, prescribed a design for the lay-out of the base. (Bussey, 2016) Elements for the base that have to be considered are the landing ellipses for cargo landers (CL), a surface habitat system (S-HAB), Mars Ascent Vehicles (MAV) to transport the crew back to orbit for their return trip and a power plant. The power plant should also be considered as a potential ISRU plant that could generate fuel for the MAV's to ascent back to orbit.

Concerning the power plant, a study on Solar Power versus Fission Power Units (FPU) for a human surface mission to Mars showed that FPU's were a preferred option considering the mass efficiency. (Rucker et al., 2016) However, the FPU will have to be placed at a safe distance of app. 1 km from the surface habitat, preferably behind a hill or mountain. Figure 3.5.10. shows the design of the FPU that is currently considered in line with the DRA 5.0. Both cargo landers are assumed to bring a 40 kW power plant that will power all vehicles and other surface systems. (Rucker, 2016) During the mission's operational phase the habitat's systems will also have to meet this maximum power demand.

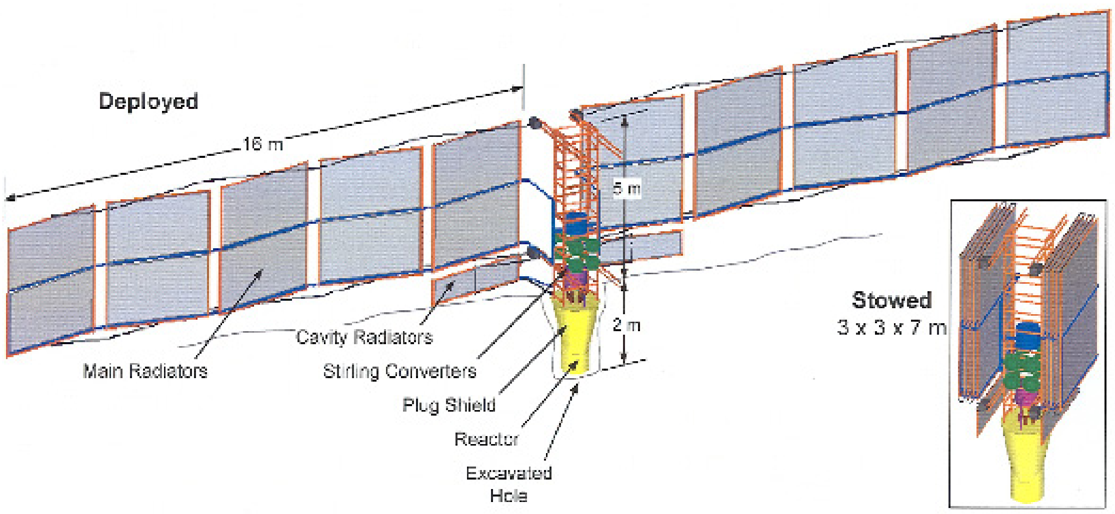


Figure 3.5.10 : Design of a 40 kW Fission Power Unit (FPU) (Rucker et al., 2016)

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**

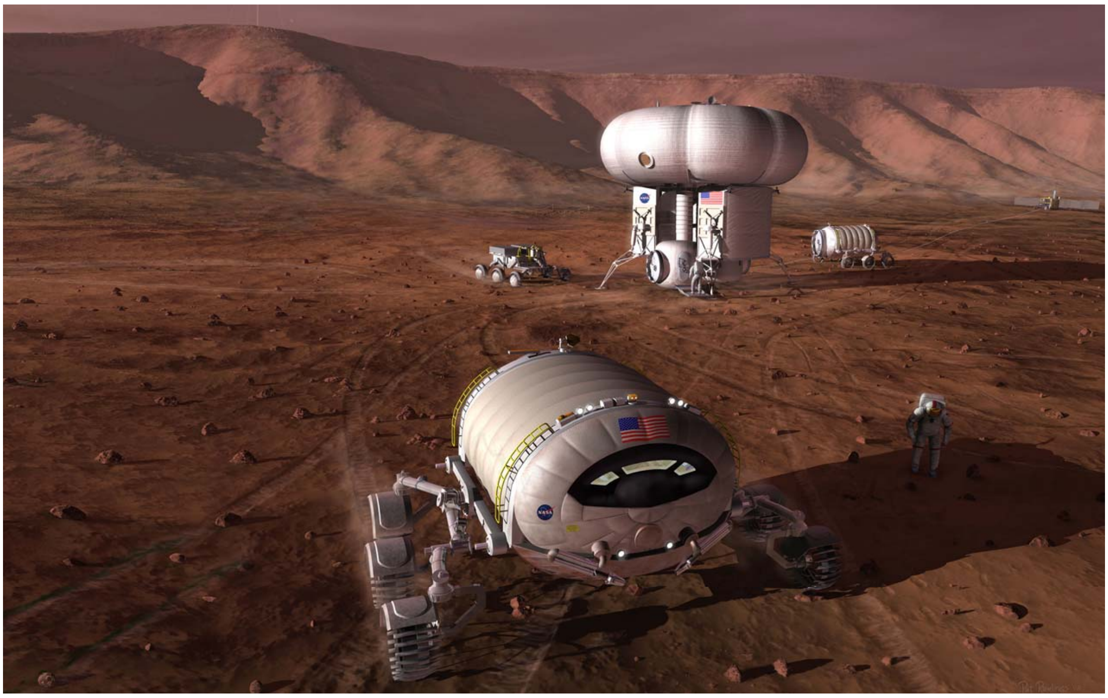


Figure 3.5.11. : Visualisation and mass estimation of Design Reference Architecture (DRA 5.0, 2009)

3.5.4. HABITAT MASS

Reduction of mass could be achieved with development of In Situ Resource Utilization (ISRU) technologies. ISRU can provide in water, oxygen, fuel and construction materials that would cut drastically in the mass-budget. (Rapp, 2012) Current transportation technologies have the capability to transport 75 mt, and future technologies to carry 130 mt are under development. (JTM, 2015) The question is, what the amount is of the allocated mass for a Martian surface habitat.

Landau (2009) names the constraints of the mission architecture in a comparative assessment. Vehicle, consumables and cargo masses are specified in terms of mt/person. Cargo is varied from 0-10 mt/ person. Cargo includes the surface habitat, laboratory, power system, etc. but not the consumables (food, air, water). A mission with no cargo implies that there are sufficient resources on the surface of Mars from previous missions. The crew requires 5 kg/day/person of consumables (derived from Zubrin's Mars Direct and NASA's DRA 5.0). If ISRU is assumed at Mars, then only 2 kg/day/person are required from Earth. The remaining 3 kg/day/person is water and oxygen produced at Mars (e.g. from a hydrogen feedstock or water excavation). (Landau, 2009) In this study it is unclear what mass is allocated to the surface hab, but the assumption does not exceed 40 metric tonnes, in line with the HIAD.

Zubrin (2011) also provides specifications in terms of metric tonnes. In the Mars Direct mission proposal a crew of four is assumed. Allocated mass for the surface habitat is divided in 14 elements that all add up to 25.2 mt. Mars Direct allocates 5 mt for the entire habitat structure. This presents some reference data for current feasibility of a manned Mars mission. The latest update relies on an architecture where a habitat module is landed on the surface and can then be further deployed.

The DRA 5.0 allocates a mass for the entire habitat of 16,5 mt and a mass of 5 mt for the expansion of the habitat module. The allocated mass of 16,5 mt is in this case not further specified into subcomponents. In NASA's design manuals a reference value for surface habitats can not be found. When architecture is mentioned it often refers to the design of either the spaceship or the mission and it's trajectory. In the Human Integration Design Handbook (HIDH) there are some dimensions specified that define the minimum space that needs to be reserved in a spaceship for humans to perform certain activities. However, most of them are based on a situation of reduced gravity, therefor there is no need for the humans to perform the activities in an upright position. (HIDH, 2010)

A recent study on the development of the Transit Habitat provided more insight in the categories and sub-systems with their allocated masses. The study summarises a list, which can be found in Appendix C. (Simon et al., 2017)

In short, from the found references for the allocated masses for the surface habitat structure and the findings that the HIAD is currently in an advanced stage of technology development, it can be concluded that the surface habitat cargo should not exceed 40 mt at most. Considering that the DRA 5.0 assumes a single cargo landing of 40 mt that has to carry the S-HAB, SEV and the second Power Unit a total mass assumption of 30 mt is preferred.

Functional Category	MASS, kg	OFFLOADED MASS, %	OFFLOADED MASS, kg	LAUNCHED MASS, kg
BODY STRUCTURES	7,361	0%	0	7,361
CONNECTION & SEPARATION SYSTEMS	649	0%	0	649
LAUNCH/TAKEOFF & LANDING SUPPORT SYSTEMS	656	0%	0	656
NATURAL & INDUCED ENVIRON PROTECT SYSTEMS	680	0%	0	680
PROPULSION SYSTEMS				
POWER SYSTEMS	1,231	0%	0	1,231
COMMAND & DATA HANDLING (C&DH) SYSTEMS	131	0%	0	131
GUIDANCE, NAVIGATION, AND CONTROL (GN&C) SYSTEMS	33	0%	0	33
COMMUNICATIONS & TRACKING (C&T) SYSTEMS	210	0%	0	210
CREW DISPLAYS & CONTROLS	76	0%	0	76
THERMAL CONTROL SYSTEMS	1,811	0%	0	1,811
ENVIRONMENTAL CONTROL SYSTEMS (ECS)	1,078	0%	0	1,078
CREW/HABITATION SUPPORT SYSTEMS	2,324	15%	340	1,984
EXTRAVEHICULAR ACTIVITY (EVA) SYSTEMS	1,121	100%	1,121	0
IN-SITU RESOURCE ACQUISITION & CONSUMABLES PRODUCTION SYSTEMS				
IN-SPACE MANUFACTURING & ASSEMBLY SYSTEMS				
MAINTENANCE & REPAIR SYSTEMS	363	100%	363	0
PAYLOAD PROVISIONS	3,732	0%	0	3,732
ABORT & DESTRUCT SYSTEMS				
MANUFACTURER'S EMPTY MASS	21,455			19,632
OPERATIONAL ITEMS - MISSION KITTED OR STOWED	1,896	100%	1,896	0
OPERATIONAL ITEMS - EQUIPMENT SPARES & PACKAGING	14,353	100%	14,353	0
OPERATIONAL ITEMS - CONSUMABLES & PACKAGING	6,082	100%	6,082	0
OPERATIONAL ITEMS - CREW				
OPERATIONAL EMPTY MASS	43,786			19,632
PAYLOAD	1,542	100%	1,542	0
EXPENDABLES - POWER AND THERMAL CONTROL FLUIDS/GASES				
EXPENDABLES - PROPULSION & REACTION CONTROL FLUIDS/GASES				
GROSS MASS at TMI	45,329	MINIMUM EMPTY MASS		19,632

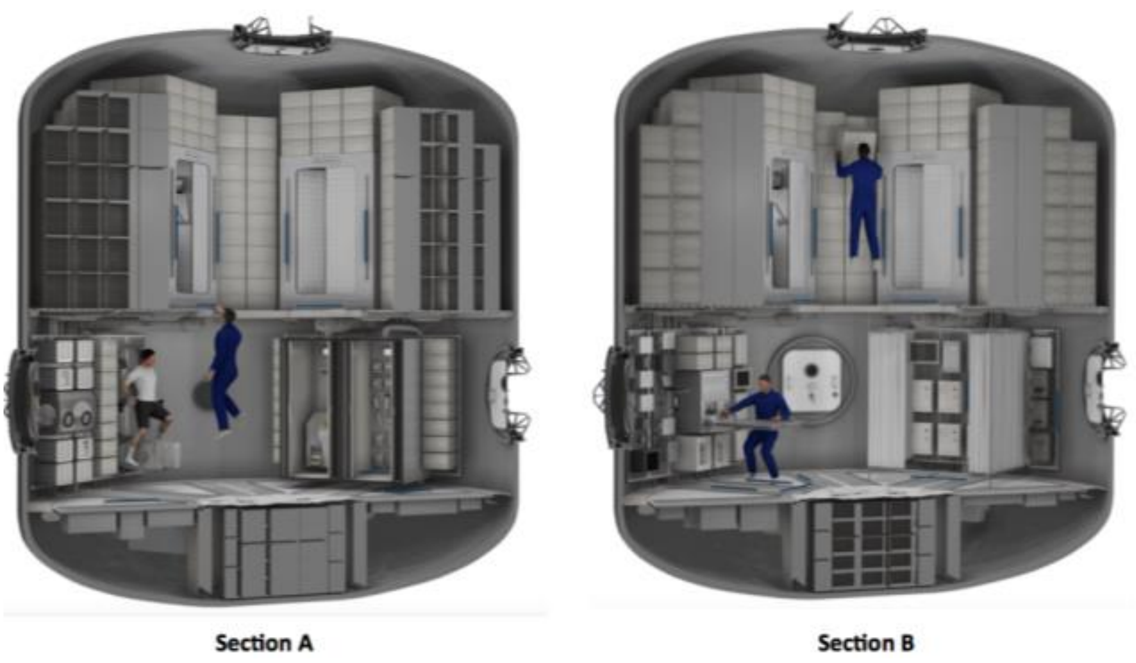


Figure 3.5.12. : Visualisation and mass estimation of Transit Habitat (Simon et al., 2017)

3.6 QUANTITATIVE CRITERIA

3.6.1. REQUIREMENTS DEFINITION

Mission design starts with formulating goals and objectives, then developing mission scenarios with system drivers for decision making and finally with formulating performance criteria. Based on the findings in this chapter, the DRA 5.0 mission proposal will be assumed as a mission baseline. The EDL that is assumed is the HIAD as any other technology, could not possibly meet the mass and volumetric budgets for a surface habitat. The chosen location based on research will be Jezero Crater. These preliminary assumptions aid in defining the technical performance criteria, or quantitative requirements, for the surface habitat. The six requirements, enhold, but are not limited to budgets for mass, volume, power and construction time, as well as location characteristics and technology readiness levels of all habitat systems.

MASS
A maximum allowable mass of 40 metric tonnes is assumed for the habitat as it has to fit the EDL design of the HIAD. Though 30 mt is the preferred option, since the Cargo Lander is assumed to additionally land a second SEV and a second FPU, research findings did not deem this to be feasible. A simplified design for the Transit habitat was calculated to exceed the 40 mt and the surface habitat is thought to be a larger system as it will be placed in partial gravity instead of micro-gravity.

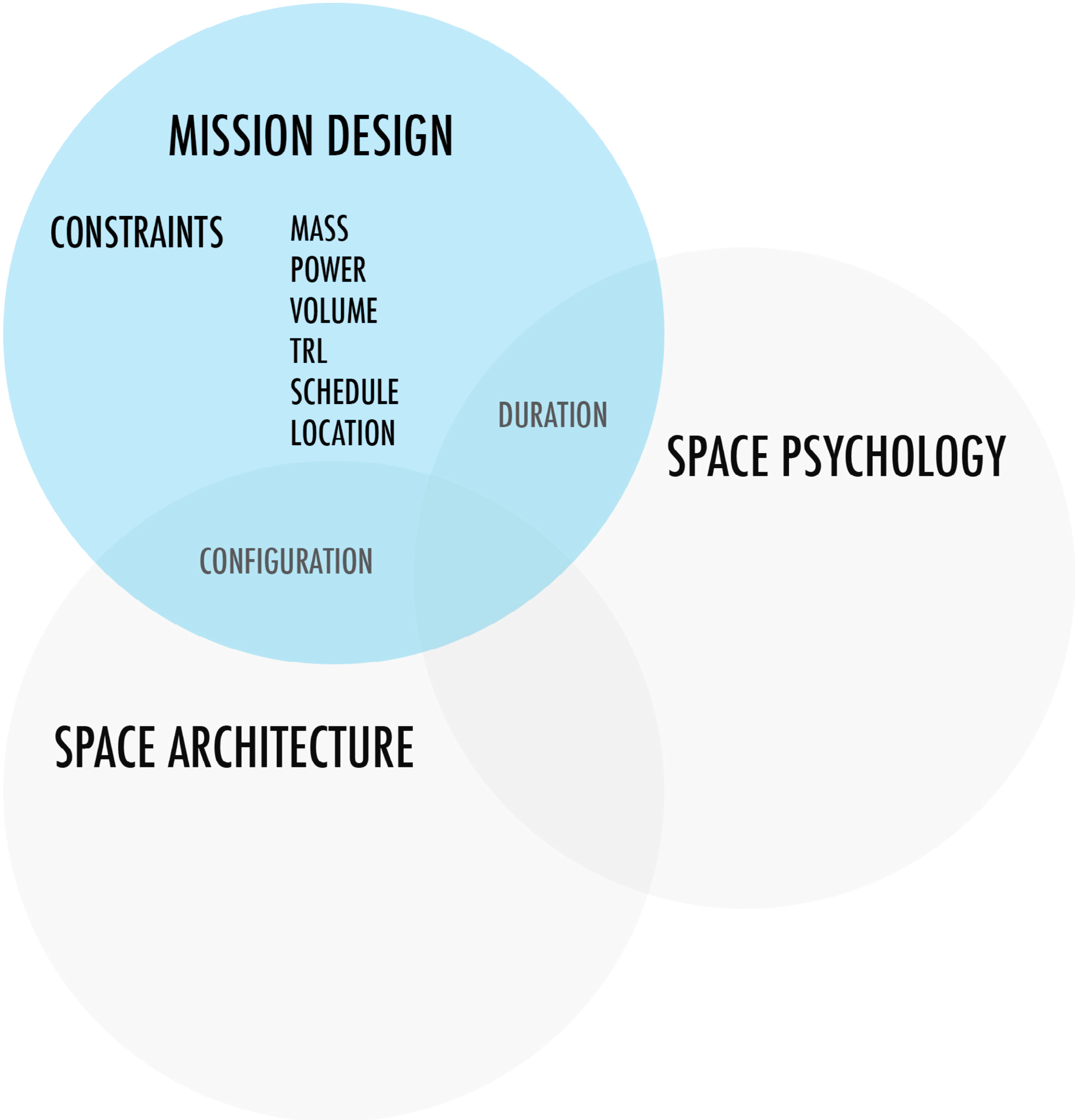
VOLUME
In it's packed configuration the payload will have to meet the dimensions for the SLS Block 2. These dimensions have a maximum diameter of either 8 or 10 m. The height is point for discussion as the habitat will form part of the total cargo fairing with several sub-systems. The cargo payload is estimated to have a maximum height of 31 m. Therefore the packed configuration of the hab will have to be a lot shorter, as it has to fit the EDL technology architecture of the HIAD with its packed configuration.

TIME
The schedule for habitat deployment and construction is assumed to not exceed 18 months. Due to the communications delay between Earth and Mars, ranging from 20 to 40 minutes, the habitat should be deployed with a minimum amounts of commands.

TRL
With risk as a system driver, the habitat systems should primarily consist of proven technologies. For this reason, the TRL for all subsystems should not be lower than TRL-6 “Proven in a Relevant Environment”.

LOCATION
The chosen location is Jezero Crater. Based on the location characteristics assumptions can be made for application of ISRU and local site characteristics and climate conditions.

POWER
The maximum power budget for both construction as during the human mission operations shall not exceed 40 kW.


MISSION DESIGN
CONSTRAINTS
MASS
POWER
VOLUME
TRL
SCHEDULE
LOCATION
DURATION
SPACE PSYCHOLOGY
CONFIGURATION
SPACE ARCHITECTURE

3.7 SUMMARY AND CONCLUSION

3.7.1. SUMMARY

Mission goals drive the mission duration and objectives. After the goals and objectives, the EDL and Behavioral Health & Performance, especially risks for radiation, are the biggest quantifiable risks for a human mission to Mars that have to be mitigated. However, for this research radiation is further left out of scope. The longer surface stay option is preferred to mitigate radiation exposure risks. Also psychological risks have to be mitigated.

The first four of the nine steps from the SMAD have been covered by NASA's findings in the past years. The system driver for the mission design from the perspective of the space architect has been defined as risk, meaning that the quantifiable risks of radiation and configuration for EDL have to be mitigated by the system design of the surface habitat. NASA is currently working on a larger EDL technology to bring humans to Mars under the name HIAD, estimated to be at TRL 6 Prototype Demonstration in a Relevant Environment.

Planning is important for mission operations, as the relatively simple task of unpacking the MER configuration took up several weeks, before being able to perform research on site. The site configuration is important in order to figure out what the position of the habitat is in the site's system. The estimated time for complete site development is thought to be 18 months, including system testing.

The quantifiable criteria for the architectural design from mission perspective concern the constructability of the habitat, based on the packed configuration of the system. Several criteria can be derived from the mission context. The six requirements enhold, but are not limited to, budgets for mass, volume, power and construction time, as well as location characteristics and technology readiness levels of all systems.

3.7.2. CONCLUSION

Mission baseline is primarily based on the DRA 5.0, which hasn't been updated in a while. However, later sources on new technology developments still fit this mission architecture. Other proposals for mission architectures have been reviewed, but were not found to provide sufficient detail and further research developments. For this reason the DRA 5.0 is assumed, but new updates have to be kept in mind, especially concerning the baseline assumptions.

With these findings for the mission baseline architecture, the habitat system can be considered as part of a larger whole. The elements and scale of the habitat have to be determined based on the baseline mission architecture. The habitat system will have to fit the formulated technical constraints and requirements.

After this initial conceptualization of the mission operations, the question of crew characterization rises. The next chapter will elaborate on the crew and psychological needs as qualitative requirements for a habitat serving within a three year isolation mission.

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04

SPACE PSYCHOLOGY

In the previous chapter a baseline for a human space exploration mission was characterized with the goal to get humans to live on Mars. The leading driver for design decision making was defined as risk, meaning that all decisions have to serve the goal of mitigating risks. Quantitative requirements have been formulated as technical constraints within the mission design.

Now that more insight has been created on the context in which the human mission will take place, it is needed to define the qualitative requirements for the habitat design from the perspective of Space Psychology. Behavioral Health & Performance has been defined as a critical risk that has to be taken into account for a human mission to Mars. In this chapter the psychological needs will be defined as qualitative design requirements. The objective of the research in this chapter is to define an overlapping design driver for the habitat design, related to both Space Psychology and Space Architecture.

	Orbital ISS Missions	Winter-Over in Antarctica	Lunar Mission	Mars Mission
Duration (in months)	4–6	9–12	6	16–36
Distance to Earth (km)	300–400	–	350–400 thou.	60–400 million
Crew size	3–6	15–100	4	6
Degree of isolation and social monotony	Low to high	Medium	High	Extremely High
Crew Autonomy	Low	High	Medium	Extremely High
Evacuation in case of emergency	Yes	No	Yes	No
Availability of in-flight support measures				
Outside monitoring	Yes	Yes	Yes	Very Restricted
2-way communication	Yes	Yes	Yes	Very Restricted
E-mail up/down-link	Yes	Yes	Yes	Yes
Internet access	Yes	Yes	Yes	No
Entertainment	Yes	Yes	Yes	Yes
Re-supply	Yes	No	Restricted	No
Visitors	Yes	No	No	No
Visual link to Earth	Yes	Yes	Yes	No

Table 4.1.1. Comparison of isolated mission characteristics (Kanas, 2009)

Stressor	Short-Duration (6 Weeks or Less)	Long-Duration (more than 6 Weeks)
Physical environment	Isolating and confining	Isolating and confining
Danger level	Potentially high	Potentially high
Mission goals	Limited to complex	Complex to highly complex
Activity level	Busy	Busy to boring
Interpersonal conflicts	Can be ignored	Can become consequential
Group dynamics	Relatively stable	Variable

Table 4.1.2. Comparison of stressor impact on short versus long-duration missions (Kanas, 2009)

4.1 SPACE PSYCHOLOGY RESEARCH

4.1.1. PSYCHOLOGY ON A MARS MISSION

Humans are commiting themselves on extending their presence in space. In order to design for the activities and circumstances that the crew will experience, it is important for the people who are involved to understand the psychological process that comes with this. Space Psychology has emerged as a discipline to study this psychological process. In considering psychological and psychiatric issues that arise in space, three sources are mostly used within Space Pschology to provide reliable information on key issues: anecdotal reports, studies from space analogue missions and simulations conducted on Earth, and research performed during actual space missions. (Kanas, 2009)

Kanas (2009) elaborates on the psychosocial stresses that the crew will be exposed to during a three year long isolation mission to Mars. Several issues may rise, which can bring several consequences. Compared to short-duration missions, long-duration missions are likely to have an increasingly larger significant impact on the crew. (Table 4.1.1.)

In addition, Mission to Mars are likely to present some new issues and challenges that can have a big influence, leading to a big rise in risk associated with psychosocial issues. This became evident from a comparison of features from various sources (Table 4.1.2.). (Kanas, 2009)

The focus of research in Space Psychology today is to study the key issues, with the objective to develop and test countermeasures that can be applied to help dealing with stressors encountered during space missions. It is emphasized that, though other sources such as anecdotes and simulations may prove useful, the primary focus should remain to learn from people's behaviour in actual space missions.

4.1.2. THE IMPACT OF DURATION

Mission duration is considered as the driving cause for human factors design and engineering, since the extended exposure to stressors that come with extreme environments magnifies all critical aspects of isolation, confinement, social organization and decision making. (Cohen, 1991)

Cohen (1991) highlights the importance of duration as an architectural program driver within design of an isolated and confined habitat. Designing a human mission to Mars, requires a human-centered design approach, with a focus on behavioral health and performance during long-duration missions. In order to mitigate the risks in degradation of behavioral health and performance of the crew, motivation over time is critical to understand for any human factor issues in long duration missions. Cohen (1991) refers to Maslow's pyramid for human motivational needs in relation to long duration space missions. Maslow defines a hierarchy in human needs, characterized from the bottom up as physiological, safety, belonging, esteem and self-actualization.

In generic space mission design, it is found that the engineering temptation to "trade-off" cost for comfort can form a "major mistake" from the human factors point of view. (Clearwater and Harrison, 1990) Cohen (1991) concludes that a shift in the hierarchical paradigm would recognize that some elements are essential to crew performance (beyond just keeping them alive and working all the time), when used to address the human needs in long-duration mission design.

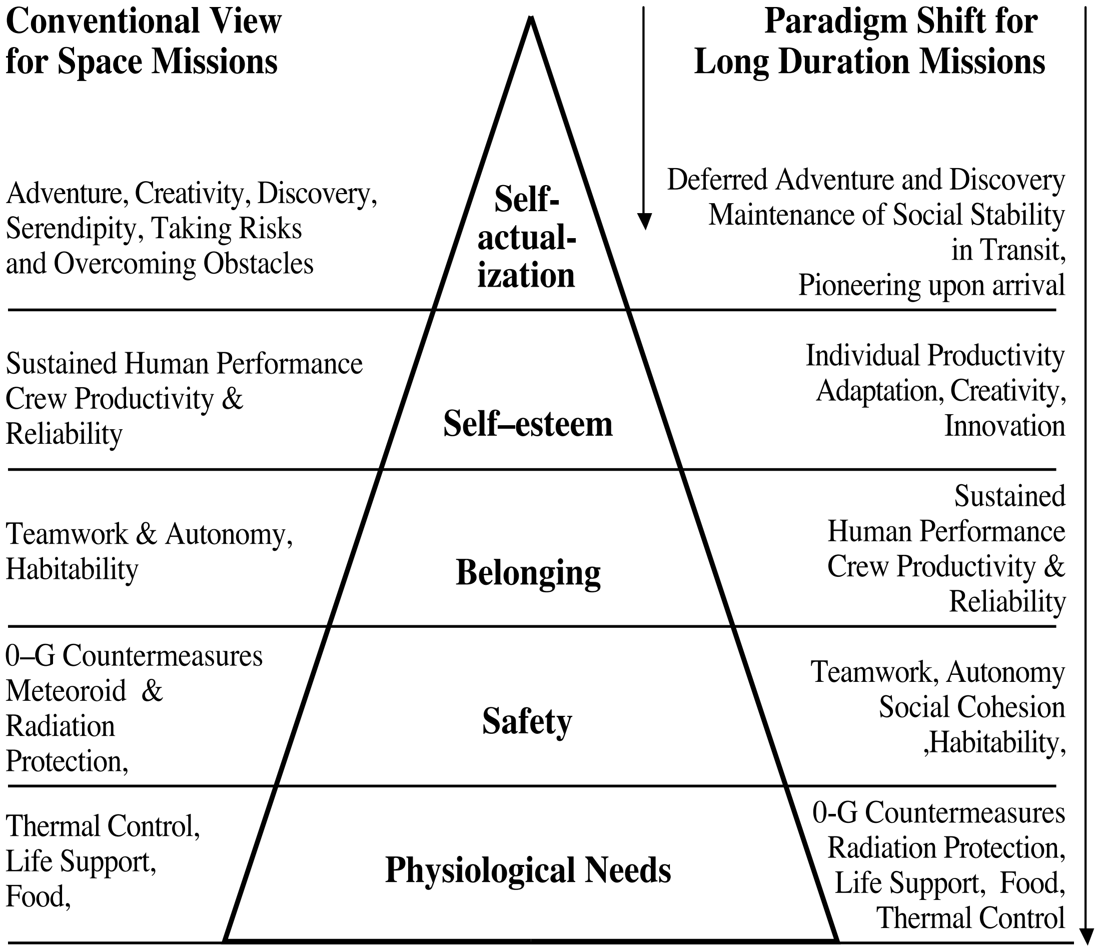


Figure 4.1.1. : Proposition for a paradigm shift in addressing motivational needs in habitat design (Cohen, 1991)

According to Cohen, the alignment of mission system engineering values and decision-making would have to shift downwards in Maslow's hierarchy for human motivation and needs. Whereas the conventional view in space mission engineering is that the intrinsic motivation of the selected crew for the mission, would suffice in it's own without requiring additional design measures to maintain the motivation. (Cohen, 1991) (Figure 4.1.1.)

Bassingthwaite (2017) explains that to support human well-being in isolated habitats the design focus includes the human psychology. When the design of an isolated and confined living environment forms a sensible response to the psychological needs that arise over time, humans are likely to be able to live anywhere. The aim of these architectures should be that the crew will not merely survive, but is able to thrive in the enclosed living environment, despite it's dangers.

Research in space habitability and isolation psychology has shown a predictable loss in motivation over time. Often, before the start of the long-duration isolation mission, crew members express an intention of completing a process or goal over the course of the mission. Over time, the desire to participate in self-driven work decreases, and more time is generally spent on other recreational activities such as playing games with other crew-members. A lack of personal investment was found as a response marked by fatigue or general apathy within the group, possibly resulting in increased feeling of helplessness or worthlessness. (Bassingthwaighte, 2017: p.86, Harrison et al., 2012)

In all, as the mission duration increases, the intrinsic motivation or the drive for self-actualization is likely to decrease. This makes human motivation an important driver for the expected behavioral health and performance of the crew as a defined risk in space mission design. The long term success of the mission is therefore dependent on human motivation and the provision of human creativity.

National Aeronautics and Space Administration

International Space Station

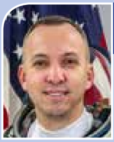
[MISSION SUMMARY]

EXPEDITION 53

began in September 2017 and ends in December 2017. This expedition includes astrophysics, technology demonstrations, cellular biology and biotechnology. Three spacewalks are tentatively planned during Expedition 53.

THE CREW:

Soyuz MS-05 Launch: July 2017 • Landing: December 2017

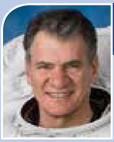


Randolph Bresnik (NASA) – Commander

Born: Fort Knox, Kentucky
Interests: travel, music, photography, weight training, sports, scuba diving, motorcycling, and flying warbirds
Spaceflights: STS-129
Bio: https://go.nasa.gov/2rq5Ssm
Twitter: @AstroKomrade

Sergey Ryazanskiy (Roscosmos) – Flight Engineer

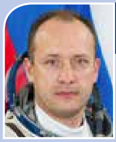
Born: Moscow, Soviet Union
Interests: Numismatics, playing the guitar, tourism, sport games
Spaceflights: Exps. 37/38
Bio: https://go.nasa.gov/2rpXfOK
Twitter: @Ryazanskiy_ISS



Paolo Nespoli (ESA) – Flight Engineer

Born: Milan, Italy
Interests: scuba diving, piloting aircraft, assembling computer hardware, electronic equipment and computer software
Spaceflights: STS-120, Exps. 26/27
Bio: https://go.nasa.gov/2rq0tlk

Soyuz MS-06 September 2017 • February 2018



Aleksandr Misurkin (Roscomos) – Flight Engineer

Born: Yershichi, Smolensk Region, Russia
Interests: badminton, basketball, downhill skiing, carting
Spaceflights: Exps. 35/36
Bio: https://go.nasa.gov/2vAiNdr

Mark T. Vande Hei (NASA) – Flight Engineer

Born: Falls Church, Virginia
Interests: exercise, camping, windsurfing and reading
Spaceflights: Expedition 53 will be his first spaceflight.
Bio: https://go.nasa.gov/2vzY0a8
Twitter: @Astro_Sabot

Joseph Acaba (NASA) – Flight Engineer

Born: Inglewood, California
Interests: camping, hiking, biking, kayaking and scuba diving
Spaceflights: STS-119, Exps. 31/32
Bio: https://go.nasa.gov/2vA7vWu
Twitter: @AstroAcaba

THE SCIENCE:

What are some of the investigations the crew is operating?

During Expedition 53, researchers will study the cosmic ray particles, demonstrate the benefits of manufacturing fiber optic filaments in microgravity, investigate targeted therapies to improve muscle atrophy and explore the abilities of a new drug to accelerate bone repair.

Figure 4.2.1. : Composition of the crew and their characteristics for Expedition 53, inhibiting the International Space Station at the time of writing.

4.2 THE CREW

4.2.1. CREWSIZE

Kanas (2009) writes extensively on human interactions concerning crew composition. Several space missions were compared and fragments of anecdotal reports were extensively studied. The study proved to what extend crew composition can have a negative impact on the psychological health and performance of an individual crewmember in a long-duration space mission. The results are summarized in Table 4.2.1.

Kanas concludes (2009, p.103):

> *"… the larger the group, the greater the tendency forleader-follower relationships to form, and the greater the stability. In odd-numbered groups, there is less likelihood for deadlocking subgroups to form in situations where non-leader directed activities are involved. Since future ISS or expeditionary class space missions may involve crews consisting of six to eight individuals, one might predict that on the basis of number alone, a crew of seven would be ideal since this would be the largest odd-numbered crew size."*

An important finding is that, concerning the crewsize, four is said to be a risky number. Crews larger than four are strongly preferred to accomodate the risk of losing one member and increase the possibility of sociological variation. (Interview Kanas, 2009)

Issue	Specific Harmful Sequelae
Crew heterogeneity due to: gender, cultural differences, career motivation and experiences, and personality	Intra-crew tension, scapegoating, long-eye phenomenon
Changes in cohesion over time	Withdrawal and territorial behavior, subgrouping
Language and dialect variations	Crew miscommunication
Crew size	Small crews of two or three people are more problematic than larger crews of six or seven and can lead to minority isolation
	Odd-numbered crews that are larger than three people can more easily achieve consensus than even-numbered crews
Leadership roles: task versus supportive	Leadership role confusion, status leveling
Crew-ground interactions: empathy, over-scheduling, autonomy, psychological closing, displacement	Crew-ground miscommunication, perceived lack of support from the ground, failure to deal with intra-crew problems, information filtration

Table 4.2.1. : Identified issues and their consequences concerning crew composition during long-duration space missions (Kanas, 2009)

4.2.2. CREW CHARACTERIZATION

After the publication of Space Pscyhology and Psychiatry in 2009, Barbara Imhof interviewed author Nick Kanas for some general recommendations to select the crew for a mission to Mars. (Interview, 2009) It was recommended to send a crew of 6 to 7 people, men and women, with multinational backgrounds, as the mission will likely be an expensive international enterprise. The age will range from 30 to 50 years old. They will have to have undergone a sufficient amount of training in various space missions and other mission simulators. It is important that they will be cross-trained in their disciplines in case one falls out. Relevant professions are a pilot, engineers, physician, geologist, biologists and other related scientific backgrounds. Two types of characteristics are important: they would have to work effectively to get their jobs done and they have to be able to work well in teams, so not too introvert and not too extravert. (Interview Kanas, 2009)

Learning from these studies and findings it is now possible to characterize the crew for the mission of the first human settlement on Mars. Figure 4.2.2. shows a possible representation of the crew, based on the given criteria by Kanas.

It can be said that seven may be an optimistic number for the crew, especially since NASA is currently designing for crews of four to six. However, considering a mission duration of 1000 days, seven is considered a minimum in this case. Today, the longest space mission that ever took place for a single crewmember is the mission on the International Space Station (ISS) of 342 days from Scott Kelly, who finished in March 2016 (NASA, 2016). During his 340 days the crew composition changed several times. ISS is hosting six to seven crew members at a time on average.

Profession	Biologist	Geologist	Physician	Physician	Engineer	Engineer	Engineer
Sex	male	female	female	male	male	female	male
Age	34	37	39	41	43	45	48
Nationality	Austrian	Spanish	American	Japanese	Russian	Chinese	American

FIgure 4.2.2. : An example of a possible crew composition for a human mission to Mars based on the identified characteristics from Kanas (interview, 2009)

4.3 DEALING WITH STRESS

4.3.1. STRESSORS AND STRESSES

During the mission the crew will be subjected to large stresses. Literature on space psychology, elaborates on stressors resulting in stresses within the crew. Kanas (2009) defines and categorises stressors and stresses that can occur in space missions:

Kanas (2009, p1-2):

> *"A stressor is a stimulus or feature of the environment that affects someone, usually in a negative arousing manner. In space, there are four kinds of stressors: physical, habitability, psychological and interpersonal. (…)*
> *A stress pertains to the reaction produced in someone by one or more stressors. In space, there are four kinds of stress that affect human beings: physiological, performance, psychological and psychiatric."*

An overview of the mentioned stressors and stresses are given in Table 4.3.1 and 4.3.2.

Physical	**Habitability**	**Psychological**	**Interpersonal**
Acceleration	Vibration	Isolation	Gender issues
Microgravity	Ambient noise	Confinement	Cultural effects
Ionizing radiation	Temperature	Danger	Personality conflicts
Meteoroid impacts	Lighting	Monotony	Crew size
Light/dark cycles	Air quality	Workload	Leadership issues

Table 4.3.1. : Identified stressors during space exploration missions (Kanas, 2009)

Physiological	**Performance**	**Interpersonal**	**Psychiatric**
Space sickness	Disorientation	Tension	Adjustment disorders
Vestibular problems	Visual illusions	Withdrawal/territorial behavior	Somatoform disorders
Sleep disturbances	Attention deficits	Lack of privacy	Depression
Bodily fluid shifts	Error proneness	Scapegoating	Suicidal thoughts
Bone loss and hypercalcemia	Psychomotor problems	Affect displacement	Asthenia

Table 4.3.2. : Examples of stresses that occur during space missions (Kanas, 2009)

TABLE 1. CRITICAL HABITABILITY I[7]

STRESSORS ON THE CREW	COUNTER-MEASURES AGAINST STRESS	DEGRADED CREW PERFORMANCE	COUNTER-MEASURES AGAINST ERROR	CREATION OF POTENTIAL SAFETY HAZARD
Volume Limitations: Insufficient Pressurized Volume, Inadequate Free Volume.	Architecture, Design, Privacy, Windows, Stowage, Sufficient Work Envelopes.	Feelings of Claustrophobia, Lack of Privacy, Irritability.	Increased Privacy or personal space, More Volume, Evacuation.	Irritability, Conflict, Paranoia.
Noise.	Vibration Isolation, Control.	Sleep Disturbances, Sleep Deprivation, Circadian Desynchronization, Poor Communication.	Earmuffs, Headsets, Drugs, Communication Devices.	Failure to Respond, Failure to Communicate, Failure to Coordinate.
Inadequate Housekeeping (or Lack thereof)	Routines and Training, Assignment of Responsibilities, Teamwork.	Environment Quality Deterioration, Unhealthy or Unsanitary Environment.	Assignment of Responsibilities, Teamwork.	Breakdown in Life Support.
Lack of Hygiene, Lack of Cleanliness.	Improve Personal Practices, Repair Hygiene Facilities, Training.	Discomfort to Others, Illness, Disease.	Group Standards, Teamwork.	Individual or group Illness, Inability to Perform Tasks, Death.

Table 4.3.3. : The Crew Safety-Human Factors Interaction Model as defined by Cohen et al. (2015) showcasing the application for critical habitability.

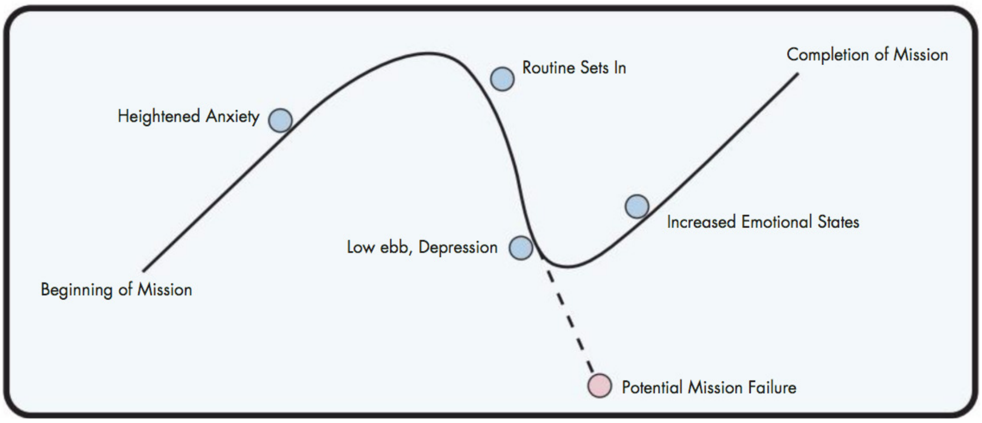


Figure 4.3.1.: Stages of mind during a long-duration isolated mission. (Bassingthwaithe, 2017)

4.3.2. PSYCHOLOGICAL PERFORMANCE

In the past decades, NASA has published extensive research in Crew Safety as part of exploration mission design. (Cohen, 2015) Cohen and Junge (1984) developed the Crew Safety-Human Factors Interaction Model as part of NASA's 'Safety Impact of Human Factors', a standard developed for the early Space Station program. In the model, a stressor can lead to degraded performance, inducing human errors and thus creation of a potential safety hazard. Stressors can be dealt with through countermeasures from various topics. The model addresses several topics of which Critical Habitability emerged as the most fundamental for crew survival in extremely long duration missions. (Cohen, 2015)

Regarding the mission duration, Kanas (2009) summarises that the general theory on stages of mind in mission design differentiates two phases: the first stage of app. six weeks where the crewmember undergoes psychological adjustment to the new situation; and the second stage that concerns the rest of the mission.

Bassingthwaite (2017) defines three stages of mind within the mission, which are not necessarily dependent on the total length of mission time. The first stage, brings heightened anxiety related to the newness of the situation and the awareness of perceived danger. This often results in positive outcomes such as increased alertness and improved performance. After some time, the routine sets in, which is when the second stage starts. Over time, the crew can experience boredome, resulting in depression and perhaps regret of joining in the mission. Some subtle social and psychological issues are often likely in beginning to manifest. The third stage starts when the end of the mission or a dramatic change is nearing. This can lead to increased emotional states, possibly resulting in accidents. For this reason, the final stage requires the greatest caution. (Bassingthwaighte, 2017)

Overall, long duration missions bring extended exposure to stressors on the crew, magnifying the overall effect on the crew's behavioral health and performance. In a space mission stressors occur, which can result in stresses that drive the need for countermeasures. (Kanas, 2009; Cohen, 2015) Increase in mission duration magnifies the effect of stressors on human psychological motivation and needs.

A focus on designing increased habitability of the environment can be a useful countermeasure to mitigate the stressors on the crew. (Kanas, 2009, Cohen, 2015) Literature suggests that habitability stress should be addressed in the architectural design of the capsule habitat, shifting the design focus to psychological needs that arise, and increase, over time. The suggested solution of designing countermeasures is easier said then done. To find the weaknesses or overseen pitfalls, in the next paragraph issues addressed by mission crew members are compared with suggested architectural design solutions.

Relevant issues identified in human factors research	Author/source
Work, outside communication, adjustments, group interaction, recreation/leisure, equipment, events, organization/management, sleep, food	Stuster Jack (2010)
The physical environment (interior space, food, hygiene, temperature and humidity, décor and lighting, odor, noise), health and leisure (recreation, exercise), privacy (crowding, territoriality), complex effects	Mary et al. (1985)
Sleep (rest, relaxation, sleep and storage), hygiene (personal hygiene, shower, toilet, housekeeping), food (store, prepare, grow, consume, and storage), work (operations, experiments, communication, education, training, and storage), leisure (free-time activities, exercise, intimate behavior, and storage)	Häuplik-Meusburger (2011)

Sources as in table

Table 4.4.1.: Relevant issues identified in human factors research (Häuplik-Meusburger et al., 2016)

Stressors associated with habitability	Architectural countermeasures	Degraded performance
Volume limitations	Interior layout, windows, virtual reality	Lack of privacy, feelings of claustrophobia
Confinement, isolation, separation	Layout (social events, visitors, private communication with family and friends)	Feelings of claustrophobia, lack of motivation, "cabin fever"
Noise and vibration	Vibration isolation and control, zoning	Sleep disturbances, poor communication
Lighting	Lighting design (natural light)	Fatigue, irritability, blurred vision

Sources Dudley-Rowley (2004)

Table 4.4.2.: Stressors for long term spaceflight and possible countermeasures (Bannova et al., 2016)

4.4 HABITABILITY

4.4.1. DEFINING HABITABILITY

Habitability is an important aspect for mission design and often point for discussion amongst architects and engineers. It is generally acknowledged in mission design that human factors engineering is likely to add to mission success. Various sources define habitability slightly different. Where Connors et al. (1985) define habitability as "*a general term that connotes a level of environmental acceptability*" (p.59), later sources argue that this phrasing doesn't cover all the aspects of it. Various other definitions were later developed. In his book Bold Endeavours, anthropologist Jack Stuster refers to Kubis' (1965) definition of habitability (Stuster, 1996 p. 40):

> *"habitability as the sum of interactions between operators and environment which include physical, physiological, psychological and social interactions"*

In Architecture for Astronauts the term 'habitability' is best explained as (Häuplik-Meusburger, 2011, p.3):

> *"a general term to describe the suitability and value of a built habitat (house or spacecraft) for its inhabitants in a specific environment (Earth or Space) and over a certain period of time."*

Before understanding how to design a habitable environment, an elaboration on issues concerning habitability in space mission design will be discussed.

4.4.2. HABITABILITY ISSUES

Research has found that impaired habitability could lead to serious psychological depreciation and even potential life threatening situations. An example of the effects of impairment witnessed during actual space missions, is the design of the window on ISS which did not include a restraint for the crew to hold on to when gazing outside. Instead they hold on to the airhose that was running next to the window. Over time, the airhose broke and air was leaking outside of the capsule. (Häuplik-Meusburger, 2011)

After his 340 day mission on the ISS, Scott Kelly gave an interview on a NASA conference. He was asked about habitability on ISS and if he had some recommendations for points of improvement. He replied that during his stay, he hadn't been bothered by the size of the space, but mostly about the noise from the technical support systems. Also, he suggested an alteration of lighting, since it is relatively simple to implement and would help with varying the perception of the space. He added that one of the frustrations is that you never leave the office, neither physically nor mentally and that made it very hard to relax. (NASA, 2016)

Analog studies of mission simulators revealed other indirect complaints concerning habitability. Mission simulators are often used to study psychological and habitational behaviour in isolation missions. NASA's Hi-SEAS missions are used to analyse crew behaviour. Bassingthwaite (2017) received some recommendations for habitation improvement of former Hi-SEAS crew-members. A generic complaint was the lack of privacy and disturbances of the noise of the treadmill within the habitat. (Bassingthwaighte, 2017)

Habitability Factor	Examples
Architecture	Overall layout, translation paths, windows, interior décor, lighting, doors, hatches, location coding, mobility aids and restraints
Living quarter design	Individual crew quarters, wardroom and meeting facilities, recreation facilities
Work station design	Displays, controls, human-computer interfacing, issues of automation, software usability, labeling and coding
Service facilities	Galley, laundry, trash management, stowage
Personal hygiene	Toilet, shower, body waste management
Specific equipment	Tools, racks, specific restraints, crew personal equipment
Environmental factors	Noise, vibration, air quality, radiation, temperature
Health management	Nutrition and food systems, sleep facilities and scheduling, microgravity countermeasure facilities, space medical facility
Facility management	Design of housekeeping tools, inventory control system
Extravehicular activities	Design of suit, tools, and workstation

Table 4.4.3.: Important habitability factors and examples (Kanas, 2009)

Effective visual and acoustic shielding against the outside
Undisturbed sleep
Individual environmental control (e.g., adjustable lighting, temperature)
Private communication via audio/video transmission and e-mail
Donning and doffing of personal clothes
Stowage of personal items
Individual recreation (i.e., availability of compact entertainment devices)
Individually adjustable decor (e.g., paintings/pictures presented on screens, adjustable color of lighting)
View outside the habitat

Table 4.4.4.: Important functions and activities to be supported by the individual crew quarters, given in order of priority (Kanas, 2009)

Mohanty et al. (2006) elaborate on findings from two other analogue mission simulators as case studies. The objective was to study the relationship between habitat design and crew psychology. The first study showed that environmentally engaging design measures promoted wellbeing of the crew by means of mitigating stresses resulting from long term confinement. It was found that detailed imagery with high optical depth, such as a view on nature, were positively perceived in confined, isolation studies in mission simulators. These could be pictures or digital images. Landscapes were most appreciated. The second study showed that there was a difference between the defined habitable volume and actual inhibited volume. A conclusion was drawn that the requirements and standards for habitability should be adjusted. Special attention should be paid to acoustics, lighting and other environmental factors. (Mohanty et al., 2006)

4.4.3. ARCHITECTURAL CONSIDERATIONS

Habitability stresses are suggested to be mitigated through architectural design and programmatic configuration. Kanas (2009) presents an overview of human factor issues concerning habitability and examples of elements that should be considered in the architectural design of the habitat. (Table 4.4.3.) Apart from the seperate programmatic functions that should support the crew, a distinct priority order is given for aspects that should be addressed in the individual crew quarter design. (Table 4.4.4.)

Apart from the formulated points of improvement for the HI-SEAS habitat, Bassingthwaighte (2017) proposed several design alterations. Important alterations concerned acoustic soundproofing, adjustable lighting, materialization, integrated routing loops and additional greenery to improve spatial quality.

Häuplik-Meusburger (2011) applies three seperate themes to evaluate habitability in six case studies of space mission habitats. The applied themes are Usability, Flexibility and Livability. Usability refers to the quality of the environment and its objects in which the crew can perform any sorts of activities during mission operations. Flexibility enholds that the habitat "*allows adjustments according to the requirements of the users, to changing mission tasks as well as unforeseen social and mission related changes*" (p. 9). And Livibility is related to physical, visual and spatial relations, including sensory perception, territoriality and privacy.

Organization of the programmatic functions and physical environment in the habitat is critical for habitability. Despite the various sources there are no commonly defined themes that can create a grip on the topic. It is important to understand the issues in order to evaluate the habitability performance of the architectural design. On a first impression, the three defined themes from Häuplik-Meusburger (2011) form a solid starting point for evaluation, yet it doesn't appear to consider the direct stressors that occurs during a mission. In order to develop a habitable design as a suitable countermeasure, habitability criteria will be formulated in the next paragraph based on the found stressors.

4.5 QUALITATIVE REQUIREMENTS

4.5.1. FROM NEEDS TO CRITERIA

In paragraph 4.2.1., the found stressors in space psychology research were given in table 4.2.1. and the stresses resulting from these stressors in table 4.2.2. Cohen (2015) explained that in order to maintain crew performance countermeasures to deal with stressors should be designed. Habitability was defined as a critical concern for crew performance on long duration missions.

Kanas' and other found stressors and complaints are categorised in (Figure 4.5.1.). In line with Cohen's hierarchy of psychological performance measures (1991) it was possible to sort them according to increased importance as duration extends. This means that the stressor is likely to have a relatively larger impact on psychological well-being when it occurs over longer periods of time. For example, environmental stressors such as temperature and noise will result in an immediate stress of a certain size. Yet, feelings of dependence for a short period will not necessarily result in a direct depreciation of psychological well-being. However, when a crew member might feel dependent for a longer period, it is likely to effect his or her mental performance during the mission.

From the categorisation, certain themes were derived that were translated to specific needs that rise as a result from the stressors. The six defined themes are the needs related to the quality of Physiology, Safety, Autonomy, Privacy, Engagement and Space.

The formulated needs fall in line with the earlier defined themes of Usability, Flexibility and Livability. Usability is answering Physiological and Safety needs. Livability is answering the needs for Privacy, Engagement and the perception of Space. And Flexibility is answering the needs for Autonomy, being able to take individual control over the environment.

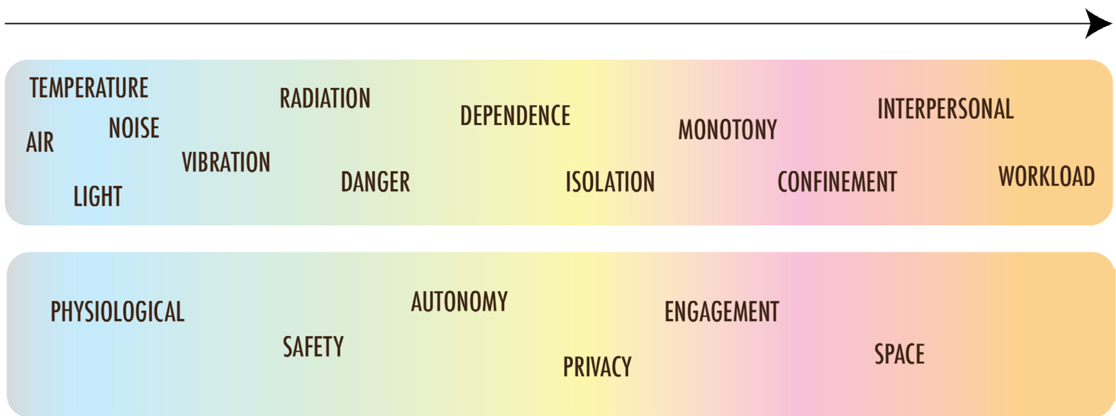


Figure 4.5.1. : Identified needs as categorised themes based on the identified stressors from Kanas (2009) and the proposed paradigm shift in relation to the Maslow pyramid by Cohen (1991)

4.5.2. DEFINITION OF HABITABILITY CRITERIA

The criteria for habitability, based on occuring needs as a result from stressors, can now be summarised as, yet not limited to, the following definitions:

PHYSIOLOGY
This criteria intends to assess whether the organization of the program answers physiological needs of the crew. It is important that the crew can get sufficient sleep without being disturbed by noise, light, vibrations or other environmental factors. The sleeping quarters in relation to allocated spaces for technical support systems will be judged.

SAFETY
The crew should feel safe within the habitat. Safety will be checked by means of double egression routes, potential failure of technical systems and measures for back-up of these systems. This could be addressed within the design through organization of several fire safety zones with seperate support systems.

AUTONOMY
The objective of the criteria is to determine to what extend the crew member is provided with the opportunity to chose. To give the crew a sense of control on their direct living conditions, several measures could be taken. One aspect is to check whether the individual can have some sort of control on their personal environment. An example could be to close a door, adjust the local climate or to be able of shutting blinds on a window to change lighting conditions.

PRIVACY
Due to extreme isolation during the mission, the crew has to be given the opportunity to record personal messages for their personal contacts at home. Undisturbed personal communication should be possible within the program. When recording, the person should not be overheard by other crew members. This also accounts for toilet visits, which could be disturbing for both the individual and other crew members. Privacy also addresses territoriality needs, which enholds having the option to have your own space where you determine the rules.

ENGAGEMENT
A confined, closed-off living space is likely to result in a sense of extreme isolation and confinement. A suggested countermeasure is to provide means that address this need for engagement, either physically and/or psychologically. All crewmembers must be able to engage effectively with their direct environment. Means to engage with the environment in a physical way, could be by providing a window or a similar effective measure. Psychological engagement can be promoted through allocating sufficient and adequate space for various socially engaging activities performed as part of leisure time.

SPACE
To prevent occurance of stresses like monotony and confinement, the allocated volumes will be assessed on size and variation. A variation in dimensions and translation paths are some aspects for designing the crew's spatial experience. Endured stay in a small space could result in confinement stress. Insufficient volume reservation to perform a task could add to this type of stress.

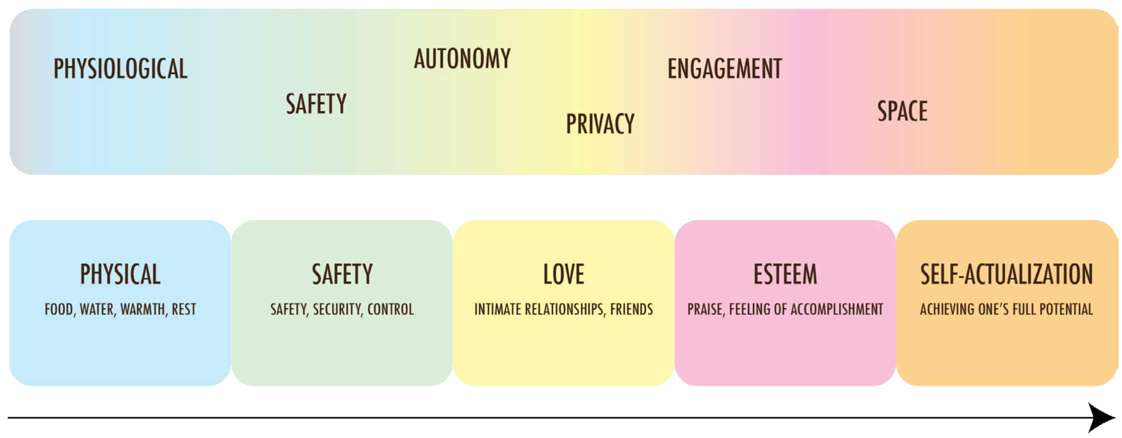


Figure 4.5.2. : Cohen (1991) suggests a paradigm shift in addressing psychological needs for designing habitability as duration extends. The identified themes could be addressed in a similar order of priority. This would enhold that the perception of space is the most critical design requirement for habitability in long-duration and highly isolate space missions.

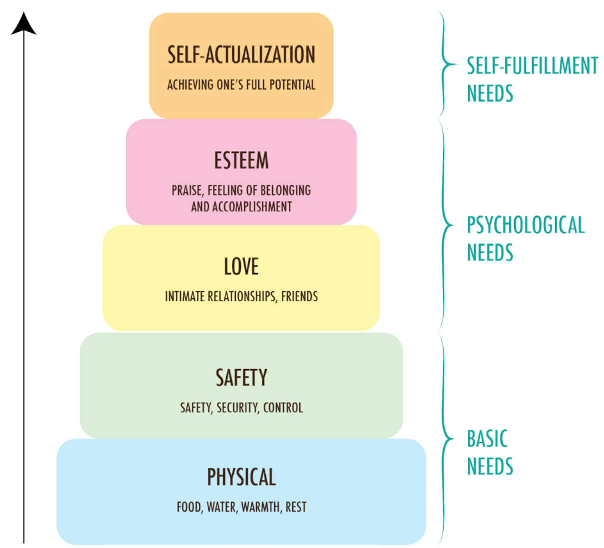


Figure 4.5.3. : Maslow's motivational needs.

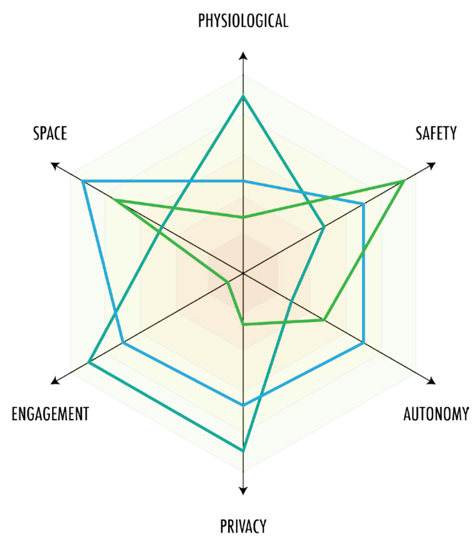


Figure 4.5.4. : In this research the identified themes are not suggested to be addressed in an order of priority, but to weigh the criteria against each other, i.e. balancing them i.r.t. overall habitability performance.

4.5.3. APPLYING CRITERIA AS QUALITATIVE REQUIREMENTS

The Maslow pyramid can be used as a paradigm to address human needs. (Cohen, 2015) Maslow's themes help in categorizing the stressors into different subsets, summarizing a particular need. These needs can form the drivers in designing habitability. As time increases, so does the importance of weighing the need and designing a suitable countermeasure. For example, in an isolated mission to Mars that would last for a minimum of three years, the crew will be exposed to an extremely long period of extreme isolation and confinement. In order to maintain the crew's psychological health, a well designed environment, that offers sufficient volume to perform a task adequately, is increasingly more important as the extended duration is likely to magnify the effect of experienced frustration. With extended duration, the perception of space increases in importance.

However, it seems more sensible to balance the needs, i.e. weighing them in relation to each other, not necessarily to prioritise one need over the other. For example, sometimes the drive to finish a task may be stronger than meeting physical needs, such as sleep or nourishment. Or the need for social belonging might drive a person to share food, even when famished. It is the job of the architect to take a position when designing the habitational experience and choosing where the design focus should lay to support the most important habitational needs.

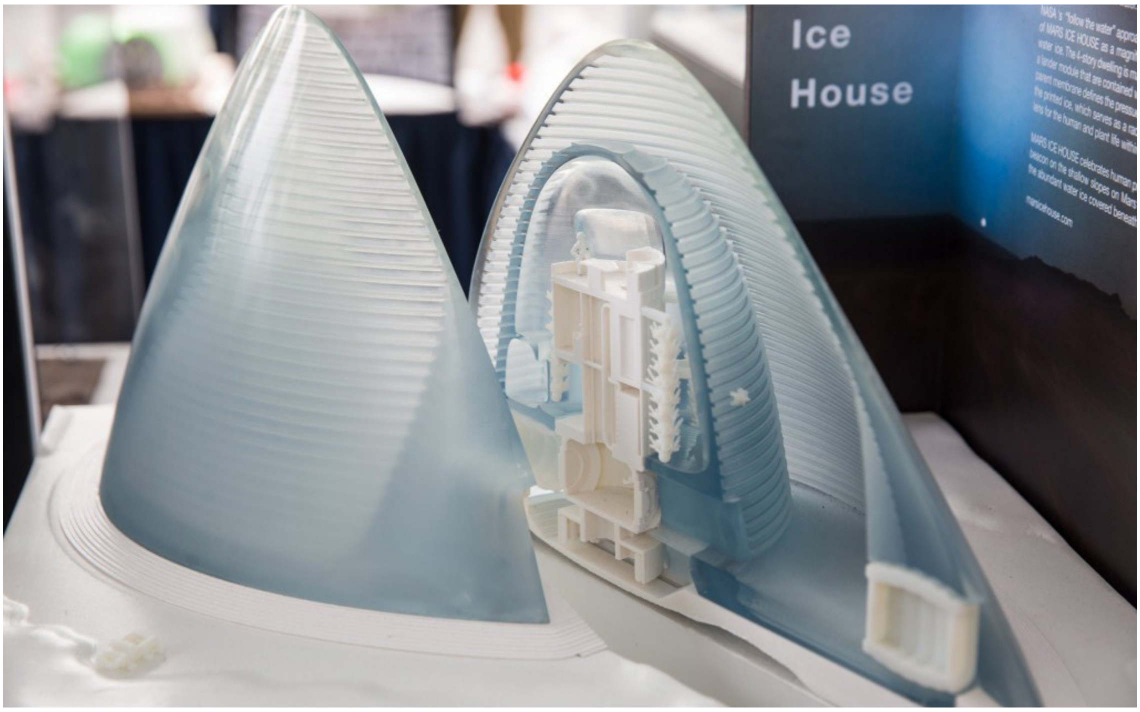


Figure 4.6.1. : The model of Mars Ice House from Clouds AO for the 3D-printed habitat design competion.

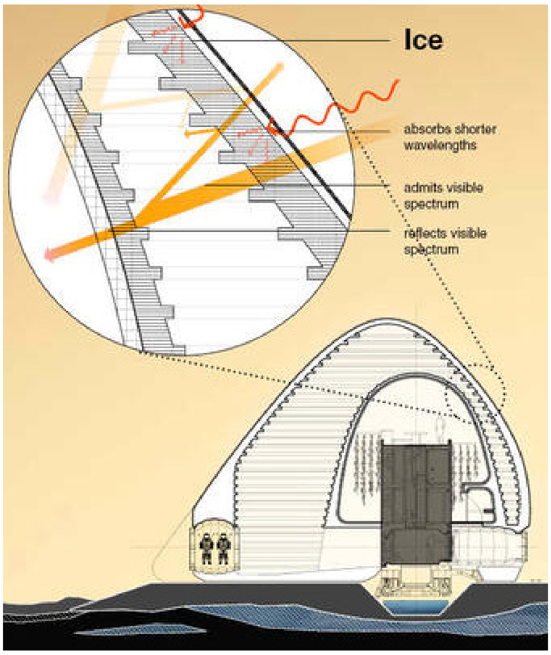


Figure 4.6.2. : The printed ice structure would absorb radiation and admits natural light.

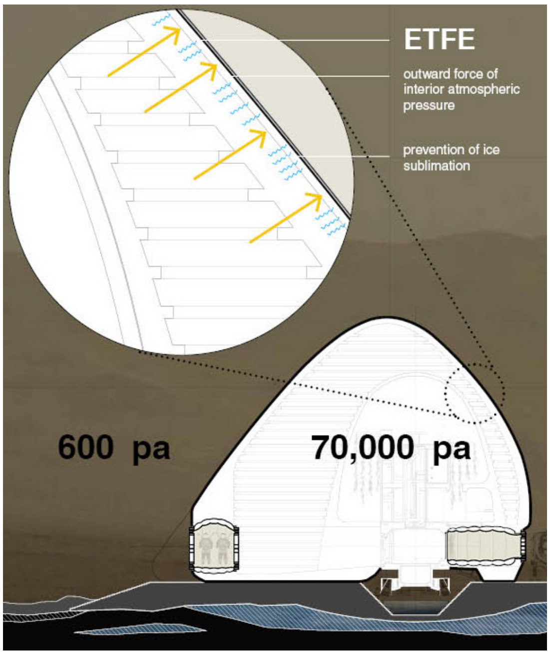


Figure 4.6.3. : Transparant membranes would mitigate pressure differences and ice sublimation.

4.6 CASE STUDY: MARS ICE HOUSE

4.6.1. PROJECT DESCRIPTION

In 2015, NASA organized a 3D-printed habitat design contest in collaboration with Berkeley University and America Makes (3DP hab, 2015). The assignment was to come up with a habitat for a crew of four for a mission of 500 days with a 3D-printed structure. The contest resulted in 165 entries from design teams all over the world. The entries were shortlisted to thirty architectural concept designs of which ten designs were nominated and the top three was awarded. First place was assigned to the team of Cloads AO with their design for Mars IceHouse, printed with ice.

4.6.2. HABITABILITY ANALYSIS

The case study was analysed according to the the formulated criteria for habitability. The intention was to validate if the criteria can form a useful aid in qualifying the habitability within the design. Elaboration on the analysis is given for each criteria.

SPACE

The program is organized as can be seen in figure 4.6.5. The main entrances consist of airlocks where EVA and other field equipment is stored and can be maintained. The seperate rooms for functional activities seem a little cramped and do not appear to have a lot of spatial variation. However, the large central “atrium” overarching most of the translations paths, does improve the perception of space. Hanging gardens in the naturally lit zone give of a spacious and green impression.

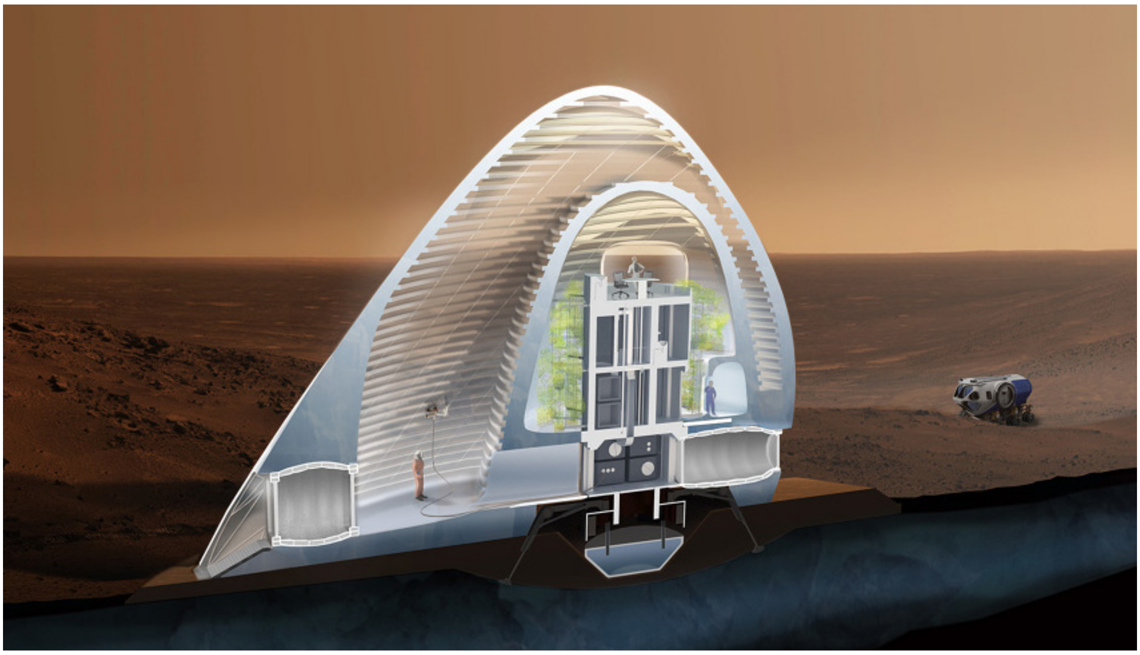


Figure 4.6.4. : Artistic impression showing how the module and inflatable airlocks are placed within the ice structure. Underground, the water is excavated with ISRU technology and stored in tanks.

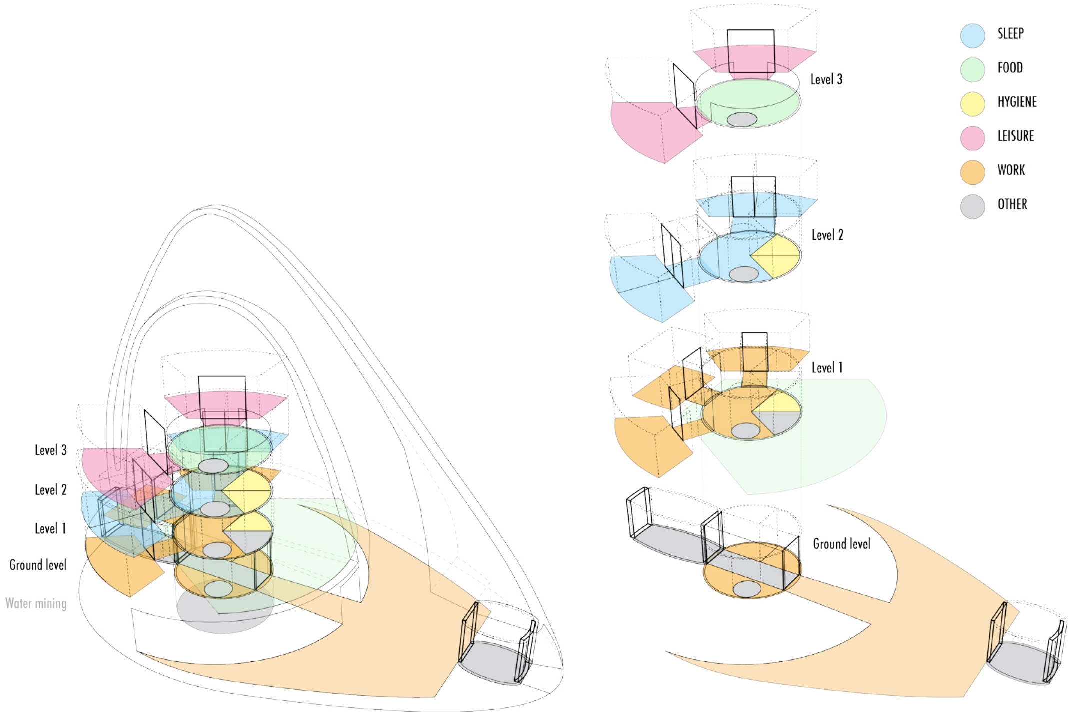


Figure 4.6.5. : Program organization and their spatial allocations.

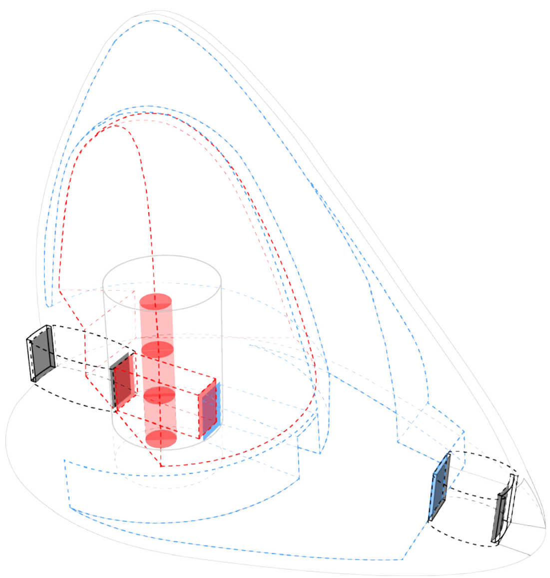


Figure 4.6.6. : Three membranes seperate three different pressure zones, each with dual egression, apart from the single staircase leading down in the core of the module.

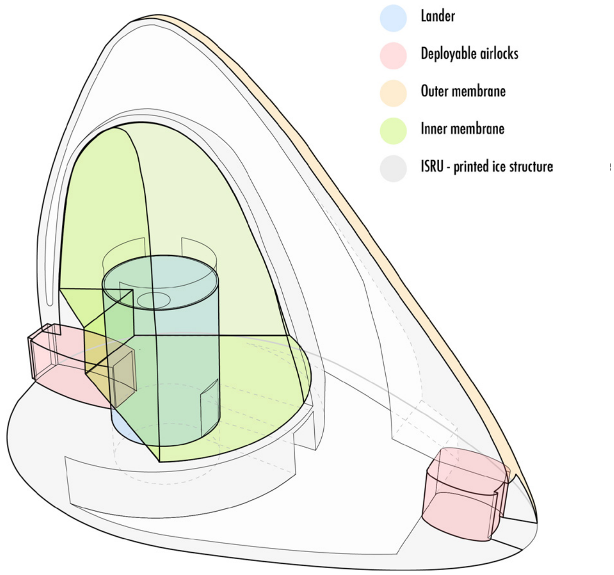


Figure 4.6.7. : Organization of the seperate structural elements within the structure.

SAFETY
Figure 4.6.6. shows that the design consists of three separate zones which each have a double egression route. However, the zone that consists of the majority of the human accomodations, does offer egression to two other zones, but the crew is only able to reach the egression doors through the single staircase that connects all floors. In the case of fire in this zone, this may bring a hazardous situation.

ENGAGEMENT
Each seperate programmatic element has a door so it can be closed off. (Figure 4.6.10.) The central core module is dominated by public translation paths. Every floor is connected to the outside with transparant ice windows, allowing the crew to connect with the surrounding environment on Mars. However, the question remains if the structure can be transparant as opposed to just translucent. If not, this would mean that the habitat would not have any windows that offer a direct view to the outside.

Social areas appear to be well organized in the design. The table and kitchen form the heart of the habitat amidst hanging gardens, where food is grown, in the central atrium. Seperate rooms in the flanges of the top floor can be accomodated to other leisure activities. An example is to accomodate games and movies in one room and exercise equipment in the other.

PHYSIOLOGICAL
The sleeping quarters are not located adjacent to a technical room, shown in figure 4.6.8. This implies that sleeping without being disturbed by noise from technical support systems can be achieved.

PRIVACY
Program that requires high privacy measures seems well-organised within the design. Non of the sleeping quarters or toilets are situated on a floor with rooms where crew is likely to dwell. Also, the rooms are surrounded by a printed ice structure. This aids in mitigating potential acoustical disturbance. The individual crew quarters are entered via a bridge, inducing semi-private translation zones which accomodates territorial behaviour.

It is questionable whether the central floor would be the best floor for the sleeping quarters, since the rooms are now placed between work and leisure areas. If there would be any acoustical transmittance to these areas, the privacy would be lost. However, the translation from work to leisure is well integrated in this way. Also, the placement of exercise as a leisure activity would not create acoustical disturbance for the working crew two floors lower.

AUTONOMY
The sleeping quarters appear to be of a sufficient volume for crew members to perform the defined activities. The room could accomodate space for storage of personal items, sleeping, dressing and even a small personal work station. This gives the crewmember the option to work or contact home in privacy.

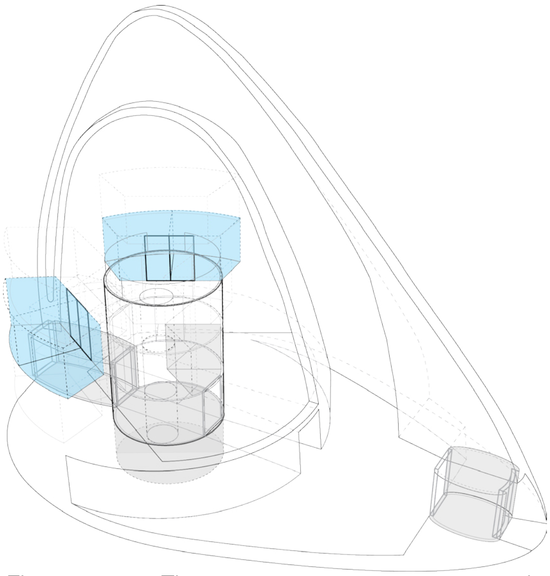


Figure 4.6.8. : The support systems are assumed to create environmental stressors like noise and vibrations. The sleeping quarters are not situated adjacent to the technical spaces.

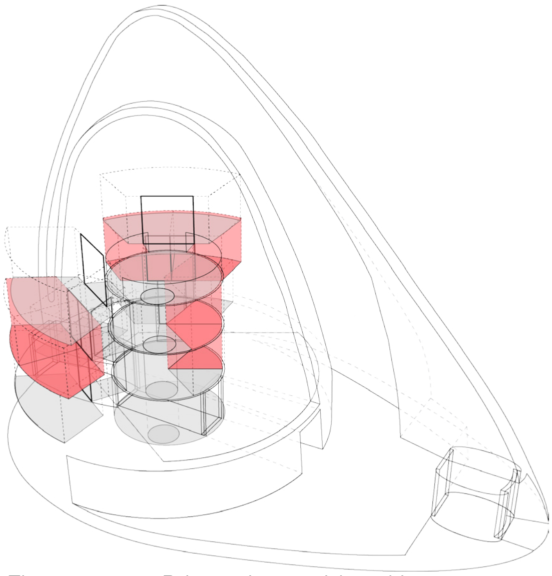


Figure 4.6.9. : Privacy is considered important in isolated and confined habitation. All private program elements are centrally placed within the habitat.

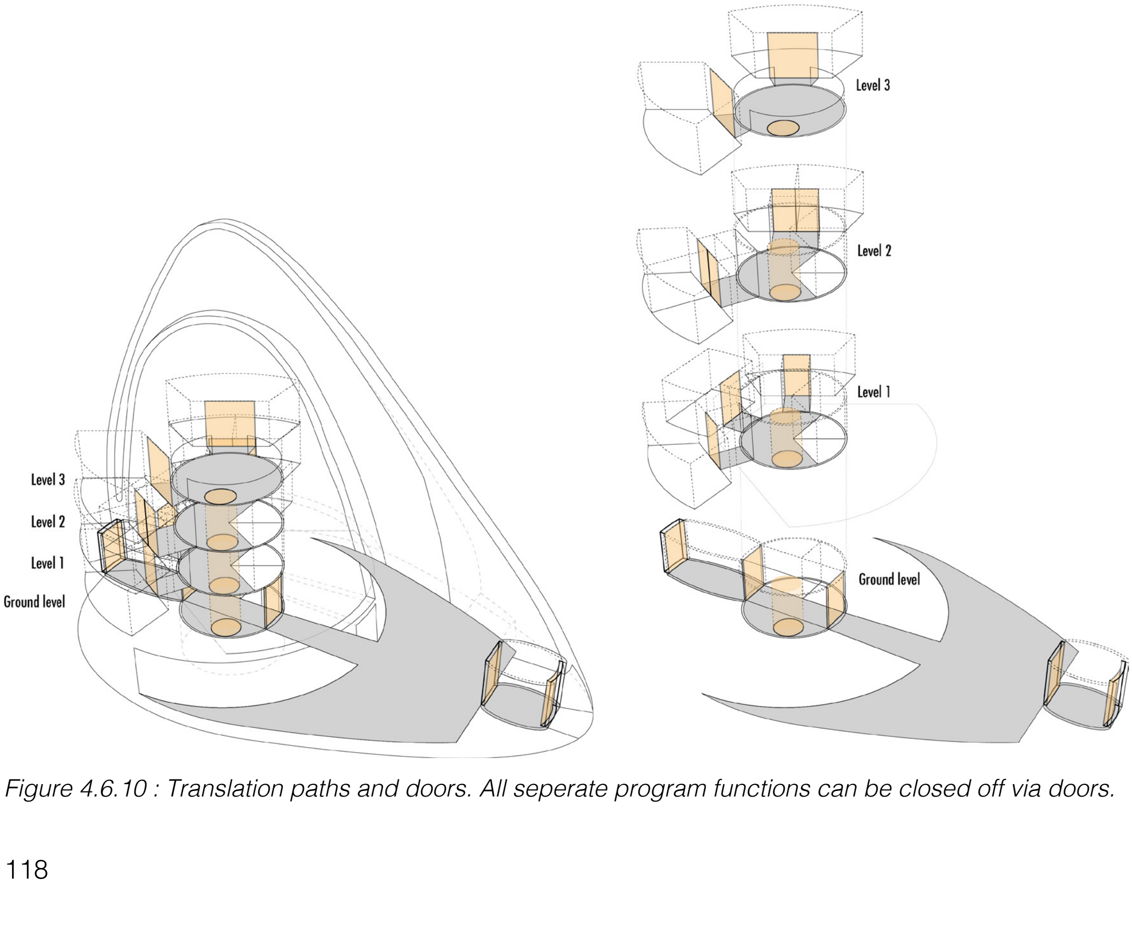


Figure 4.6.10 : Translation paths and doors. All seperate program functions can be closed off via doors.

4.6.3. CRITERIA EVALUATION

A thorough analysis based on the defined criteria, proved to be a constructive exercise in discovering the integrated qualities that enhance habitability. The safety analysis exposed the issue of egression through a single staircase within the central program. In all, Mars Ice House comes out as a surface habitat design with many integrated architectural qualities that could act as countermeasures for stressors and stress. The architectural means that were addressed in the analysis ranged from program organization and allocation for the functional activities to sightlines and spatial perception.

Acoustic and lighting were often expressed as generic complaints concerning habitability. Under various criteria special attention was paid to sound egression possibilities and effects of lighting conditions. It is recommended that the architectural design can be judged based on the formulated themes, but special attention remains to be paid to mitigating the found complaints that occurred in other design cases.

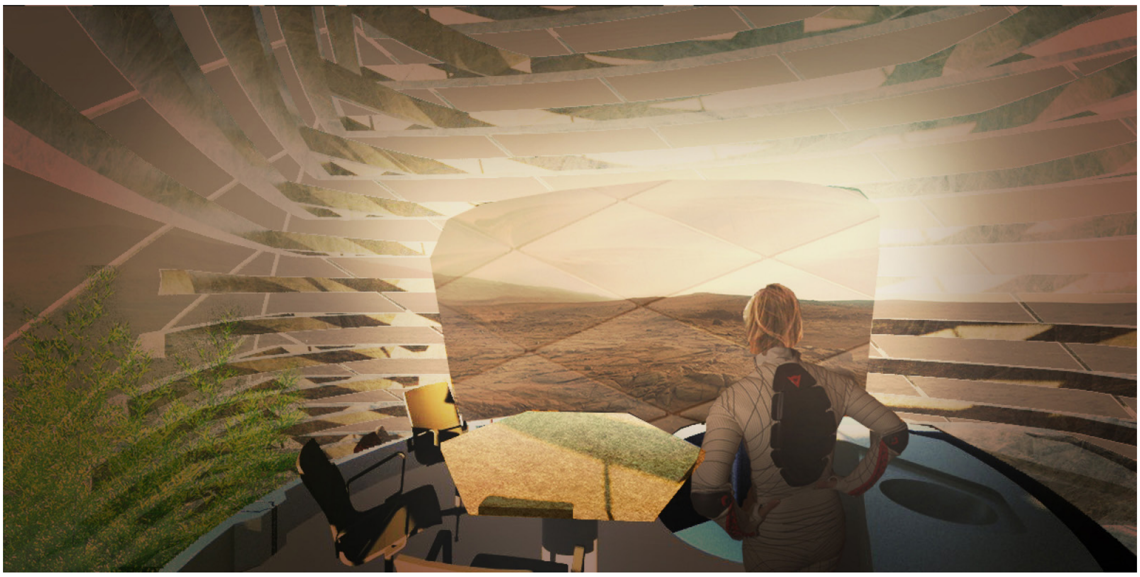
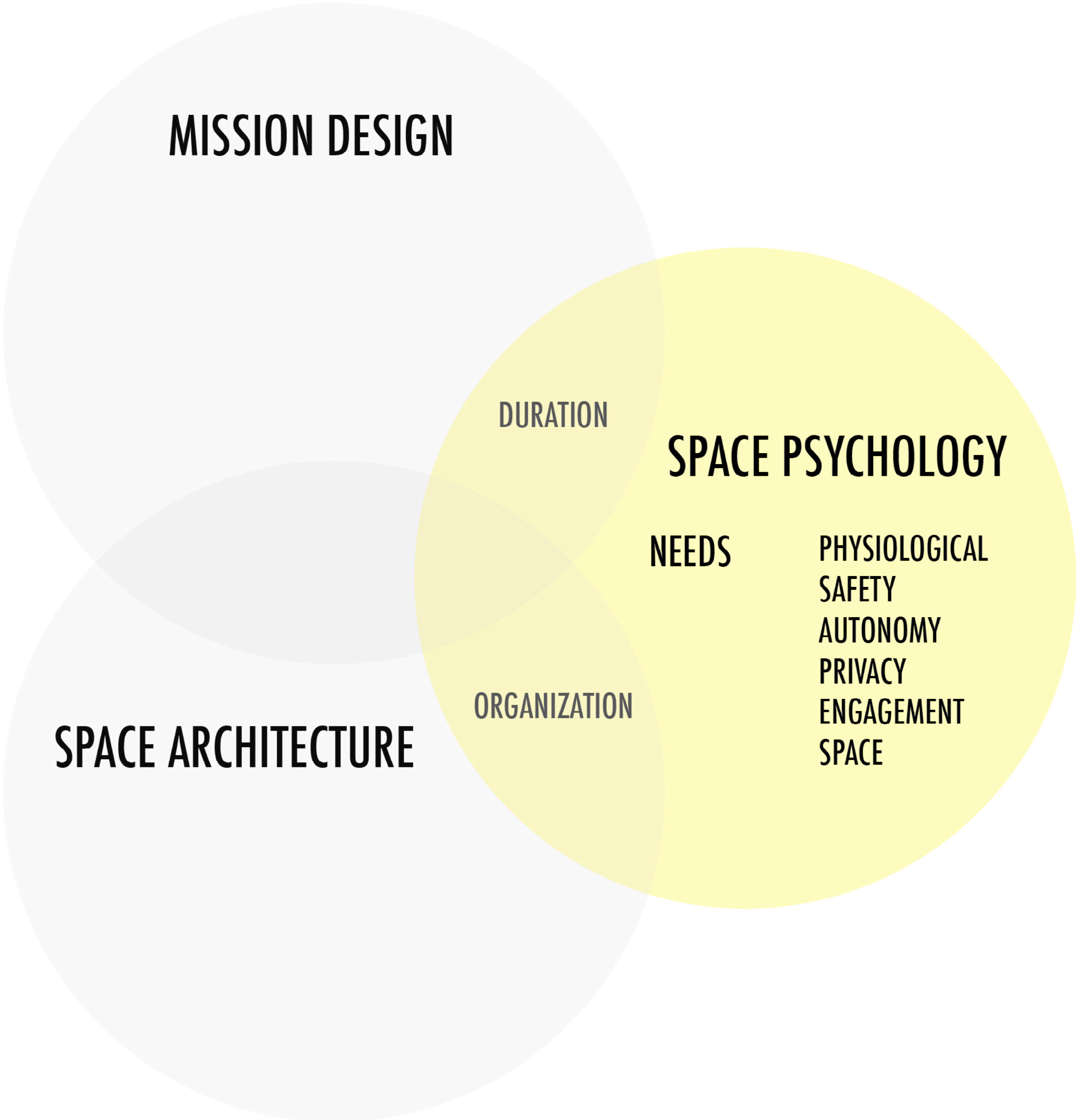


Figure 4.6.11 : Artistic impression of the view through one of the windows in Mars Ice House


MISSION DESIGN
DURATION
SPACE PSYCHOLOGY
NEEDS
PHYSIOLOGICAL
SAFETY
AUTONOMY
PRIVACY
ENGAGEMENT
SPACE
ORGANIZATION
SPACE ARCHITECTURE

4.7 SUMMARY AND CONCLUSION

4.7.1. SUMMARY

Mission duration magnifies stressor impact, therefore maintaining the crew's motivation is important for designing habitability, as it is considered critical for mission success. A habitat should not be designed for the crew to merely survive, but also to thrive in the isolated and confined living environment. The most desirable crewsize for a mission was found to be a crew of seven with different nationalities and backgrounds.

Space psychology is interesting for architecture as both disciplines are concerned with habitability for optimal risk mitigation concerning Behavioral Health & Performance. Within aerospace engineering, these issues are often addressed under the term Human Factors Engineering. Complaints concerning habitability were found and categorized. This has been related to the recommendations from literature on architectural design for habitability. Organization of the program functions is crucial for habitability, but it is not directly clear how to judge habitability within an architectural design. An exercise in categorising stressors into thematic needs resulted in some initial criteria. These were evaluated with a case study and proved to be of value.

The defined criteria to judge habitability in an architectural design were defined as the needs for safety, autonomy, engagement, privacy, space and physiological well-being. Habitability within the architectural design, should not be evaluated in order of priority, but all needs criteria should be balanced and weighed in relation to each other. The formulated qualitative requirements are merely a starting point for the architect to address habitability in the design. Leading complaints found in other mission habitats should be considered during the qualitative evaluation.

4.7.2. CONCLUSION

Habitat designs within space engineering, where the habitat is a part of the mission design, should avoid monotony, leading to boredom, and include variety as much as possible. Architectural means are suggested to be applied as a countermeasure to mitigate this risk. A categorization of the identified stressors that occur in space missions, related to Maslow's pyramid and the paradigm shift for long-duration mission design, led to a set of themes that could function as criteria. An analysis based on these formulated criteria could help the architect in qualifying the design's habitability. However, during evaluation, special attention remains to be paid to identified issues in prior inhibited space architectures. These issues include environmental factors, such as acoustics, lighting and thermal conditioning.

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05

SPACE ARCHITECTURE

Behavioral Health & Performance has been defined as a critical risk that has to be taken into account for a human mission to Mars. Research in Mission Design has resulted in quantitative requirements and research on Space Psychology has resulted in the formulation of qualitative requirements for the architectural brief of the martian surface habitat.

In this chapter the program elements will be defined as architectural design requirements. The objective of the research in this chapter is to further define the design drivers for the habitat design from the perspective of the Space Architect, overlapping with both Mission Design and Space Psychology.

Figure 5.1.1. : Visualisation of a design for a martian surface habitat (Courtesy of SICSA)

Task	Engineering approach	Architectural approach
Problem definition	Product-oriented	Process-oriented
Approach	Linear (analysis) start at the beginning of the process	Nonlinear and iterative (synthesis), start at critical points, then adjust
Workflow	Workflow from the start to the end, done with numbers (quantitative methodology)	Workflow anywhere in the project, done with models (qualitative methodology)
Solution	There is one ideal solution, most decisions are quantifiable	There are many solutions, some decisions are quantifiable

Table 5.1.1. : Engineering and architectural approaches throughout the design processes (Hauplik-Meusburger et al., 2016, p.12)

5.1 SPACE ARCHITECTURE

5.1.1. SPACE ARCHITECTURE AS A DISCIPLINE

Human factors engineering and research for living in isolated and extreme environments started in the 1950s. (Hauplik-Meusburger, 2017) With the publication of *Living Aloft* in 1985, NASA first addressed the importance of designing for habitability as a seperate functional requirement in the human mission design process. Conners et al. (1985) defined habitability in space as a critical aspect to address during mission development. Over the years various definitions for habitability have evolved. Hauplik-Meusburger et al. conclude (2016, p.105):

> *"All these definitions imply that it is the job of the space architect to create an environment that is safe and comfortable for people to live and work within."*

In all, space architecture has only recently been established as a distinct specialistion combining the discipline of the engineer and the architect. In 2002, Space Architecture was first established as an official education track in the US. (Duerk, 2002) Currently Sasakawa International Center for Space Architecture (SICSA), based in Houston (TX, USA), is the only educational institution that offers a full program that only focusses on teaching space architecture. Nine other educational institutions in the world offer courses on space architecture. (Bannova et al., 2016)

Space architecure concerns the integration and organization of functions and systems. For this reason it is important to know what systems and what programmatic functions should be integrated in the habitat. The task for the architect is to synthesize functional organization and system configuration in one integrated product. Cohen's (1991) conclusion to let qualitative needs drive habitable design for long duration exploration missions, will form the starting point of brief definition within this chapter. Later paragraphs will elaborate on the elements of the habitat system.

5.1.2. ARCHITECTURAL ENGINEERING

In conventional architectural design, the architect plays a leading role in development of the building. The architect is trained to develop a design and integrates generic engineering principles based on expertise and rule of thumb. In a later stage, after the initial design is drafted, the engineer performs calculations on the design, which can result in required alterations. Eventually, through this iterative process the building design spirals between disciplines until a final design is made and built. As Bannova et al. state (2016, p.14):

> *"The architectural discipline is multidisciplinary by its nature. It builds upon a basic understanding of engineering, aesthetics and social sciences."*

Due to further advancement in engineering solutions and an increase in complexity, the need to integrate architecture with engineering resulted in a new design discipline of architectural engineering. As the circumstances of the location get more extreme, a larger emphasis is put on the engineering and technical performance of the habitat. This often results in decisions which compromise the habitable quality. The research in this chapter will focus on further definition of qualitative and quantitative elements within the brief for a martian surface habitat. Secondly, the design approach for the architectural engineer will be considered.

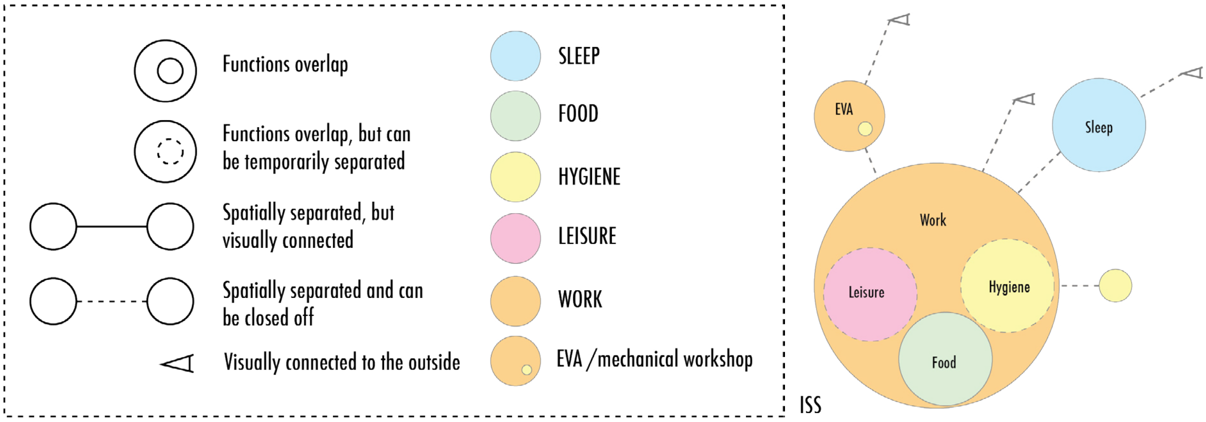


Figure 5.2.1. : Methodology to analyse functional program and their relations (Hauplik-Meusburger, 2011)

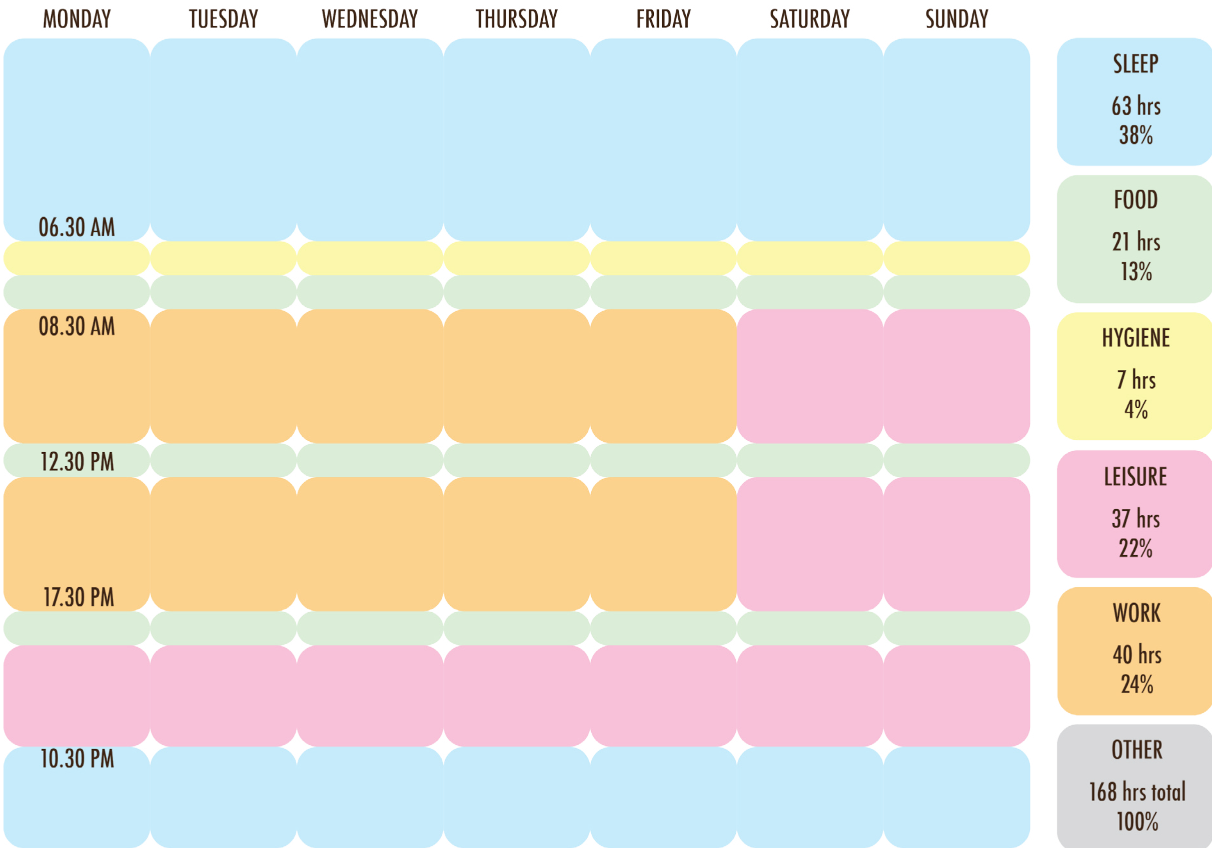


Figure 5.2.2. : Scheduling activities showed the amount of time in which the functional space allocation has to perform in supporting the operational activiteis of the crew

5.2 PROGRAM AND ORGANIZATION

5.2.1. CREW ACCOMMODATIONS

In literature, the crew accomodations, or program outfitting, is often a vague and undefined parameter. However, some generic assumptions for program requirements can be found.

Genta (2017) lists several programmatic functions that would be required in a martian habitat. These include a galley or kitchen; communal spaces; individual crew quarters; hygiene facility; medical facilities; work spaces; a radiation storm shelter; ECLSS; laboratories; mechanical maintenance workshop; greenhouse; airlocks and hatches and plenty of storage facilities.

Bannova and Hauplik-Meusburger (2016) list a similar list of functions that should be supported within the architectural program of capsule habitats. These include public spaces; private quarters; work and/or laboratory areas; life support systems; use of robotics; surface mobility systems; EVA access; plant growth; multiple access and circulation paths.

Whitmore et al. (2015) has defined several functional areas within habitable volumes for long-duration exploration missions. The areas are allocated to activities which include berthing, dining and communal activities, stowage and access, workspace, exercise, hygiene and translation paths.

Based on an extensive analysis of several experienced orbital architectures, a categorisation of activities within the program of a capsule habitat has been made. (Hauplik-Meusburger, 2011) The five categories are Sleep, Food, Hygiene, Leisure and Work, with a sub-category of EVA-workshops. The analysis shows how these seperate programmatic functions relate to each other. The method of using a bubble-diagram to show the programmatic organization, proves to be an effective tool for a quick overview in differences between orbital architectures and it's perceived living experience.

5.2.2. DURATION EFFECTS

Considering the brief for a capsule habitat, it is required to define allocated spaces for seperate functions. The analysis based on the five categories forms a strong starting point, but when considering the total necessity of required space within the volume, one important element was missing. The programmatic analysis did not consider the spaces required for technical support systems. Also, the activities based approach, gives a major insight in the type of activities, but not necessarily in the amount of time spent to perform these activities.

A hypothetical schedule for a martian astronaut provided insight in the amount of time spent for certain activities and thus the intensity, due to duration, of the perceived environment in which the activities take place. The study shows that leisure time (22%) is almost equal to the amount of time spent on working (24%). Each of these programmatic elements have to be supported by technical systems within the capsule, meaning that the “other” space allocation for technical support systems is required to function at all times.

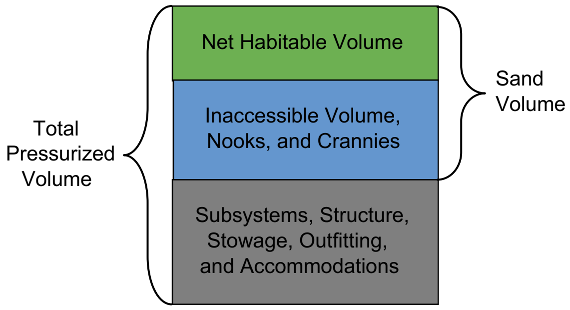


Figure 5.2.3. : Breakdown of pressurized volumes that define habitable volume (Simon et al., 2012)

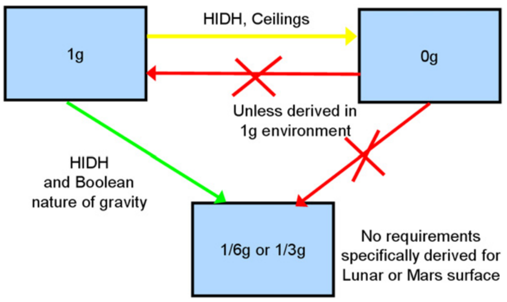


Figure 5.2.4. : Illustration of utility functions from several design standards to determine preference of habitable volume values beyond requirements (Simon et al., 2012)

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

Table 5.2.1. : Exploration Mission Parameters defined as baseline assumptions by Whitmore et al. (2015)

5.2.3. VOLUMETRIC REQUIREMENTS

Bassingthwaighte (2017, p.121) explains that one of the most important architectural drivers in Isolated and Confined Environmental (ICE) design can be summarised in the idea of space. Since the 1950s many volumetric studies have been performed. Habitable volume requirements are important to determine for functional space allocation. An insufficient amount of habitable volume could lead to significant psychological stresses, resulting in a decreased crew performance and creation of a potential safety hazard, causing mission failure.

In 2015, NASA published a study on net habitable volume requirements for long duration space missions. (Whitmore et al., 2015) However, the standard only defines volumetric requirements for habitation in microgravity. Other standards from NASA, such as the Human Integrations Design Handbook (HIDH) and Man Systems Integration Standard (M-SIS), explain that volumetric requirements in partial gravity should be derived from those in full earth's gravity. (Figure 5.2.4.)

Simon et al. (2012) performed a study to determine the net habitable volume requirements and developed a calculation method to determine the utility. Net habitable volume is here defined as "*a minimum required amount of free or accessible volume necessary for the crew to perform tasks without incurring physical, physiological, or psychological impairment for the duration of the mission*."

Utility theory is explained as "the concept of different values assigned for the extent to which a variable exceeds its requirement". In other words this means that the chosen value for volumetric design requirements should reflect the desired level of performance beyond a minimum requirement. As Simon et al. state (2012, p. 72):

> *"... simply designing to the anticipated minimum volume to eliminate impairment for a design is not the only consideration. For example, providing increased volume beyond the requirement may provide significantly improved human comfort, safety, or productivity; however it may also have diminishing returns as the volume becomes spacious to the point of being wasted."*

In many standards, the minimum habitable volume requirements are based on findings from two methods: (a) task analysis and (b) experience-based sizing. Several shortcomings were found from the application of both methods, such as potential functions that could overlap in their space allocations and the outdated sizing of equipment in prior mission system architectures.

The mathematical calculation method to test the design for requirements on net habitable volume proved to be satisfying. Simon et al. (2012) conclude that parametric studies would identify the driving variables causing measurement differences for the same habitat.

Whitmore et al. (2015) emphasize that certain baseline assumptions drive the volumetric design requirements. The assumptions for their study are shown in Table 5.2.1. From this study, can be concluded that exact volumetric design requirements for the architectural brief can only be defined after definition of the exact baseline parameters. These baseline parameters should be derived from the mission architecture.

SLEEP

Functional activities that fall under the category **SLEEP** are:
- *Sleeping*
- *Relaxing*
- *Private communication*
- *Dressing*
- *Storage of personal items*

FOOD

Functional activities that fall under the category **FOOD** are:
- *Cooking*
- *Dining, drinking; basically consuming*
- *Growing crops*
- *Waste management*
- *Food storage for weekly consumption*
- *Food storage for the entire mission*

HYGIENE

Functional activities that fall under the category **HYGIENE** are:
- *Body wash*
- *Toilet*
- *Laundry*
- *Housekeeping*

LEISURE

Functional activities that fall under the category **LEISURE** are:
- *Exercise*
- *Playing games*
- *Entertainment, movies, television*
- *Group activities, for entire team*
- *Talking; allow sub-grouping (thus variation in gathering spaces)*
- *Relaxing*

WORK

Functional activities that fall under the category **WORK** are:
- *Laboratory*
- *Mechanical Workshop for repairing items*
- *Extra Vehicular Activity suits and support systems*
- *Technical Maintenance tool storage*
- *Experiments*
- *Sample storage*

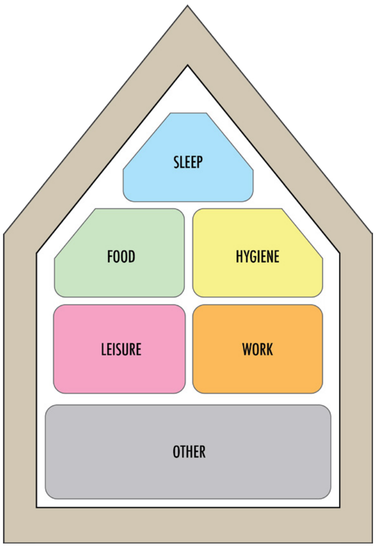
OTHER

Functions that fall under the category **OTHER** are:
- *Environmental Control and Life Support System (ECLSS)*
- *Power Supply and Storage System*
- *Thermal Control System*
- *Communication Systems*
- *Control Systems*
- *Data Management and Storage Systems; such as servers*

5.2.4. FINDINGS

Categorisation of activities, prove to be a sensible starting point as a programmatic driver for the architectural brief. When considering the requirements and defining allocated spaces for the activities, some other important space allocations, i.e. for technical support systems, tends to be overseen. A reason for this could be that the architect is primarily concerned with organisation of activities in relation to the user's experience. However, the placement of the technical support system can have a major impact on the environmental experience. It is therefore important, that the architect also considers organization of the the technical space as an integral part of the design task.

Assigning the volumetric requirements to seperate elements of the brief was found to be a difficult task. Space allocation is directly related to the functional activities, which in turn are defined by the baseline assumptions of the mission architecture and the mission objectives. For example, crew characterization follows from the required crew size, which follows from mission objectives and duration. The characterization defines the necessary disciplines which might use different tools and thus perform different kind of functional activities. Parametric studies could aid in analysing the requirement drives and defining the required net habitable volume. (Simons et al., 2012)



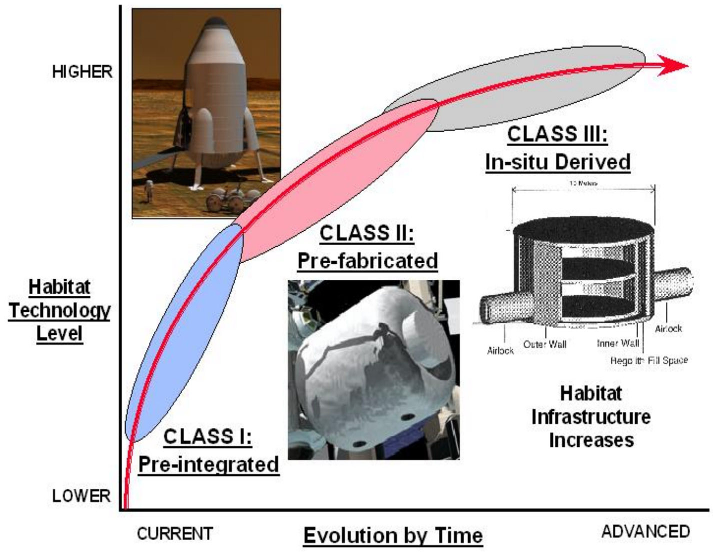


Figure 5.3.1. : Space Architecture Classifications (Kennedy, 2002)

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.

Sources Badescu (2012)

Table 5.3.1.: Construction methods and examples for space architecture (Hauplik-Meusburger et al., 2016)

5.3 CHARACTERIZATION

5.3.1. TYPOLOGIES

Space architecture focuses on habitat development in an extreme and unusual environment (EUE) also referred to as stressfull environments (Suedfeld, 2000). A capsule habitat makes it possible for humans to survive in an environment that would otherwise be lethal, such as polar regions, space or ocean depths. Suedfeld (2000) defines capsule habitats as a type of isolated and confined environment (ICE), which overlaps with the EUE. Suedfeld states (2000, p228-229):

> *"Typically, capsule environments are remote from other communities, are located in places where the physical parameters are inimical to human life, and are difficult to enter or leave. They are inhibited by artificially composed groups of people who are removed from their normal social networks and who carry out specific tasks and procedures."*

Howe and Sherwood (2000) categorise space architecture into three different categories: earth-based analogues, orbital and planetary-surface architectures. Bassingthwaite (2017) elaborates on a similar distinction and defines planetary habitats as the only type that could be labeled as permanent.

5.3.2. STRUCTURAL CLASSIFICATION

Space habitats can be categorized by a certain classification. Kennedy (2002) defines three classes. Class I refers to habitats that are preintegrated-entirely manufactured, integrated, and ready to operate when delivered to space or the final operation location. Class II is prefabricated and is space- or surface-deployed with some assembly or setup required. Class III is in-situ derived, with its structure manufactured using local resources available on the Moon or Mars. Wilkinson (2016) extends the classification within space architecture to Class IV, where the design is constructed solely from local materials and Class V where the constructing machines fabricate themselves in-situ.

In a similar way, Genta (2017) elaborates on four possible approaches to realise a Martian habitat. The first approach falls within Class I. This is a 'metal' habitat (one built in the same manner as the modules of space stations), that will be built on Earth, sent to LEO, carried to Mars orbit, and finally landed on the surface.

The second, falls within Class II. An inflatable habitat (such as are built on Earth) will be sent to LEO, carried to Mars orbit, and finally landed on the surface. Since it will not be inflated until it is in place, its stowed configuration will take up much less volume aboard the lander (or perhaps the same volume will be allocated in order to carry a larger habitat). It will probably be much lighter, easier to land, and easier to deploy.

The third approach of a 'masonry' habitat, falls within Class III, and will be built using regolith and other materials found on the site. All that will need to be delivered from Earth are the construction tools, specialized units such as airlocks and internal apparatus.

The fourth approach, would be a 'cave' habitat, which would exploit either a cave or a lava tube. This solution may increase the habitable space while minimizing the mass to be brought from Earth. It would also offer protection against radiation.

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 5.3.2. : Design parameters for orbital planetary and mobile habitats compared, adapted from Cohen (1996) (Hauplik-Meusburger et al., 2016)

Genta elaborates on the inflatable approach (2017, p186-188):

> *"To increase the internal space, the habitat may be deployable, inflatable, or assembled from several sections on Mars, ideally in an automated, self-deployable manner. The simplest option is an inflatable habitat. (...) By the time of a Mars mission, this technology will be mature. Actually, it is easier to produce an inflatable module for Mars than for space. The substantial experience gained with large air supported structures on Earth may be applied in building inflatable habitats on Mars. In this case, the greater pressure differential between the inside and the outside may require using a stronger membrane, but it will also permit placing regolith on at least a part of the habitat to protect the interior from radiation."*

In the late nineties, NASA performed some extensive research on inflatable structures for space under the name Transhab. (Kennedy, 2002) Unfortunately the Transhab was never fully developed, but Robert Bigelow decided to continue the work and founded a company under the name Bigelow. (Bigelow, 2017) In 2015, a first conceptual model for an inflatable structure in space was tested on the International Space Station (ISS), under the name Bigelow Expandable Activity Module (BEAM). The first measurements and findings revealed that the radiation levels inside the BEAM are similar as within the rest of the ISS. (NASA BEAM, 2016)

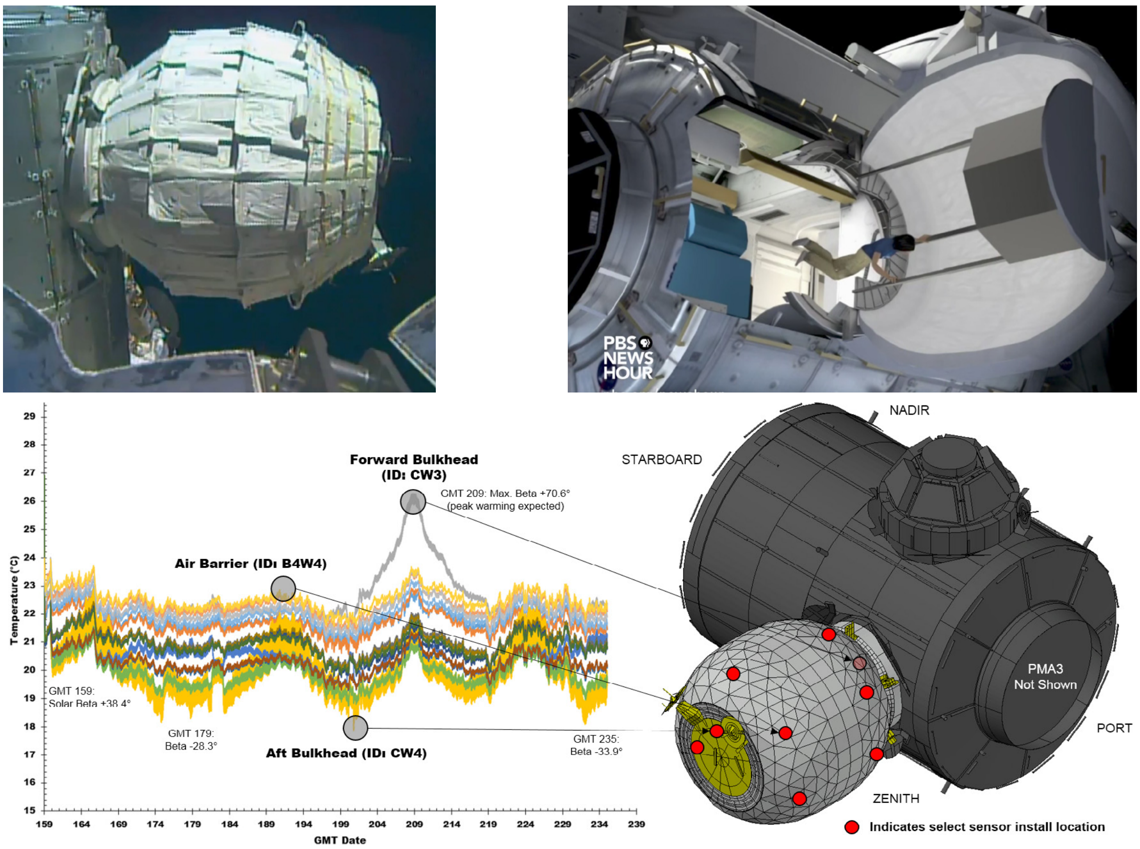


Figure 5.3.2. : The Bigelow Expandable Activity Module was connected to the International Space Station in 2015 to test the performance of inflatable structures in a space environment.

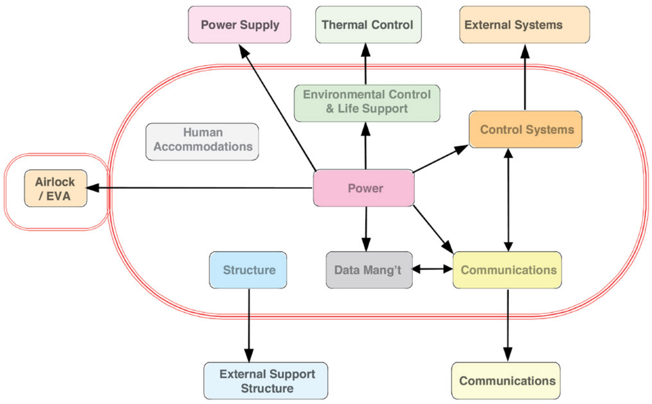


FIgure 5.4.1. : Habitat system elements and their relations (Kennedy, 2002)

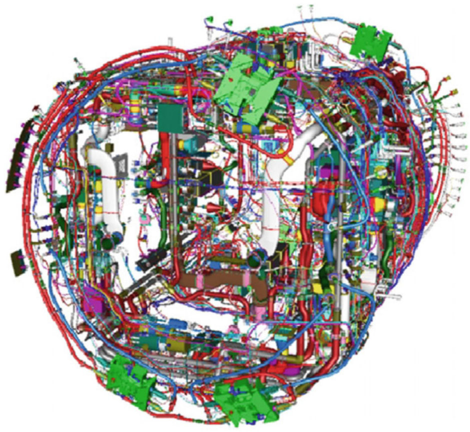


Figure 5.4.2. : Complexity of the ECLSS in Node 2 from the ISS. The complexity of the ECLiSS comes from having to interconnect the ECLSS of six other modules. (Hauplik-Meusburger et al., 2016)

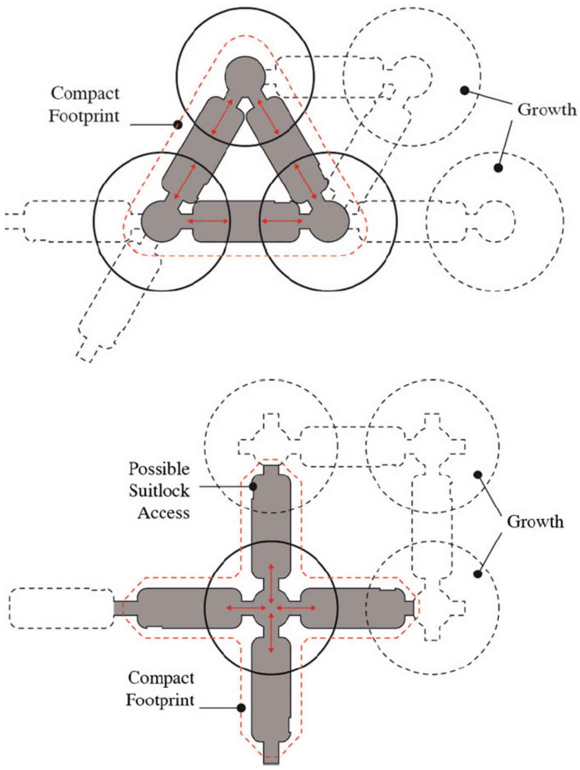


Figure 5.4.3. : Variations in footprint related to settlement strategy (Bannova, 2007)

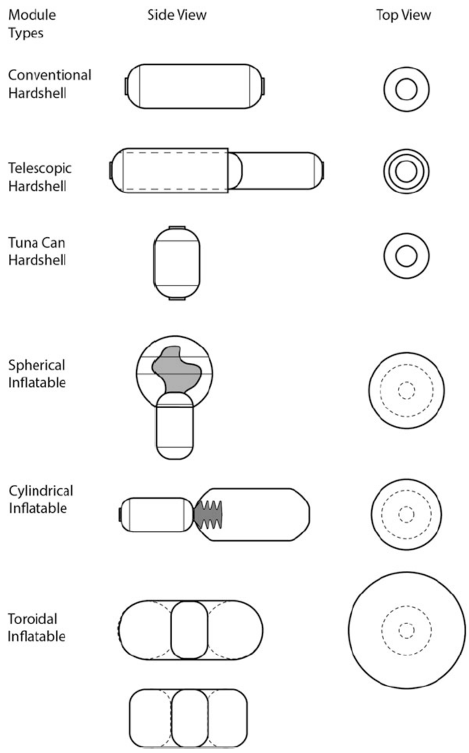


Figure 5.4.4. : Several module configurations (Bannova, 2007)

5.4 SYSTEM CONFIGURATION

5.4.1. HABITAT ELEMENTS

Kennedy (2002) explains that Space Architecture is comprised of launch vehicles, pressure vessels (modules) and the systems to support human life. Many elements, systems, and hardware are involved within these broad categories. The launch vehicles are a part of this vernacular as they constrain the size and mass that will be transported to orbit. Through defining these essential elements, it is possible to think of the space habitat as a system that should include and support all of these separate elements. An overview of the defined elements and their interfaces is given in Figure 5.4.1.

Each capsule habitat within space architecture requires a different design approach, but all have to meet the requirements of providing a pressurized environment for the humans to live and work within.

Common requirements, regardless of destination, include the following (Kennedy, 2002, p.4):

- *Crew safety*
- *Acceptable physiological and psychological support for humans*
- *Successful accommodation of mission objectives*
- *Reliable structural integrity with adequate safety margins*
- *Forgiving failure models (e.g., leak before rupture)*
- *Ability to be tested to a high level of confidence before being put into service*
- *Ability to be integrated with available launch systems*
- *Straightforward outfitting and servicing*
- *Easily maintained*
- *Long design life*
- *Commonality at the system or subsystem level*

Hauplik-Meusburger and Bannova (2016) elaborate on the complexity of the environmental control and life support system (ECLSS). Node 2 from the ISS is an interconnecting element for six other modules. This necessity has a drastic influence on the configuration of the fluid systems. (Figure 5.4.2.). For this reason the ECLSS will be a central starting point concerning the program organization and configuration of the habitat, as all spaces have to be connected to this system.

5.4.2. STRATEGIC CONFIGURATION

Bannova (2007) elaborates on the importance of the settlement strategy, as it influences the design configuration. It is assumed that the goal of planetary surface exploration is to establish a permanent settlement that is independent of resupply. In particular, the following issues have to be considered when developing a settlement strategy (Hauplik-Meusburger, 2016, p. 206):

- *Ease of surface transportability and deployment*
- *Access/egress availability*
- *Configuration and evolution growth capacity*
- *Maintenance operability*
- *Power availability*
- *Research targets*
- *Resource availability*

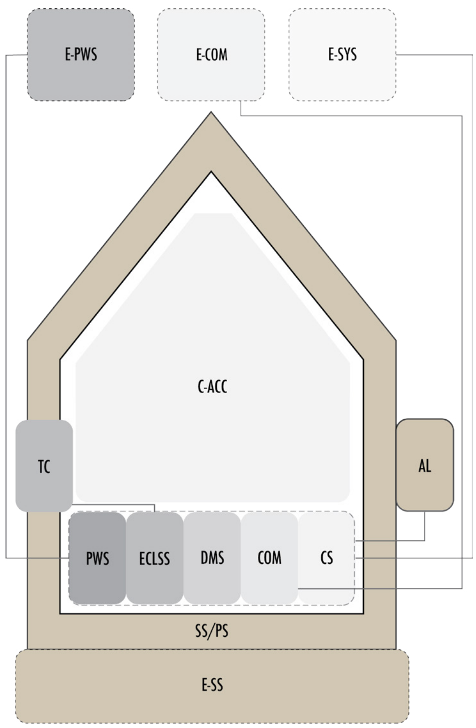
icon	description	mass (kg)
C-ACC	Crew Accomodations	tbd
SS/PS	Support Structure/ Pressure Shell	7500
ECLSS	Environmental Control and Life Support System	2500
PWS	Power Supply System	1250
CS	Control Systems	200
COM	Command and communications Systems	200
DMS	Data Management and Storage	100
TC	Thermal Control System	1500
E-SS	External Support System	tbd
AL	Airlock and EVA systems	1500
E-PWS	External Power Supply System	5000
E-SYS	External Surface Systems	7000
E-COM	External Communication Systems	N/A

Table 5.4.1. : Preliminary estimate for several sub-systems and elements based on findings in literature. (A. Scott Howe et al., 2000; Simon et al., 2017)

For future long-term missions, the design has to incorporate evolutionary site development. Geometric growth options are fundamentally determined by the numbers and placements of interfaces between individual habitat elements, internal and external airlocks, and potentially, pressurized surface rovers. These interfaces determine surface geometry options, which in turn, drive site development strategies and establish dual egress crew safety characteristics. Different types of modules have to be compared and assessed in relation to those considerations.

5.4.3. FINDINGS

Given the seperate system elements and their interfaces, a diagram of the system and it's configuration within the architectural design can be made. Earlier studies have examined mass allocations for conceptual designs for Lunar ICE habitats. (Howe et al., 2000) Some generic mass allocations have been defined and summarized to come to an estimated mass budget for the habitat. However, only few studies have been done and often the detailed list of mass allocations for which exact elements are missing. Another issue is that several sub-elements are addressed in each study under a different name or category. Further research is required, which would be beneficial as a starting point for the system configuration within the capsule. As a result, it would be possible to derive the maximum size and mass that could be landed with the chosen EDL-procedure. This would provide insight in the number of rocket launches required to construct the habitat.



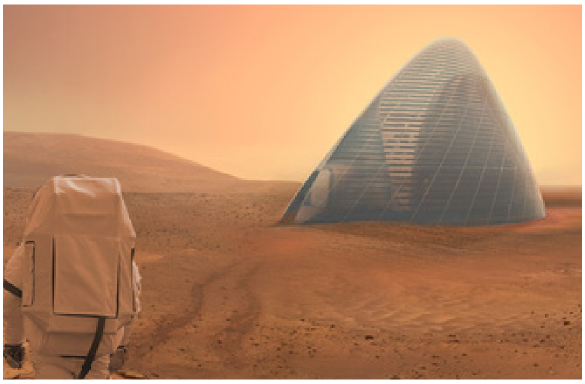


Figure 5.5.1. : Mars Ice House by CloudsAO

Figure 5.5.2. : Team Gamma's design from Foster and Partners

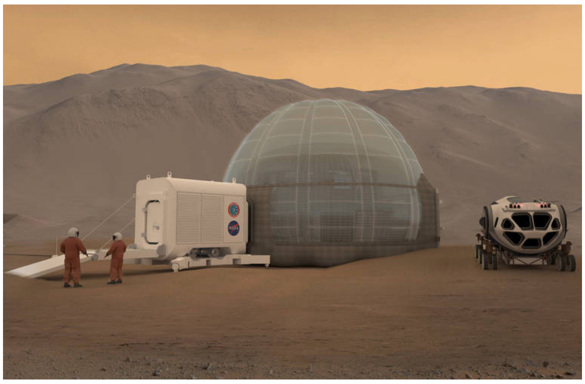


Figure 5.5.3. : Mars Ice Home by CloudsAO

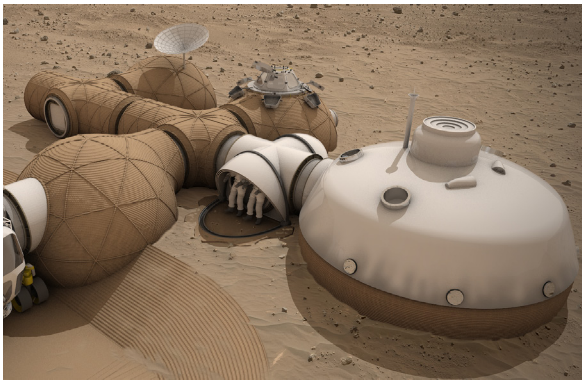


Figure 5.5.4. : LavaHives by Liquifer

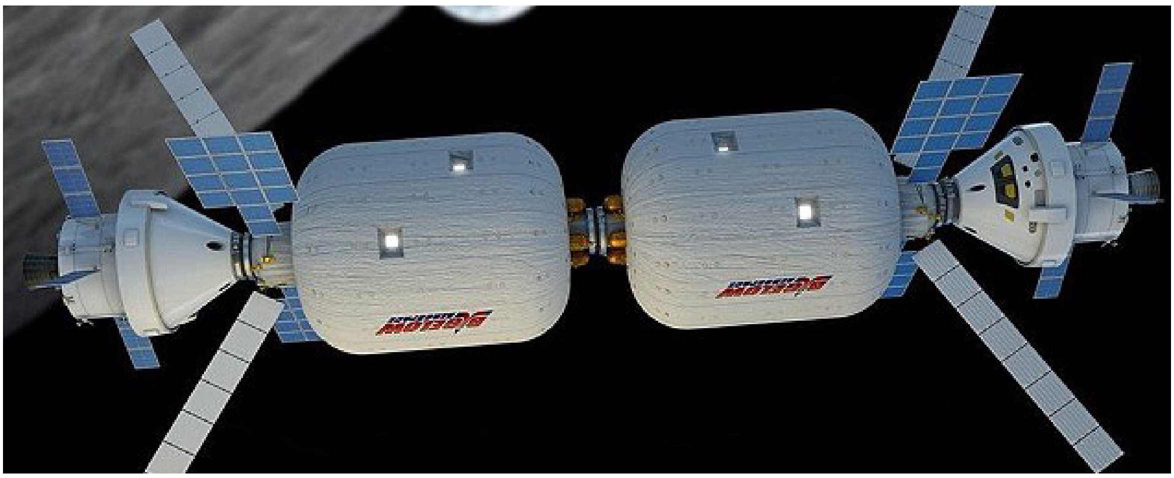


Figure 5.5.5. : Bigelow's impression based on the earlier developed Transhab Module by NASA

5.5 CASE STUDIES ANALYSIS

5.5.1. CASE STUDY SELECTION

In 2015, NASA organized a 3D-printed habitat design contest in collaboration with Berkeley University and America Makes (3DP hab, 2015). The contest resulted in 165 entries from design teams all over the world. The entries were shortlisted to thirty architectural concept designs of which ten designs were nominated and the top three was awarded. First place was assigned to the team of Cloads AO with their design for Mars IceHouse, a 3D-printed ice structure. Team GAMMA, a design team from the architecure firm Foster and Partners, was awarded second place and nominated by the public choice award for their proposal for a regolith sintered habitat with a swarm of robots. And the design team from the company Liquifer with their design LavaHives was nominated third place. The top three of this design competition will form the starting point of the analysis.

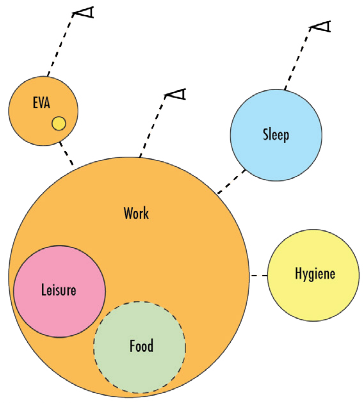
In 2016, Clouds AO published their latest design for a new and improved concept of the martian surface habitat. (CloudsAO, 2016) The design was developed in collaboration with NASA. After reviewing the evolved design, called Mars IceHome, many similarities could be found with the design for NASA's TransHab. The TransHab was developed in the late nineties by a team of space architects under NASA's supervision, but further development was cancelled in the early start of the new millennium (Kennedy, 2002). These similarities reveal an overlap in certain baseline assumptions. For this reason, the designs for Mars IceHome and TransHab will also be analysed in this thesis. The objective of the case study assessments is to expose certain strengths and weaknesses in these space architectures, so lessons can be drawn for the architectural engineer.

5.5.2. PROGRAM ORGANIZATION ANALYSIS

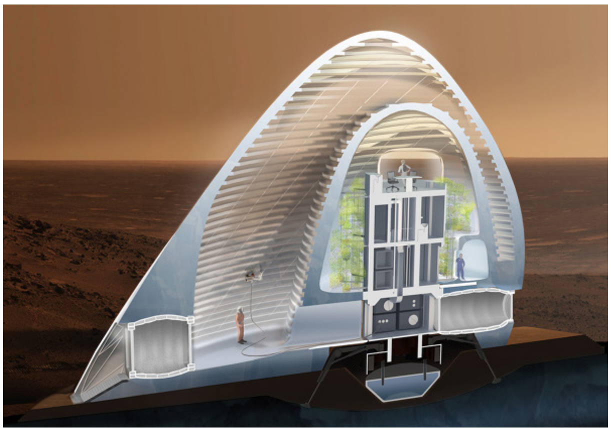
All the designs were compared and evaluated according to the bubble diagram strategy that was explained in paragraph 5.2. (Pages 144 and 145) When reviewing the analysis, the architectural considerations in the interest of the space psychology, i.e. feasible habitability, were weighed.

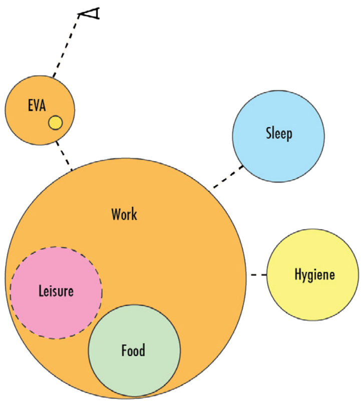
In paragraph 4.4 issues concerning habitability were identified. As was concluded in chapter 4, these should be considered when qualifying the program organization. A complaint was the lack of variation in program outfitting (lights, noise, draft due to high ventilation rate) and variation in spatial perception related to the functional activities.

It was decided, that emphasis should be put on leisure activities due to the highly isolated conditions on a Mars mission, which will bring higher crew autonomy. The crew's motivation should remain high, in order to optimise the crew's performance. This can be done through facilitating sufficient space for leisure activities. Also related to variation in spatial perception, it was decided that the allocated space for work should avoid overlap with the allocated space for leisure.

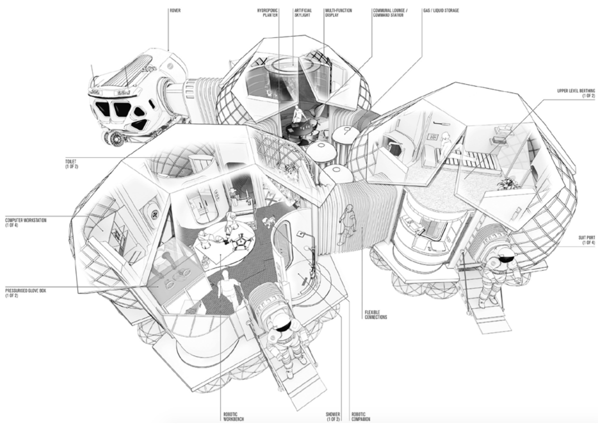


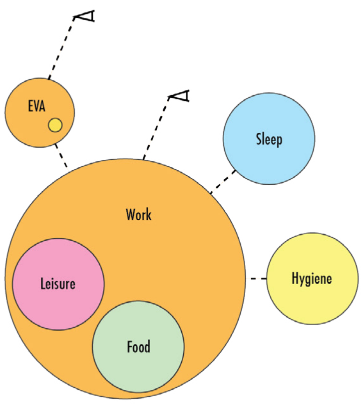
Mars IceHouse



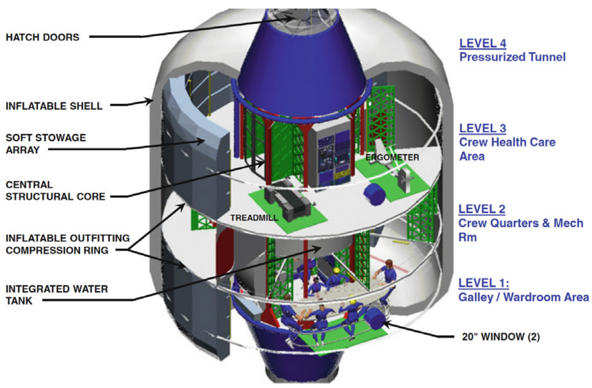


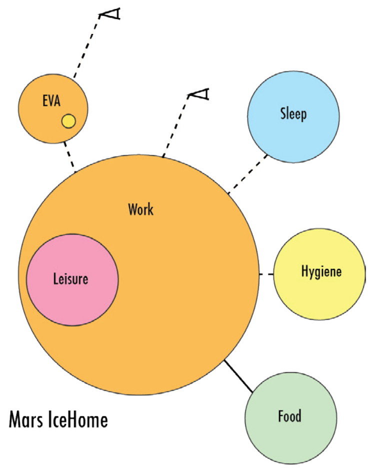
Team GAMMA

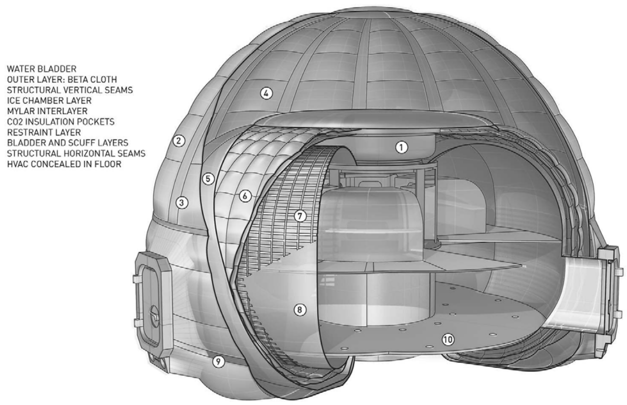


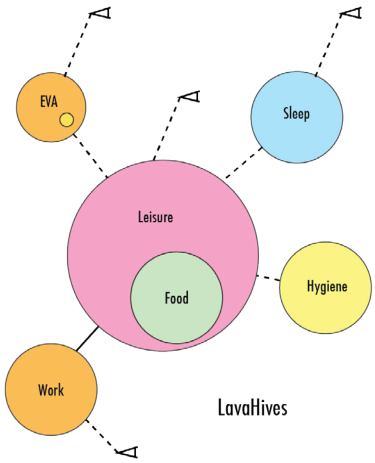


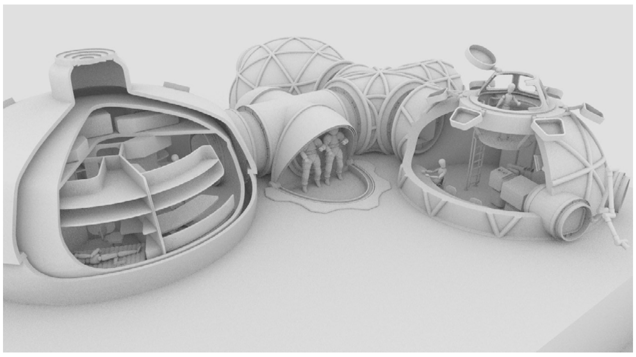
Transhab

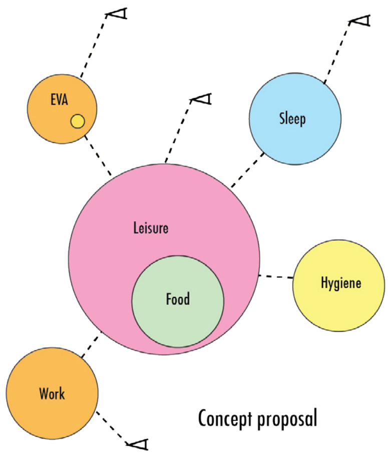


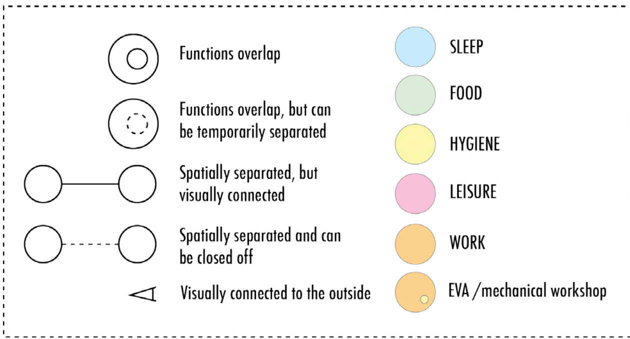

EVA
Work
Sleep
Leisure
Hygiene
Mars IceHome
Food


WATER BLADDER
OUTER LAYER: BETA CLOTH
STRUCTURAL VERTICAL SEAMS
ICE CHAMBER LAYER
MYLAR INTERLAYER
CO2 INSULATION POCKETS
RESTRAINT LAYER
BLADDER AND SCUFF LAYERS
STRUCTURAL HORIZONTAL SEAMS
HVAC CONCEALED IN FLOOR


EVA
Sleep
Leisure
Hygiene
Food
Work
LavaHives




EVA
Sleep
Leisure
Hygiene
Food
Work
Concept proposal


Functions overlap
Functions overlap, but can be temporarily separated
Spatially separated, but visually connected
Spatially separated and can be closed off
Visually connected to the outside
SLEEP
FOOD
HYGIENE
LEISURE
WORK
EVA /mechanical workshop

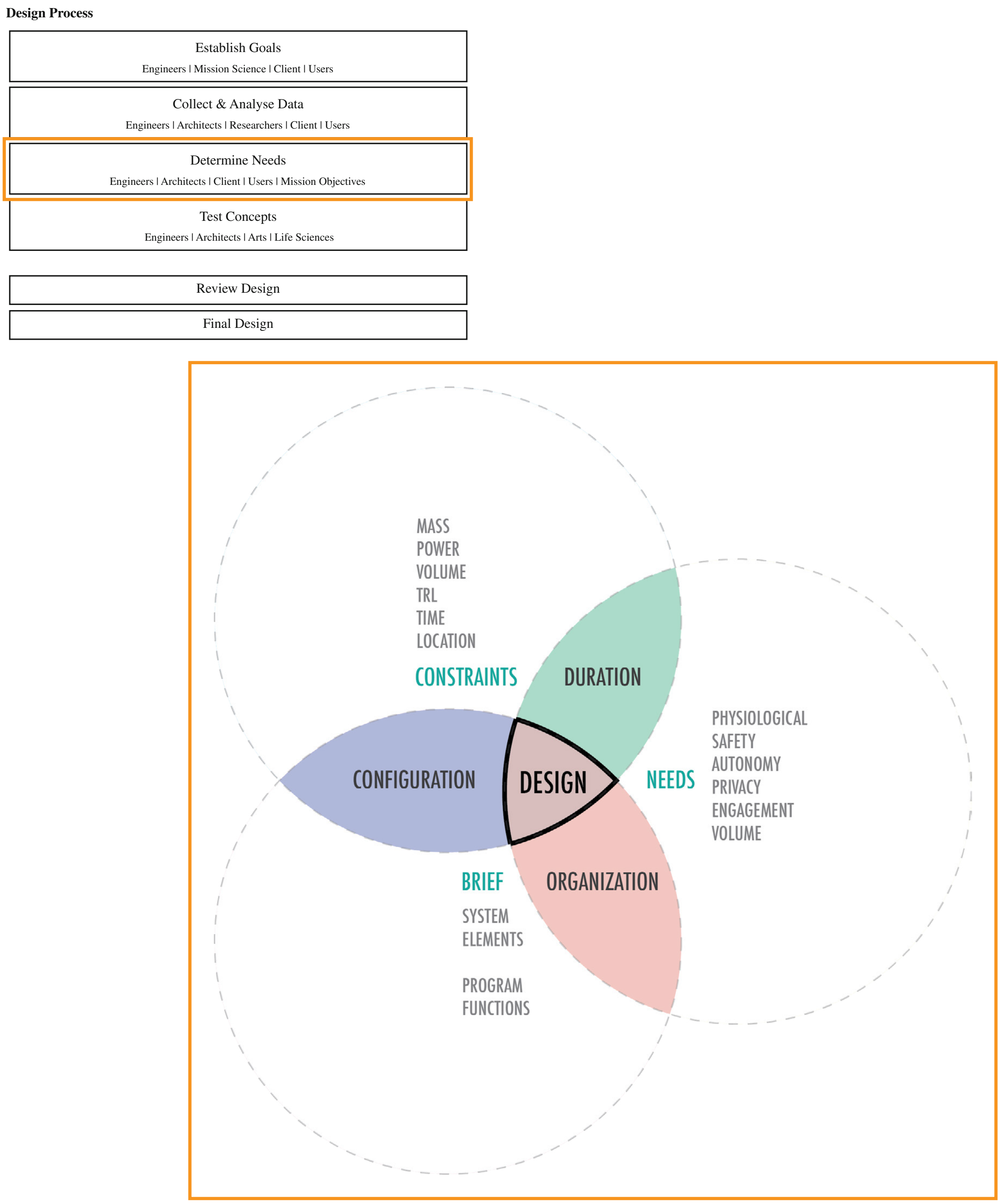


Figure 5.6.1 : Position of the brief in the design process of the space architect as given by Bannova et al. (2016) and the chosen design drivers in this study

5.6 ASSEMBLING THE BRIEF

5.6.1. POSITION OF BRIEF

In order to answer the main research question of finding the aspects to consider in designing a martian surface habitat, the design process for architectural design development will be discussed. This way the position of the brief within the process will be defined and the aspects that drive decisions on criteria for configuration and organization for the habitat.

Cohen (1990) defines designing as the following:

> *"Designing refers to the process of translating intentions or requirements into a physical form that embodies the operational and organizational aspects of an human endeavour. (...) designing is a strategic activity, whether by intention or default. It influences flexibility in all areas of productive activity and may be responsible for the future viability of any product, program or project. (...) Designing involves analysis, matching, selection, evaluation and integration functions in all problem solving domains."*

Both the architect and the engineer are designers. The steps within the design process of the architect and engineer are often evaluated and defined in various literature. In general, the process is described as starting with a problem or assignment; taking a position; formulating criteria or relevant values; develop an intial solution; testing the solution on the set values and criteria; followed by an evaluation of findings to support the proposed solution.

Bannova et al. (2016) elaborate on the position of the space architect in differentiated phases of space design development. The approach they define in space habitat design is depicted in (figure on the left). Concerning the design stages, Bannova et al. (2016, p. 16) state:

> *"The space architecture approach combines engineering thinking with criteria related to habitability and human factors, such as considered in architecture and industrial design, plus including other disciplines such as medicine and science."*

The process is explained that after the definition of the mission goals and objectives by the client and mission engineers, data will be collected and analysed to build up to a list of requirements. Considering human factors engineering in space mission decision, a strong emphasis is put on habitability to increase chances of succes for the human mission. Habitability is mostly studied in space psychology, therefore the input of the psychological experts is especially important for the space architect's design process.

Griffin (2010) emphasizes that there are major differences between the development process of the architect and the engineer. (Table 5.1.1.) The engineer often applies a linear approach with a strong emphasis on qualitative decision making to come to an optimal result. The architect takes on an iterative design process, guided by qualitative design decisions, often on different levels of scale. The space architect will have to address both quantitative as qualitative criteria during development of the design for a martian surface habitat.

The previous chapters form the result of collecting and analysing data concerning mission design, space psychology and space architecture. The final brief assembly fits in the following phase of determining the needs and requirements for the surface habitat as a system.

5.6.2. SPACE HABITAT DESIGN DEVELOPMENT

For assembling the brief as a list of requirements for the surface habitat, the input from mission engineering and human factors engineering have to be defined and valued in relation to the overall system requirements. Paragraph 6.2 will elaborate on elements of the brief and the relations that influence design decision making.

During the collection and analysis of data, some preliminary overlapping design drivers for the brief were defined. The defined drivers are Duration, Organization and Configuration. Academic literature from the field of Space Architecture backed the found drivers with studies into the different topics. Cohen (2008) found that duration drives crewsize which in turn drives the volumetric requirements for the habitat. Yet, crewsize can not be defined as a direct driver for volume since public functions don’t necessarily result in a linear increase in size. Hauplik-Meusburger (2011) found that the organization of programmatic functions and their relations form an important attribute in designing habitability. Bannova (2007) argued that strategic configuration should be considered by the space architect in order to optimize benefits. These drivers will have a strong influence on the valuation of the design outcome. (Figure 5.6.2.)

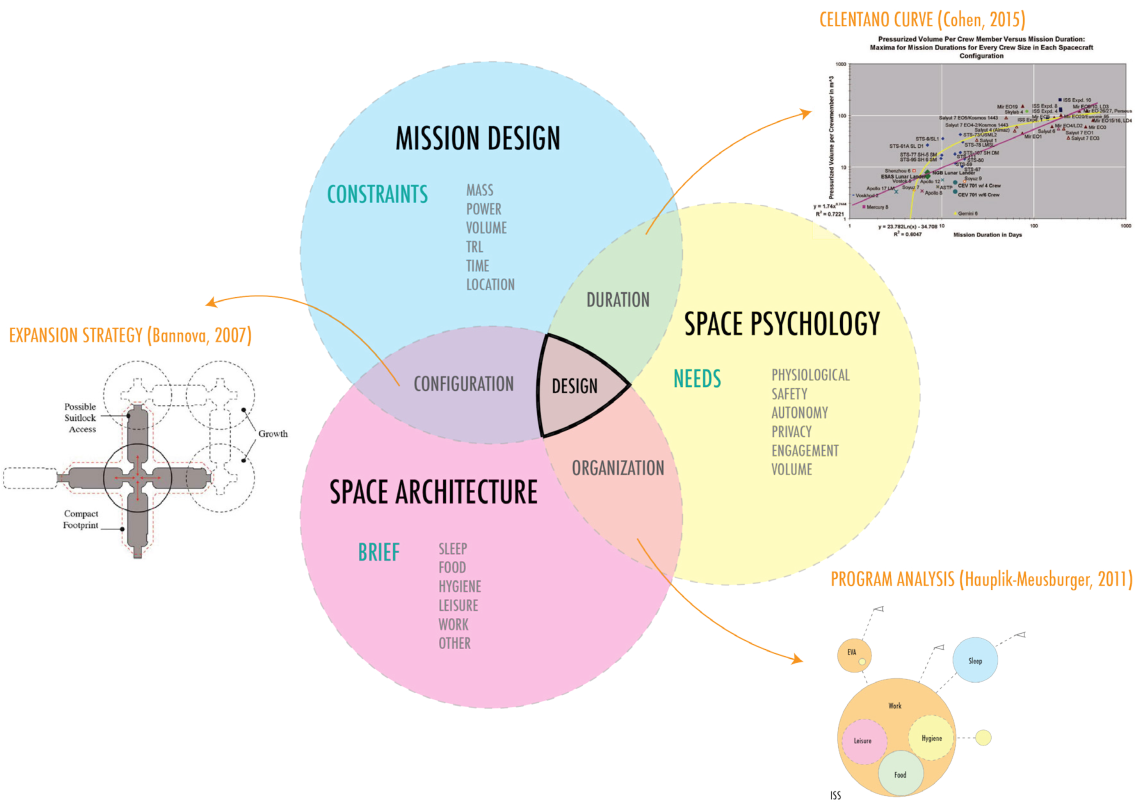


Figure 5.6.2: The defined overlapping design-drivers were backed by findings in academic research in Space Architecture

5.6.3. BRIEF ELEMENTS

The space architect has to consider engineering, aesthetics and social sciences, balancing the quantitative and qualitative requirements in the architectural design through system configuration and program organization. (Figure 5.6.3.) System elements and program functions relate to exterior and interior circumstances with requirements related to qualifying the constructability and habitability.

After drafting a preliminary brief, based on data from the three different disciplines, the architect will take the lead in developing various concepts for the habitat system. Testing of various concepts, will result in a preliminary design. During the review of the design an iteration will take place between the architect and mission engineers as well as the space psychologists. The architect will communicate the chosen strategy for configuration and organization, where the engineer and psychologist will reflect, together with the architect, on the constructability and habitability of the proposed design solution.

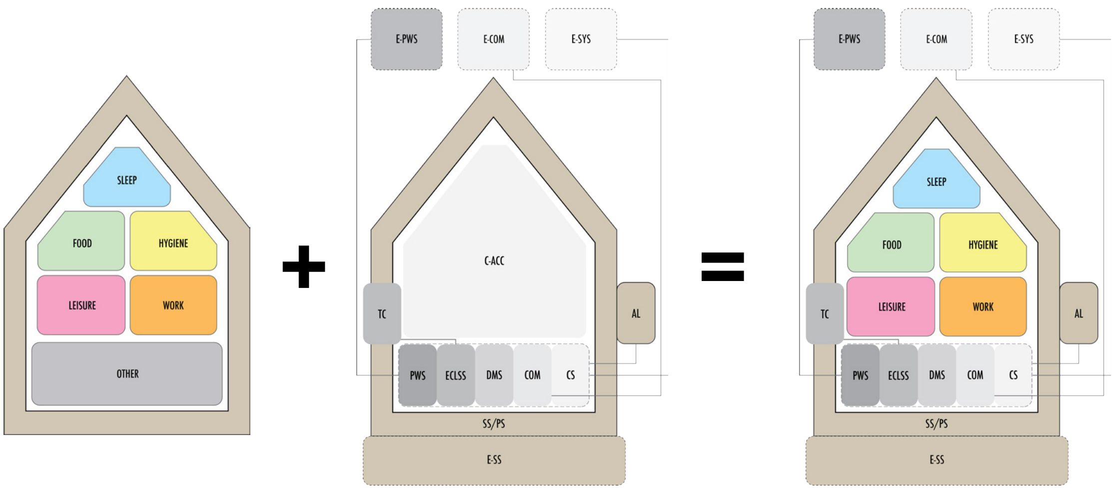
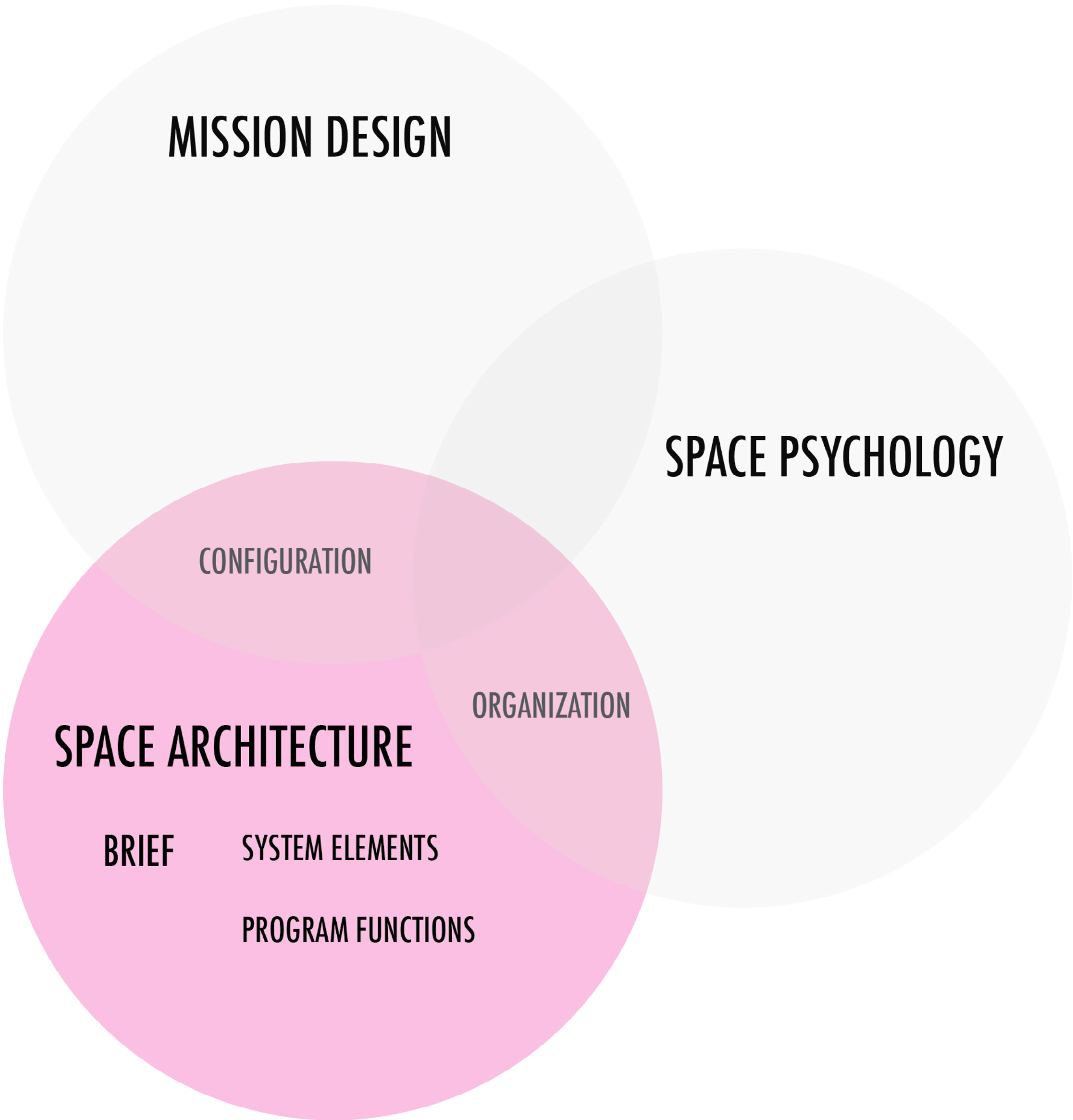


Figure 5.6.3. : The space architect will have to synthesize system configuration and program organization in one integrated design for the habitat.


MISSION DESIGN
SPACE PSYCHOLOGY
CONFIGURATION
ORGANIZATION
SPACE ARCHITECTURE
BRIEF
SYSTEM ELEMENTS
PROGRAM FUNCTIONS

5.7 SUMMARY AND CONCLUSION

5.7.1. SUMMARY

The space architect has to consider engineering, aesthetics and social sciences, balancing the quantitative and qualitative requirements in the architectural design through system configuration and program organization.

Duration drives crewsize and crewsize drives volume, but number of crew is not a direct variable of volume. In architectural research of functional space allocation little attention was put on spatial reservation for technical support systems. A study on volumetric requirements differentiates different kinds of volume of which net habitable volume is merely a sub-component within system sizing. Yet, this volume was found to be driving for system sizing. Quantification of required volume depends on the necessary functional activities that have to be allocated within the spatial boundaries. After definition of the functional activities that have to serve the mission objectives, a parametric design study could help in determining the most efficient spatial configuration that supports a maximised crew performance.

Space architecture research distincts habitation systems for space exploration in several typologies and classes, based on the choice for the structural system. This categorisation leads to a definition of different types of system elements which all have to be integrated in the design of the habitat. Due to variation in definition of system elements, exact mass allocations and system sizing is hard to determine for different sub-systems and was found to be a time consuming process. To come to correct and coherent estimations, further research has to be done.

An evaluation of the design process for the surface habitat revealed new insights on the complexity and importance of interdisciplinary collaboration for succesfull product development. It was found that formulation of the brief fits in the process after exact definition of the mission baseline architect with its objectives and required functional activities. For this reason it was hard to come a meticulously quantified brief.

5.7.2. CONCLUSION

It is the job of the space architect to combine the quantitative and qualitative requirements in one integrated design for the surface habitat. The design will have to support constructability due to the strategy for configuration as well as crew performance via habitability due to the program organization.

To come to tangible results within the limited timeframe, the findings for the design requirements ought to be tested through a preliminary design exercise. Some preliminary findings from research were assumed to be driving several decisions that have to be made during the process of design. These assumptions will be tested through a design exercise in the following chapter. A conceptual design will be developed to discover what considerations form the intial design drivers in surface habitat design.

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06

DESIGN

The methodological framework has been completed with chosen design parameters based on various disciplinary perspectives. Based on research the values have been defined that drive the design decisions for a surface habitat. The quantitative and qualitative criteria will be applied to evaluate the feasibility of the design.

In this chapter the results of a preliminary design exercise are presented. The objective of the exercise is to evaluate whether the gathered data that led to formulation of parameters within the framework, proves to be of sufficient value for the architectural engineer to start designing.

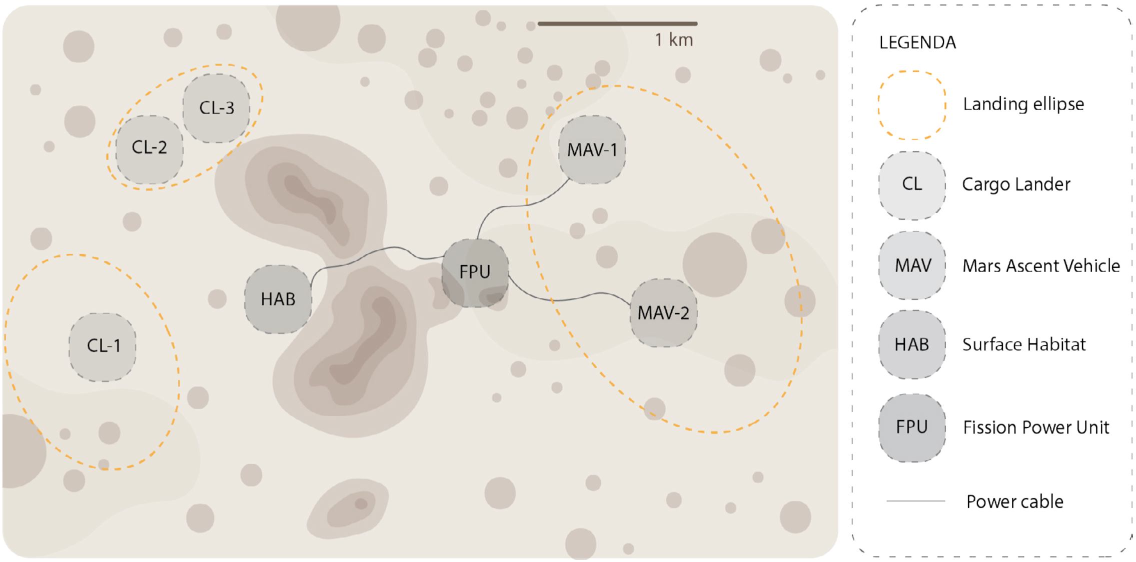


Figure 6.1.1. : Visualisation of chosen site configuration based on DRA 5.0 and the HLS2-workshop.

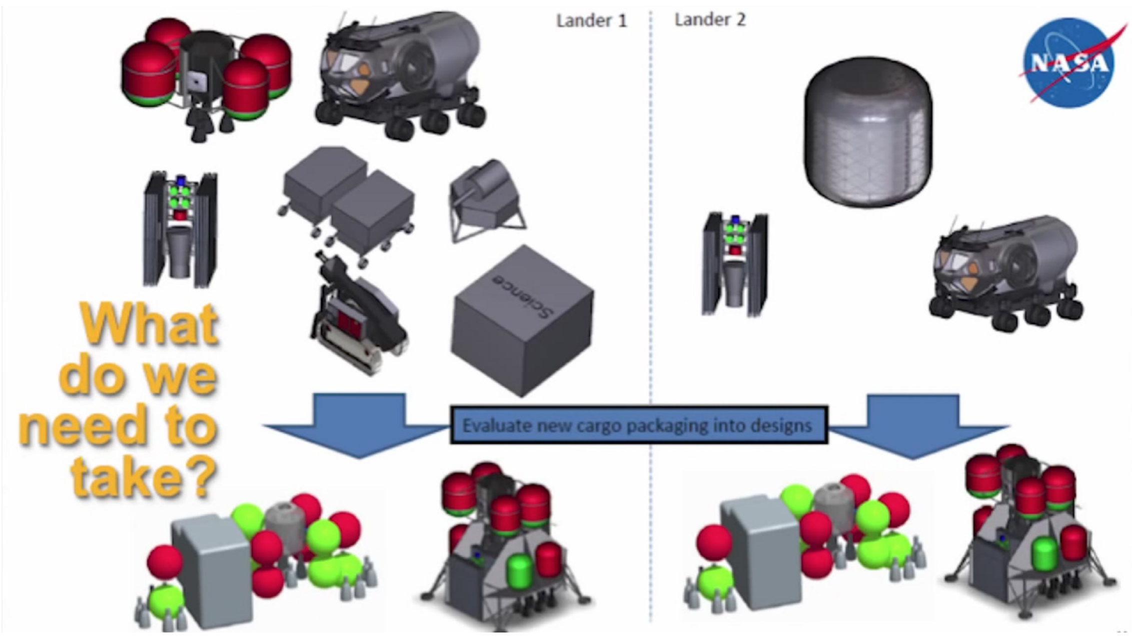


Figure 6.1.2. : Visualisation of cargo elements (youtube NASA lecture series 2017)

6.1 SITE PLANNING

6.1.1. BUILD UP OF SITE ELEMENTS

In the DRA 5.0 the pre-deploy strategy was defined as the preferred option, meaning that the base on Mars is in place and operating, before the crew arrives. It assumes two cargo landers with various mission equipment. The first lander will bring a Mars Ascent Vehicle (MAV), a Space Exploration Vehicle (SEV), the first Fission Power Unit (FPU), two fetch rovers, a drill, an ISRU unit for in-situ propellant production and a science kit. The second lander will carry the surface habitat, a second FPU and a second SEV. (Figure 6.1.2.) Both cargo landers will be launched and landed two years before the crew arrives. Within the period the base will have to be set up and operational. If all systems are tested and checked for approval, then the crew launches and leaves Earth. This mission architecture is defined as the pre-deploy strategy.

Based on the findings, a second habitat module will have to be launched in order to meet the habitability and volume requirements, limited by system sizing constraints related to the HIAD EDL, as will be explained in paragraph 6.3.1. The pre-integrated habitat modules will be positioned in a similar fashion as the MAV's through retropropulsion hovering, aided by the SEV's and fetch rovers. The additional mobility surface vehicles will connect the modules to the power supply system. After the habitat systems are positioned and all set-up, the structure will be covered in a sufficient amount of regolith to shield against radiation. The habitat and FPU will be roughly 1 km apart and seperated by mountains due to potential safety risks of the nuclear power plant.

Figure 6.1.3. : Impression of design on site

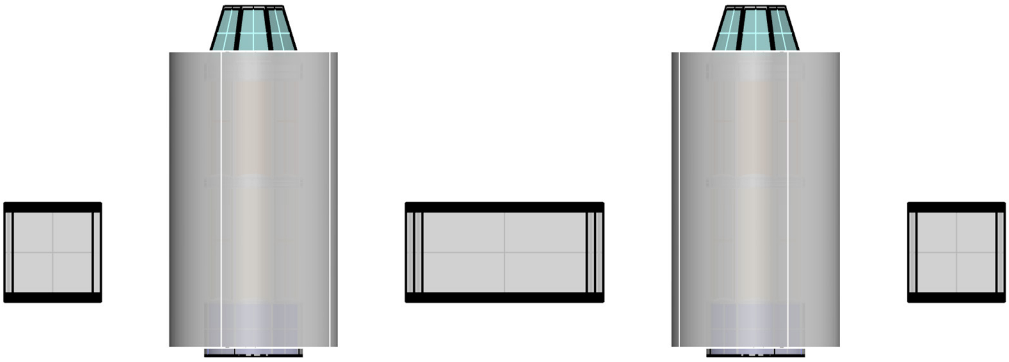


Figure 6.2.1.: Position modules and airlocks and connect power supply system to external power plant

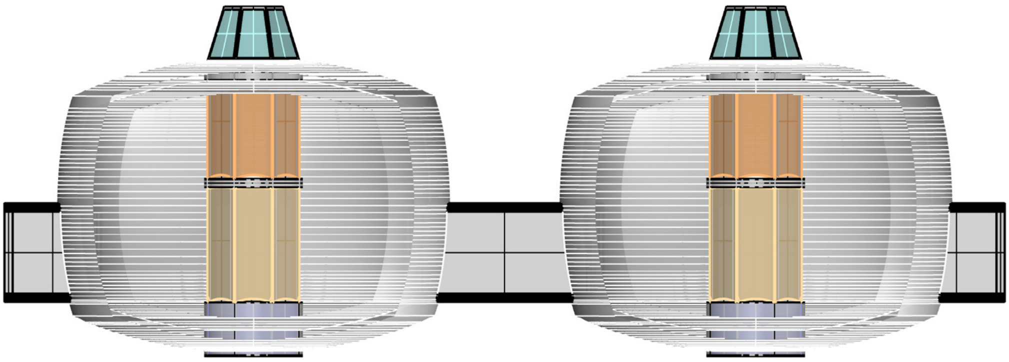


Figure 6.2.2.: Inflate membranes and CO_2-insulation pockets, connect airlocks to hatches

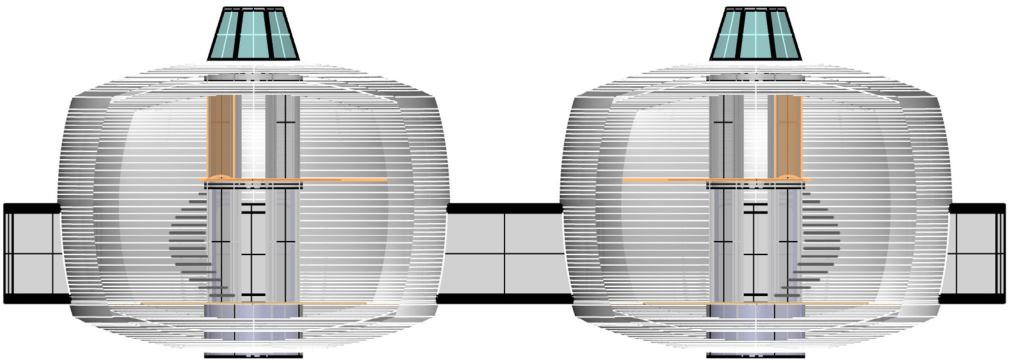


Figure 6.2.3.: Unfolding of floors and stairs

6.2 CONFIGURATION

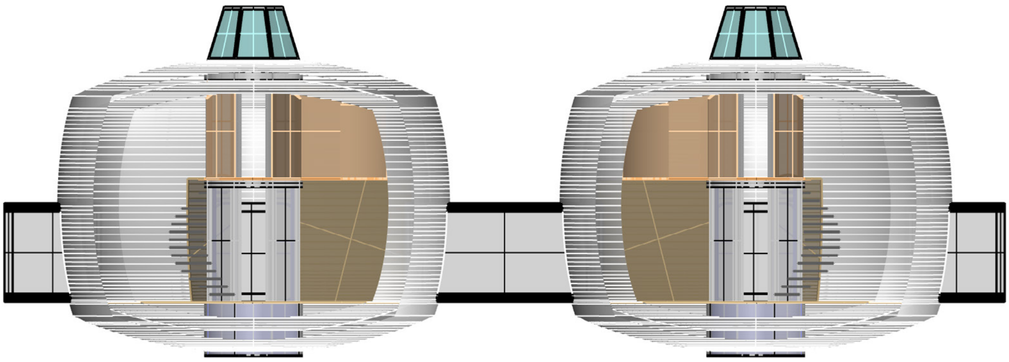


Figure 6.2.4.: Extrude rolled up interior separation walls from central module

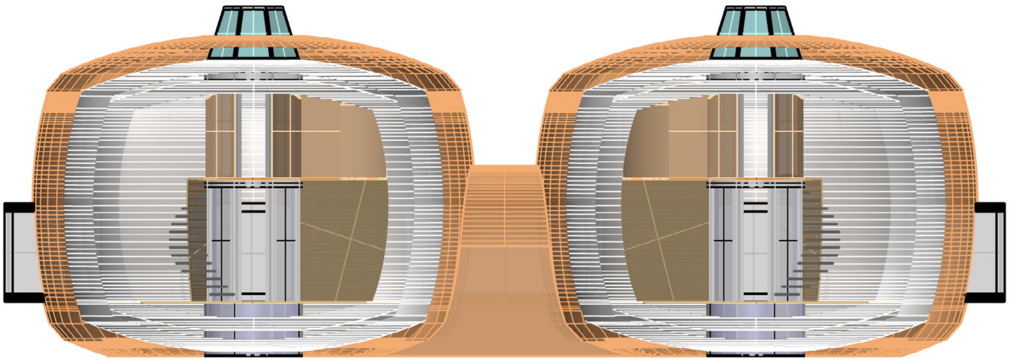


Figure 6.2.5.: After testing performance of all systems, cover modules with regolith

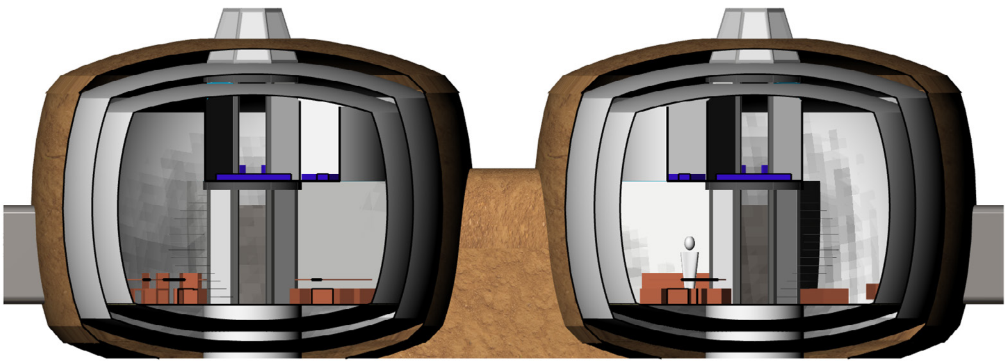


Figure 6.2.6.: Rendered impression of interior with furniture arrangement

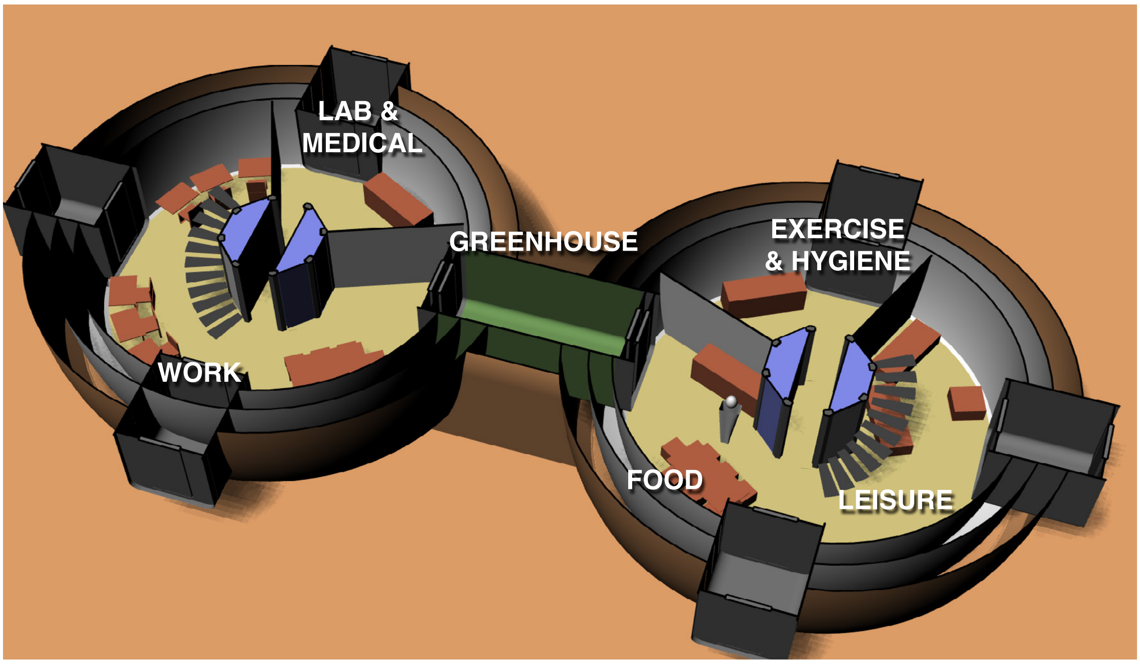


Figure 6.3.1. : Organization of ground floor, work and lab module (left), leisure and exercise module (right)

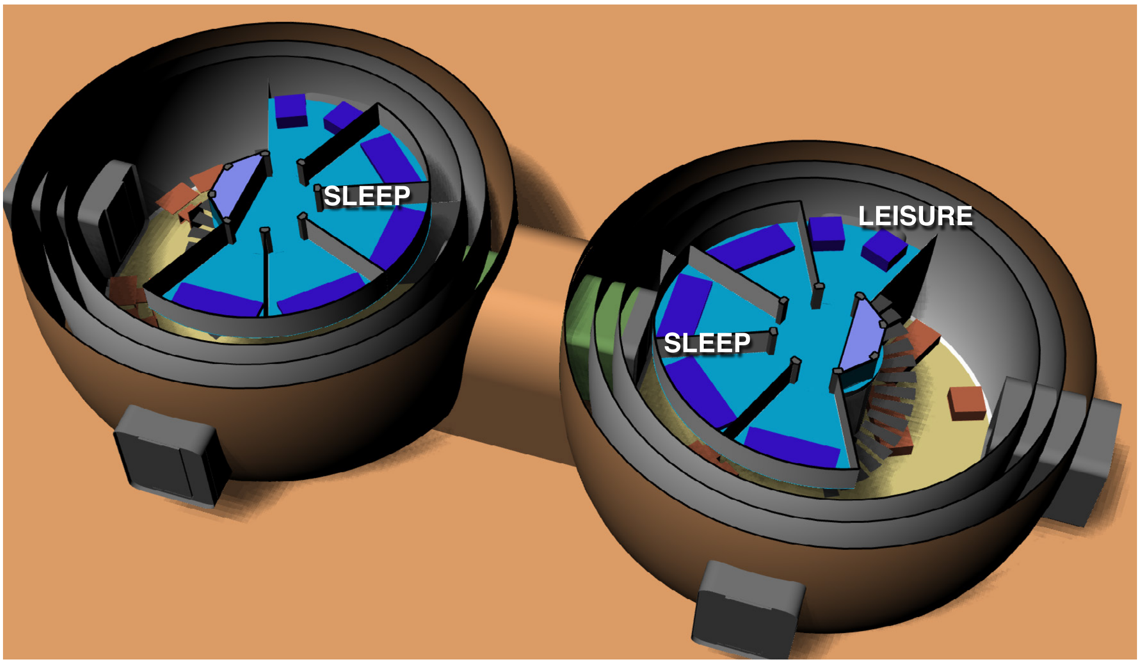


Figure 6.3.2. : Organization of elevated floor with individual crew quarters and landing

6.3 ORGANIZATION

6.3.1. DESIGNING THE PROGRAM ORGANIZATION

As was concluded in paragraph 5.5., the program organization should have a strong focus on sufficient allocated space for leisure activities and include as much variation in spatial perception as possible. However, considering the technology development of the habitat, a modular approach is preferred. The dimensions of the cargo-lander and the mass requirements for the HIAD EDL, drive the system sizing of the module. A foldable structure will save on volumetric requirements for the cargo fairing. Height is not necessarily the main issue, yet the maximum dimensions for the diameter of the cargo fairing for the SLS are estimated to be between 8 and 10 meters. These limitations steer the design to include multiple floors as opposed to single floors with large spans. Also, the ECLSS and other technical support systems will have to be pre-integrated in a central core module and connected to all the separate rooms.

In paragraph 4.2., the crew characterization for a long-duration isolation mission to Mars was recommended as a heterogenous crew of seven with different disciplines and backgrounds. A crew of seven requires a significantly larger habitable volume, resulting in the decision to allocate the functional program and the required space in two modules instead of one. This simultaneously integrates the suggestion of avoiding overlap between leisure and work activities.

The quantitative constraints, resulted in a compromise on program organization. The chosen bubble diagram configuration as a conclusion from the case study analysis was altered. (Figure 6.3.3.) Where a program with a primary focus on leisure was suggested based on the analysis, the configuration limitations drove to the decision of two similar sized modules, with one module focussing on leisure and the other focussing on work. Still, the volume would not leave sufficient room for storage of consumables. Also, the technology and space for growing food crops has to be considered and was thought to be done in a highly controlled environment. For this reason, the connection between the modules was solved as a translation module with integrated food growing and storage facilities, that can serve a double purpose of a radiation storm shelter in case of a Solar Particle Event.

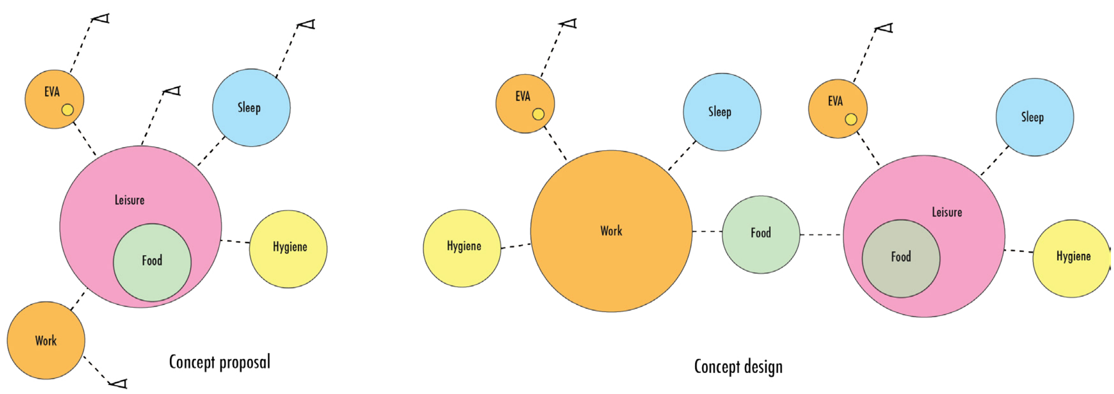


Figure 6.3.3. : Design intention vs. design outcome

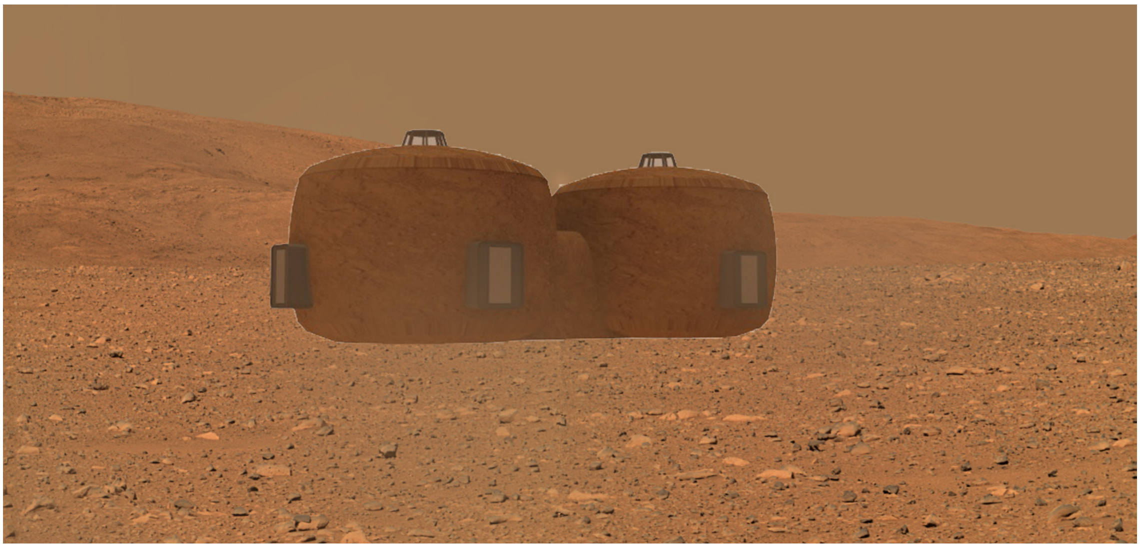


Figure 6.3.4. : Rendered impression of habitat on the surface of Mars

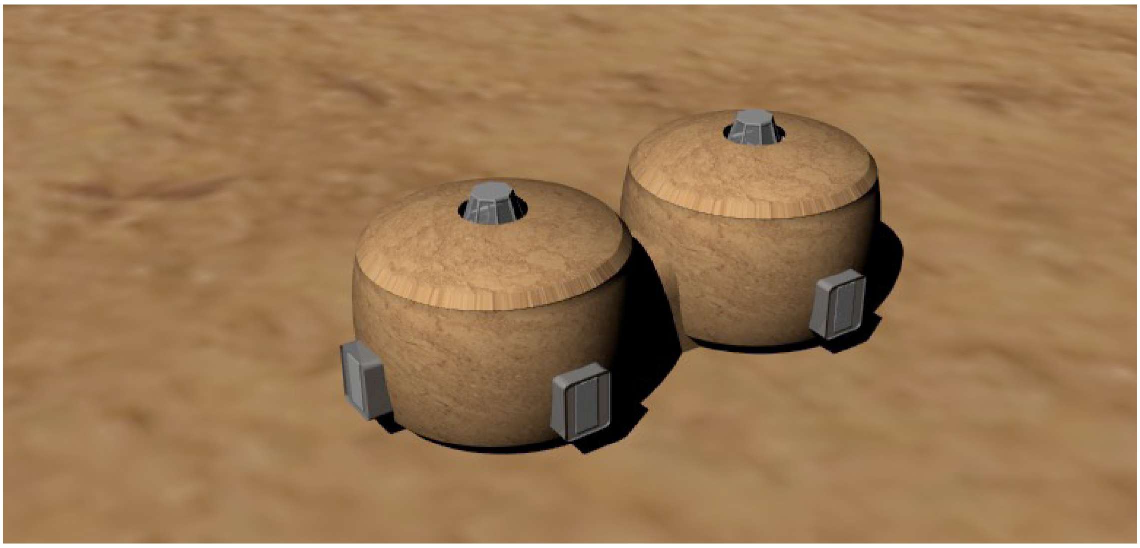


Figure 6.3.5. : Rendered impression of habitat on the surface of Mars

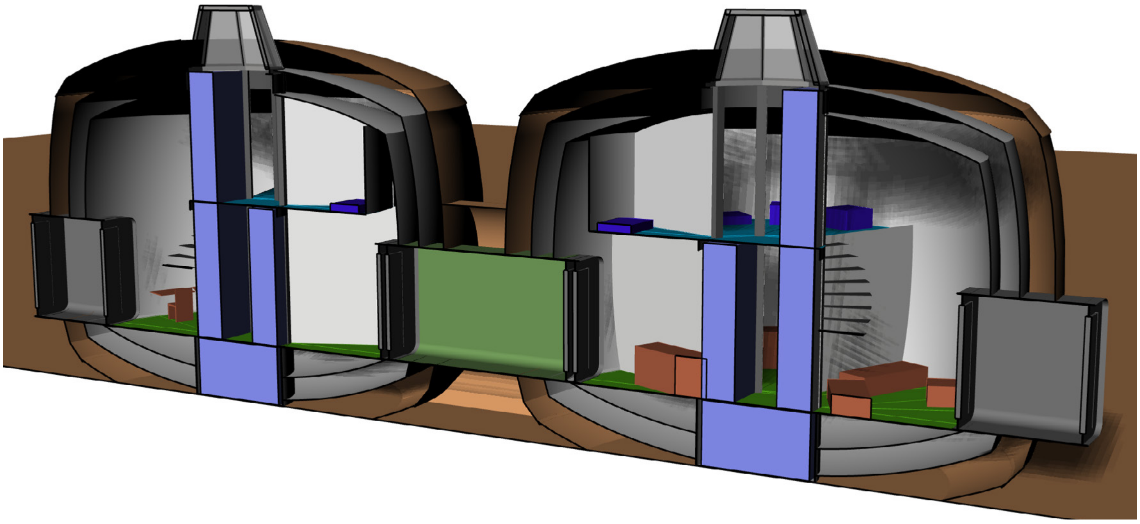


Figure 6.3.6. : Technical space integrated in central module. The green house module forms a translation path between work and leisure activities. Also, the connection module serves a double purpose as a storm shelter.

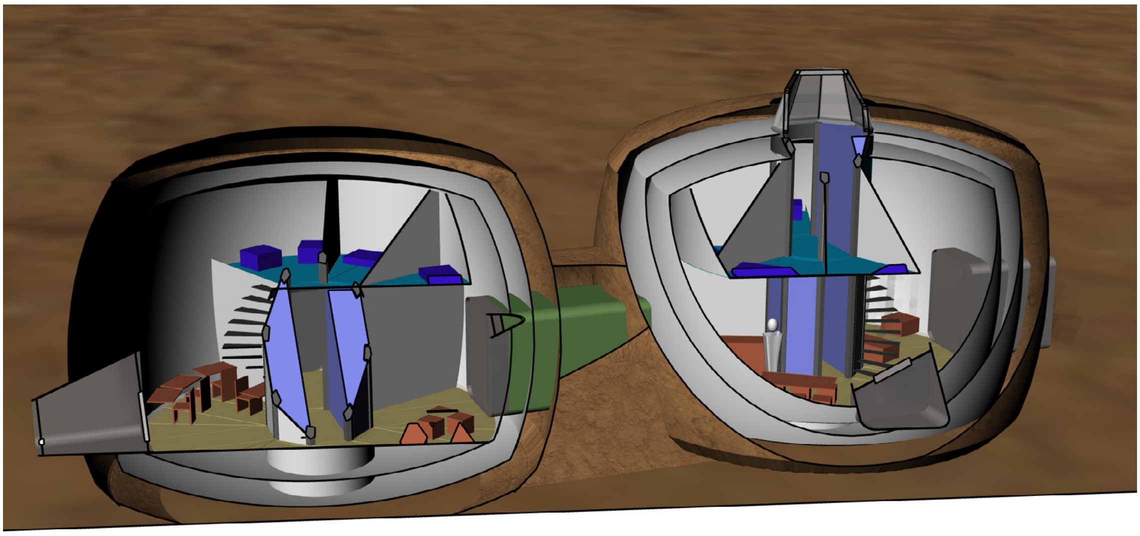


Figure 6.3.7. : The crossection shows an impression of spatial perception and interior arrangement.

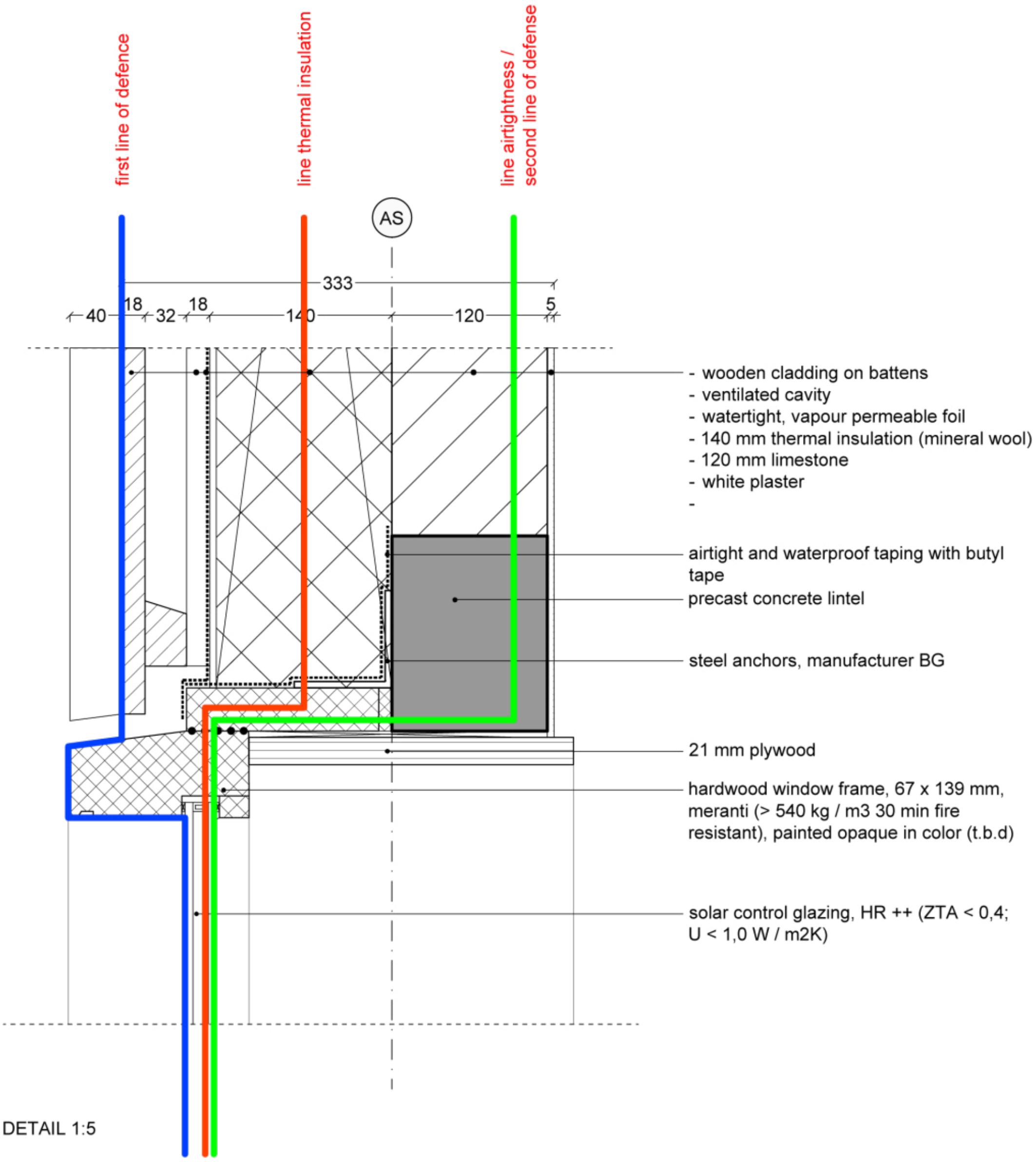


Figure 6.4.1. : A building construction on Earth has to consider the lines and paths for physical requirements of the facade (Bergsma, 2016) A martian facade has to consider similar lines. Yet a major distinction is that in addition, the facade has to consider the lines for radiation shielding, meteoroid impact and an airtight pressurization restraint layer. Also, concerning detailing the joints and seems, abbrasive dust has to be considered on Mars.

6.4 CONCLUSION

6.4.1. BALANCING QUANTITY AND QUALITY

From the initial design outcome can be seen that the program organization of the habitat drives both functional as well as the qualitative requirements. Due to the decision of a crew of seven for a three year isolation mission, the required volume of the habitat increased and therefore the quantity of system elements.

Several design decisions steered towards making the decision of designing two modules for the habitat instead of a single module set-up. An initial reason was to mitigate the risk of technological failure of the habitat support system and therefore spreading the program over two separate systems.

Another reason was the outcome of the qualitative organization analysis (bubble-diagrams) which led to the decision of a separation of leisure and work activities that would be connected via a translation path.

The third reason, to fit the habitat module within the dimensions of the cargo payload for the transport technologies currently under development, a constraint was set according to the EDL requirements for the HIAD.

The fourth reason was, to apply a prefab module with an inflatable pressure shell with molded in airlocks and foldable floors around a central core module that contained the pre-integrated life support systems. This configuration led to height constraints and therefore constraints to the maximum radius of the circular habitat. Due to the maximum radius, there was also a limit to the maximum amount of volume that could be achieved within one module. This lead back to fitting the qualitative requirements concerning the spatial experience.

In all, the design exercise proved the necessacity of a continous iteration between disciplinary perspectives to balance quantitative and qualitative requirements.

6.4.2. ARCHITECTURAL ENGINEERING FINDINGS

Since Earth and Mars have different climatic conditions, there are several major differences to be solved in the design of the structure. Designing a structure for Earth, the architect has to consider several lines within the building’s structure. These lines are the structural paths, the thermal line (thermische lijn), the water restraint or waterproof lijn (waterkerende lijn) and the vapor permeable line or layers (dampdoorlatende lijn).

For Mars, different paths and lines should be considered in development of the structure. The structural line also has to be considered, which might work slightly different or has different constraints, since the gravity on Mars is roughly 38% of that of Earth. The second line is the pressure restraint layer, due to the huge atmospherice pressure difference of Mars in relation to Earth. This should be airtight and therefore internal moisture also has to be coped with due to this layer. The thermal line is also important, because of the extremely low temperatures on Mars. And finally a radiation protection line should be integrated in the structural design, apart from the storm shelter.

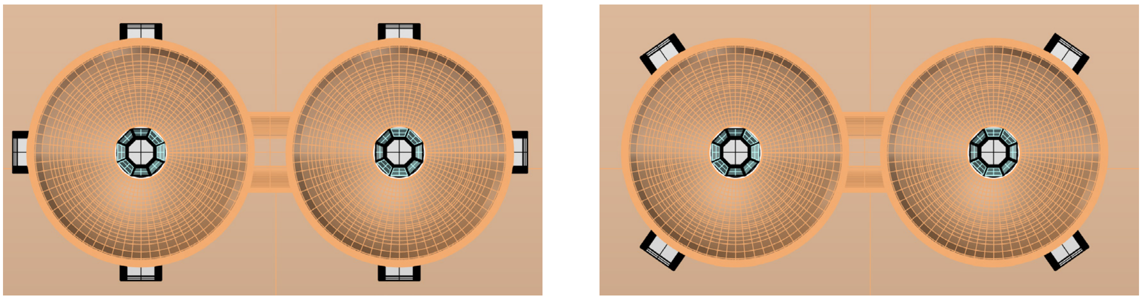


Figure 6.4.2. : A triangular footprint and set-up, as opposed to a cruciform, will result in less molded in airlocks and seems, decreasing the mass and required number of seems of the inflatable membranes.

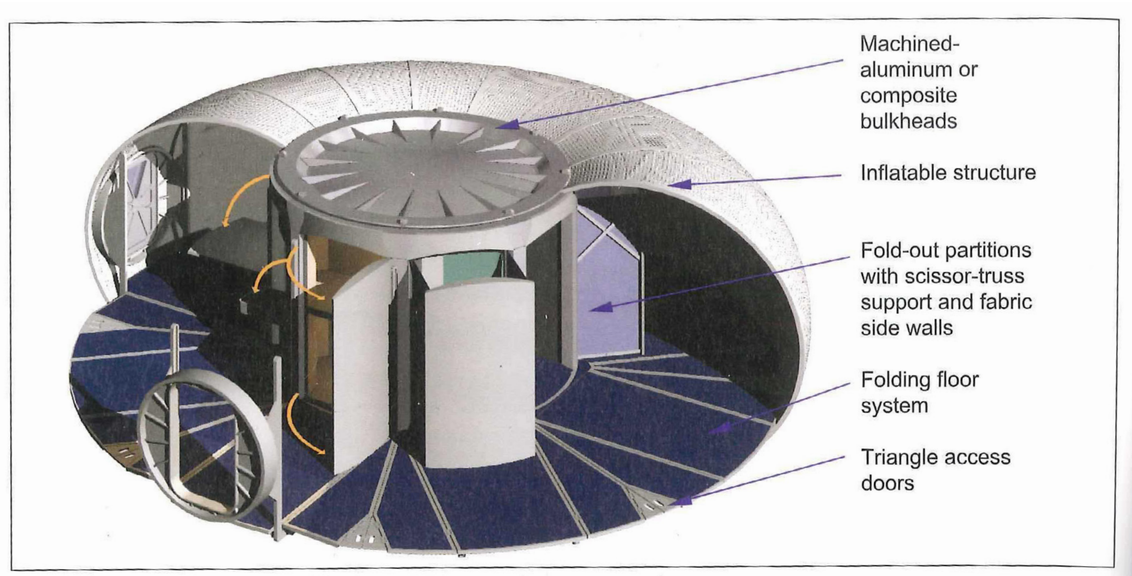


Figure 6.4.3. : The decision of applying integrated foldable floors, drives the floor height and maximum radius of the floors within the module. (A. Scott Howe et al., 2000)

6.4.3. DISCUSSION

Different design decisions in earlier stages could result in a completely different configuration and organization of the design. It was found, that in all, the technical constraints related to the EDL technology are the primary drivers of the habitat configuration. The EDL determines the mass budget and the volumetric budget and configuration, resulting in limitations on maximum dimensions and system sizing per module. Other elements of the payload that will be landed on the surface should also be considered as the FPU drives the power limit for construction and operation of the surface habitat. In the same way, the tools for construction such as ISRU systems and excavation rovers for the regolith should fit the same payload.

In addition, the settlement and expansion strategy forms another driver for the system configuration. Organization of the footprint drives the decision of placement of airlocks and connecting supporting systems. The hatches have to connect the habitat to other surface systems like the Space Exploration Vehicles (SEV). Also, access to the surface for Extra Vehicular Activity (EVA), or a walk in the spacesuit, has to be accomodated within the design. The cruciform configuration will drive the choice for more hatches, adding mass to the system. Positioning of the hatches is therefore point of discussion. A continous routing through the architectural program is strongly recommended. A continous circulation path would enhance the spatial experience for the inhabitants, as they will be able to “circle around” within the architectural program and supporting autonomy in choice of routing to reach a destination. However, the number of hatches necessary is directly related to the requirements of connecting to external surface systems.

6.4.4. EVALUATION BASED ON FORMULATED CRITERIA

In this preliminary design exercise a first emphasis was put on volumetric design considerations. Volumetric requirements were earlier defined as leading design drivers in system design and sizing. The volume was found to be important for the perception of habitability and therefore the crew’s well-being and thus chances on mission success. During the design process the formulated criteria for habitability were leading drivers for design decisions. Attention was paid to spatial variation and perception, physiological needs, safety measures, privacy requirements, engagement opportunities for large and sub-groups and build in autonomy with flexibility in furniture arrangements and interior seperation possibilities. The perceived quality of the design organization would have to be validated through an analogous test mission, which would have to form an integral part of development in order for the design to achieve the desired HRL.

The initial technical constraint of volume led to many iterations in design configuration. When the volume configuration will result in a preliminary draft, an evaluation of mass and power budget requirements are likely to result in many more design alterations. In addition, the buildings construction method would have to fit within the schedule. Finally, the location characteristics and soil composition would have to suffice to meet the building construction design requirements related to radiation shielding and other mentioned lines. In short, having the design to meet the quantitative design requirements will be a very time consuming process requiring a lot of disciplinary interaction resulting in many iterations. The planning of the process for developing the habitat as a sub-system of the overall mission architecture is very important to consider in relation to the total estimated time for overall mission development.

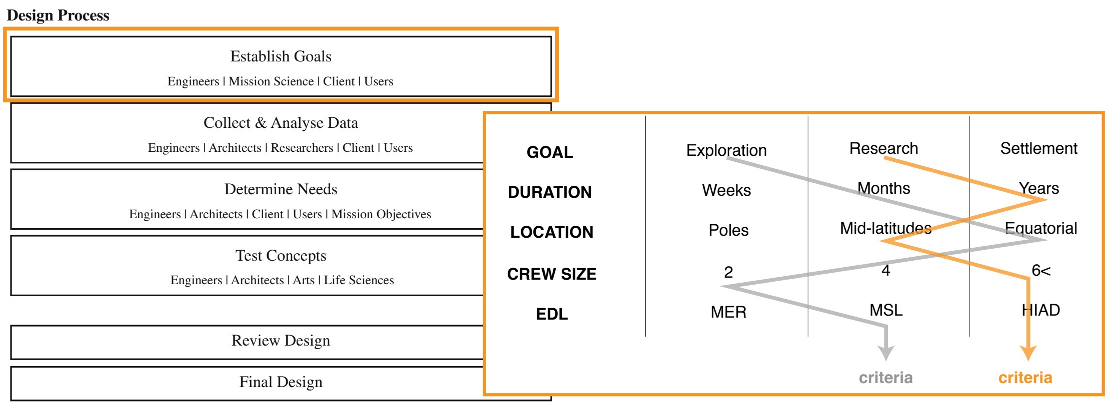


Figure 6.4.4. : Different design decisions in earlier stages related to mission architecture result in other criteria and requirements which in turn change the design parameters for the surface habitat system.

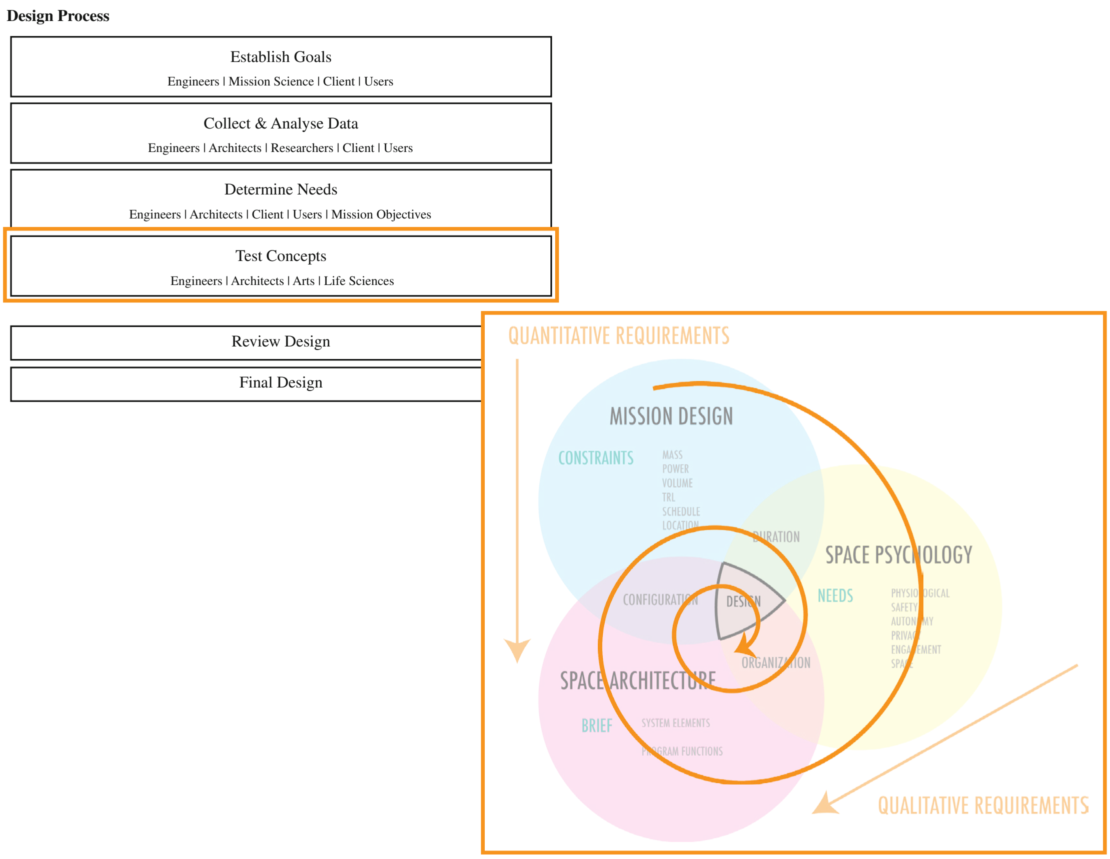


Figure 6.4.5. : During the process of designing and testing of concepts a constant evaluation and iteration should take place between the various involved experts in order to come to a feasible design.

6.4.5. CONCLUSION

The design exercise proved to be a valuable method to test formulated assumptions on the needed information and requirements definition. It was found that the mission baseline architecture drives the assumptions for habitat system configuration requirements and habitable organization criteria. Certain assumptions have to be made in earlier stages of the surface habitat development process. Several parameters were found to be of driving importance. The parameters are shown in Figure 6.4.4. As can be seen, different baseline parameters can result in completely different design criteria and requirements.

Reviewing the preliminary design based on the formulated quantitative and qualitative requirements provided new insights in the complexity of the design assignment. To develop a surface habitat will be a very costly and time-consuming process, and requires many interdisplinary iterations and design considerations. (Figure 6.4.5.)

07

CONCLUSION

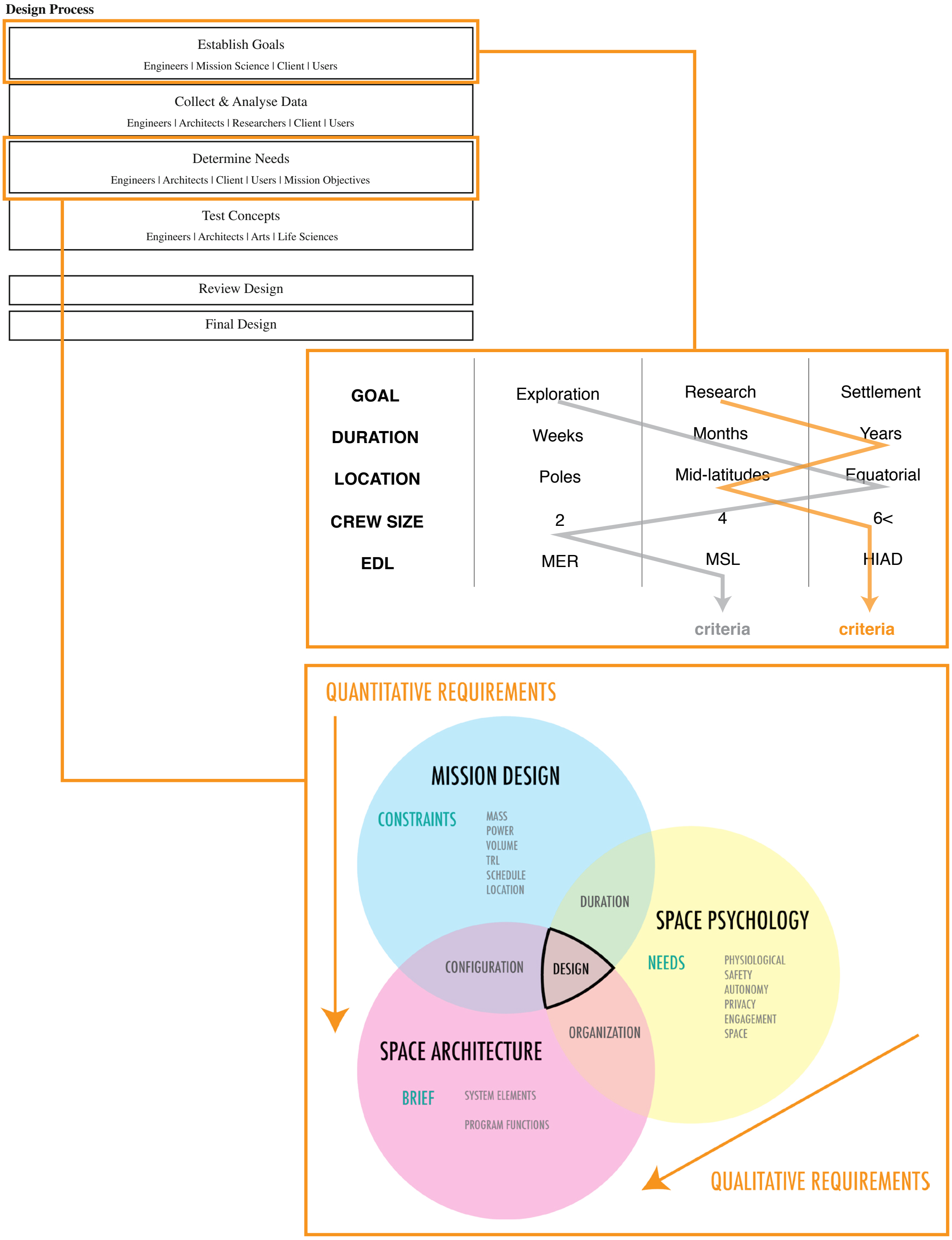


Figure 7.1.1. : Application of the framework in the design process of the space architect with the chosen design parameters based on the research findings.

7.1 CONCLUSIONS

7.1.1. TOWARDS AN EVOLVABLE DESIGN STRATEGY

The architect has to synthesize quantitative constraints and qualitative requirements into one integrated design. For extreme circumstances, such as a mission to Mars, it was found that the mission architecture forms the baseline for the design parameters that the architect has to consider. The mission architecture will result in the baseline assumptions for mission objectives, duration, crew size, location, logistics and functional activities. Based on these assumptions the criteria for constructability of the surface habitat can be quantified. In addition, the characteristics of the crew and their psychological and physical needs can be defined. These requirements will then form the driving parameters for the space architect.

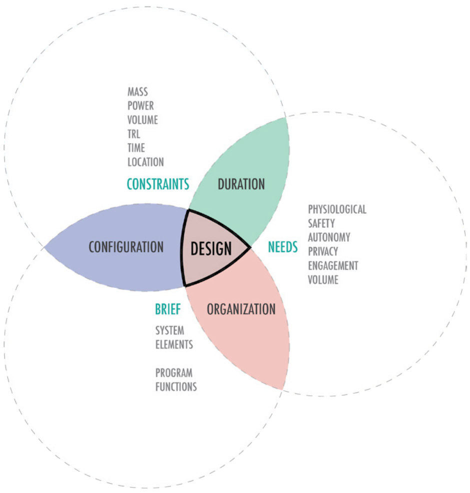
During habitat development a continuous design iteration will be necessary between the architect and mission engineers as well as space psychology experts. The architect will develop the habitat's configuration of system elements and organization of functional activities. In turn, the other experts will evaluate the proposal based on the constructability and habitability of the habitat system, therefore qualifying the design in terms of its feasibility.

Some preliminary criteria for the design evaluation have been defined. The criteria related to constructability enhold, but are not limited to, fitting the budgets of mass, power, volume and the schedule as well as having the chosen sub-systems to meet the required TRL's and the building construction to meet the requirements for technical performance based on characteristics of the chosen location.

The criteria related to habitability enhold, but are not limited to, meeting the physiological needs and safety measures for psychological well-being, facilitating privacy, engagement opportunities and autonomy in organizing the physical and psychological perception of the environment as well as a creating a positive perception of the enclosed space.

The objective of the research was to formulate a list of requirements as a brief for the habitat. A quantified brief was found to be a difficult task to complete within the set time frame, as the mission architecture forms the baseline assumption for formulating exact design requirements. Defining a quantified mission architecture, was a difficult and complex task and is normally allocated to mission engineering experts. However, based on extensive analysis of mission architectural design and engineering, some preliminary parameters could be defined.

Finally, a design exercise was conducted to test application of the design parameters based on the formulated quantitative constraints and qualitative criteria. The result of the preliminary design revealed insight in the complexity of the design task at hand and the need for a continuous interdisciplinary design iteration between experts from both mission engineering and space psychology. These iterations will be of vital importance in order to come to a final habitat design which will be feasible in terms of constructability and habitability and add to achieving mission success. The defined framework will form a starting point in shaping this design process, thus resulting in an evolvable design strategy.



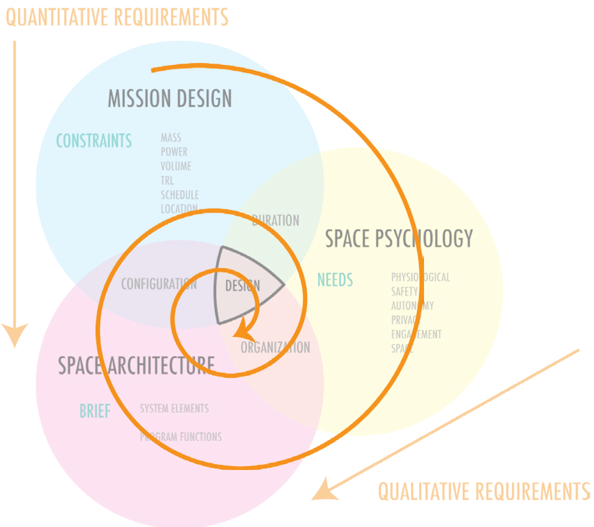


Figure 7.2.1. : Chosen design parameters, based on research findings, as keydrivers for the architectural engineering design of the surface habitat for the first human settlement on Mars.

Figure 7.2.2. : Development of the design requires a constant interation between the various disciplines, meaning that the design process should be organised as an interdisciplinary process between multiple experts with various disciplines and backgrounds.

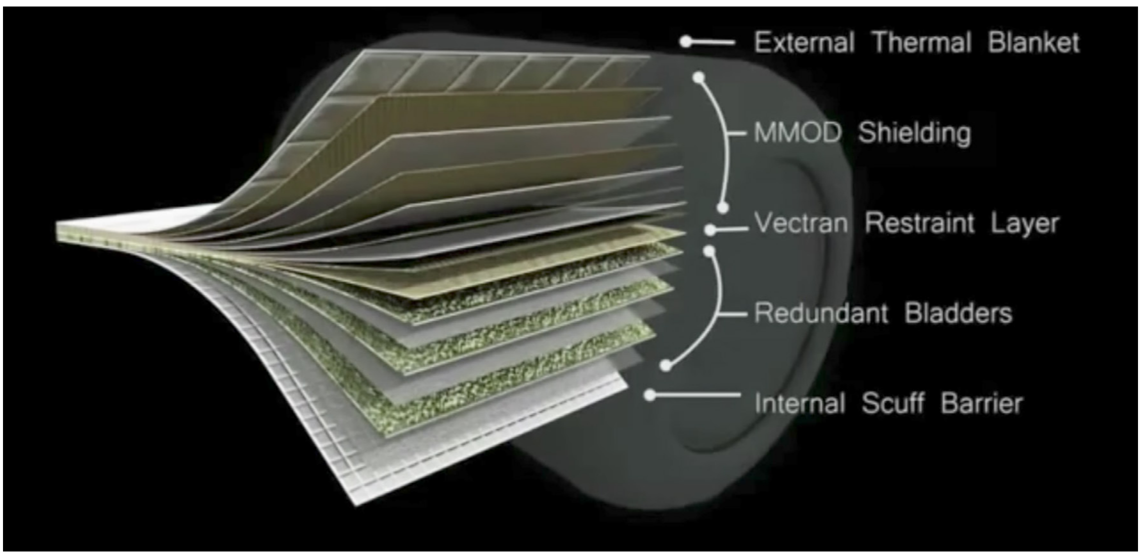


Figure 7.2.3. : The layering of Bigelow's inflatable technology can be used as a starting point and reference for further development of detailing the building construction.

7.2 RECOMMENDATIONS

7.2.1. RECOMMENDATIONS RELATED TO RESEARCH FINDINGS

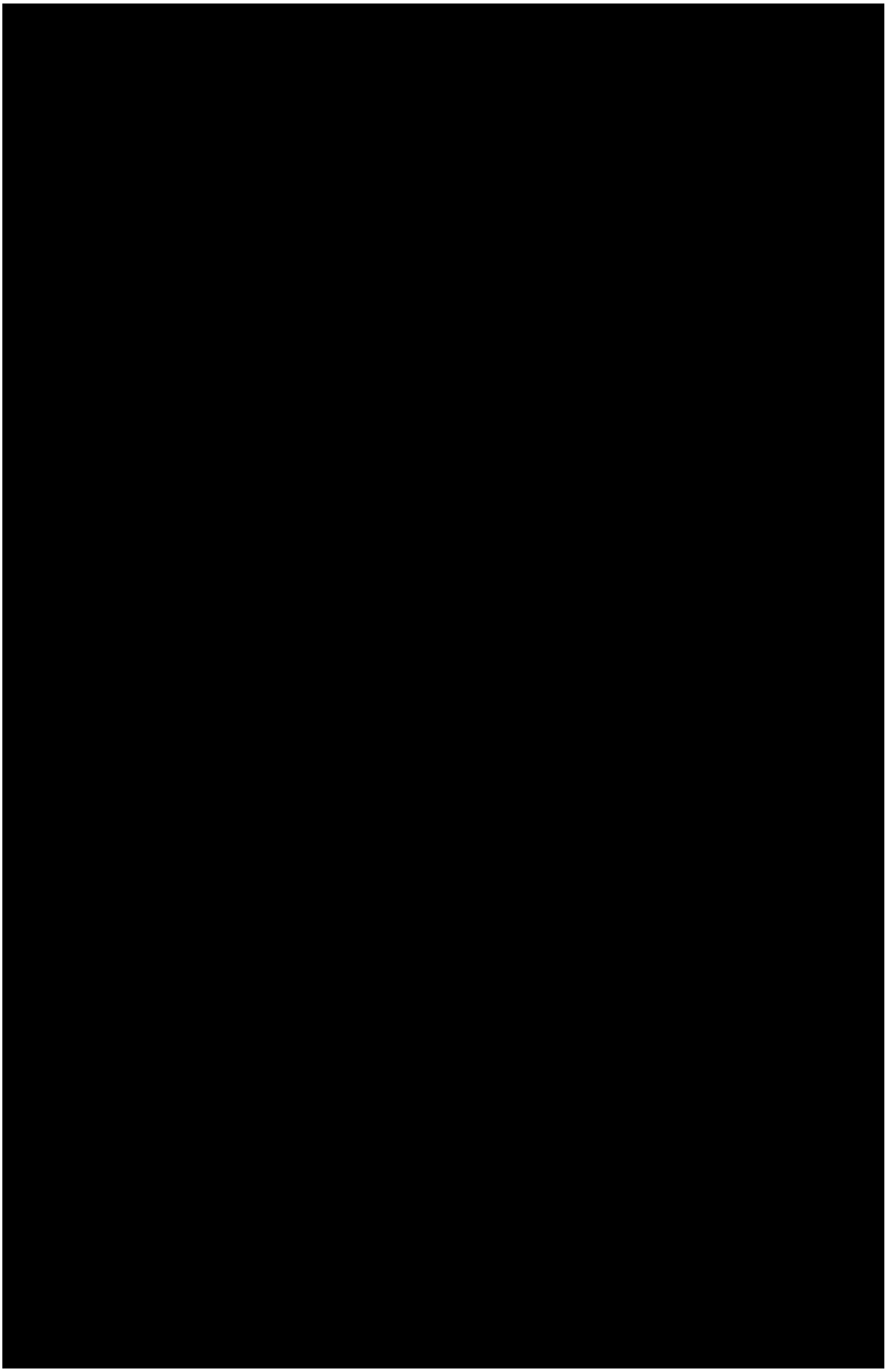
In this first application of the framework, duration was decided as an overlapping design driver between mission design and space psychology, as it can be directly related to volume requirements and habitat system sizing. After a discussion with Sandra Hauplik-Meusburger and Olga Bannova, it was discussed that a Concept of Operations could also be considered as an overlapping driver that requires discussion between the Mission Design experts and the Space Psychology experts.

This framework is merely a starting point, and first of it’s kind in giving space psychology a firm position in the design process. The chosen parameters can result in many different design outcomes, dependent on the position that the space architect choses to take. In this research a subjective emphasis was put on logistical constraints and motivational performance needs. The framework is a tool for a collaborative multidisciplinary design and iterative process. It reflects the stakeholder interests of multiple team members and the leading topics for their feedback loops. (Figure 7.2.1. and 7.2.2.)

7.2.2. RECOMMENDATIONS RELATED TO DESIGN FINDINGS

For future designers, it would be very valuable to research a parametric optimization of volume requirements and impacts on system sizing and mass, related to the EDL technologies. This is a complex puzzle and would be very valuable, also in wider application in generic architectural design for Earth. A strongly recommended starting point would be the study of Simon on Net Habitable Volume (2012). For this particular design outcome it would also be interesting to do a trade-off study on cost vs. risk on one versus two modules, to develop an exact quantification strategy for the volumetric optimization.

Also further elaboration on construction methodologies and facade detailing can be done. Especially important is the impact of radiation requirements on the layering and sizing of the building construction. A starting point could be to study the inflatable technology from Bigelow (Figure 7.2.3.)



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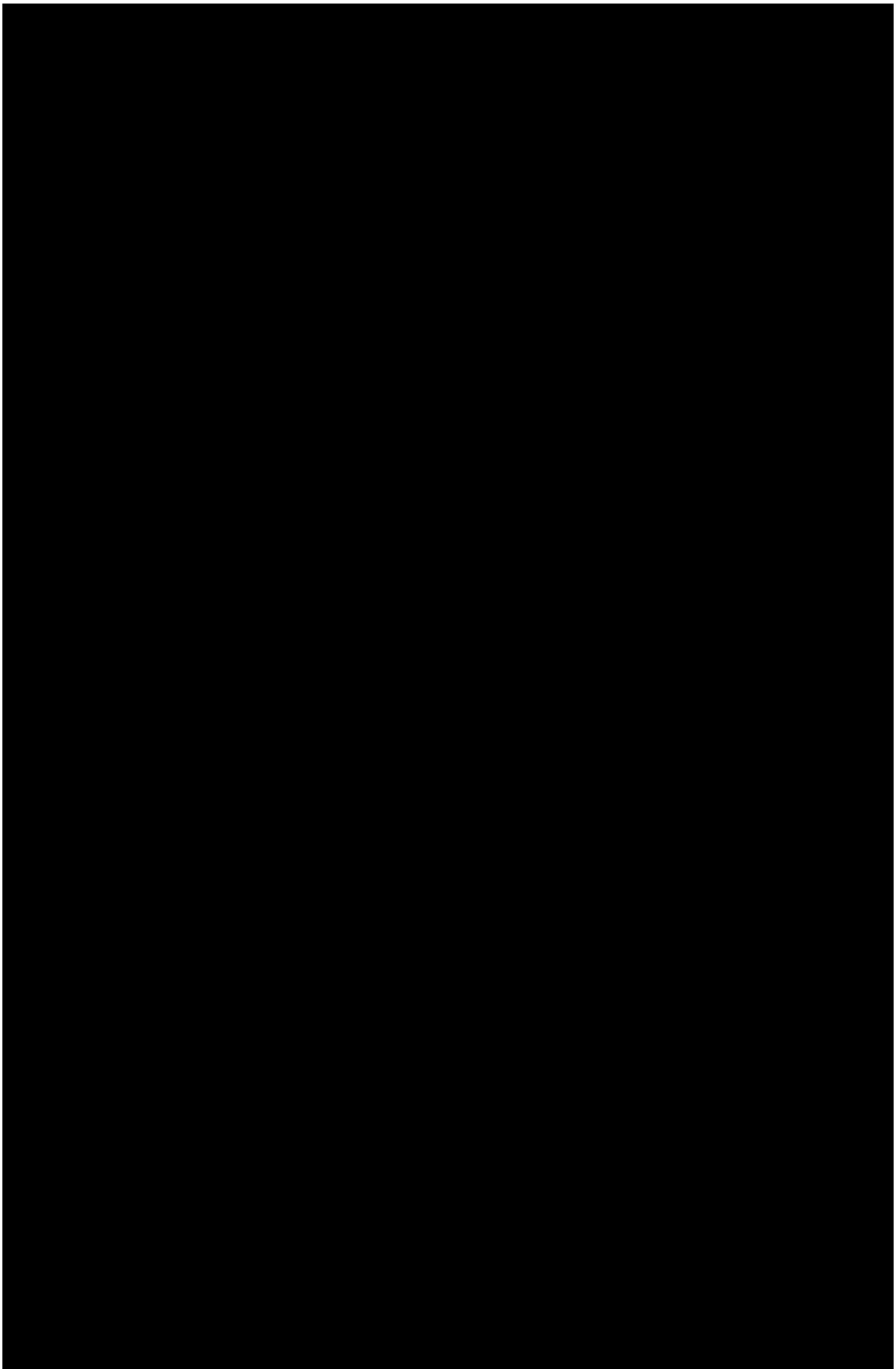

APPENDICES

APPENDIX A: FEEDBACK

Ir. Kevin Cowan MBA

Comments received on September 29, 2017:

OVERALL

Carlijn has referenced all the relevant, major studies regarding realistic, crewed Mars missions. She has taken digested and evaluated the studies ranging from launch alternatives, habitat studies, and reliable, reference mission architectures. This is an impressive, comprehensive compilation which would hold its weight in a comparable study at Aerospace Engineering.

This is certainly the foundation upon which a further study of establishing crewed facilities on Mars should be based. If someone is going to take the next step in this line of study, they could pick up this report and know which elements and driving factors are important. They would know where to start and where to find more info. This was her goal, and she met it admirably.

It is important to note that Carlijn did this study as a one-person job. This type of study is typically done with a large team of people over many years; even the conceptual study teams at our faculty (Aerospace Engineering) are typically ten students working full time for ten weeks. The fact that she was able to pull the right resources, structure them, and make sense of them in the allotted time, all while balancing the typical aerospace drivers with the needs of the architectural study is impressive.

The completeness of Carlijn's coverage, as well as the depth to which she has familiarized herself with the material as gleaned through our discussion, is genuinely impressive. Well done!

POINTS FOR IMPROVEMENT

There is always room for improvement, of course. Here are a few tips:
Concerning the quantitative requirements: all the right elements are there, but the conclusions could be more prominent. Perhaps define lower and upper limits as a range for key parameters, mass for example. In formulating the criteria, I missed the last step. It is now known that we need to think of volume, so what does this exactly mean? How many launches would we need then. If the scope and time permits, try to answer that question;

More prominently emphasize links between architecture and aerospace engineering. For example, what quantitative limits are there to the design drivers? What are the key things I'd want to know for each of the six criteria in relation to architecture?

Add a List of Abbreviations;

Mention what missions you did and did not consider. Go back to the three defined risks for humans, consider mentioning radiation even though it was out of scope here.

<u>OTHER COMMENTS</u>

DRA 5.0 is not really old or outdated considering space mission and planning timeframes;

It's good that you've formulated several criteria and not one of primary importance. As you've learned: they're all interconnected and must thus be considered in relation to each other;

Interesting to see the lines of the building construction and the additional lines to consider for Mars. What would be the order in which to address them, and are variations possible?

The reasoning behind your design sounds like the right first choice to me:

> Sufficient volume
> has to fit EDL
> mass not sufficient for radiation shielding
> thus cover inflatable with regolith.

DArch. Tristan Bassingthwaigthe

Comments received on October 30, 2017:

Hi Carlijn!

Hopefully this reaches you in time, I'll leave the notes you requested below, just a super fast thing because I'm looking at it now, you might want to change the first sentence of your introduction to "In 1492, roughly 500 years ago, Columbus came to the new world". I only mention this because I have heard more than a few people take umbrage at the idea he discovered it, as the Vikings beat him by a lot and the natives beat him by a lot more than that ;) On to the comments!

My overall impression of the work is that you've got a good spread of research topics, covering the major categories needed to describe the issues related to planetary habitation. A major component of ICE habitation will involve understanding the long term needs of inhabitants and including information regarding these "softer" topics will ensure the final work is successful. The thesis enables a fundamental understanding of weather, resources, psychology, construction, and mission architecture for getting people to Mars. Mixing hard and soft topics will be fundamental in future missions.

As for points of improvement, my only suggestions focus on expanding the comprehension of some topics, such as a quick inclusion of ion drive engines and how that might influence mission architecture (I may have missed this if included, I couldn't read all of it of course). I like the breadth of the work, I would enjoy being able to read more deeply into the presented topics.

I enjoyed that your thesis was able to cover many extremely technical topics, of which I have little in-depth understanding, as well as more generalized research focusing on people or mission architecture. While it would take a further iteration of the paper to create real depth of understanding in some of the topics, few works show the ways in which the technical aspects of space habitation influence human factors aspects. This would be an excellent paper to provide a base understanding of Mars habitation for those looking to understand the means and methods of space exploration.

Hope this is sufficient! Go rock your work and graduate man!

Best,
Tristan

APPENDIX B: TRL & HRL

Elaboration on Technology Readiness Levels (TRL) and Habitation Readiness Levels (HRL) and their relations. (Hauplik-Meusburger and Bannova, 2016)

Table 3.11 Listing of technology readiness levels in respect to common engineering terms, and explanation and examples (Mankins 1995; European Space Agency [TRL] 2008; Cohen 2012)

TRL	TRL definition (commonly used engineering/R&D terms)	Explanation and examples
TRL 1	Basic principles observed and reported (scientific research)	At this level, basic scientific research has resulted in the observation and reporting of basic principles. Example: scientific research of basic properties of materials, such as nanotechnology applied to generate more efficient solar cells, thermo-regulating materials, radiation shielding
TRL 2	Technology concept and/or application formulated (systems analyses, pre-phase a studies)	Identification or 'invention' of practical applications for observed physical principals. Example: potential applications of a new superconducting material for thin film devices and in instruments
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept (laboratory experiments)	Initiation of active research and development of the concept elements. This includes both analytical and experimental approaches to proving a particular concept. (Elements of a fabrication device for thin film silicon solar cells development on the Moon: proof-of-concept lab research)
TRL 4	Component and/or breadboard validation in a laboratory environment (component, breadboard)	Active research and development of the concept as a system. Example: fabrication of thin film silicon solar cells on the Moon project
TRL 5	Component and/or breadboard validation in a relevant environment (high-fidelity breadboard, engineering breadboard, function-oriented model)	Validation of the total applications (component-level, sub-system level, or system-level) in a 'simulated' or somewhat realistic environment. Example: VASIMR propulsion system elements vacuum chamber testing
TRL 6	System/subsystem model or prototype demonstration in a relevant environment—ground or space (high-fidelity laboratory prototype, engineering qualification model. subsystem model, system model)	The innovative approach is demonstrated by an actual system prototype in a space environment. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. Example: All-Terrain Hex-Limbed Extra-Terrestrial Explorer, (ATHLETE) demonstration; Desert RATS Field Tests on the Black Point Lava Flow in Arizona; model of a system tested with a scale model

TRL	TRL definition (commonly used engineering/R&D terms)	Explanation and examples
TRL 7	System prototype demonstration in a space environment (system demonstration)	An actual system prototype is demonstrated in a space environment. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: Mars rovers: Spirit, Opportunity, Curiosity; unmanned Orion test flight
TRL 8	Actual system completed and "flight qualified" through test and demonstration—ground or space (theoretical first unit, flight unit, flight spare)	In almost all cases, this level is the end of true 'system development' for most technology elements. Example: sky-crane soft landing technique delivered curiosity rover to Mars and crashed in a safe distance from the rover
TRL 9	Actual system "flight proven" through successful mission operations (mission operations, flight qualified hardware)	In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. Example: loading and testing new control algorithms and software updates of curiosity rover computer system

Table 4.1 Definition of the habitation readiness level 1 in relation to the respective technical readiness level (Connolly et al. 2006, p. 3–4; ESA (TRL) 2008)

HRL	Definition of the habitation readiness level 1	TRL
Demonstration of the technology	Human factors, crew systems, and life support research related to habitation systems	Any TRL
	An HRL Level 1 Habitation System is a system in a preliminary conceptual stage where interior and exterior designs, functions, and subsystem suites are still being researched. The requirements for the habitation system and its associated crew operations may also be in a very preliminary stage with many TBDs remaining to be resolved. A focus on crew-related factors such as life support, crew accommodations, and human factors requirements is emphasized. An HRL 1 habitation system includes a preliminary list of functions, the number of crew needed to complete the function, the basic equipment the crew will use, a basic idea of the volume required, and rationale for the allocation decisions	

Table 5.1 Definition of the Habitation Readiness Levels 2–4 in relation to Technology Readiness Levels (Connolly et al. 2006, p. 5; ESA [TRL] 2008)

HRL	Definition of the Habitation Readiness Levels 2–4	TRL	Definition of the Technology Readiness Levels
2	Habitation design and concepts, functional and task analysis An HRL Level 2 Habitation System is at a stage where requirements and operations assumptions have been firmed up, but still preliminary. The habitation system concept has matured to a point where interior and exteriors designs, functions, subsystem suites, etc. are being traded rather than researched. To comply with the Habitation Readiness Level 2 the design stage has to cover development of habitation and design concepts, functional and task analysis with reference to mission objectives, environmental characteristics, and potential in situ resources	Any TRL	
3	Internal configuration, functional definition and allocation, use of reduced scale models An HRL Level 3 Habitation System is at a stage where a spatial and operational allocation for all habitation system functions has been completed for the concept, including human functions per an assumed operations concept and mission timeline. Volume assignment, equipment assignment, analysis for co-location, separation, and adjacency, as well as vehicle volume integration have been performed. The external and internal concept is modeled with virtual systems and as reduced scale physical modules. The models generated allow the flexibility to accommodate change, validate the accommodation of the human, analyze the concept for various other factors (e.g. lighting, reach, collision avoidance, functional allocation of volume), and present the concept in three dimensions	>6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space) Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application
4	Full-scale, low-fidelity mockup evaluations An HRL Level 4 Habitation System is at a stage where using the information generated in the analysis and conceptual design development, full scale mockups are developed to allow for the evaluation of crew tasks to assist in verification of human operations compatibility with the design. Habitat volumes are evaluated with the full-scale mockup. Mockup fidelity is at a low level such that most habitat subsystems are non-functional		

Table 6.1 Definition of the habitation readiness levels 5–9 in relation to technical readiness levels 6–9 (Connolly et al. 2006, p. 5; ESA [TRL] 2008)

HRL	Definition of the habitation readiness levels 5–9	TRL	Definition of the technical readiness levels 6–8
Demonstration of the technology			
5	Full-scale, high-fidelity mockups, human testing and occupancy evaluations An HRL Level 5 Habitation System is at a stage where the individual technologies required for the habitat have reached the level that has a system/subsystem model or prototype demonstration in a relevant environment, attaining a **TRL 6** for all systems or subsystems. Mockup fidelity is at a high level such that most habitat subsystems are functional. At this level, human testing using the active systems can be performed. Any redesign necessary for the systems is performed and testing is repeated as required	>6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space) Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application
6	Habitat and deployment field testing An HRL Level 6 Habitation System is at a stage where an operational habitation system is taken into a relevant field environment for full-scale, integrated activation and testing at an Earth-ambient internal pressure	>7	System prototyping demonstration in an operational environment (ground or space) System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available
	Testing of the Technology and Technology Operations		
7	Pressurized habitat prototype testing An HRL Level 7 Habitation System is at a stage where a fully operational integrated prototype habitation system is tested at the internal pressures required for the mission application	>8	Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space) End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed
8	Actual systems completed and "flight qualified" through test and demonstration An HRL Level 8 Habitation System is at a stage where the integrated habitation system is the actual "flight qualified" system that has completed qualification testing. Compliance to the habitation system requirements	>8	

(continued)

Table 6.1 (continued)

HRL	Definition of the habitation readiness levels 5–9	TRL	Definition of the technical readiness levels 6–8
	and standards has been verified by test, analysis, or a combination thereof		
9	Actual system "flight proven" through successful mission operations. An HRL Level 9 Habitation System is at a stage where the habitation system has been flown, deployed and made operational. It has demonstrated that it has met mission objectives. Post mission-debrief data will assist in defining any aspect of the habitation system that requires improvement, and changes in the collection of technologies and their overall integration and configuration can be addressed and applied as lessons learned	>8	

APPENDIX C: VOLUME ESTIMATIONS

Summary of general allocation of volumes and area as defined by Adams (1999). (Hauplik-Meusburger and Bannova, 2016)

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 m^3 [494.4 f^3]
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 m^3 [579.1 f^3]
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 m^3 [54.4 f^3]
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 m^3 [83.6 ft^3]
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 m^3 [171.2 ft^3]
Changing clothes	Volume provided should allow free movement of the entire body	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.19 m^3 [77.3 ft^3]
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 m^3 [77.3 ft^3]
Personal Hygiene Partial G surface habitat		H: 215 [84″] L: 101 [39″] W: 202 [80″]	4.38 m^3 [154.6 ft^3]
Waste management Toilet partial G		H: 201 [79″] W: 90 [35″] D: 105 [41″]	1.9 m^3 [67.0 ft^3]
Waste management Toilet Micro-G	Requirements for personal hygiene station might be added to waste management		4.09 m^3 [144.4 ft^3]
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 m^3 [76.6 ft^3]
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 m^3 [176.5 ft^3]

(continued)

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	H: 215 [84″] L: 300 [118″] D: 205 [80″]	13.2 m^3 [466.1 ft^3]
	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″]		
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]

APPENDIX D: MEL LIST TRANSHAB

Master Equipment List as defined by Simon et al. (2017)

Functional Category Definitions
Manufacturer's Empty Mass:
Manufacturers Empty Mass is the mass of the element or vehicle "as built" and includes the mass of the structure, engines, furnishings, installations, systems and other equipment that are considered an integral part of an element or vehicle. It also includes closed system fluids (e.g., hydraulic fluid, heat transfer fluid). The mass does not include such items as propellant, payload, potable water, removable equipment or other operational items.
Operational Items:
Items required to perform a particular mission/operation, including crew and the non-fixed/removable items required to support the crew both inside and outside of the vehicle, such as pressure suits, personal gear, life support items (e.g., air, food, water, medical kits), and crew accessories (e.g., maintenance tools). Also includes consumable service items for such functions as power generation and thermal control. Typical examples are reactant supplies for fuel cells and auxiliary power units and open-loop working fluids used to carry away excess heat, such as water or ammonia. (Note: for phase change materials and closed-loop working fluids, reference Thermal Control Systems). In addition, includes propellant and service items, remaining in a vehicle, which are not usable. [Derived from MIL-M-38310B, App. B, para. B.40.17 & B.40.21, and typical aircraft practice] (new)
Operational Empty Mass:
Operational Empty Mass is the sum of the Manufacturer's Empty Mass and the mass of the Operational Items. It is the mass of the element or vehicle including items necessary for operation, excluding usable propellant and the payload.
1. Body Structures
The basic and secondary load carrying members, exclusive of the non-structural components used for induced environmental protection. (MIL-M-38310B, App. B, para. B.40.2) *Primary Structure* (Pressurized and/or Unpressurized) That part of a flight vehicle or element which sustains the significant applied loads and provides main load paths for distributing reactions to applied loads. Also the main structure which is required to sustain the significant applied loads, including pressure and thermal loads, and which if it fails creates a catastrophic hazard. If a component is small enough and in an environment where no serious threat is imposed if it breaks, then it is not primary structure. *Secondary Structure* - The internal or external structure which is used to attach small components, provide storage, and to make either an internal volume or external surface usable. Secondary structure attaches to and is supported by primary structure.
2. Connection and Separation Systems
Physical interfacing equipment required to connect (and/or separate) one or more element structural load paths, electrical paths, and/or fluid paths during its use. This may also include any external ground handling or launch or transit vehicle services (mounts, power, purges, etc.). (New)
3. Launch/Takeoff and Landing Support Systems
Items that provide the vehicle with the capability to be launched from or brought to rest with respect to a mass. Enter descriptive or location data, as appropriate, for clarification of the function served. (MIL-M-38310B, App. B, para. B.40.4)
4. Natural and Induced Environments Protection Systems
The devices which in themselves, or in combination, protect the vehicle or element structure and its contents from the detrimental effects of radiation (e.g., solar, ionizing and galactic cosmic), micrometeoroids and orbital debris (MMOD), induced heat and noise, contamination (e.g., surface dust), and corrosion. [derived from: MIL-M-38310B, App. B, para. B.40.3]
5. Propulsion Systems
Propulsive items which provide flight path thrust and acceleration and include rocket engines, nuclear engines, propulsive devices, and related equipment, such as fuel systems, oxidizer systems, and pressurizing systems. Also includes propellant tanks, if not integral with the body structure. [derived from: MIL-M-38310B, Appx. B, para. B.40.5; JSC 23303, p. 5]
6. Power Systems
Devices and systems for collecting and storing energy, as well as generating or converting various forms of energy into available power that is distributed to vehicle system electrical and/or mechanical loads from *centralized* sources. Includes: dedicated energy storage source material and their containers (e.g., electrochemical storage devices); storage containers and distribution equipment for consumable energy source materials, along with associated heaters, insulation, and instrumentation); dedicated mechanical and/or electrical power converters such as distributed high pressure hydraulic or pneumatic pumps, or fuel cell devices, power inverters; and a means of distributing and regulating power to various vehicle systems loads, including such equipment as pressurized fluid distribution lines, hoses, accumulators, valves, and/or electrical controllers, instrumentation, and switch gear, cables, harnesses, etc. (Note: localized or distributed power systems are nominally bookkept with the equipment they are in direct support of). [New]
7. Command and Data Handling Systems
Avionics equipment that: programs and commands various vehicle elements, modules and subsystems; monitors and predicts vehicle performance and equipment status, and reconfigures systems for safe, stable, or

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advantageous configuration; and distributes, collects, formats and/or stores information for other on- and off-board purposes. [New]

8. Guidance, Navigation, and Control Systems

Equipment and associated algorithms for directing vehicle motion, subdivided into the following functions:
Guidance - Determines the vehicle's desired location/path, velocity, and attitude (orientation)
Navigation - Provides estimates for the vehicle's current state (position, velocity, attitude, attitude rate, etc.)
Control - Steers attitude of vehicle to follow guidance commands while achieving good dynamic response (stability)

Note: Control equipment includes the devices for spatial alignment and stabilization (typically thrusters, reaction wheels, control moment gyroscopes, or aerodynamic surfaces), termed effectors, that produce reactive forces on the vehicle. Aerodynamic and spatial controls include the electro-mechanical, hydraulic, or pneumatic actuation system, from the actuator source to the item actuated. [derived from: MIL-M-38310B, Appx. B, para. B.40.6]

9. Communications and Tracking Systems

The equipment required for all means of communication within, emanating from, and received by the vehicle or element. Includes transmitters, receivers, antennas, power amplifiers and filers, as well as dedicated sensors, instrumentation, cabling, pointing and mounting hardware, and electronics. [derived from: MIL-M-38310B, Appx. B, para. B.40.11, and JSC 23303, p. 7]

10. Crew Displays and Controls

Crew displays and controls are the items consisting of operator input control devices at crew stations and other locations of all types, including various touch/motion controllers and other hybrid display and control devices, as well as other manual input devices, such as switches, pedestals, and levers. Actuation of the controls may be accomplished manually, or with power-assisted devices and equipment. Displays include those that are permanently installed or movable. Does not include carry-on operational items such as laptop computers and other mobile electronic devices (see Operational Items).. (MIL-M-38310B, App. B, para. B.40.15)

11. Thermal Control Systems

The devices which collect, transport, distribute, and radiate/reject internally generated forms of heat. [New]

12. Environmental Control Systems

Controls internal atmospheric environmental conditions such as temperature, pressure, humidity, atmospheric constituents, and odor for personnel and equipment. [derived from: MIL-M-38310B, App. B, para. B.40.12]

13. Crew/Habitation Support Systems

Items within the crew cabin, such as accommodations, fixed life support equipment, cargo handling, furnishings and built-in emergency equipment. (MIL-M-38310B, App. B, para. B.40.14)

14. EVA Support Systems

Systems, services and equipment that are permanently fixed to the element or module to support extravehicular activity by crew personnel. Includes fluid and gas services provided, internal airlocks (external airlocks are generally covered as a seperate element).

15. In-situ Resource Acquistion and Consumables Production Systems

Equipment that generates and transfers fluids for consumption or use by other equipment and/or crew; e.g., propellants, breathing air supply, and water. Includes fixed equipment that extracts or acquires raw materials from vehicle surroundings and any necessary test equipment and storage areas and/or containers. (New)

16. In-space Manufacturing and Assembly Systems

Equipment that manufactures/fabricates items or provides off-line sub-assembly and test of such items. (New)

17. Maintenance and Repair Systems

Includes equipment used for conducting maintenance and support tasks, such as handling/manipulation, disassembly/reassembly, calibration and repair. Includes equipment for storage of tools and instruments associated with these routine maintenance and on-demand repairs.

18. Payload Provisions

Items consisting of payload structural attachments and those for providing electrical power, command, data handling, thermal control, and payload handling/manipulation services (e.g., Remote Manipulator System). (New)

19. Abort and Destruct Systems

Systems that act on malfunctions which will endanger personnel or damage equipment. These systems may also initiate remedial action automatically or perform upon command for emergency conditions detected by the system. [derived from MIL-M-38310B, App. B, para. B.40.16]

Payload

Items stored aboard the spacecraft typically comprising cargo, passengers, scientific instruments, or experiments. Also includes non-fixed carriers or pallets that are required to structurally support payloads. (New)

Propulsion and Reaction Control Expendables

Expendable items for propulsion and flight control functions, including any reserve and bias amounts. This includes propellant for a main propulsion system that provides the bulk of the propulsive energy (i.e., delta V), as well as propellant for an auxiliary propulsion system (e.g., orbital maneuver system). Also included are propellants dedicated to reaction or attitude control of the vehicle (i.e., propellants for control jet thrusters). Additionally, this category includes any solids/fluids/gases used for the purpose of propulsion system starting/igniting, pressurizing propellant tanks, or for purging of propulsion system lines and components of contaminants, such as debris and moisture.

Master Equipment List as defined by Simon et al. (2017) System masses

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
0.0.0	HAB										
1.0.0	BODY STRUCTURES			10	-	6,166.65	19.38%	1,194.84	7,361.49	0.00	7,361.49
1.1.0		PRIMARY STRUCTURE - PRESSURIZED		9	-	4,890.65	19.21%	939.64	5,830.29	-	-
1.1.1			PRESSURE SHELL	1	4,631.25	4,631.25	20.00%	926.25	5,557.50	-	-
1.1.2			WINDOWS	4	8.25	33.00	20.00%	6.60	39.60	-	-
1.1.3			HATCHES	4	56.60	226.40	3.00%	6.79	233.19	-	-
1.1.4			DOORS	0	0.00	0.00	0.00%	0.00	0.00	-	-
1.2.0		PRIMARY STRUCTURE - UNPRESSURIZED		0	-	0.00	0.00	0.00	0.00	-	-
1.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
1.3.0		SECONDARY STRUCTURE - INTERNAL		1	-	1,276.00	20.00%	255.20	1,531.20	-	-
1.3.1			STRUCTURAL SUPPORT TRUSSES	1	1,276.00	1,276.00	20.00%	255.20	1,531.20	-	-
1.3.2			WALLS	0	0.00	0.00	20.00%	0.00	0.00	-	-
1.3.3			FLOORS	0	0.00	0.00	20.00%	0.00	0.00	-	-
1.4.0		SECONDARY STRUCTURE - EXTERNAL		0	-	0.00	0.00	0.00	0.00	-	-
1.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
1.B.0		*SPARE BODY STRUCTURES EQUIP & PACKAGING*		*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
1.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
2.0.0	CONNECTION & SEPARATION SYSTEMS			7	-	589.60	10.01%	59.02	648.62	0.00	648.62
2.1.0		DOCKING/BERTHING INTERFACE MECHANISMS		7	-	589.60	10.01%	59.02	648.62	-	-
2.1.1			PASSIVE IDSS-COMPLIANT DOCKING MECHANISM	2	128.60	257.20	10.00%	25.72	282.92	-	-
2.1.2			ACTIVE IDSS-COMPLIANT DOCKING MECHANISM	1	332.00	332.00	10.00%	33.20	365.20	-	-
2.1.3			FLEXIBLE PROBES WITH RESISTORS	4	0.10	0.40	25.00%	0.10	0.50	-	-
2.2.0		SEPARATION EQUIPMENT		0	-	0.00	0.00	0.00	0.00	-	-
2.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
2.9.0		CONNECTION & SEPARATION SYS INSTALLATION		0	-	0.00	0.00	0.00	0.00	-	-
2.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
2.B.0		*SPARE CONNECTION & SEPARATION EQUIP & PACKAGING*		*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
2.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
2.C.0		*CONNECTION & SEPARATION SYSTEMS CONSUMABLES & PACKAGING*		*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
2.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
2.D.0		*CONNECTION & SEPARATION SYSTEM RESIDUALS*		*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
2.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
3.0.0	LAUNCH/TAKEOFF & LANDING SUPPORT SYSTEMS			1	-	546.75	20.00%	109.35	656.10	0.00	656.10
3.1.0		LAUNCH SUPPORT EQUIP		1	-	546.75	20.00%	109.35	656.10	-	-
3.1.1			LAUNCH/LANDER INTEGRATION	1	546.75	546.75	20.00%	109.35	656.10	-	-
3.2.0		LANDING GEAR		0	-	0.00	0.00	0.00	0.00	-	-
3.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
3.3.0		DEPLOYABLE AERODYNAMIC DEVICES		0	-	0.00	0.00	0.00	0.00	-	-
3.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
3.4.0		VERTICAL LANDING DECELERATION EQUIP		0	-	0.00	0.00	0.00	0.00	-	-
3.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
3.9.0		LAUNCH/TAKEOFF & LANDING SPT SYS INSTALLATION		0	-	0.00	0.00	0.00	0.00	-	-
3.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
3.B.0		*SPARE LAUNCH/LANDING SPT EQUIP & PACKAGING*		*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
3.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
3.C.0		*LAUNCH AND LANDING SUPPORT CONSUMABLES & PACKAGING*		*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
3.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
3.D.0		***LAUNCH AND LANDING SUPPORT RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
3.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
4.0.0	**NATURAL & INDUCED ENVIRON PROTECT SYSTEMS**			**1**	-	**567.00**	**20.00%**	**113.40**	**680.40**	**0.00**	**680.40**
4.1.0		**RADIATION PROTECTION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.1.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.2.0		**MMOD PROTECTION EQUIP**		**1**	-	**567.00**	**20.00%**	**113.40**	**680.40**	-	-
4.2.1			MMOD	1	567.00	567.00	20.00%	113.40	680.40	-	-
4.3.0		**THERMAL PROTECTION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.4.0		**VIBRO-ACOUSTIC PROTECTION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.5.0		**PRESSURE DIFFERENTIAL PROTECTION EQPIPMENT**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.5.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.6.0		**CONTAMINATION CONTROL EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.6.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.7.0		**COATINGS (CORROSION-PROTECTION)**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.7.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.9.0		**PROTECTION SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
4.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
4.B.0		***SPARE PROTECTION SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
4.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
4.C.0		***PROTECTION SYS CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
4.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
4.D.0		***PROTECTION SYS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
4.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.0.0	**PROPULSION SYSTEMS**			**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
5.1.0		**MAIN POWER PLANTS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
5.1.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
5.2.0		**MAIN PROPELLANT MGMT & DISTRIB SYSTEMS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
5.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
5.3.0		**AUXILIARY POWER PLANTS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
5.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
5.4.0		**AUXILIARY PROPELLANT MGMT & DISTRIB SYSTEMS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
5.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
5.9.0		**PROPULSION SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
5.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
5.B.0		***SPARE PROPULSION SYSTEM EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.D.0		***PRESS, PURGE & PROP CTL RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.F.0		***MAIN PROPULSION SYSTEM PROPELLANT***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.F.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.G.0		***AUXILIARY PROPULSION SYSTEM PROPELLANT***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.G.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.I.0		***PROPULSION CONTROL/START & SHUTDOWN CONSUMABLES***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.I.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.J.0		***MAIN & AUX PROP SYS PRESSURIZATION CONSUMABLES***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.J.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
5.K.0		***MAIN & AUX PROP SYS PURGE CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
5.K.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
6.0.0	**POWER SYSTEMS**			**37**	-	**1,034.00**	**19.02%**	**196.68**	**1,230.68**	**0.00**	**1,230.68**
6.1.0		**MAIN POWER SOURCE EQUIP**		**12**	-	**648.00**	**12.22%**	**79.20**	**727.20**	-	-
6.1.1			BCDU (6KW BATTERY CHARGE DISCHARGE UNIT)	6	30.00	180.00	18.00%	32.40	212.40	-	-
6.1.2			BATTERY (5400 W*HRS @ 60% DOD)	6	78.00	468.00	10.00%	46.80	514.80	-	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
6.2.0		**MAIN POWER MGMT & DISTRIBUTION SYSTEMS**		**25**	-	**386.00**	**30.44%**	**117.48**	**503.48**	-	-
6.2.1			DDCU (12KW DC TO DC CONVERTER UNIT)	2	40.00	80.00	18.00%	14.40	94.40	-	-
6.2.2			BDDCU (2KW 120V -120V BI-DIRECTIONAL DC TO DC CONVERTER UNIT	2	10.00	20.00	18.00%	3.60	23.60	-	-
6.2.3			MBSU (MAIN BUS SWITCHING UNIT 2-100A, 4-50A SWITCHES)	2	11.00	22.00	18.00%	3.96	25.96	-	-
6.2.4			MBSU (MAIN BUS SWITCHING UNIT 1-100A, 10-15A SWITCHES)	2	15.00	30.00	18.00%	5.40	35.40	-	-
6.2.5			PDU - INTERNAL	6	8.00	48.00	18.00%	8.64	56.64	-	-
6.2.6			PDU - EXTERNAL	2	10.00	20.00	18.00%	3.60	23.60	-	-
6.2.7			PUP (PORTABLE UTILITY PANEL)	8	2.00	16.00	18.00%	2.88	18.88	-	-
6.2.8			SPACECRAFT BUS HARNESS POWER	1	150.00	150.00	50.00%	75.00	225.00	-	-
6.3.0		**AUXILIARY POWER SOURCES**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
6.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
6.4.0		**AUXILIARY POWER MGMT & DISTRIB SYSTEMS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
6.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
6.9.0		**POWER SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
6.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	
6.A.0		***POWER SYS MISSION KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
6.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
6.B.0		***SPARE POWER SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
6.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
6.C.0		***POWER GENERATION CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
6.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
6.D.0		***POWER GENERATION RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
6.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
7.0.0	**COMMAND & DATA HANDLING (C&DH) SYSTEMS**			**14**	-	**107.00**	**22.38%**	**23.95**	**130.95**	**0.00**	**130.95**
7.1.0		**FLIGHT COMPUTER, MEMORY/STORAGE**		**7**	-	**26.00**	**20.38%**	**5.30**	**31.30**	-	-
7.1.1			C&DH COMPUTERS & MISCELLANEOUS C&DH FUNCTIONS	4	4.00	16.00	25.00%	4.00	20.00	-	-
7.1.2			DATA RECORDER	2	2.00	4.00	25.00%	1.00	5.00	-	-
7.1.3			OPERATIONS RECORDER	1	6.00	6.00	5.00%	0.30	6.30	-	-
7.2.0		**CRITICAL COMMAND & MONITORING NETWORK EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
7.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
7.3.0		**OPERATIONAL INSTRUMENTATION EQUIP**		**2**	-	**3.00**	**25.00%**	**0.75**	**3.75**	-	-
7.3.1			HI-RATE SWITCH	2	1.50	3.00	25.00%	0.75	3.75	-	-
7.4.0		**DEVELOPMENTAL & TEST INSTRUMENTATION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
7.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
7.5.0		**DEDICATED VIDEO DISPLAY & CONTROL NETWORK EQUIP**		**3**	-	**8.00**	**5.00%**	**0.40**	**8.40**	-	-
7.5.1			TV VIDEO COMPRESSOR	1	2.00	2.00	5.00%	0.10	2.10	-	-
7.5.2			TV VIDEO ENCRYPTOR	1	1.00	1.00	5.00%	0.05	1.05	-	-
7.5.3			TV VIDEO RECORDER	1	5.00	5.00	5.00%	0.25	5.25	-	-
7.6.0		**C&DH CABLES/DATA BUSSES (FLT CRITICAL, SYS MGMT)**		**2**	-	**70.00**	**25.00%**	**17.50**	**87.50**	-	-
7.6.1			TTP CABLING	1	60.00	60.00	25.00%	15.00	75.00	-	-
7.6.2			HIGH-RATE CABLING	1	10.00	10.00	25.00%	2.50	12.50	-	-
7.9.0		**C&DH SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
7.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
7.A.0		***C&DH MISSION-KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
7.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
7.B.0		***SPARE C&DH SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
7.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
8.0.0	**GUIDANCE, NAVIGATION & CONTROL (GN&C) SYSTEMS**			**8**	-	**28.00**	**18.00%**	**5.04**	**33.04**	**0.00**	**33.04**
8.1.0		**DEDICATED GN&C COMPUTERS/PROCESSORS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
8.1.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
8.2.0		**NAVIGATIONAL AIDS & CONTROL SENSORS**		**8**	-	**28.00**	**18.00%**	**5.04**	**33.04**	-	-
8.2.1			EXTERIOR RENDEZVOUS LIGHTS	6	4.00	24.00	18.00%	4.32	28.32	-	-
8.2.2			EXTERIOR DOCKING LIGHTS	2	2.00	4.00	18.00%	0.72	4.72	-	-
8.3.0		**MOMEMTUM MANAGEMENT SYSTEMS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
8.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
8.9.0		**GN&C SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
8.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
8.A.0		***GN&C MISSION-KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
8.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
8.B.0		***SPARE GN&C SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
8.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
8.D.0		***CONTROL SYS RESIDUAL***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
8.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
8.H.0		***CONTROL SYS EXPENDABLES***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
8.H.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
8.J.0		***CONTROL SYS PRESSURIZATION CONSUMABLES***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
8.J.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
8.K.0		***CONTROL SYS PURGE CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
8.K.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
9.0.0	**COMMUNICATIONS & TRACKING (C&T) SYSTEMS**			**53**	-	**199.70**	**5.00%**	**9.99**	**209.69**	**0.00**	**209.69**
9.1.0		**PROXIMITY RF COMM EQUIP**		**4**	-	**21.70**	**5.00%**	**1.09**	**22.79**	-	-
9.1.1			UHF SPACE TO GROUND ANTENNA W/ RADOME	1	1.40	1.40	5.00%	0.07	1.47	-	-
9.1.2			STRING SWITCH	1	0.10	0.10	5.00%	0.01	0.11	-	-
9.1.3			ELECTRA TRANSCEIVER A (INCLUDES SOLID STATE POWER AMPLIFIER-SSPA)	1	10.10	10.10	5.00%	0.51	10.61	-	-
9.1.4			ELECTRA TRANSCEIVER B (INCLUDES SOLID STATE POWER AMPLIFIER-SSPA)	1	10.10	10.10	5.00%	0.51	10.61	-	-
9.1.5			MISC CABLING AND BRACKETS (TBD)	0	0.00	0.00	5.00%	0.00	0.00	-	-
9.2.0		**RANGING AND LOCATING EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
9.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
9.3.0		**DEEP SPACE COMM/NAV EQUIP**		**28**	-	**134.00**	**5.00%**	**6.70**	**140.70**	-	-
9.3.1			X-BAND LOW GAIN ANTENNA A (TX/RX) AND POLARIZERS	1	0.80	0.80	5.00%	0.04	0.84	-	-
9.3.2			X-BAND LOW GAIN ANTENNA B (TX/RX) AND POLARIZERS	1	0.80	0.80	5.00%	0.04	0.84	-	-
9.3.3			X&KA-BAND HIGH GAIN ANTENNA PRIME REFLECTOR (3M)	1	19.10	19.10	5.00%	0.96	20.06	-	-
9.3.4			HIGH GAIN ANTENNA FEED	1	1.60	1.60	5.00%	0.08	1.68	-	-
9.3.5			HIGH GAIN ANTENNA GIMBALS AND DRIVE MOTORS	1	45.00	45.00	5.00%	2.25	47.25	-	-
9.3.6			WAVEGUIDES AND COAX	1	8.30	8.30	5.00%	0.42	8.72	-	-
9.3.7			ANTENNA MISC	1	1.10	1.10	5.00%	0.06	1.16	-	-
9.3.8			KA-BAND TRAVELING WAVE TUBE AMPLIFIER (TWTA)	1	0.80	0.80	5.00%	0.04	0.84	-	-
9.3.9			KA-BAND ELECTRONIC POWER CONVERTERS	1	1.50	1.50	5.00%	0.08	1.58	-	-
9.3.10			X-BAND TRAVELING WAVE TUBE AMPLIFIER (TWTA) A	1	0.95	0.95	5.00%	0.05	1.00	-	-
9.3.11			X-BAND TRAVELING WAVE TUBE AMPLIFIER (TWTA) B	1	0.95	0.95	5.00%	0.05	1.00	-	-
9.3.12			X-BAND ELECTRONIC POWER CONVERTERS	1	3.00	3.00	5.00%	0.15	3.15	-	-
9.3.13			DIPLEXERS AND BRACKETS	1	1.80	1.80	5.00%	0.09	1.89	-	-
9.3.14			WAVEGUIDE TRANSFER SWITCHES	1	1.50	1.50	5.00%	0.08	1.58	-	-
9.3.15			MICROWAVE COMPONENTS	1	1.40	1.40	5.00%	0.07	1.47	-	-
9.3.16			MISC TWTA HARDWARE	1	0.20	0.20	5.00%	0.01	0.21	-	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)										
		COMMON EQUIPMENT GROUP (TIER 2)									
			UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
9.3.17			SMALL DEEP SPACE TRANSPONDER A (FUTURE: UNIVERSAL SPACE TRANSPONDER-UST)	1	3.00	3.00	5.00%	0.15	3.15	-	-
9.3.18			ULTRA-STABLE OSCILLATOR A	1	1.70	1.70	5.00%	0.09	1.79	-	-
9.3.19			SMALL DEEP SPACE TRANSPONDER B (FUTURE: UNIVERSAL SPACE TRANSPONDER-UST)	1	3.00	3.00	5.00%	0.15	3.15	-	-
9.3.20			ULTRA-STABLE OSCILLATOR B	1	1.70	1.70	5.00%	0.09	1.79	-	-
9.3.21			FREQUENCY MULTIPLIER AND BRACKETS (A,B,C,D)	4	0.10	0.40	5.00%	0.02	0.42	-	-
9.3.22			OPTICAL MODULE - CISLUNAR OPTION B (10CM APERTURE)	1	13.06	13.06	5.00%	0.65	13.71	-	-
9.3.23			MODEM MODULE	1	11.52	11.52	5.00%	0.58	12.10	-	-
9.3.24			CONTROLLER ELECTRONICS	1	3.62	3.62	5.00%	0.18	3.80	-	-
9.3.25			INTERFACE ELECTRONICS	1	7.20	7.20	5.00%	0.36	7.56	-	-
9.3.26			INTERFACE CABLING (TBD)	0	0.00	0.00	0.00%	0.00	0.00	-	-
9.4.0		**TIMING EQUIP**		**2**	-	**10.00**	**5.00%**	**0.50**	**10.50**	-	-
9.4.1			DSAC: DEEP SPACE ATOMIC CLOCK (FUTURE VERSION)	2	5.00	10.00	5%	0.50	10.50	-	-
9.5.0		**COMM/NAV POINTING AIDS**		**1**	-	**14.00**	**5.00%**	**0.70**	**14.70**	-	-
9.5.1			APIC: ADVANCED POINTING IMAGING CAMERA (MEL FOR: FIRST DEMONSTRATION VERSION)	1	14.00	14.00	5.00%	0.70	14.70	-	-
9.6.0		**COMM SECURITY (COMSEC) EQUIP**		**16**	-	**8.00**	**5.00%**	**0.40**	**8.40**	-	-
9.6.1			FIPS 140-2 APPROVED DECRYPTION UNIT	4	0.50	2.00	5.00%	0.10	2.10	-	-
9.6.2			KEY STORAGE MEMORY DEVICE	4	0.25	1.00	5.00%	0.05	1.05	-	-
9.6.3			FIPS 140-2 APPROVED ENCRYPTION/PROCESSING UNIT	4	1.00	4.00	5.00%	0.20	4.20	-	-
9.6.4			KEY STORAGE MEMORY DEVICE	4	0.25	1.00	5.00%	0.05	1.05	-	-
9.7.0		**AUDIO-VISUAL EQUIP**		**2**	-	**12.00**	**5.00%**	**0.60**	**12.60**	-	-
9.7.1			TV CAMERA	1	3.00	3.00	5.00%	0.15	3.15	-	-
9.7.2			DIGITAL AUDIO SYSTEM	1	9.00	9.00	5.00%	0.45	9.45	-	-
9.8.0		**COMM CABLES AND RF INTERCONNECTIONS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
9.8.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
9.9.0		**C&T SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
9.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
9.A.0		***C&T MISSION-KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
9.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
9.B.0		***SPARE C&T SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
9.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
10.0.0	**CREW DISPLAYS & CONTROLS**			**3**	-	**61.00**	**25.00%**	**15.25**	**76.25**	**0.00**	**76.25**
10.1.0		**VISUAL DISPLAYS (E.G., MONITORS, INDICATORS)**		**1**	-	**42.00**	**25.00%**	**10.50**	**52.50**	-	-
10.1.1			DISPLAYS	1	42.00	42.00	25.00%	10.50	52.50	-	-
10.2.0		**TOUCH, MOTION & VOICE CONTROL DEVICES**		**2**	-	**19.00**	**25.00%**	**4.75**	**23.75**	-	-
10.2.1			CONTROL SET	1	10.00	10.00	25.00%	2.50	12.50	-	-
10.2.2			HAND CONTROLLER	1	9.00	9.00	25.00%	2.25	11.25	-	-
10.3.0		**CAUTION & WARNING ELECTRONICS**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
10.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
10.9.0		**CREW DISPLAYS & CONTROLS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
10.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
10.A.0		***CREW DISP & CTLS MISSION-KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
10.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
10.B.0		***SPARE CREW DISP & CTLS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
10.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)										
		COMMON EQUIPMENT GROUP (TIER 2)									
			UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
11.0.0	ENVIRONMENTAL CONTROL SYSTEMS (ECS)			453	-	2,346.98	23.09%	541.82	2,888.80	729.53	3,618.33
11.1.0		**ENVIRONMENTAL MONITORING & PROTECTION EQUIP**		**1**	-	**20.00**	**20.00%**	**4.00**	**24.00**	-	-
11.1.1			FIRE DETECTION AND SUPPRESSION	1	20.00	20.00	20.00%	4.00	24.00	-	-
11.2.0		**VENTILATION & PRESSURE CTL EQUIP**		**5**	-	**226.14**	**20.00%**	**45.23**	**271.37**	-	-
11.2.1			ATMOSPHERIC CONTROL SYSTEM	1	42.00	42.00	20.00%	8.40	50.40	-	-
11.2.2			COMMON CABIN AIR ASSEMBLIES (CCAAS)	1	58.65	58.65	20.00%	11.73	70.38	-	-
11.2.3			AVIONICS AIR ASSEMBLY	1	12.40	12.40	20.00%	2.48	14.88	-	-
11.2.4			ATMOSPHERIC CIRCULATION	1	9.87	9.87	20.00%	1.97	11.84	-	-
11.2.5			ATMOSPHERIC MICROBIAL CONTROL	1	103.22	103.22	20.00%	20.64	123.86	-	-
11.3.0		**ATMOSPHERIC REVITALIZATION EQUIP**		**6**	-	**652.35**	**20.00%**	**130.47**	**782.82**	-	-
11.3.1			CO2 REMOVAL	1	141.12	141.12	20.00%	28.22	169.34	-	-
11.3.2			CO2 REDUCTION (SABATIER)	1	131.15	131.15	20.00%	26.23	157.38	-	-
11.3.3			O2 GENERATION	1	244.02	244.02	20.00%	48.80	292.82	-	-
11.3.4			TRACE CONTAMINANT CONTROL SUBASSEMBLY (TCCS)	1	46.65	46.65	20.00%	9.33	55.99	-	-
11.3.5			ACM - ATMOSPHERE COMPOSITION MONITORING ASSEMBLY	1	54.30	54.30	20.00%	10.86	65.16	-	-
11.3.6			SAMPLE DELIVERY (CHANGE TO SAMPLE ANALYSIS?)	1	35.11	35.11	20.00%	7.02	42.13	-	-
11.4.0		**ACTIVE THERMAL CONTROL SYSTEM**		**206**	-	**1,125.92**	**25.00%**	**281.48**	**1,407.40**	-	-
11.4.1			[WATER/PG COOLANT INCLUDED WITH LINES]	1	0.00	0.00	25.00%	0.00	0.00	-	-
11.4.2			INTERNAL TCS - WATER/PG COOLANT PUMPS	2	6.75	13.50	25.00%	3.38	16.88	-	-
11.4.3			INTERNAL TCS - WATER/PG ACCUMULATORS	2	21.60	43.20	25.00%	10.80	54.00	-	-
11.4.4			INTERNAL TCS - WATER/PG LINES (WITH COOLANT)	1	35.21	35.21	25.00%	8.80	44.01	-	-
11.4.5			INTERNAL TCS - FLOW CONTROL VALVE	1	4.00	4.00	25.00%	1.00	5.00	-	-
11.4.6			INTERNAL TCS - SURVIVAL HEATER	1	3.00	3.00	25.00%	0.75	3.75	-	-
11.4.7			INTERNAL TCS - COLDPLATES (SS)	8	4.00	32.00	25.00%	8.00	40.00	-	-
11.4.8			INTERNAL TCS - FILTERS	4	0.40	1.60	25.00%	0.40	2.00	-	-
11.4.9			INTERNAL TCS - LIQUID TO LIQUID HEAT EXCHANGER	1	15.00	15.00	25.00%	3.75	18.75	-	-
11.4.10			INTERNAL TCS - ISOLATION VALVES	2	0.24	0.48	25.00%	0.12	0.60	-	-
11.4.11			INTERNAL TCS - CHECK VALVES	2	1.73	3.46	25.00%	0.87	4.33	-	-
11.4.12			INTERNAL TCS - FILL PORTS	2	0.60	1.20	25.00%	0.30	1.50	-	-
11.4.13			INTERNAL TCS - AVIONICS FAN	1	2.00	2.00	25.00%	0.50	2.50	-	-
11.4.14			INTERNAL TCS - AVIONICS HEAT EXCHANGER	1	11.00	11.00	25.00%	2.75	13.75	-	-
11.4.15			INTERNAL TCS - TEMPERATURE SENSORS	3	0.10	0.30	25.00%	0.08	0.38	-	-
11.4.16			INTERNAL TCS - FLOW SENSORS	1	0.60	0.60	25.00%	0.15	0.75	-	-
11.4.17			INTERNAL TCS - LIQUID LEVEL SENSORS	2	0.25	0.50	25.00%	0.13	0.63	-	-
11.4.18			INTERNAL TCS - PRESSURE SENSORS	3	0.10	0.30	25.00%	0.08	0.38	-	-
11.4.19			[HFE 7200 COOLANT INCLUDED WITH LINES]	1	0.00	0.00	25.00%	0.00	0.00	-	-
11.4.20			EXTERNAL TCS - HFE 7200 COOLANT PUMPS	2	6.75	13.50	25.00%	3.38	16.88	-	-
11.4.21			EXTERNAL TCS - HFE 7200 PRIMARY ACCUMULATOR	1	97.60	97.60	25.00%	24.40	122.00	-	-
11.4.22			EXTERNAL TCS - HFE 7200 BACKUP ACCUMULATOR	1	32.50	32.50	25.00%	8.13	40.63	-	-
11.4.23			EXTERNAL TCS - HFE 7200 LINES (WITH COOLANT)	1	42.10	42.10	25.00%	10.53	52.63	-	-
11.4.24			EXTERNAL TCS - COLDPLATES	8	1.31	10.48	25.00%	2.62	13.10	-	-
11.4.25			EXTERNAL TCS - FILTERS	4	0.40	1.60	25.00%	0.40	2.00	-	-
11.4.26			EXTERNAL TCS - REGENERATOR	1	12.66	12.66	25.00%	3.16	15.82	-	-
11.4.27			EXTERNAL TCS - RADIATOR FLOW SPLIT VALVE	1	2.00	2.00	25.00%	0.50	2.50	-	-
11.4.28			EXTERNAL TCS - REGENERATOR FLOW CONTROL VALVE	2	4.00	8.00	25.00%	2.00	10.00	-	-
11.4.29			EXTERNAL TCS - ISOLATION VALVES	8	1.73	13.84	25.00%	3.46	17.30	-	-
11.4.30			EXTERNAL TCS - CHECK VALVES	6	0.24	1.44	25.00%	0.36	1.80	-	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
11.4.31			EXTERNAL TCS - FILL PORTS	2	0.60	1.20	25.00%	0.30	1.50	-	-
11.4.32			EXTERNAL TCS - TEMPERATURE SENSORS	3	0.10	0.30	25.00%	0.08	0.38	-	-
11.4.33			EXTERNAL TCS - FLOW SENSOR	1	0.60	0.60	25.00%	0.15	0.75	-	-
11.4.34			EXTERNAL TCS - LIQUID LEVEL SENSORS	2	0.25	0.50	25.00%	0.13	0.63	-	-
11.4.35			EXTERNAL TCS - PRESSURE SENSORS	3	0.10	0.30	25.00%	0.08	0.38	-	-
11.4.36			RADIATORS	121	5.95	719.95	25.00%	179.99	899.94	-	-
11.5.0		**PASSIVE THERMAL CONTROL SYSTEM**		**235**	-	**322.57**	**25.00%**	**80.64**	**403.21**	-	-
11.5.1			WALL HEATERS	2	3.00	6.00	25.00%	1.50	7.50	-	-
11.5.2			HATCH HEATER	4	3.00	12.00	25.00%	3.00	15.00	-	-
11.5.3			MLI BLANKETS	229	1.33	304.57	25.00%	76.14	380.71	-	-
11.9.0		**ECS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
11.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
11.A.0		***ECS MISSION-KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
11.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
11.B.0		***SPARE ECS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
11.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
11.C.0		***ECS CONSUMABLES & PACKAGING***		***3***	-	***637.69***	***14.40%***	***91.84***	-	***729.53***	-
11.C.1			*O2 STORAGE AND SUPPLY (INCLUDES O2 MASS?)*	*1*	*124.30*	*124.30*	*20.00%*	*24.86*	-	*149.16*	-
11.C.2			*N2 STORAGE AND SUPPLY (INCLUDES N2 MASS?)*	*1*	*303.39*	*303.39*	*20.00%*	*60.68*	-	*364.07*	-
11.C.3			*LIOH CANISTERS (30 DAYS)*	*1*	*210.00*	*210.00*	*3.00%*	*6.30*	-	*216.30*	-
11.D.0		***ECS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
11.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
12.0.0	**CREW/HABITATION SUPPORT SYSTEMS**			**206**	-	**1,910.25**	**19.55%**	**373.37**	**2,283.62**	**13,773.29**	**16,056.91**
12.1.0		**LIVING & WORKSPACE ACCOMMODATIONS**		**110**	-	**280.08**	**16.90%**	**47.34**	**327.42**	-	-
12.1.1			HANDRAILS AND WORK INTERFACE FIXTURES (FCDT ASSUMPTIONS)	1	52.00	52.00	11.00%	5.72	57.72	-	-
12.1.2			RESTRAINTS	1	50.00	50.00	20.00%	10.00	60.00	-	-
12.1.3			MAINTENANCE WORKSTATION STRUCTURES AND PARTITIONS	0	85.00	0.00	20.00%	0.00	0.00	-	-
12.1.4			GENERAL LIGHT	40	1.00	40.00	20.00%	8.00	48.00	-	-
12.1.5			TASK LIGHT	40	0.50	20.00	20.00%	4.00	24.00	-	-
12.1.6			MANUAL LIGHTING CONTROL	8	0.01	0.08	20.00%	0.02	0.10	-	-
12.1.7			WORK SURFACES	1	40.00	40.00	10.00%	4.00	44.00	-	-
12.1.8			CLOSEOUT PANELS (GALLEY)	3	6.00	18.00	20.00%	3.60	21.60	-	-
12.1.9			CREW WORK DESK	4	3.00	12.00	20.00%	2.40	14.40	-	-
12.1.10			ACOUSTIC PARTITIONS	12	4.00	48.00	20.00%	9.60	57.60	-	-
12.2.0		**WATER SYSTEM**		**8**	-	**551.75**	**20.00%**	**110.35**	**662.10**	-	-
12.2.1			WATER TREATMENT	1	388.67	388.67	20.00%	77.73	466.40	-	-
12.2.2			WATER RECOVERY SYSTEM (WRS) WITH TANKAGE	1	72.04	72.04	20.00%	14.41	86.44	-	-
12.2.3			MICROBIAL CHECK	1	1.84	1.84	20.00%	0.37	2.21	-	-
12.2.4			PROCESS CONTROLLER	1	36.91	36.91	20.00%	7.38	44.29	-	-
12.2.5			WATER QUALITY MONITORING	1	8.64	8.64	20.00%	1.73	10.37	-	-
12.2.6			WATER DELIVERY SYSTEM	1	20.65	20.65	20.00%	4.13	24.79	-	-
0.2.6			SINK, SPIGOT FOR HYDRATION OF FOOD & DRINKING WATER	1	15.00	15.00	20.00%	3.00	18.00	-	-
12.2.7			HANDWASH/MOUTHWASH FAUCET	1	8.00	8.00	20.00%	1.60	9.60	-	-
12.3.0		**FOOD SYSTEMS**		**3**	-	**612.20**	**20.00%**	**122.44**	**734.64**	-	-
12.3.1			FREEZERS (NOT INCLUDING FOOD)	1	496.00	496.00	20.00%	99.20	595.20	-	-
12.3.2			FOOD WARMERS	2	58.10	116.20	20.00%	23.24	139.44	-	-
12.4.0		**WASTE SYSTEMS**		**4**	-	**183.75**	**20.00%**	**36.75**	**220.50**	-	-
12.4.1			URINE COLLECTION SYSTEM	1	4.55	4.55	20.00%	0.91	5.46	-	-
12.4.2			SOLID WASTE COLLECTION	1	58.40	58.40	20.00%	11.68	70.08	-	-
12.4.3			SOLID WASTE BULK COMPACTOR/STORAGE	1	8.80	8.80	20.00%	1.76	10.56	-	-
12.4.4			TRASH COMPACTOR/TRASH LOCK	0	150.00	0.00	20.00%	0.00	0.00	-	-
12.4.5			TRASH TO GAS SYSTEM	1	112.00	112.00	20.00%	22.40	134.40	-	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)										
		COMMON EQUIPMENT GROUP (TIER 2)									
			UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
12.5.0		**EXERCISE SYSTEMS**		**1**	**-**	**282.00**	**20.00%**	**56.40**	**338.40**	**-**	**-**
12.5.1			FIXED EXERCISE EQUIPMENT	1	282.00	282.00	20.00%	56.40	338.40	-	-
12.6.0		**MEDICAL SYSTEMS**		**0**	**-**	**0.00**	**0.00**	**0.00**	**0.00**	**-**	**-**
12.6.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
12.7.0		**FIXED CREW EMERGENCY EQUIP**		**80**	**-**	**0.47**	**20.00%**	**0.09**	**0.57**	**-**	**-**
12.7.1			EMERGENCY LIGHT	8	0.05	0.40	20.00%	0.08	0.48	-	-
12.7.2			EMERGENCY LIGHTING MARKERS	72	0.00	0.07	20.00%	0.01	0.09	-	-
12.9.0		**CREW/HAB SPT SYS INSTALLATION**		**0**	**-**	**0.00**	**0.00**	**0.00**	**0.00**	**-**	**-**
12.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
12.A.0		***CREW/HAB MISSION-KITTED OR STOWED ITEMS***		***28***	***-***	***903.34***	***12.68%***	***114.57***	***-***	***1,017.91***	***-***
12.A.1			*VACUUM (PRIME + 2 SPARES)*	*3*	*8.67*	*26.01*	*20.00%*	*5.20*	*-*	*31.21*	*-*
12.A.2			*LIGHTWEIGHT TRAUMA MODULE*	*1*	*26.00*	*26.00*	*20.00%*	*5.20*	*-*	*31.20*	*-*
12.A.3			*AED*	*1*	*3.73*	*3.73*	*20.00%*	*0.75*	*-*	*4.48*	*-*
12.A.4			*ECG*	*1*	*8.50*	*8.50*	*20.00%*	*1.70*	*-*	*10.20*	*-*
12.A.5			*ULTRASOUND*	*1*	*3.70*	*3.70*	*20.00%*	*0.74*	*-*	*4.44*	*-*
12.A.6			*PATIENT RESTRAINT SYSTEM*	*1*	*18.20*	*18.20*	*20.00%*	*3.64*	*-*	*21.84*	*-*
12.A.7			*MEDICAL WORKSTATION STRUCTURE*	*1*	*18.20*	*18.20*	*20.00%*	*3.64*	*-*	*21.84*	*-*
12.A.8			*PRIVACY CURTAIN*	*1*	*8.00*	*8.00*	*20.00%*	*1.60*	*-*	*9.60*	*-*
12.A.9			*MISCELLANEOUS LONG DURATION MEDICAL DEVICES*	*1*	*100.00*	*100.00*	*20.00%*	*20.00*	*-*	*120.00*	*-*
12.A.10			*EMERGENCY O2 MASKS*	*4*	*1.50*	*6.00*	*20.00%*	*1.20*	*-*	*7.20*	*-*
12.A.11			*FIRE EXTINGUISHER*	*1*	*20.00*	*20.00*	*0.00%*	*0.00*	*-*	*20.00*	*-*
12.A.12			*OPERATIONAL SUPPLIES*	*1*	*80.00*	*80.00*	*3.00%*	*2.40*	*-*	*82.40*	*-*
12.A.13			*LAPTOP*	*3*	*2.00*	*6.00*	*20.00%*	*1.20*	*-*	*7.20*	*-*
12.A.14			*PRINTER*	*1*	*9.00*	*9.00*	*20.00%*	*1.80*	*-*	*10.80*	*-*
12.A.15			*OCSS SUITS AND 2 SHORT UMBILICALS*	*4*	*21.25*	*85.00*	*11.00%*	*9.35*	*-*	*94.35*	*-*
12.A.16			*OCSS SUIT KITS (ARCM SERVICING AND SUIT KITS FOR 2 SUITS)*	*1*	*265.00*	*265.00*	*11.00%*	*29.15*	*-*	*294.15*	*-*
12.A.17			*EQUIPMENT (STILL & VIDEO CAMERAS, LENSES, ETC.)*	*1*	*120.00*	*120.00*	*20.00%*	*24.00*	*-*	*144.00*	*-*
12.A.18			*PORTABLE EXERCISE EQUIPMENT ALLOCATION*	*0*	*0.00*	*0.00*	*20.00%*	*0.00*	*-*	*0.00*	*-*
12.C.25			*RECREATION & PERSONAL STOWAGE*	*1*	*100.00*	*100.00*	*3.00%*	*3.00*	*-*	*103.00*	*-*
12.B.0		***SPARE CREW/HAB SPT SYS EQUIP & PACKAGING***		***0***	***-***	***0.00***	***0.00***	***0.00***	***-***	***0.00***	***-***
12.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	*-*	*0.00*	*-*
12.C.0		***CREW/HAB SPT SYS CONSUMABLES & PACKAGING***		***25***	***-***	***12,373.61***	***3.09%***	***381.77***	***-***	***12,755.38***	***-***
12.C.1			*FOOD*	*1*	*8,276.12*	*8,276.12*	*3.00%*	*248.28*	*-*	*8,524.40*	*-*
12.C.2			*H20*	*1*	*384.00*	*384.00*	*3.00%*	*11.52*	*-*	*395.52*	*-*
12.C.3			*COOKING/EATING SUPPLIES*	*1*	*8.00*	*8.00*	*20.00%*	*1.60*	*-*	*9.60*	*-*
12.C.4			*PERSONAL HYGEINE KIT*	*1*	*19.80*	*19.80*	*3.00%*	*0.59*	*-*	*20.39*	*-*
12.C.5			*HYGIENE CONSUMABLES / WCS WIPES*	*1*	*709.64*	*709.64*	*3.00%*	*21.29*	*-*	*730.93*	*-*
12.C.6			*TOWELS*	*1*	*139.32*	*139.32*	*3.00%*	*4.18*	*-*	*143.50*	*-*
12.C.7			*COMMUNITY HYGIENE KIT*	*1*	*4.72*	*4.72*	*20.00%*	*0.94*	*-*	*5.66*	*-*
12.C.8			*WASTE COLLECTION - FECAL CANISTERS*	*1*	*990.00*	*990.00*	*3.00%*	*29.70*	*-*	*1,019.70*	*-*
12.C.9			*WASTE COLLECTION - URINE PREFILTER*	*1*	*275.00*	*275.00*	*3.00%*	*8.25*	*-*	*283.25*	*-*
12.C.10			*FECAL/URINE COLLECTION BAGS (CONTINGENCY)*	*1*	*167.20*	*167.20*	*3.00%*	*5.02*	*-*	*172.22*	*-*
12.C.11			*TRASH BAGS*	*1*	*135.60*	*135.60*	*3.00%*	*4.07*	*-*	*139.67*	*-*
12.C.12			*HEALTH CARE CONSUMABLES*	*1*	*406.80*	*406.80*	*3.00%*	*12.20*	*-*	*419.00*	*-*
12.C.13			*WIPES (HOUSEKEEPING)*	*1*	*198.88*	*198.88*	*3.00%*	*5.97*	*-*	*204.85*	*-*
12.C.14			*FIRST AID KIT*	*2*	*9.10*	*18.20*	*20.00%*	*3.64*	*-*	*21.84*	*-*
12.C.15			*CONVENIENCE MEDICATION PACK*	*1*	*2.81*	*2.81*	*20.00%*	*0.56*	*-*	*3.37*	*-*
12.C.16			*EMERGENCY MEDICAL TREATMENT PACK*	*1*	*2.81*	*2.81*	*20.00%*	*0.56*	*-*	*3.37*	*-*
12.C.17			*IV SUPPLY PACK*	*1*	*6.17*	*6.17*	*20.00%*	*1.23*	*-*	*7.40*	*-*
12.C.18			*MEDICAL DIAGNOSTIC PACK*	*1*	*4.04*	*4.04*	*20.00%*	*0.81*	*-*	*4.85*	*-*
12.C.19			*MEDICAL SUPPLY PACK*	*1*	*2.92*	*2.92*	*20.00%*	*0.58*	*-*	*3.50*	*-*
12.C.20			*MINOR TREATMENT PACK*	*1*	*3.88*	*3.88*	*20.00%*	*0.78*	*-*	*4.66*	*-*
12.C.21			*ORAL MEDICATION PACK*	*1*	*2.67*	*2.67*	*20.00%*	*0.53*	*-*	*3.20*	*-*
12.C.22			*PHYSICIAN EQUIPMENT PACK*	*1*	*2.54*	*2.54*	*20.00%*	*0.51*	*-*	*3.05*	*-*

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
12.C.23			*TOPICAL & INJECTABLE PACK*	*1*	*3.37*	*3.37*	*20.00%*	*0.67*	-	*4.04*	-
12.C.24			*CLOTHING (LAUNDRY)*	*1*	*609.12*	*609.12*	*3.00%*	*18.27*	-	*627.39*	-
12.D.0		***CREW/HAB SPT SYS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
12.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
13.0.0	**EXTRAVEHICULAR ACTIVITY (EVA) SUPPORT SYSTEMS**			**14**	-	**968.30**	**17.16%**	**166.16**	**1,134.46**	**222.73**	**1,357.19**
13.1.0		**EVA EQUIP AND SERVICE INTERFACES**		**9**	-	**196.00**	**11.29%**	**22.12**	**218.12**	-	-
13.1.1			EVA PATH LIGHTING	8	1.00	8.00	18.00%	1.44	9.44	-	-
13.1.2			PERMANENT HARDWARE (DON/DOFF STAND, UMBILICALS, UMBILICAL INTERFACE PANEL, POWER SUPPLY, BATTERY CHARGER, FPR, VACUUM PORT, ETC.)	1	188.00	188.00	11.00%	20.68	208.68	-	-
13.2.0		**INTERNAL AIRLOCK EQUIPMENT**		**5**	-	**772.30**	**18.65%**	**144.04**	**916.34**	-	-
13.2.1			AIRLOCK STRUCTURE	1	420.00	420.00	18.00%	75.60	495.60	-	-
13.2.2			AIRLOCK CO2 REMOVAL	1	181.30	181.30	20.00%	36.26	217.56	-	-
13.2.3			DEPRESSURIZATION PUMP & SUPPORT	1	98.00	98.00	18.00%	17.64	115.64	-	-
13.2.4			AIRLOCK RECYCLE PUMP	1	70.00	70.00	20.00%	14.00	84.00	-	-
13.2.5			AUDIO SYSTEM (AIRLOCK)	1	3.00	3.00	18.00%	0.54	3.54	-	-
13.3.0		**EVA SYSTEMS FIXED STORAGE SPACE**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
13.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
13.9.0		**EVA SPT SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
13.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
13.A.0		***EVA SUITS, TOOLS & PACKAGING***		***3***	-	***92.37***	***11.00%***	***10.16***	-	***102.53***	-
13.A.1			*PLSS - PORTABLE LIFE SUPPORT SYSTEM*	*0*	*355.00*	*0.00*	*11.00%*	*0.00*	-	*0.00*	-
13.A.2			*EVA SUIT*	*0*	*540.00*	*0.00*	*11.00%*	*0.00*	-	*0.00*	-
13.A.3			*M-EMU (MARS SURFACE SUITS)*	*0*	*190.00*	*0.00*	*11.00%*	*0.00*	-	*0.00*	-
13.A.4			*EVA TOOLS AND EQUIPMENT*	*1*	*69.37*	*69.37*	*11.00%*	*7.63*	-	*77.00*	-
13.A.5			*LARGE HABITAT COMMUNICATION (ARCM COMM. KITS) (STOWABLE OR PERMANENT??)*	*2*	*11.50*	*23.00*	*11.00%*	*2.53*	-	*25.53*	-
13.B.0		***SPARE EVA SPT SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
13.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
13.C.0		***EVA SPT SYS CONSUMABLES & PACKAGING***		***2***	-	***116.70***	***3.00%***	***3.50***	-	***120.20***	-
13.C.1			*O2 (AIRLOCK REPRESS?)*	*1*	*98.40*	*98.40*	*3.00%*	*2.95*	-	*101.35*	-
13.C.2			*N2 (AIRLOCK REPRESS?)*	*1*	*18.30*	*18.30*	*3.00%*	*0.55*	-	*18.85*	-
13.D.0		***EVA SPT SYS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
13.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
14.0.0	**IN-SITU RESOURCE ACQUISITION & CONSUMABLES PRODUCTION SYSTEMS**			**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
14.1.0		**RAW MATERIAL EXTRACTION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
14.1.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
14.2.0		**PROPELLANTS, FLUIDS/GASES PROCESSING & HANDLING EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
14.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
14.3.0		**MATERIAL PROCESSING & HANDLING EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
14.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
14.9.0		**RESOURCE ACQ & CONSUM PROD SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
14.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
14.A.0		***RESOURCE ACQ & CONSUM PROD MISSION-KITTED OR STOWED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
14.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
14.B.0		***SPARE RESOURCE ACQ & CONSUM PROD SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
14.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
14.C.0		***RESOURCE ACQ & CONSUM PROD SUPPLY STOCKS & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
14.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)	COMMON EQUIPMENT GROUP (TIER 2)	UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
14.D.0		***RESOURCE ACQ & CONSUM PROD SUPPLY RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
14.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
15.0.0	**IN-SPACE MANUFACTURING & ASSEMBLY SYSTEMS**			**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
15.1.0		**COMPONENT FABRICATION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
15.1.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
15.2.0		**MANUAL/ROBOTIC ASSEMBLY & FINISHING EQUIPMENT**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
15.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
15.3.0		**FIXED MANUF & ASSEMBLY STORAGE SPACE**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
15.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
15.4.0		**MANUF & ASSY STORAGE EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
15.4.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
15.9.0		**MANUF & ASSY SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
15.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
15.A.0		***MANUF & ASSY MISSION-KITTED OR STOWABLE ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
15.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
15.B.0		***SPARE MANUF & ASSY SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
15.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
15.C.0		***MANUF & ASSY SYS CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
15.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
15.D.0		***MANUF & ASSY SYS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
15.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
16.0.0	**MAINTENANCE & REPAIR SYSTEMS**			**24**	-	**316.00**	**24.42%**	**77.18**	**393.18**	**2,287.93**	**2,681.11**
16.1.0		**ROBOTIC & HANDLING EQUIP**		**24**	-	**316.00**	**24.42%**	**77.18**	**393.18**	-	-
16.1.1			HUMANOID ROBOT	2	125.00	250.00	25.00%	62.50	312.50	-	-
16.1.2			HUMANOID ROBOT STORAGE AND CHARGING STATION	2	20.00	40.00	25.00%	10.00	50.00	-	-
16.1.3			EXTERIOR ROBOTICS AREA LIGHTING	8	1.00	8.00	18.00%	1.44	9.44	-	-
16.1.4			EXTERIOR SURVEILLANCE LIGHTING	12	1.50	18.00	18.00%	3.24	21.24	-	-
16.2.0		**REPAIR AND CALIBRATION EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
16.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
16.3.0		**MAINTENANCE & REPAIR SYSTEMS STORAGE EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
16.3.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
16.9.0		**MAINTENANCE AND REPAIR SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
16.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
16.A.0		***MAINT & REPAIR MISSION-KITTED OR STOWABLE ITEMS***		***17***	-	***2,130.19***	***6.67%***	***142.15***	-	***2,272.33***	-
16.A.1			*MAINTENANCE EQUIPMENT (IVA)*	*1*	*1,840.40*	*1,840.40*	*3.00%*	*55.21*	-	*1,895.61*	-
16.A.2			*ELCTR/MECHANICAL TOOL SET*	*1*	*1.00*	*1.00*	*30.00%*	*0.30*	-	*1.30*	-
16.A.3			*HATCH UNJAMMING TOOL SET*	*1*	*5.00*	*5.00*	*30.00%*	*1.50*	-	*6.50*	-
16.A.4			*SOLDERING KIT*	*1*	*6.80*	*6.80*	*30.00%*	*2.04*	-	*8.84*	-
16.A.5			*DRILLING KIT*	*1*	*39.80*	*39.80*	*30.00%*	*11.94*	-	*51.74*	-
16.A.6			*METAL CUTTING AND BENDING KIT*	*1*	*62.20*	*62.20*	*30.00%*	*18.66*	-	*80.86*	-
16.A.7			*METALLURGICAL ANALYSIS KIT*	*1*	*10.26*	*10.26*	*30.00%*	*3.08*	-	*13.33*	-
16.A.8			*SURFACE BONDING KIT*	*1*	*23.50*	*23.50*	*30.00%*	*7.05*	-	*30.55*	-
16.A.9			*ELECTRONICS ANALYSIS AND REPAIR KIT*	*1*	*6.80*	*6.80*	*30.00%*	*2.04*	-	*8.84*	-
16.A.10			*COMPUTER INSPECTION, TESTING, AND REPAIR KIT*	*1*	*5.00*	*5.00*	*30.00%*	*1.50*	-	*6.50*	-
16.A.11			*CAD AND SOFTWARE WORKSTATION*	*1*	*0.00*	*0.00*	*30.00%*	*0.00*	-	*0.00*	-
16.A.12			*MATERIAL HANDLING KIT*	*1*	*20.20*	*20.20*	*30.00%*	*6.06*	-	*26.26*	-
16.A.13			*PRECISION MAINTENANCE KIT*	*1*	*1.36*	*1.36*	*30.00%*	*0.41*	-	*1.77*	-
16.A.14			*3D PRINTING KIT*	*1*	*16.50*	*16.50*	*30.00%*	*4.95*	-	*21.45*	-
16.A.15			*SOFT GOODS KIT*	*1*	*26.47*	*26.47*	*30.00%*	*7.94*	-	*34.41*	-
16.A.16			*THERMOPLASTICS KIT*	*1*	*50.00*	*50.00*	*30.00%*	*15.00*	-	*65.00*	-
16.A.17			*DUST MITIGATION KIT*	*1*	*14.90*	*14.90*	*30.00%*	*4.47*	-	*19.37*	-

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)										
		COMMON EQUIPMENT GROUP (TIER 2)									
			UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
16.B.0		***SPARE MAINT & REPAIR SYS EQUIP & PACKAGING***		***1***	-	***12.00***	***30.00%***	***3.60***	-	***15.60***	-
16.B.1			*SPARES*	*1*	*12.00*	*12.00*	*30.00%*	*3.60*	-	*15.60*	-
16.C.0		***MAINT & REPAIR SYS CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
16.C.1			*RAW MATERIALS*	*0*	*0.00*	*0.00*	*30.00%*	*0.00*	-	*0.00*	-
16.D.0		***MAINT & REPAIR SYS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
16.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
17.0.0	**PAYLOAD PROVISIONS**			**5**	-	**2,523.50**	**28.81%**	**727.05**	**3,250.55**	**0.00**	**3,250.55**
17.1.0		**PAYLOAD SUPPORT EQUIP**		**3**	-	**1,231.00**	**30.00%**	**369.30**	**1,600.30**	-	-
17.1.1			MULTIPURPOSE WORKSTATION WITH PAYLOADS/INSTRUMENTATION	1	706.50	706.50	30.00%	211.95	918.45	-	-
17.1.2			GLOVEBOX	1	441.50	441.50	30.00%	132.45	573.95	-	-
17.1.3			EXTERNAL PAYLOADS AVIONICS	1	83.00	83.00	30.00%	24.90	107.90	-	-
17.2.0		**PAYLOAD COMAND & DATA NETWORK EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
17.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
17.3.0		**PAYLOAD MANIPULATION EQUIP**		**1**	-	**600.00**	**25.00%**	**150.00**	**750.00**	-	-
17.3.1			EXTERNAL ROBOTICS (FOR EXTERNAL PAYLOAD MANIPULATION)	1	600.00	600.00	25.00%	150.00	750.00	-	-
17.4.0		**PAYLOAD STORAGE EQUIP**		**1**	-	**692.50**	**30.00%**	**207.75**	**900.25**	-	-
17.4.1			COLD STOWAGE	1	692.50	692.50	30.00%	207.75	900.25	-	-
17.9.0		**PAYLOAD PROVISIONS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
17.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
17.A.0		***PAYLOAD MISSION KITS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
17.A.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
17.B.0		***SPARE PAYLOAD PROVISIONS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
17.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
17.C.0		***PAYLOAD PROVISIONS CONSUMABLES & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
17.C.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
17.D.0		***PAYLOAD PROVISIONS RESIDUALS***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
17.D.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
18.0.0	**ABORT & DESTRUCT SYSTEMS**			**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
18.1.0		**ABORT & DESTRUCT ELECTRONICS EQUIP**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
18.1.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
18.2.0		**DESTRUCT ORDNANCE**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
18.2.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
18.9.0		**ABORT & DESTRUCT SYS INSTALLATION**		**0**	-	**0.00**	**0.00**	**0.00**	**0.00**	-	-
18.9.1			[ENTER COMPONENT/SUBASSY]	0	0.00	0.00	0.00%	0.00	0.00	-	-
18.B.0		***SPARE ABORT & DESTRUCT SYS EQUIP & PACKAGING***		***0***	-	***0.00***	***0.00***	***0.00***	-	***0.00***	-
18.B.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	*0.00*	-
	MANUFACTURER'S EMPTY MASS			**836**	-	**17,364.73**	**20.81%**	**3,613.10**	**20,977.83**	-	-
	OPERATIONAL ITEMS										
		OPERATIONAL ITEMS - MISSION KITTED OR STOWED		***48***	-	***3,125.89***	***8.54%***	***266.88***	-	***3,392.77***	-
			[TIER 3 ITEMS FOUND IN SBS 1.0 THROUGH 19.0]	***48***	-	***3,125.89***	***8.54%***	***266.88***	-	***3,392.77***	-
		OPERATIONAL ITEMS - EQUIPMENT SPARES		***4***	-	***4,569.20***	***3.07%***	***140.32***	-	***4,709.52***	-
			[TIER 3 ITEMS FOUND IN SBS 1.0 THROUGH 19.0]	***1***	-	***12***	***30.00%***	***3.60***	-	***15.60***	-
			HABITAT SPARES (IVA)	***1***	***3,723.10***	***3,723.10***	***3.00%***	***111.69***		***3,834.79***	
			HABITAT SPARES (EVA)	***1***	***642.00***	***642.00***	***3.00%***	***19.26***		***661.26***	
			CTBS (SPARES AND MAINTENANCE)	***1***	***192.10***	***192.10***	***3.00%***	***5.76***		***197.76***	

SBS ID	COMMON FUNCTIONAL CATEGORY (TIER 1)			Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Manuf Empty Mass (kg)	Predicted Total Operational Items Mass (kg)	Predicted Total Tier 1 Category Mass (kg)
		COMMON EQUIPMENT GROUP (TIER 2)									
			UNIQUE COMPONENT/SUB-ASSEMBLY (TIER 3)								
		OPERATIONAL ITEMS - CONSUMABLES		*31*	-	*13,850.10*	*3.60%*	*498.77*	-	*14,348.88*	
			[TIER 3 ITEMS FOUND IN SBS 1.0 THROUGH 19.0]	*30*	-	*13,128.00*	*3.63%*	*477.11*	-	*13,605.11*	-
			CTBS (CONSUMABLES)	*1*	*722.10*	*722.10*	*3.00%*	*21.66*		*743.76*	
		OPERATIONAL ITEMS - RESIDUALS									
			[TIER 3 ITEMS FOUND IN SBS 1.0 THROUGH 19.0]	*0*	-	*0.00*	*0.00*	*0.00*	-	*0.00*	-
		OPERATIONAL ITEMS - CREW									
			[ACCOUNTED AT VEHICLE LEVEL]	-	-	-	-	-	-	-	-
	OPERATIONAL ITEMS			919	-	38,909.93	11.61%	4,519.06	-	**22451.17**	
19.0.0	**PAYLOADS & RESEARCH**			**2**	-	**1,556.50**	**30.00%**	**466.95**	-	-	**2,023.45**
19.1.0		***CARGO***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.1.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
19.2.0		***SCIENTIFIC RESEARCH EXPERIMENTS***		***2***	-	***1,556.50***	***30.00%***	***466.95***	-	-	***2,023.45***
19.2.1			*EXTERNAL PAYLOAD PLATFORM WITH PAYLOADS*	*1*	*370.00*	*370.00*	*30.00%*	*111.00*	-	-	*481.00*
19.2.2			*NOTIONAL HUMAN RESEARCH PROGRAM (HRP) PAYLOADS*	*1*	*1,186.50*	*1,186.50*	*30.00%*	*355.95*	-	-	*1,542.45*
19.3.0		***TECHNOLOGY R&D EXPERIMENTS***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.3.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
19.4.0		***ENGINEERING R&D EXPERIMENTS***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.4.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
19.5.0		***EDUCATION & PUBLIC OUTREACH EXPERIMENTS***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.5.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
19.6.0		***PASSENGERS & CARRIED ITEMS***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.6.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
19.7.0		***STANDARD CONTAINERS & CARRIERS***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.7.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
19.8.0		***CUSTOM CONTAINERS & CARRIERS***		***0***	-	***0.00***	***0.00***	***0.00***	-	-	***0.00***
19.8.1			*[ENTER COMPONENT/SUBASSY]*	*0*	*0.00*	*0.00*	*0.00%*	*0.00*	-	-	*0.00*
	PROPULSION & REACTION CONTROL EXPENDABLES			**0**	-	**0.00**	**0.00**	**0.00**	-	-	**0.00**
	GROSS ITEM CONTRIBUTIONS			**0**	-	**1,556.50**	**30.00%**	**466.95**	-	-	**2,023.45**
GROSS MASS				**919**	-	**40,466.43**	**12.32%**	**4,986.01**	**20,977.83**	**22451.17**	**45,452**


TU Delft