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PERMANENT CREWED MARS BASE BY 2030 - OUTCOMES OF AN INTERDISCIPLINARY, MULTINATIONAL STUDENT WORKSHOP

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Indisputably, we live at the dawn of a novel space exploration era, with the space sector undergoing significant changes. The International Space Station (ISS) is nearing the end of its lifespan and a competitive space industry is emerging. It is characterised by an ongoing redistribution of responsibilities between government agencies and private enterprise, with all stakeholders setting ambitious goals for future missions. Recently, interest in the next crewed space exploration mission has grown continuously. Driven by these developments, the Space Station Design Workshop (SSDW) 2017 in Stuttgart, Germany, posed the challenge to conduct the preliminary analysis and develop a viable proposal for the establishment of a permanent crewed space station in the vicinity of Mars by the year 2030. Two multinational, interdisciplinary teams of twenty students each were given one week to develop their own solutions and present them to experts from industry and academia. The authors, Team Blue, have outlined a design for a Mars surface station, called HUMANS2MARS. This proposal requires the development of mission-specific modules, while the launchers to be used include the foreseen state-of-the-art at the late 2020s, such as the Space Launch System from NASA and Falcon Heavy from SpaceX. Designing such a mission from scratch in one week posed great challenges, either innate in the technical and programmatic difficulties of the mission, or resulting from the time constraints and group dynamics of the project. The main technical challenges can be grouped into two sets. The first includes those related to mass and payload limitations of the mission and launching costs. The second consists of those related to the human element of the mission. Due to the hostile Martian environment, like the extreme radiation levels during transit and unexplored psychological pressure on the crew, the complexities associated with humans introduce significant uncertainties. Potential solutions to the problems discovered have been proposed and are presented in this paper - within the framework of a multicultural and interdisciplinary workshop. The major risks of the proposed mission are identified and possible mitigation strategies and backup scenarios are discussed, thus providing a starting point for future research and detailed studies. The complexity of the mission and nature of the SSDW require addressing a great variety of challenges under severe time constraints. A crucial factor in the success of this effort has been the multidisciplinary and diverse academic background of the participants. This enabled the team to overcome these numerous obstacles in often unconventional ways.

Keywords: Space station, Mars exploration, Student workshop, Conceptual design, Feasibility study

1. Introduction

The authors' intention for writing this paper is to describe the outcomes of Team Blue's efforts during the week-long Space Station Design Workshop 2017. The objective of this paper is not only to inform the reader about the proposed technical solution for a permanently crewed Mars base, but also to describe the associated technical, financial, and operational challenges. The proposed concept should not be understood as the optimal final design, but rather as a source to draw ideas from.

The Space Station Design Workshop is an annual international and interdisciplinary workshop conceived by the Institute of Space Systems (IRS) at the University of Stuttgart, Germany. In order to reflect the dynamic and diverse nature of space exploration missions, 40 participants from various backgrounds are selected. They are carefully chosen between undergraduate and graduate students, as well as young professionals to cover a broad range of backgrounds, far exceeding the traditional aerospace engineering fields. The workshop provides a basis for the students to investigate in depth the challenges of future space exploration missions and facilitates international and multidisciplinary collaboration. The 40 participants are divided into two teams: Team Red and Team Blue. Within this setting, each student is able to contribute according to their expertise, enabling the team to tackle problems in an innovative way. During the workshop, the focus is therefore not only on technical, but also on various soft skills such as team work, team management, and resolving conflicting opinions.

The mission statement was presented at the beginning of the workshop by a virtual customer. It changes every year to reflect the current development in global exploration road-maps. To satisfy the needs of the customer, the two teams have to come up with creative and innovative solutions in only five days. Besides lectures, the students also received direct training and supervised guidance of professionals from academia and industry such as the European Space Agency (ESA), the Institute of Space Systems (IRS), Airbus GmbH, the German Aerospace Center (DLR), Astos Solutions GmbH, ABK Stuttgart, Politecnico di Milano, PRICE Systems, and Sensitec GmbH.

For the 2017 edition, the focus was on the design of the first permanently crewed settlement in the vicinity of Mars in a concurrent engineering environment. Not only is the establishment of the first crewed station in the vicinity of Mars a major engineering achievement paving the way for future deep-space missions, but it also is of high scientific interest. Going to Mars provides a brilliant opportunity for humans to obtain knowledge, test technology, mitigate political and economical conflicts, break the barriers between nations and countries, and provide the ground for productive cooperation. Furthermore, it provides the means to evaluate scenarios for post-Earth humankind. Mars has been a place where life is thought to have been present in the past, offering a great possibility to study its evolution, as well as its possible continuation.

In this context, the concept designed by our team, Team Blue, features a crewed space station directly on the Martian surface that provides the opportunity to expand human and robotic presence on the Red Planet. Moreover, it allows for extended exploration and scientific research opportunities on the Martian surface as well as in orbit.

The proposed concept focuses on three main objectives:

First, it allows for extensive human and robotic exploration beyond the current frontiers, enabling new insights into the Martian system.

Second, it allows for further research investigations on the formation and evolution of our Solar System, not only to better understand the world we live in, but also to help us foreseeing future changes on Earth itself.

Third, it allows to study the origin and history of life, adding new pieces of information about the heritage of human mankind to the existing puzzle.

In the remainder of the paper, we first give a literature review (section 2), describe the high-level mission architecture (section 3), provide a description of each subsystem (section 4), show contingency scenarios for our design (section 5), unresolved challenges and future work (section 6), and end with a conclusion (section 7).

2. Literature review and history of space exploration

While lunar missions and the accomplishments of the United States (US) in the 1960s are widely celebrated, it is often forgotten that Mars mission started at the same period - 1960s-70s. As stated by E. Howell in her summary of all Mars Missions to this day [1], they never had the same success ratio that lunar missions had. This illustrates the huge increase in complexity when trying to adapt a lunar mission into a Martian mission. The first recorded attempt was made in 1960 by the Union of Soviet Socialist Republics (USSR), while the first successful mission was US Marina 4 in 1965. During the 1970s-80s, increasing image resolution of Martian photographs raised scientists interest, leading to attempted landings on Mars, which were unsuccessful. The 1990s missions to Mars have been managed and performed with an increasing level of success. Those missions have mainly involved rovers and orbiters to explore the surface, atmosphere, and underground of Mars and its two moons, Phobos and Deimos [1].

In its strategy for future decades, the US National Aeronautics and Space Administration (NASA), mentioned its continuous interest to discover and explore Mars [2]. While changes in the US political scene sometimes affect the agencys direction, Mars has never been removed from its goals.

In 2018, the focus on the red planet has not faded and Mars is not only targeted by space agencies but also by new actors from the private sector. Indeed, Mars has also raised commercial interest from companies like the Space Exploration Technologies Corporation (SpaceX). Mars has been the companys very first objective since it was founded in 2002. In order to make it possible, SpaceX had to focus on the development of launchers with enhanced capabilities. Indeed, they have developed the Falcon Heavy and in 2017 they presented the plans for the massive Big Falcon Rocket (BFR); the only launcher that is supposed to be able to carry up to 150 metric tons to the surface of Mars [3].

Lately, there has been an increased focus on the Moon as a testbed and a gateway towards Mars missions, a shift also related with the recent change in NASA administration [4]. However, Mars still remains one of the first objectives of the agency. Mars 2020 is the next rover mission by NASA and will be very similar to the Mars Science Laboratory (MSL) rover which is still active on Mars [5],[6]. Mars 2020 will search for signs of past life while exploring a site likely to have been habitable [4].

In 2016, the European Space Agency (ESA) stated its ambition to create a Moon Village which would be the result of an international collaboration between different public agencies and private aerospace actors [7].

However, multiple missions or instruments are included in ESAs roadmap such as the seismic instrument on INSIGHT launched in May 2018 and the upcoming ExoMars 2020 mission. INSIGHT is a robotic lander designed and built by NASA whose main goal is to study the interior of Mars [8]. Like Mars 2020, ExoMars will also seek traces of life in the form of biomolecules or biosignatures.

Despite the complexity and the challenges of Martian missions, other space agencies are trying to reach Mars too. The China National Space Administration (CNSA) has planned a project called Mars Global Remote Sensing Orbiter, Lander and Small Rover which intends to deploy an orbiter, a lander, and a rover on Mars by 2021 [9]. In 2018, the Chinese space agency made a public announcement to inform the public of the status of this project [10].

The Japan Aerospace Exploration Agency (JAXA) has two missions in preparation: the Mars Terahertz Microsatellite [11] and the Martian Moons Exploration [12].

Those two spacecraft both contain instruments from other space agencies. India plans to launch Mars Orbiter Mission 2 (MOM 2) after the success of MOM 1 and developed a collaboration to build a lander with the French Space Agency, Centre National dEtudes Spatiales (CNES) [13].

Lately, there have been initiatives from the private sector to work on Mars missions like from Blue Origin, a rocket company which intends to send humans initially back to the Moon before Mars, and Mars City Design, a company which intends to explore the questions of how to best live and love on Mars? more than just focusing on getting there [14].

Very recently, in July 2018, the discovery of liquid underground water on Mars is even more encouraging for the future of Mars missions. This will generate interest for more crewed Mars missions which could benefit from this on-site water [15].

Over the years several mission architectures have been developed. Two different types will be explained briefly: A Mars Sample Return (MSR) mission and a permanently crewed habitat (colonisation).

Recently, ESA and NASA signed a statement of intent to collaborate on a mission that will bring back samples from Mars. This will give us the opportunity to analyse the samples in much greater detail, verify the results independently, and re-analyse the samples if needed. The proposed mission would consist of three smaller missions. First, NASAs 2020 Mars Rover will collect up to 31 small surface samples, put them in containers, and prepare them for a later pickup. NASAs rover will be joined by ESAs ExoMars rover in 2021, which will drill up to two meters deep into the Martian soil to search for evidence of life. A second mission will provide a small rover that is capable of landing nearby and retrieving the prepared samples. It then brings the containers to a Mars Ascent Vehicle (MAV) that launches the samples into Mars orbit. The third and last mission will send a spacecraft to Mars orbit which will rendezvous with the samples and is able to bring them back to Earth safely. [16]

In 2016, Elon Musk unveiled plans for Mars colonisation. His plan involves a reusable rocket, which will launch a spacecraft carrying up to 100 people into orbit. The rocket booster will then return to a pinpoint launch pad for an upright landing. The rocket will launch again carrying a fresh load of fuel to top up the transport ships tanks. Once the tanks are filled, the cargo has been transferred, and the Mars rendezvous timing is right, the colonists will depart for Mars. SpaceX proposes the first launch for 2022 and is planning on flying to Mars in 2024, with two crewed vehicles. By that stage, Musk plans to be able to build a base on the Martian surface in order to synthesise fuel for return journeys back from Mars [18][19][20][21].

While most of those proposed concepts focus on shorter mission durations, our objective was to design a permanent crewed Mars base during the workshop. This came with additional challenges that we had to overcome. Furthermore, the before-mentioned concepts are proposed by large organisations with significant resources, whereas our concept was developed during one week by 20 students. In the following section we describe the high-level mission architecture of our concept before we go into the description of each subsystem.

3. Mission Architecture

3.1 *Landing site selection*

As the first task during the workshop, a landing site for our permanently crewed Martian base had to be selected. The Figures of Merit (FoM) for the landing site selection have been the accessibility for autonomous vehicles, the difficulty of an accurate landing, the scientific significance based on results from past missions, and the possibility of traces of life of any form.

The location selected for the station is the Gale Crater, located at 5.4°S and 137.8°E on the Martian surface. It has a diameter of roughly 154 km and ranges between -1 km and +4.5 km in altitude, including a massive mountain peak in the center of the crater. A variety of other possible locations have been examined during the preliminary considerations, including polar craters and other interesting areas, such as Utopia Planitia. Gale crater has been the landing site for the Curiosity rover in 2012, providing extremely interesting soil analysis results, which indicate the existence of vast amounts of water in the past. An additional factor leading to this selection has been the radiation protection provided by the craters high edges.

3.2 *Mission architecture*

A mission to establish a permanently crewed habitat at the Gale Crater inevitably consists of multiple stages. Our mission architecture consists of two parts: a robotic cargo operation followed by a crewed mission. The first stage is required to set up the station, which can only start after all necessary parts are in place and ready for assembly. The outline of the mission is depicted in Fig. 1.

The first step is the launch of an orbiter, two inflatable Martian habitats, a Mars Ascent Vehicle (MAV), and cargo into a super synchronous orbit (perigee x apogee: 300 km x 90,000 km). Those components are assembled to form a cargo ship using robotic arms, which then begins its journey to Mars (the transfer orbits are explained in section 3.3). Just before the cargo ship reaches the Sphere of Influence (SOI) of Mars, the habitats, the MAV, and the cargo are separated. They enter the atmosphere of Mars and touch down softly in the designated landing zone. The orbiter stays in a Mars Stationary Orbit (MSO; altitude above surface: h = 17,000 km; inclination i=0).

In a second step, a Deep Space Habitat (DSH) will be launched into LEO, where a manned crew module (carrying six astronauts) will dock to the DSH. This assembly will then travel towards MSO. Once at MSO, it will dock to the orbiter that is already in place. The six astronauts will now begin the assembly of the ground station using telerobotics.

Once the ground station is operational, the astronauts enter the MAV and descent to the Martian surface. Orbiter, DSH, and the crew module stay in orbit. After a stay of about 500 days, also referred to as a conjunction type mission, three astronauts enter the MAV, launch to MSO, and dock to the orbiting structure (orbiter, DSH, crew module). Then, the astronauts move to the DSH and begin their flight back to Earth, with the orbiter and the MAV staying in MSO. Once they arrive in LEO, the crew capsule separates and returns to Earth. The reusable DSH stays in LEO where it is maintained and refueled. Now a new crew consisting of three astronauts is launched into LEO and docks with the DSH. The assembly of DSH and crew capsule then travels to MSO, where it docks to the orbiter/MAV assembly and the crew moves into the MAV and descents to the Martian surface. The DSH, the orbiter, and the new crew capsule stay in orbit. From here on this cycle is maintained over the whole mission duration.

3.3 *Transfer orbits*

Cargo. To establish a Martian base, a rather complex cargo mission is required. This mission will provide all needed infrastructure and cargo for assembly of the Martian base. The cargo transporter will be powered with an electrical propulsion system consisting of five engines producing a total thrust of 22.5 N. First, this cargo ship is assembled (multiple cargo transporters) in a super-synchronous orbit (perigee x apogee: 300 x 90,000 km), as this drastically decreases the transfer time to Mars. The cargo ship will have a dry mass of approximately 600 t, requiring 150 t of propellant. Once this structure is fully assembled, the electric propulsion system will start firing in the perigee and it will take around 7.5 years to spiral to Mars, where it will insert into a MSO. The advantage of this trajectory and the electric propulsion is the minimal fuel consumption of just 20 t of propellant per year and this aspect was considered more important than the duration of flight. The next necessary step is the de-orbiting of the cargo to the Martian surface. The challenging part here is that the orbiter has to reach MSO, while the cargo transporters designated for the surface have to begin their atmospheric entry before reaching MSO. Hence, the cargo transporters will have to be separated from the orbiter and from each other just before reaching the SOI of Mars. Combined with a small impulsive burn, the de-orbit is initiated and will be explained in more detail in section 4.2,

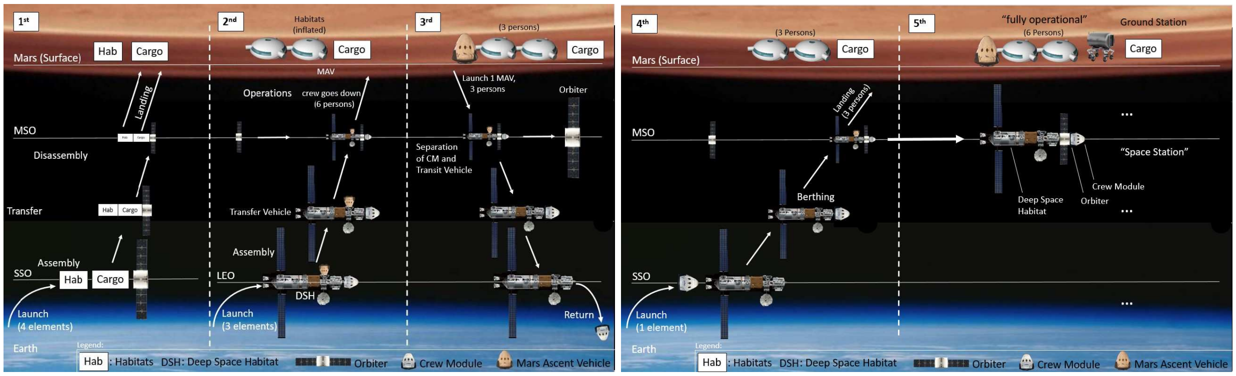

Fig. 1: Mission outline

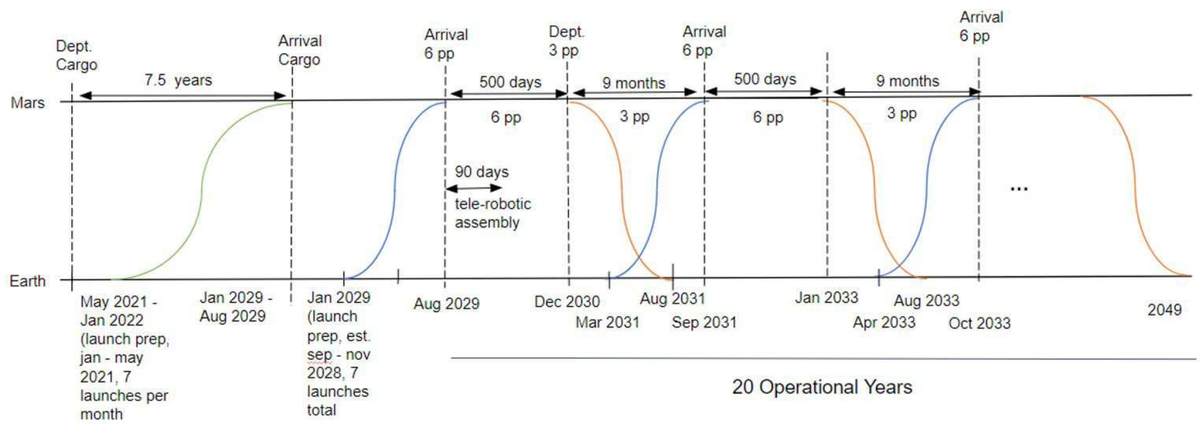

Fig. 2: Mission timeline

dealing with entry, descent, and landing (EDL).

Crewed Phase. For the mission which will take the crew from Earth to Mars, there are two main parameters that need to be considered: duration of travel, which is relevant for the radiation dose, and the delta-v required for the journey, which is relevant for the mass of propellant. Both parameters vary for different launch windows.

The basic requirement for the workshop was that the human operations must start by 2030, the duration of travel must be less than nine months, and the delta-v must be optimised in order to save propellant mass.

Considering this, the NASA trajectory browser tool [22] was used for the trajectory analysis. There were several assumptions made during the workshop to calculate the transfer orbit within the limited time frame:

- the trajectory from Mars to Earth is assumed to take the same amount of time and delta-v as from Earth to Mars,
- the duration of staying on Mars is assumed as 500 days, due to launch windows and crew rotation,
- the worst case of delta-v (5,2 km/s) and transfer duration (240 days) was assumed for subsystems design, preparing the S/C for all cases. The delta-v is the sum of the escape and insertion maneuvers from a LEO of 400 x 400 km altitude to a 17,000 x 17,000 km altitude orbit, both of them with 0 of inclination.
- suitable launch windows open up roughly every two years. The used launch windows can be seen in Fig. 2.

3.4 *MAV*

Lastly, there is the need to take the crew onto the Martian surface. For that purpose, a MAV is used. The trajectory of the MAV between MSO and the Martian surface (and return), including the delta-v budget, can be seen in Fig. 3. The descent trajectory is presented on the left and the ascent trajectory is presented on the right. It was assumed that the entry phase starts at 50 km altitude.

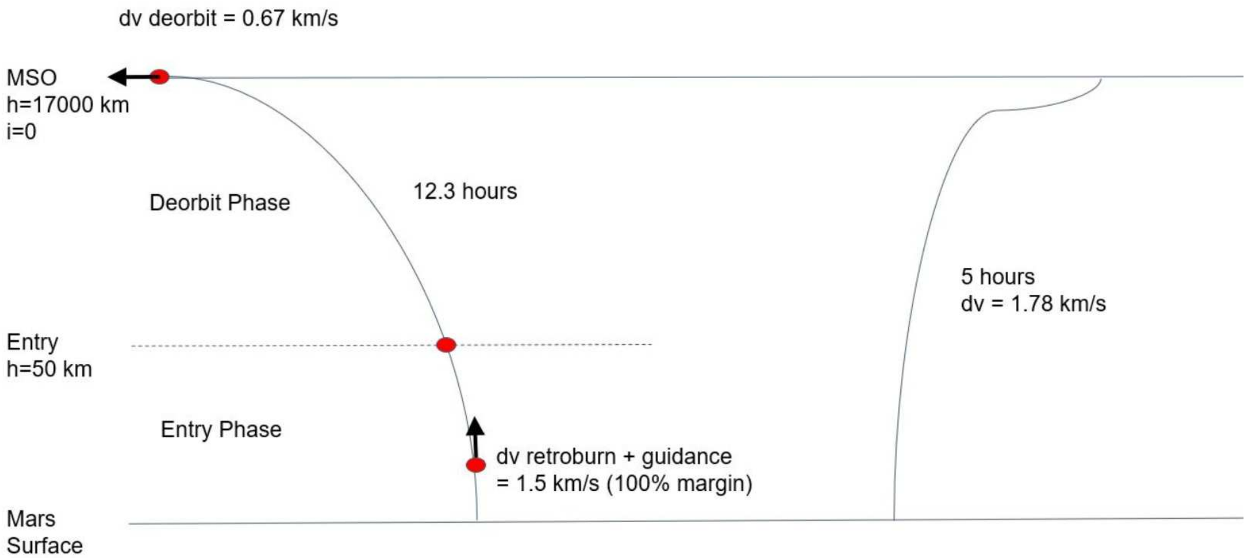

Fig. 3: MAV trajectory with delta-v budget

4. Subsystem descriptions

For a permanent crewed base on Mars, systems face multiple challenges like low temperatures, dust storms, a very thin atmosphere mainly consisting of carbon dioxide, high radiation levels, the long distance from Earth to Mars, and rough terrain. Since each system consists of several subsystems with many interfaces, at least one person worked on each subsystem during the workshop. The subsystem requirements were derived from the system requirements by the system engineer and iterated with the person responsible for the respective subsystem.

Some subsystem are highly integrated and are therefore described together in this section: (1) the Mars habitat; (2) entry, descent, and landing (EDL) & propulsion; (3) communications; (4) power & thermal; (5) robotics & extravehicular activity; and (6) environmental control and life support & human factors.

To increase efficiency and to reduce mass, risks, and costs, we aimed to make us of as many synergies as possible. The major synergy is the use of water for thermal control, radiation protection, and also human factors of the habitat. Moreover, the robotic vehicle design was made modular to enable transportation of the crew, robotic exploration, and EVA activities. Using the Martian environment is crucial for a smart mission design. Based on that, the Mars habitat is 3D-printed using Martian regolith. A further synergy is created by using hibernation which decreases the requirements for the environmental control and life support system and lowering the mental stress of the crew on the transit to Mars. Last, the communication system is designed to enable the communication between all systems during the different stages of the mission.

4.1 *Mars habitat (Inflatable structure)*

An inflatable structure is proposed as shelter for a permanent crewed settlement and environment of research. It is made of layers of Polyethylene (PE) with a foldable structural foundation. The designed unit is 12 m in diameter and 3 m in height. It has a structural volume of about 348 cubic meters and can be inflated with air. The habitat has three doors: one main door and two redundant doors for the addition of new modules. The inner part of the expandable structure is made of carbon composites.

As a protection against the Martian environment, the pressurised settlement must be resistant to environmental forces. To minimise severe damage of internal structures, the inflatable external structure is covered with 1.5 m of 3D-printed Martian regolith. The printed regolith should have a distance tolerance of 1 m to the external module skin. To reduce the risk of resonance coincidence event against an unpredicted quake, the sufficient damper interface must be applied in between the module surface and the Martian soil. The damping material should have high toughness, viscoelasticity, and self healing capability, such as polyampholyte [23].

As a cosmic radiation protection, the PE layer is filled with liquid water which is expected to be acquired in-situ on Mars. After the structure is fully filled, the pressure is gradually equalised or lowered to environmental pressure on Mars to get rigid-ice inside the structure. The ideal volume of the water required is around 86 cubic meters and a thickness of 0.5 m is required. The sodium and calcium found on Mars could help to increase the structural robustness for further planetary infrastructure [24][25][26][27].

4.2 *Entry, descent, and landing (EDL) & Propulsion*

The propulsion & transport for this Mars mission is divided into two phases. The first is the preparatory phase which consists of the transportation of the cargo capsules that will be assembled in Low Earth Orbit and will fly from LEO to MSO using a Solar Electric Propulsion (SEP) system. SpaceXs Falcon Heavy system was considered as the major means to launch cargo packages through 35 launches plus one Ariane 5 launch lifting the solar panels for the cargo transport vehicles. The second phase will be the direct transfer of the Crew and Deep Space Habitat (DSH). For the crew carrying vehicles, heavier launchers are required. Two Space Launch System (SLS) rockets will transport the DSH, the Orion Multi Purpose Crew Vehicle (MPCV), and the return propellant to LEO, while the propellant for the Earth-Mars transfer is provided by five additional Falcon Heavy launchers. The DSH will be equipped with life support systems for the 240 day transfer to Mars orbit. If SpaceXs interplanetary transport system is ready for use by 2030, it would make a significant reduction of the number of launches possible

Significant technological developments were assumed to be usable by 2030 for reentry and landing, such as the usability of inflatable heat shields and more accurate guidance during reentry. We assume that the Mars Science Laboratory reentry vehicle can be scaled up by a factor of seven using no parachute, but an inflatable ablative heat shield, and more maneuvering propellant for lowering the cargo package to the ground. This allows for the 5 t packages to re-enter and land individually. Other than the cargo packages, the MAV, which has a maximum total mass of 40 t, including 32 t of propellant, needs to be fully reusable. It must therefore use a radiative heat shield. The high ballistic coefficient of the MAV design would usually lead to the need for even more propellant, but we considered the use of retractable structures that increase the aerodynamic cross-section of the vehicle. These retractable structures can further be extended to act as landing legs on the Martian surface.

4.3 *Communication*

The communication subsystem is responsible to ensure all communications with Earth during transit and on the surface of Mars.

Three different space communication subsystems were identified: (1) Telemetry, tracking and control (TT&C), for controlling the spacecraft and orbiter, getting status and failure feedback from its subsystems, and for exact position determination; (2) a subsystem to ensure the contact between the crew and the ground; and an (3) emergency subsystem to use in case of an emergency. Additionally, the Mars orbiting module has a data downlink subsystem for scientific data.

During such a long crewed mission, transmission of high data rates are needed in order to share photos and videos. For telecommands, subsystems monitoring, and teleoperations, radio frequency communication has been selected, since only low data link is required.

Optical communication can provide high-throughput solutions while keeping the mass and dimensions feasible. This type of communication system seeks to address the limitations of radio frequency communications. However, it still faces several challenges. While radio waves can be sent out in a broad beam blanketing target areas with its signal, optical communications telescopes must be extremely precise. Interference with Earth's atmosphere also poses a challenge for optical communications, since clouds and mist can interrupt and refract the laser beam. Radio frequency systems also suffer from atmospheric attenuation due to weather but have the capability to penetrate clouds.

In general, the atmospheric absorption of Mars practically does not affect the communication link, but sandstorms may have a great impact. The static electricity from Mars dust can cause large-scale and high-intensity discharge phenomena on communication equipment and high-speed movement of sand particles is likely to cause serious damage. Therefore, communications must not be carried out under conditions of strong sand and dust storms.

4.4 *Power & Thermal*

Nuclear or solar energy can be used to produce electricity for deep space and interplanetary research, by means of on-board nuclear energy sources, radioactive isotopes, and solar panels. Despite the average solar flux in the vicinity of Mars being about 586 W/m^2, which is almost three times less than in Earth orbit, gathered experience shows that the use of photovoltaic elements proved to be the most effective and feasible way of power generation. Moreover, they are the safest and most reliable power supply system for manned missions [28][29]. Current technologies provide multi-junction solar panels with efficiencies up to 40% [30], low levels of degradation (e.g. UltraFlex Solar Array Systems), and even self-cleaning options [31]. This allows their use not only for Mars orbiters, but also for rovers and land-based habitats.

The electrical power system is supposed to provide power for all the spacecraft, rovers, and the Mars Surface Habitat (MSH). During the first transport mission to MSO, the electric propulsion system appears to be the main power consumer (515 kWe). Considering the successful experience of using solar panels for Mars mis-

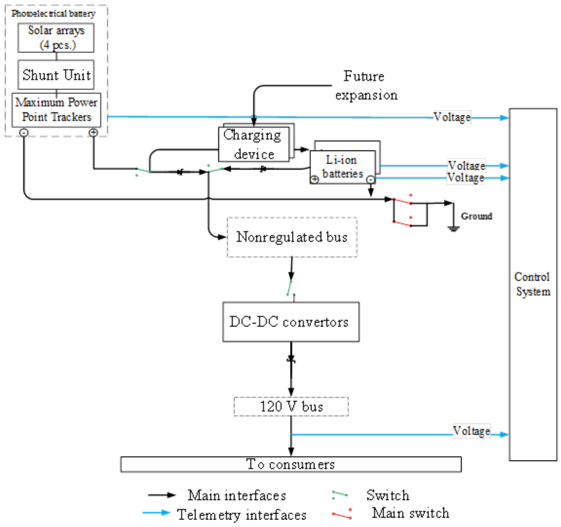

Fig. 4: Power System interaction diagram

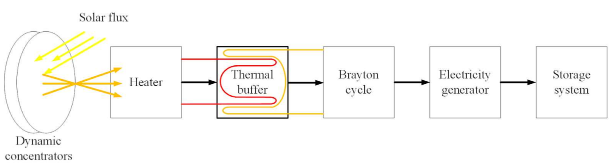

Fig. 5: Concept of the thermal power plant

sions, the present design uses roll-out solar panels onboard the Mars orbiter, which is a part of the cargo assembly. The calculated mass and area of the power generation system is about 4 t and 220 m^2 . In case of emergency or lack of solar power, there is a need for energy storage by means of buffer batteries. The most efficient, lightweight, and reliable type of electric accumulator is Li-ion chemical batteries. According to the calculations, the added mass for the most efficient VL 51ES Safts modular batteries [32] onboard the Orbiter appears to be about 4 t (depth of discharge 60%). While landing on Mars, the first step is to set up a provisional solar power station that enables rovers to recharge batteries during periods of non illumination. In this manner, the setup of the station can be performed consistently. Rovers have their own electrical power system consisting of UltraFlex solar arrays and Li-ion batteries (a similar system was used on the Phoenix rover [33]). The Power System interaction diagram is shown in Fig. 4.

On the other hand, three month long dust storms incapacitate the main source of energy for the surface base. Additionally, the enormous mass of batteries required for overcoming this period of time with no solar power, results in an unfeasible launch program. Hence, an alternative source of power with the use of Mars regolith as a

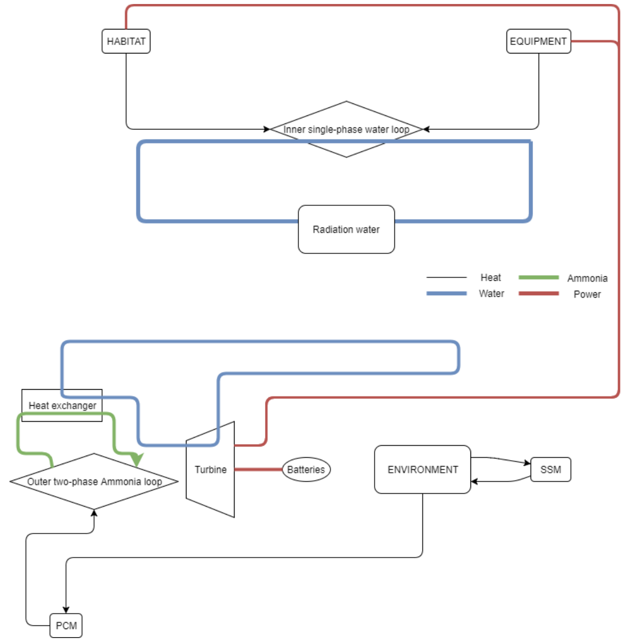

Fig. 6: Thermal control system of the surface station

heat accumulator has been considered [34].

The concept of the power plant is shown in Fig. 5. This redundant system is based on thermal to electrical energy conversion and provides a sustainable and long-term way of energy generation in the harsh Martian environment. This is a clear example of the highly synergistic subsystems (especially power, thermal, and radiation) design, due to the great complexity of manned deep-space missions, in terms of safety, technology, mass, and cost.

Likewise, the electrical power system sizes the thermal control system for both in orbit and ground stations, since its main design constraint is the rejection of the peak power (30 kW and 40 kW, respectively), in case of emergency. Additionally, the thermal control system must ensure that the temperatures of components, instruments, and habitats are within acceptable ranges [35], as well as avoiding large thermal gradients.

The architecture for the orbiting station is very similar to the one used on the ISS, employing 22 deployable heat-pipe radiators (8 m^2 and 0.11 t each) [36][37]. The spacecraft surfaces are insulated with -cloth aluminised with Al-Teflon. Ten heaters are installed for emergency cases. The heat is internally conducted by an ammonia loop [38][39][40].

The thermal control system of the surface station is schematically depicted in Fig. 6. It is worth to note the absence of radiators and heaters. This is possible due to the large mass of water needed for radiation protection, which is going to be used in an inner single-phase water loop (1

Habitat	Technology	Parameter							
In-orbit	Heat Pipe	Eff	α (BOL)	ϵ (293 K) (BOL)	Total Surface [m^2]	Non-isotherm conversion factor	Temperature range [K]	Weight [kg]	Max. Power [kW]
	Radiator	0.8-0.9	0.3	0.8	170	0.92	290-310	2380	100
	β - cloth	α (BOL)		ϵ (293 K) (BOL)	Surface [m^2]	Degradation: increasing α [%/year]		Weight [kg]	
			0.22	0.9	340.86		10		400
Ground	Second Surface	Thickness [mm]	α (BOL)	ϵ (293 K) (BOL)	Surface [m^2]	Degradation: increasing α [%/year]	Weight [kg]	Density [kg/m^3]	Shape
	Mirror "SSM"	50	0.8	0.08	192.5	2	2500	24000	Hex.
	Phase Change	Type	Density [kg/m^3]	Latent Heat Capacity [kJ/kg]	Specific Heat Capacity [kJ/kg]	Energy provided/ 135 days of storms	Phase Change Temperature [C]	Weight [kg]	
	Material "PCM"	E-50	1325	218	3.28	10	-49.8		2450

Table 1: Thermal control system characteristics

kg/s, allowing a ΔT=10 °C) to control the temperature of the habitat and the equipment. This is a second example of the mentioned subsystem synergies. On the other hand, the semi-spherical surface of the station is covered with hexagonal second surface mirrors (SSM), due to its exceptional absorbance and emissivity characteristics as well as its low degradation [41].

Apart from the thermal power plant, a phase change material unit (PCM) is installed for power production and storage. The heat rejected by the PCM is conducted by an outer two-phase ammonia circuit, which needs to be isolated from the environment. It is especially important to note that the ammonia loop is not in the habitat, because of its toxicity. Table 1 summarises these technologies and their main properties.

4.5 *Robotics and Extravehicular Activity (EVA)*

For our H2-Mars mission, there are many tasks that can be mastered by either the crew, robotic systems, or in a collaborative approach to ensure a successful permanently crewed base on Mars. Some of the main tasks for the crew and the robotic systems are: (1) Integration of the cargo spaceship and (2) of the DSH in Earth orbit; (3) transportation of the modules inside the landing ellipse to the desired base location on Mars; (4) building the needed infrastructure (especially for power production); (5) 3D-printing of the base with the use of Martian regolith; (6) inspection and repair of the surface station and infrastructure; (7) transportation of the crew on Mars; (8) human and robotic exploration on Mars including EVAs; and (9) Withstanding the harsh conditions on Mars like high radiation levels, low temperatures, temperature fluctuations, dust storms, and the uneven terrain.

For task (1) and (2), robotic arms like the Shuttle Remote Manipulator System (SRMS) on the ISS could be used, in case automatic docking is not an option. By using modules with pre-installed rail sections, an extensible rail system could be created, allowing the robotic arms to move. To reduce integration time and ensure redundancy, two robotic arms could be used. For task (3), a rover de-

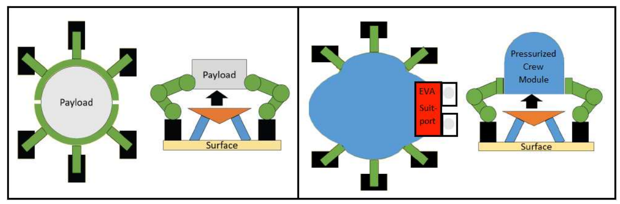

Fig. 7: ATHLETE rover with docking ability to cargo (left) and to a pressurised crew module (right)

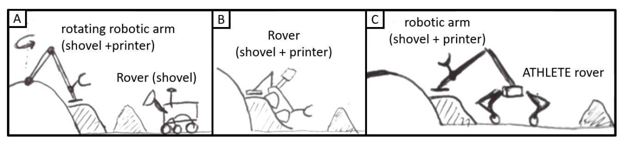

Fig. 8: 3D-printing concepts using robots: A. Robotic arm on substructure prints the regolith supplied by a rover, B. 3D-printing rovers carry regolith and print while climbing the base, C. ATHLETE rover docked to a robotic arm with printing tool and shovel

sign similar to NASA's ATHLETE rover [42] is chosen. The rover consists of two rover halves with three degrees-of-freedom (DoF) limbs each, each with a 1 DoF wheel attached. The two rover halves can traverse independently. Therefore, the rover halves can land in separate landing capsules. The rover halves can dock to cargo or to a pressurised crew module, which also fulfills challenge (7) (see Fig. 7).

As an additional function, the ATHLETE rover can be equipped with tools like shovels, drills, or gripping devices [42]. This allows the rover to place and connect systems which is helpful to fulfill challenge (4). One of the biggest challenges is building the base (5). Currently, NASA selected the top ten 3D-printed Mars habitat concepts at the 3D-printed habitat challenge [43]. For our mission we came up with several concepts shown in Fig. 8 but chose option B which is based on a 3d-printing concept for a lunar base by ESA.

This decision was made due to a trade-off between mass, cost, and complexity. However, a 3D-printing technology with proven feasibility has to be used for the final mission. The more automated this process can be done the less the robots have to be teleoperated from Mars orbit. The latency is far smaller than if teleoperated from Earth [44]. However, in our mission design the crew only stays three months in Mars orbit which is a short time to successfully construct the base. Therefore, testing the whole procedure on earth teleoperated from the ISS could help to increase efficiency and to identify risks.

Challenge (6) can either be mastered by teleoperated robots or, when the crew is on Mars, supported by an EVA. EVAs are sometimes needed since designing and certifying a robot to perform tasks beyond known requirements is extremely costly and not yet mature enough to replace humans [45]. This implies that for task (6), human presence on the Martian surface is beneficial since exploration often means facing unexpected situations. However, to allow EVAs, a system to safely enter and leave the base/vehicle is needed. For Mars, the combined airlock/suitlock/suitport meets all the performance requirements of either the airlock, the suitlock, or the suitport [46]. Possible surface suits could be the NDX-1 of the Human Spaceflight Laboratory at the University of North Dakota (UND) [47], NASA's Z-2 spacesuit [48], or the Biosuit [49]. The suit has to protect the astronaut from the harsh Martian environment but also allow the human to move freely and work efficiently.

For the exploration of Mars (8), there are the following systems and strategies: multiple exploration rovers that are either autonomous, teleoperated, or controlled on EVA in a side-to-side collaboration; helicopter drones [50] for advanced and time efficient localisation, path planning and navigation for rovers and on EVA, for inspecting the base, and also as a short interlink for communication; and payload or toolbox stations where the rovers can attach and change experimental payloads as well as tools. This enables redundancy, the ability to upgrade, variability, a service for custom experiments, and mass reduction of the rover. The general challenge (9) must be met by adequate system designs like radiation shielding, robust thermal design, redundant dust sealing, and locomotion systems that can traverse on soil and uneven terrain.

4.6 *Environmental control and life support & Human factors*

Several assumptions about technology availability were made in order to design this system around the cutting edge technologies that should be available by 2030. The first key assumption is that the Deep Space Habitat (DSH) can be hibernated upon arrival to Mars and subsequently restarted when the crew is ready to return to Earth. This will save consumables, because there will not be a crew onboard. However, it increases risk because this type of hibernation has never been proven in space. In the same vein, we also assume as the second key assumption that the Environmental Control and Life Support (ECLS) system equipment for the surface habitat can be landed on the Martian surface ahead of the crews arrival. This capability is essential for the proposed mission architecture and should be developed and feasible by the 2030s.

The ECLS system consists of four subsystems: (1) an atmospheric control system (ACS), (2) a water provision system (WPS), (3) a food provision system (FPS), and (4) a waste management system (WMS). Each subsystem was designed to be as regenerable as possible using the ELISSA software. Four ECLS system configuration candidates were chosen with varying levels of regenerability: (1) all consumable, (2) mostly consumable, (3) over half regenerable, and (4) over 75% regenerable. Each of these was programmed into ELISSA and evaluated to show the evolution of equivalent system mass (ESM) over time for a period of 700 days. Configuration 3 was ultimately chosen because of its low rate of change of ESM over time due to the incorporation of half regenerable technologies.

A key design decision for the ECLS system was to hibernate the crew during the eight month transit to Mars. This has the potential to reduce the consumable mass for this mission by 30-50% and better protect the crew from radiation and psychological stress during transit. This technology is currently at a low TRL, as it has not been tested in space.The company SpaceWorks is working under a grant from NASA to develop it and it is assumed that it will be available by the 2030s. The crew will hibernate for six months during the eight months transit, waking up for the last two months to prepare for landing.

4.6.1 *Mars Habitat*

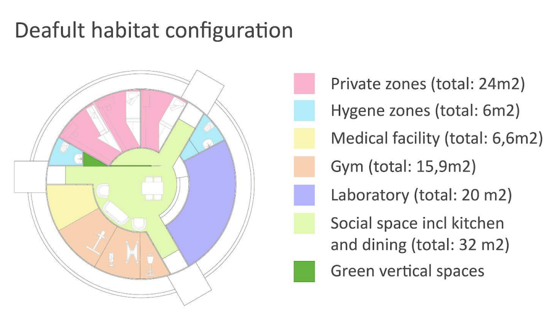

Fig. 9: Habitat default configuration for three people

One inflatable habitat unit fits three crew members, but it is designed to accommodate up to six people in case of

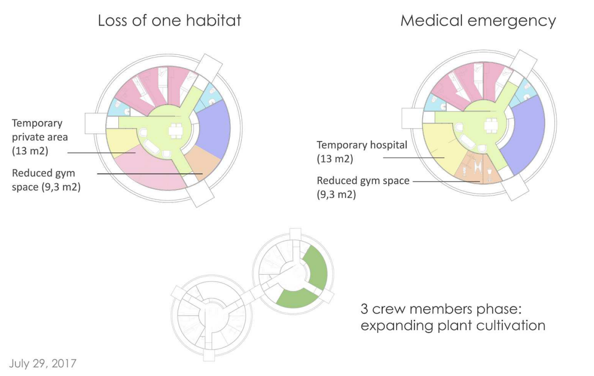

Fig. 10: Emergency Scenario 1 - Loss of one habitat. The crew of six can be accommodated inside one habitat

Fig. 11: Social space perspective view - kitchen, dining, and relaxation area in the center of the habitat, with access to natural light through a top water window. Photobioreactor visible on the left.

emergency (see Fig. 9 and Fig. 10). The walls and furniture are designed to be modular, i.e. interior walls can be easily moved, creating or cutting off spaces, according to the crews needs. The design assumes two habitats for the entire mission, which incorporate significant degrees of flexibility following the mission stages: the time of 500 days when there are six crew members on the Martian surface and the nine months period when only 3 crew members are on the planet.

Doubling crucial areas of the habitat is important for redundancy as well as physiological comfort of the crew. At the time when only three crew members are present, one of the habitats will periodically change the function to increase the green spaces and plantation area which can be used for crops and air purification.

The habitat interior promotes warm materials and home-like feeling of familiar spaces. Water was chosen as a base of the structure that enhances radiation protection of the crew and acts as a water storage (see Fig. 11 and Fig. 12). As such, water also forms part of the interior

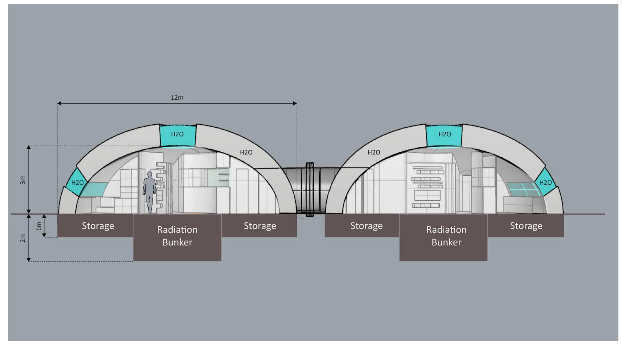

Fig. 12: Habitat module

environment, providing natural light to enter the habitat from the side water windows and from the top, which is important for the psychological comfort and well-being of the crew. Water as an interior element has calming properties and is a direct connection to familiar earth environment.

5. Contingency scenarios

Throughout the mission numerous factors could lead to a mission failure. For this reason plans for escaping from the Martian surface need to be developed and other risks need to be mitigated accordingly.

5.1 *Escape plans*

In case of a failure of one of the surface habitats, the second habitat can be modified to accommodate all crew with reduced scientific operation. It is ensured that one MAV, capable of carrying all crew to a low Mars orbit within a week after a significant failure on the ground is operational at all times. Additionally, the DSH remains in orbit during the whole mission and can be used as an escape pod. However, the usage of the DSH presents additional challenges: the re-crewing of a space station after an extended time of absence has not been demonstrated so far and needs to be addressed in the design of the DSH.

5.2 *Major risks*

If the Mars habitat cannot be assembled in the one month of teleoperation, the crew would have to stay on the DSH for an extended period of time. They would thus be consuming the DSH's supplies for a longer time. This would largely reduce error margins for an unplanned escape from the Martian surface.

In a mission to low earth orbit or to the moon, urgent problems can be solved in collaboration with ground crew on Earth. However, crew and spacecraft on a Mars mission must be much more autonomous, as communication times can be significant. Thus, the mission design requires that a temporary communication failure could be contained for longer than in LEO or on lunar missions. Nevertheless, a long-term failure of all communication systems could be critical to the mission, as long-term problems might need expertise or computational power from the Earth to be fixed properly.

The most significant risk in this mission is a crash of the MAV upon Mars descent, as this event would most likely mean a loss of all crew. While significant experience has been gained on re-entry on earth, Martian soft landings remain challenging.

Launch windows to Mars occur every two years if we consider a reasonable Δv and propellant/tank sizes. In case of a critically failed launch with supplies, the mission can be highly compromised. In a crewed mission to Mars the resulting consequence might be having an unoccupied station on Mars, as the crew would have to be moved to a later launch window.

The first cargo spacecraft launched towards Mars uses electrical propulsion. Only recently electrical propulsion systems have been used in larger satellites with highly promising results. However, the size of the proposed cargo vessel for this mission requires engines capable of very long-term operation at a relatively high level of thrust. As the proposed launch of the craft would not be long in the future, delays in the development of the engines could pose a significant threat to mission success.

Several events could lead to a mission failure during crew ground operations as well. Firstly, a failure of both habitats' pressurisation systems or a rupture of the habitats could significantly harm astronauts and put the whole mission at threat. Secondly, a long-term dust storm, as they frequently occur on Mars, could render the solar panels useless, so other means of generating power need to be found. Thirdly, a loss of the ATHLETE rovers, either through crash on descent or through any other failure mode, could compromise the mission. The rovers are a key component not only for assembling the habitat but also during regular operation, as many EVAs can be avoided by the use of the ATHLETEs. Lastly, a failure of the CO_2 removal system would compromise the safety of the astronauts severely and would necessarily require ground base evacuation.

5.3 *Mitigation strategy*

Regarding the start time of ground operations, a communication failure, a MAV crash, failure of the pressurisation system, or ATHLETE rover failure, adequate safety factors and redundancies must be used to mitigate risks. In this scope, the DSH's supplies must be larger than in an ideal estimation, numerous distinct communication and pressurisation systems will be used and more rovers than needed are transported to Mars. With redundancy on the mission level being no option for the MAV, a failure of it becomes the most significant risk to the mission and can only be mitigated by large safety factors, internal redundancies in the design of the MAV, and extensive testing prior to a crewed launch.

In case of a missed launch window, the next one could be used as a substitute. This solution would necessarily delay the whole mission planning and be costly. Furthermore, the team might need to request a launcher which is not among the ones used for the rest of the mission.

The risks due to a 3-month dust storm could be mitigated by the use of turbines powered by ISRU-generated methane, batteries, and a minimal consumption mode where science activities and EVAs are avoided as much as possible.

6. Unsolved challenges

This study provides an outline of a possible Mars mission. However, several issues that have not yet been addressed in detail remain challenging for an implementation of the mission. In this scope, future work should focus on the further development of ISRU technologies to increase settlement opportunities and significantly reduce the launch costs connected to the material transfer. Moreover, the overall safety would be improved, since the landing of heavy machinery on Mars is a risky operation due to its thin atmosphere. No previous mission exists with such a long-term radiation exposure of humans, representing one of the major concerns for a mission to the Red Planet. Even though solutions are being proposed, the problem is still unsolved and more effort should be put into the development of new and reliable technologies. A global collaboration is also fundamental to level out the mission costs, increase popularity, and drive progress.

Funding (no return of investment). A Mars mission of the proposed size will be expensive. A first rough estimate was set at 300 billion $ USD (2017 basis), which is roughly 16 times NASA's 2017 budget or about eight times the current world's spending on space [17]. Even if all space nations collaborated to make this mission possible, it would strain their economies significantly. Much of the money spent on this mission however will provide no return of investment. While some developments could provide possibilities for spin-off products that can be economically used on Earth, other technologies are very specific to space exploration and the Martian environment. Thus, finding funding for such an endeavor is a major unsolved challenge.

Cosmic galactic radiation. To this day, the effects of long term exposure to cosmic galactic radiation are uncertain. Furthermore, protective measures are likely to require large masses for shielding of the crew. On Mars, the proposed water and plastic shell of the habitat can provide some protection. However, as nor protection comparable to Earth's magnetic field neither atmosphere can be created artificially, much of the long-term effects remain uncertain to this day. In the future, these effects could be studied thoroughly.

Self-sufficiency. Generally, it is desirable to provide additional redundancy throughout every mission phase. Especially, the resilience of the ground base is critical for the overall mission success. Ideally, the ground base should be able to become fully self-sufficient in the future. This would be an important step in permanent colonisation of the Martian surface.

7. Conclusion

With this paper we summarised Team Blue's winning proposal for the SSDW 2017. The mission architecture for a permanent crewed Mars base is presented together with a more detailed description of the key subsystems and their synergies. For this mission several contingencies and mitigation strategies are discussed. We identified some unsolved challenges, often caused by non-technical aspects, that need to be overcome to make such a mission reality.

Specifically, we discovered three innovative solutions and synergies: First, the hibernation during transfer, which significantly reduces the required ECLS supplies, reduces the physical stress of the astronauts and facilitates the shielding against radiation. Second, the modular habitats on the surface of Mars provide expansion options and flexibility for contingency operations. Third, an outer layer of water does not only protect the astronauts from radiation, but also acts as storage of thermal energy.

Furthermore, the international and interdisciplinary approach of the SSDW created a great learning experience for the whole team. Not only did we acquire technical knowledge from each other and the experts, but we also further enhanced our skills to work on a highly complex challenge in a dynamic team. Based on the high success of this workshop, we believe that the challenge of a crewed Mars mission can only be solved with a worldwide connected community of interdisciplinary teams and researches.

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