MARS OPERATIONS

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***Abstract*—A minimal viable mission of a two people crew to Mars is studied in the current report, focusing on the Mars operation section. The Mars operation part concerns all aspects related to the base, operation, and space suits design for a Mars mission. The main results show a 20 days mission on Mars with a base made of one descent vehicle and an inflatable airlock module, radiation protection from a boron polymer with lower density than aluminum, life support systems sufficient for survival on Mars, and power production from solar panels. Water consumption and recycling systems are disregarded as they are handled by the human aspect team. Exploration will be made possible thanks to Mars-adapted space suits and drone scouting and imaging. Enough batteries for up to two days of sandstorms are also provided. Finally, some off-nominal scenarios are investigated.**

***Index Terms*—Mars, Pythomspace, Candor Chasma, Human spaceflight**

I. INTRODUCTION

FROM the highest mountain to the deepest ocean, humanity is driven by exploration, curiosity, and thirst for discovery, and Tom and Tina Sjögren from Pythom Space are no exception. Planning a human Mars mission that could be launched between 2024 and 2026, these two Swedish explorers are designing within their company all the rockets, spacecraft, and landers to make it as simple and low-mass as possible. Mars is indeed the easiest planet to reach from Earth for a human mission, and having humans on Mars would be a major milestone for mankind.

In this report, several assumptions were made: first, a spaceship containing Tom and Tina will reach Low Mars Orbit (LMO). From LMO, a first Mars Descent Vehicle (MDV) designed by Pythom Space with ascent propellants and supplies will descend. If the first landing is successful, a second lander with the crew will follow. One of the two landers will also function as a MAV (Mars Ascent Vehicle). The landing on Mars is set at Candor Chasma at altitude -4 500 meter (7.25S, 72.25W), as low altitude, and hence higher pressure, helps the landing.

II. MARS ENVIRONMENT

Mars is the fourth planet of the Solar System in terms of distance from the Sun with a diameter almost half of Earth's, but with a significantly smaller mass. The red planet orbits around the Sun every 687 Earth days, whereas the typical Martian day, called 'sol', consists of approximately 24.5 hours. Of this time, 10 hours correspond to day conditions and 14.5 to night conditions, as long as non-visible solar energy is concerned. Mars also experiences seasons, twice as long as the ones on Earth [1].

Table I: A collection of relevant properties

Property	Value
Diameter	6 787 km
Gravitation	3.721 ms^{-2} [1]
Solar flux	590 Wm^{-2} [1] [2]
Radiation level	54.79 millirads/day
Temperature interval	-140 °C to 35 °C [3]
Average temperature	-53 °C
Surface atmospheric pressure	640 Pa [3]
Crater atmospheric pressure	over 1 200 Pa [4]

A. Atmosphere

The atmospheric pressure on the surface accounts for 640 Pa. Other features of the Red Planet are listed in table I. The atmosphere is composed of 95.3% carbon dioxide, 2.7% nitrogen, 0.03% water vapour and 2% other gases [1]. Being unbreathable, for long-duration missions, a pressurised environment providing oxygen to the astronauts should be used.

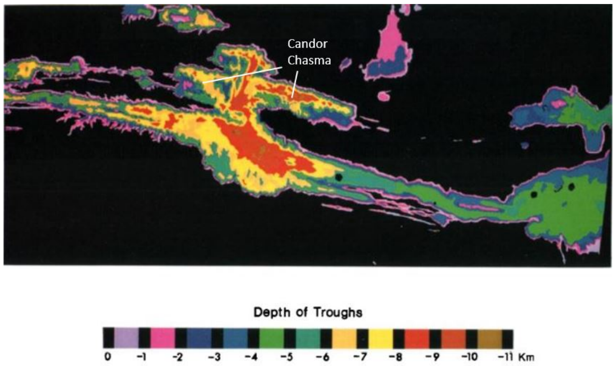

Figure 1: Elevation map of Valles Marineris [6].

B. Geology

Regolith is the main component of martian soil: reddish colored, it is made of sand and dust. The dust particles that have been observed so far could be highly reactive if in contact with water [5]. In this case, severe health issues (inflammation or cancer) would arise if airborne dust enters the human body. Apart from regolith, Mars's surface is scattered with stones and rocks, it is totally dry, with craters, inactive volcanoes and enormous canyons [1]. The biggest one, Valles Marineris, runs for 4 000 km just south and roughly parallel to the martian Equator.

Valles Marineris can be divided into several individual canyons, which can be up to 8 km deep and 200 km wide [6]. One of these canyons, Candor Chasma, will be the landing site of the mission: its average width is around 50 km [7]. Apart from its unique geomorphological features, previous missions showed that Candor Chasma is the most water-rich area of Valles Marineris. It could be in form of water ice mixed with regolith, just beneath the surface, so in a position accessible even with a simple drill [4]. An important goal of the mission would then be discovering the form of water under the canyon, i.e., whether it is water ice or it is chemically bounded to minerals in the soil. Figure 1 shows a map of Valles Marineris and its elevation: Candor Chasma lies several kilometers beneath the surrounding plateau. Moreover, from geologic studies on Valles Marineris [6], one can see that irregular deposits represent almost the entirety of Candor Chasma floor. Thus, a rover for transportation will not be feasible for the mission due to the difficulties it would face in moving around in such a harsh environment. A better solution would be the support of drones in the exploration, which could avoid rocks and uneven terrains by flying above them, and at the same time, they could benefit from the higher atmospheric pressure at the bottom of the crater, compared to the surface-level pressure on Mars.

Indeed, the atmospheric pressure at the bottom of the crater is believed to be over 1 200 Pa [4]. Even with this higher pressure and even with the velocity a martian storm can achieve, the wind it generates won't be an issue for the astronauts as the pressure is still too low to harm them. The only problem would be the dust covering solar panels. Moreover, the walls of the canyon, which have an average slope of 20°[7], are affected by a number of landslides, whose origin is still uncertain, whether they were created by rock avalanches or debris flows. They can reach quite relevant dimensions (up to 800 km^2 [7]), it may be interesting further explore them. Other features of Candor Chasma that are still unknown and will require more accurate inspections may include caves.

C. Radiation

Mars's surface is exposed to considerably higher radiation levels compared to Earth since the red planet lacks a protective magnetosphere. Moreover, its atmosphere and magnetosphere are not thick enough to absorb the huge amount of cosmic radiation coming from SPE (solar particle events) and GCR (galactic cosmic rays). Some measurements have shown that the continuous radiation levels are about 20 rads/year, which is about 2.5 times higher than on the ISS. In addition to that, some occasional solar proton events can generate peaks of radiation levels between 100 – 2 000 millirads in a day. [8]

Protons constitute the majority of SPE, and therefore, their energy is low enough to be repelled by the base structure [9]. GCR are, in their majority, composed of protons (fully ionised atoms), however, there are some heavier elements as well, that possess high atomic number ($Z > 10$) and high energy ($E > 100$ GeV). These heavier particles are mostly hydrogen, (approximately 89 %) [10], which can strip atoms from materials, e.g. base shielding, space suits, and equipment. This can cause a sub-atomic cascade of ionised particles, leading to electromagnetic radiation, which can generate defects in materials, making them more brittle and changing their mechanical and physical properties.[11] [12]

The possible ways to avoid radiation damage are increasing distance to the source, lower exposure time and to use shielding. A thicker shielding gives better protection, although there is a limit and the gain of thickening will eventually decline. [13] Increasing the thickness will lead to a higher level of secondary radiation, which can be even worse for biological tissue [14]. Nevertheless, it is possible to neutralize the particles by reducing their speed. For this to happen, they should collide with atomic nuclei that have similar masses, such as hydrogen. If that's the case, the energy splits between the original particle and the rebounding nucleus [15].

D. Mars weather

One major issue on Mars are the so-called dust devils, sandstorms that typically occur during the afternoon due to the heat dissipated from the planet's surface, and that can obscure regions of Mars for some time with speeds between 17-30 ms^{-1}. There is also the risk of global sandstorms which can occur once or twice a martian year. A rough estimation from observations predicts around 100 local sandstorms a martian year. The duration of these local storms is usually a few days, they more frequently occur in the latitude belt 10° to 20° N and 20° to 40° S. [16]

However, considering that the mission will be carried out in a crater, at an extremely low altitude, one should not worry about major storms that can last several days because they usually occur around elevated plateaus [17]. Some minor storms can of course still occur, a way for trying to avoid them would be to land on Mars when the planet is less close to the Sun, as during this period of its orbit has been found that sandstorms are less frequent. This will be easily done as, from the mission design report, the orbiter will spend around 300 days around Mars, allowing to choose the descent period.

III. THE BASE AND ITS NECESSARY SUBSYSTEMS

Mars holds favorable qualities, i.e. moons, polar ice caps, and a day-night period similar to the Earth's. However, Mars temperatures are low, there is no breathable air (atmosphere mainly composed of CO_2), and the ground is poisonous to human beings. Consequently, in order to stay longer on Mars's surface than a couple of days, it will be necessary to build a Mars hub capable of protecting against such harsh conditions and to provide a center for operations.

A. Radiation shielding

There have been several general proposals on how to build a habitable base on Mars and often the main difficulty has been the radiation protection. One idea was to have a base built directly into the ground which would be naturally shielded against radiation. Another proposal has been to build something above ground using inflatable modules enclosed with ceramics made of Martian soil. These ideas would most likely require the help of robots using a 3-D printing technique called "sintering", where sand is melted using x-rays. A third idea has been to build shielding into one of the lander vehicles that will be transformed to a base, and then have a smaller radiation shelter (located in for example a hollow water tank) in case of solar flare outbreaks. [8]. However, the aim of Pythomspace's mission is to use the shell of one of the descent vehicles as a base, and to have the shielding built-in or added on to it, to make it as simple and low mass as possible.

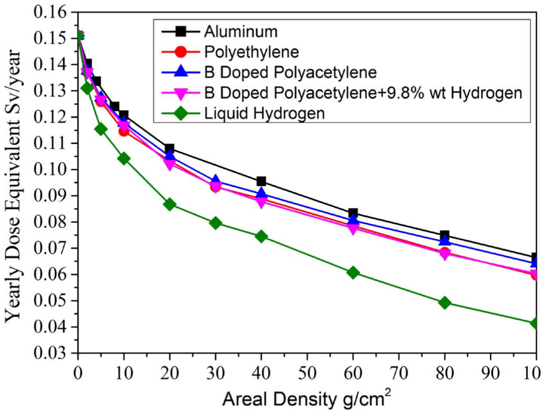

Figure 2: Radiation shielding materials compared with aluminium, the most commonly used material for spacecraft. Reducing radiation exposure is possible by neutralising the speed of high energy particles coming from the GCR by making them collide with atomic nuclei with similar atomic number, such as hydrogen [10].

As depicted in Figure 2 Hydrogen is known to be an effective substance against GCR and SPE. Unfortunately, hydrogen is not a structural material and in liquid form it is not feasible to cover the base with it. However, NASA has developed boron nitride nanotubes (BNNT), that have properties suitable for Space applications, where with a 30 cm thickness of BNNT's provides a 20 % more radiation protection than other materials. [12]. Consequently, the Olympus 1 and 2 will be made out of an alloy of BNNTs and aluminium thus providing the necessary protection.

B. Oxygen production and carbon dioxide removal

In order to maintain a liveable environment inside the base, conditions supporting human life shall be guaranteed, i.e., providing the astronauts with breathable oxygen and removing the carbon dioxide produced with the respiration process. Usually, these functions are fulfilled with two different subsystems, but given the requirement of minimizing mass, an alternative solution has been looked for, searching for a system that could satisfy both operations at the same time. The solution has been found in MOXIE (Mars Oxygen ISRU Experiment), which was included in the Mars2020 mission aboard the Perseverance rover, and had the goal of showing the feasibility of producing oxygen from Mars atmosphere, rich in carbon dioxide [18]. This technology was primarily intended to produce oxygen that could be used as fuel for rockets of future Mars exploration missions, but the gas could be also used to provide a breathable environment to humans.

Anyways, MOXIE proved to work in the martian environment in the Mars2020 mission [19], but as it produces only 10 grams of oxygen per hour the bigger version of it should be used [20]. The scaled-up version of the MOXIE is equipped with a compressor that provides it with CO_2 and compresses the gas, which is then heated up and thanks to electrolysis split into oxygen and carbon monoxide, which is returned to the atmosphere. The oxygen production rate is 100 g/hour [20], which may still not be enough. However, it could be assumed that in some years better performances could be reached, allowing for an oxygen production rate of around 200 g/hour. This seems a reasonable assumption, considering that the scaled-up version of the MOXIE presented a 1000% improvement in performance compared to the MOXIE Perseverance is equipped with. If the oxygen production rate is assumed to be 200 g/hour and given that the chemical reaction is $2CO_2 \longrightarrow 2CO + O_2$, the rate of removal of carbon dioxide from the air is 550 g/hour.

From Human Aspect group inputs carbon dioxide emissions have been found to be 1 kg per day per human and that its concentration should not exceed 0.5% [21]. Giving a volume of the base of 19 m^3, the volume of carbon dioxide should not exceed 0.095 m^3. However, it can be easily verified that even with the MOXIE working only four hours a day it would be possible to remove the whole amount of carbon dioxide produced by the two astronauts in a day. Consequently, for planning the amount of time the MOXIE should work a day, one should look at oxygen requirements. Small modifications shall also be performed in order to allow the MOXIE to get CO_2 both from inside and from the outer atmosphere, as the concentration inside the base won't be enough to guarantee a steady oxygen production. Assuming an oxygen consumption for two humans of 1 500 L/day, which corresponds to 2.14 kg, one can see that the MOXIE is capable of producing this amount of breathable air in around 12 hours, leaving some margin for safety reasons and considering the slightly longer duration of the martian day. This equipment won't consequently work all day long, but cycles are considered. This scaled-up version of the MOXIE would have mass and power consumption 35 kg and 1 193 W respectively [20]. With the working strategy explained before, it will need 14 316 Wh/day. However, the MOXIE production rate would not be sufficient for the initial pressurisation of the base as waiting for it to produce enough oxygen to entirely fill the volume of the shelter will take too long. A solution would be having a supply of breathable air just for pressurising the base and then using MOXIE just as equipment for keeping an acceptable rate of oxygen inside. Hence, considering a volume of the base of 19 m^3, a total mass of 23.3 kg of air should be brought to Mars, considering the air density at 1 bar. The pressure of this air can be increased up to a point where it takes 2 m^3 in volume. A tank for keeping it as well as a pump for the initial pressurisation of the base should be considered as well. The total mass of air, tank, and pump is assumed to account for 35 kg, for a volume of 2 m^3.

C. *Water and food supply*

On average, an astronaut requires about four liters of water per day to drink, prepare food, and personal hygiene [22]. However, in order to ensure that water supply will not be a problem in case of an emergency or if it is necessary to make oxygen through electrolysis, it is assumed they will need 5 liters per day/person. Consequently, the total mass of water and food necessary for a 20-day mission is 16.7 kg/day, as handled by the Human aspect team. [21].

D. *Heating system*

Because Mars is, in general, a cold planet, the temperature inside the habitat becomes an important aspect. Therefore one must account for thermal systems that can provide heat when needed [23].

Electrical resistance heater pads are intended to be used around the base walls. Each electrical heating pad, has a wire connected to an electric source, and when the current flows through it, the high resistance wire gets hot, thus warming up the habitat's atmosphere. Each heating pad, with dimensions 10 cm $\times$ 10 cm, weighs approximately 2.53 g and needs 10 W to operate. Consequently, the base will be equipped with $\approx$5 pads that will lead to a power consumption of 50W. Moreover, for reducing the number of pads and thus the thermal requirements, a Multi-Layer Insulation has been thought to cover the base. Given a density of 1.2 kgm^{-2}, this accounts for a weight of 37.7 kg.

IV. BASE DESIGN AND ASSEMBLY

The orbiting transfer vehicle around Mars will launch two lander vehicles. Olympus 1 will transport cargo and some propellants needed for descent and ascent, Olympus 2 will carry the crew and propellant needed for ascent. The base camp will be built from Olympus 1, which will be equipped with the necessary protection and the added life support system needed for survival on Mars. The Olympus 2 will be primarily used for the ascent, however, both vehicles should be able to be used for the ascent in case of emergency.

Both vehicles will have a maximum width of 2.5 m and a maximum height of 4 m, which will give an approximate maximum volume of 19 m^3 due to the cylindrical shape and a conical top. Because of its shape, the positioning of Olympus 1 for the base will be kept as it has landed, upright and on four legs. This means that the entrance to the base will be at least 1 m above ground, which indicates that in order for the crew and the equipment to go up and down, there will be a small ladder and some rope to lift up equipment if needed, it might also be possible to jump due to the lower gravitation on Mars. Olympus 1 will have a deployable rigid porch outside the hatch for which Tom and Tina can fit on together, as well as some possible equipment. On this porch, there will be a connected airlock module.

A. Airlock

The airlock module on the porch is necessary to isolate the inside of the base from the Martian atmosphere and its problematic dust. The danger related to this dust can be read about in section II-B as well as in the report from Human Aspects [21]. Present airlocks differ a lot in design as well as function. They are usually either integrated into the vehicle or an extra module divided into single- or dual chambers. For missions to Mars, it would be necessary to have a dual-chamber since it would provide redundancy in the case of failure, as well as minimize gas loss during the depress and repress cycles. Furthermore, a dual-chamber is essential for better dust control and will also help with suit maintenance. However, adding an extra module for the airlock would require more volume and mass beside the descent vehicle.

Although, ever since the 1950s the idea of inflatable modules has been studied, and as early as 1965 the first EVA was made using the inflatable airlock Volga[24] As well as on the ISS there has been an inflatable module, named BEAM, active since 2016 [25]. Therefore, an airlock made of an inflatable fabric pressure shell supported by a lightweight structure rigid enough to withstand the atmospheric pressure difference and a rigid metallic hatch would be a good feasible solution for this mission, since it allows for a reduced mass and volume. [26] A rigid hatch is needed because lightweight soft hatches currently have a too low TRL. But the concept will continue being pursued by NASA and the industry. [24]

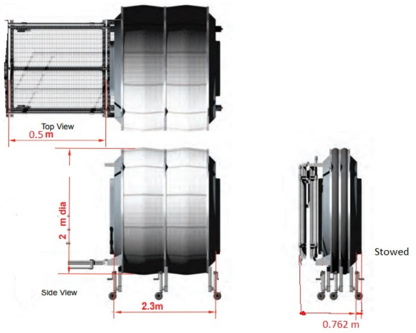

Figure 3: Design of the Dual-Chamber Hybrid Inflatable Suitlock (DCIS) [27]

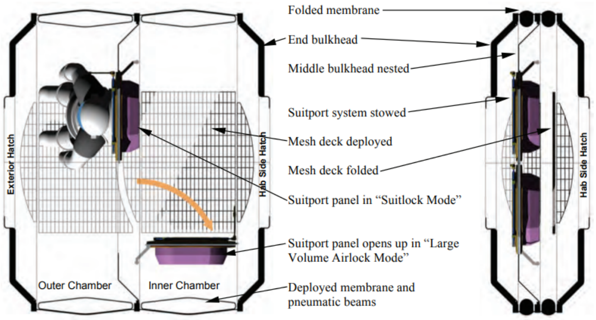

Figure 4: Top view of DCIS [27]

The chosen airlock will be built on previous concepts and technologies. Its design will mainly be based on a downsized version of the DCIS from 2011 seen in figure 3 and 4. The two chambers can make it easier to manipulate the pressure in each chamber and allow for an easier transition and shorter pre-breathe times for EVAs. The design will also have integrated compressed air nozzles to generate an air shower that will remove the dust from the suits. The design can also be used with two suitports incorporated into the middle wall section. Generally, the design needs to be downsized as much as possible to reduce the mass, and in order to estimate this mass, some inspiration was taken from the Advanced Inflatable Airlock (AIA) System. The AIA concept from the year 2002 had a mass of 482.62 kg which included fabric, support systems, hatches, hard structure, and a 20 % margin.[28] Since the mass of one hatch and the support system can already be counted for in Olympus vehicle this number gets reduced. Furthermore, it is assumed that all the previous and current progress in inflatable modules, as well as the increasing studies in the technology of lightweight structures and materials compared to the ones of the AIA more than 20 years ago, would make it feasible to design an inflatable airlock with a volume of 7.226 m^3 and an approximate weight of 100 kg. [29]

B. *Design of living area*

In order to design the living area, the volume of the propellant and all the subsystems need to be estimated. Their respective masses are also important to consider since they need to be distributed evenly to balance the vehicle. The two tanks containing the propellant will have volumes of 1.637 m^3 and 0.8512 m^3, according to [30], and in addition to that approximately 1.784 m^3 is given from Human aspects [21], for other human needs besides the described subsystems in this report.

The conceptual design of the habitat is seen in figure 5 is going to be two floors with a maximum height of 2 m each, and a connection via a ladder attached to the wall through an opening between the floors. Both floors are based on the idea to try and use as much of the walls as possible for storage and subsystems, as well as having the ability to tuck things away easily. Windows will be installed on both floors for convenient visual surveillance to the outer environment of the base (such as checking on the solar panels). Since pure BNNT is transparent, it could be included in the glass panels of the windows for radiation protection. It's potential of making bulletproof glass, work excellent for the base window in case of flying gravels during the Martian sandstorms [31]. The lighting of the habitat will come from led lights, assumed to require in total 50 W.

The ground floor seen in figure 6 will have a kitchen area as well as an isolated hygiene area in order to avoid any contamination. The dining area in the middle of the room can be tucked away as well as the exercise equipment. The safety and emergency equipment is placed close to the door for quick access.

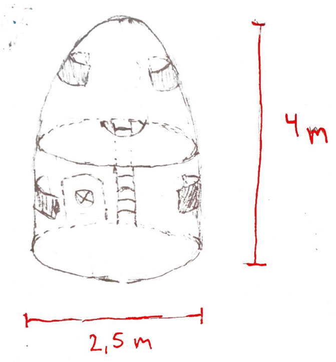

Figure 5: Overall view of the conceptual design of the habitat

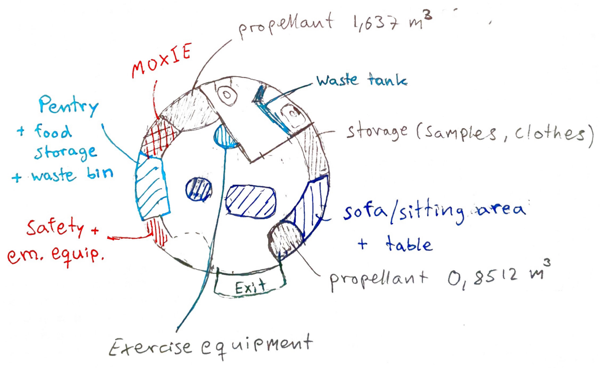

Figure 6: A sketch, from above, of the ground floor

The top floor seen in 7 have a smaller volume and a lower ceiling due to the conic shape, therefore the sleeping area is located there. The head-side of the bed will be partly integrated into the wall and the rest will be extendable, with an inflatable mattress on top. For some flexibility concerning their sleeping schedule, the plan is to have the bed divided into two sections, which will make it possible for one to sleep at a time and to save some room for other activities. This will make it possible to sit closer to the middle of the room, where the ceiling is higher, and work at the extendable desk placed next to the control panels in the wall,

V. MARS OPERATIONS

A human mission could realise many different experiments on Mars other than exploration. The current report will mention some experiments of interest that could be conducted during Tom and Tina's stay on the surface, but will also show that some automated experiments could be conducted without the crew itself. Especially since the optimal walking speed on the surface of Mars

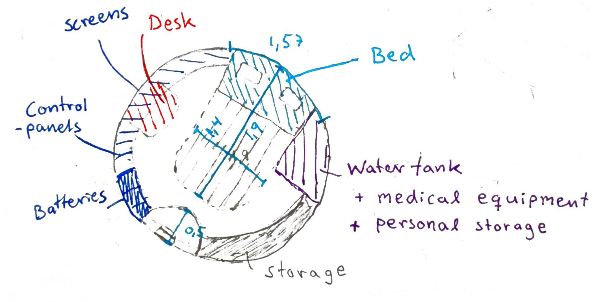

Figure 7: A sketch, from above, of the top floor

will be around 3.4 km/h, which is noticeably lower than the average walking speed on Earth is closer to 5.5 km/h, exploration on foot might not be the most effective option. [32] The reduced gravity on Mars will also affect the mobility of the crew, which means that simple tasks like picking up samples from the ground can be challenging.

A. *Transportation*

As seen before, a rover cannot be a feasible option both for the requirement of keeping the mass as low as possible and for the rough terrain that would be possible to encounter at the bottom of Candor Chasma. Moreover, Tom and Tina's objectives are mainly focused on exploration on foot, however, one of the main aspects of the operations on Mars is to ensure safety for the crew. As seen in sub-section II-C, the amount of time that can be spent outside of the base is limited. Moreover, as the crew is not specialised in scientific studies, having automated data collection devices is fundamental in order to help the scientific community but also to increase the chances of funding. This is why using light-weighted drones to do both pre-exit analysis and sensor imaging is considered. Indeed, drones controlled from the base could be used for scouting the points of interest that Tom and Tina could later visit, reducing the time spent outside searching for a destination. They could also include sensors, thermal cameras, and recording devices that could do automated imaging and scanning, the interesting data could then be either sent to Earth or stored and retrieved once the mission returns, avoiding the communication limitations currently existing. Drones can fly on Mars as proven by Ingenuity from Nasa [33].

However, the Ingenuity helicopter is not optimised for the current mission, as it is designed to operate on its own and is thus composed of solar panels, huge batteries, and a communication system up to the Earth. The current mission will store the data collected by drones on radiation-shielded drives, and returned to Earth for analysis, to save all weight and energy consumption required by communication systems. Two drones were selected and will be adapted to work in the Martian atmosphere.

Figure 8: Mavic Air 2 drone folded

Figure 9: Diatone short range drone

The first one would be used from inside of the base to explore its surroundings and prepare for expeditions. It thus requires some batteries, distance operation, and sensors. This drone will have an attached infrared camera and sensors, to give valuable data for the scientific community once the mission is complete. A first trade-off selected a design based on the Mavic Air 2, in Figure 8, for its low weight (570 g) its capacity to be folded to reduce its volume, its long-distance operation (up to 15 km) and its autonomy (more than 35 minutes) [34]. The other drone, smaller, would be very useful during outside operations, for scouting and on-site imaging. It thus requires to be lightweight to be carried by the crew outside, and could even be used to scout cave/non-easy to reach areas that are too dangerous for human exploration. The base design selected was a Diatone drone, in Figure 9, selected for it very small size and weight (less than 300 g) [35], and because it is currently used for geology exploration on Earth.

Of course, these designs are optimised to work on Earth, and will need bigger blades as Mars atmosphere is thicker and batteries resistant to lower temperatures, as well as some sort of shielding from dust. Also, as for Ingenuity helicopter, the blades will need to rotate faster (up to 10 times faster than the initial design on Earth) reducing the autonomy of the drones. The total mass for the drones subsystem is estimated to be 1 kg, considering also spare parts.

B. Equipment and maintenance

Given that the main goal of the mission is showing that human survival on the red planet is feasible, no complex experiments should be brought to Mars, both because this would obviously increase the mass and because Tom and Tina would need extra training to perform experiments as they are not scientists. Of course, some sample collection can be included, as it is not a complicated task and it does not add a relevant mass on the way back. The crew could note the exact coordinates of each sample and then return everything to Earth. An approximation of 10 kg of rocks and soil could be collected. Some simple experiments proposals are however written here, just in case there is some room available left for equipment. For example, a small drill may be considered, like the one that was used in the Apollo missions. That drill could dig up to 3 meters deep and may then be a useful tool for taking samples under martian soil, where water is more likely to be present [36]. This drill requires 399 W for being used and has a mass of 13.4 kg. A financing proposal could be to accept "self-operating" experiments that just need to be brought to Mars and that could function in autonomy, like additional cameras on the drones or ionosphere radio scanning from the ground, allowing for the mission to increase subventions without having to develop its own experiments. Finally, communication with Earth has been looked into by the logistics group [37].

VI. SPACE SUITS

A. Fundamental requirements

Below is a list of the fundamental requirements the suit must have.

- Oxygen supply
- Minimal protection against radiation
- An internal pressure of at least 0.4 bar
- Communication functionality
- Temperature control against the harsh cold climate and vacuum space.
- CO_2 and wastes removal system

These are the functions that the space suit must have for basic survival in both the outer space area and on-Mars surface, before including other useful but not primary functions.

B. Mobility

Since most outside missions will be carried out on foot, it is vital that the suit has decent mobility. The conventional spacesuits used by astronauts for space missions, do not provide enough flexibility in order for the explorers to walk or climb normally on Mars's surface. This is mainly due to its pressurisation method which is simply a balloon of pressurised air inside the suit which creates a somewhat balloon shape.

Figure 10: Conceptual design of MIT's BioSuit [38]

A more appropriate option is the MIT BioSuit, which is a mechanical counter-pressure (MCP) suit [38], for the interior counter-pressure mechanism. Instead of the conventional gas pressurisation method, it utilizes the elastic memory-foam material to form a layer that can compress the skin directly (shown in Figure 10). The compression would obviously be able to recreate the 1-bar atmospheric pressure. With such a design feature and the elastic nature of the material, joints motion range (which is highly important when it comes to high mobility) would be high.

C. Oxygen supply

During the expedition, whether it is working in outer space or exploring the Mars surface, the crews would need an oxygen supply for up to 8 hours. For safety purposes, a backup gas tank (amount for 1 hour) would be installed for an emergency. Since the base would use the same air composition and pressure as on Earth, it would be the same for the Martian suits so that depressurisation could be skipped.

Considering that the missions would sometime be more physically demanding (ex. climbing), a consumption rate of 0.6 L per minute of oxygen was assumed. In other words, with a total of 9 hours supply (8 hours mission

+ 1-hour emergency), about 324 L or 0.4 kg of air would be included. (All the mentioned values were done with an air pressure of 1 bar). Since air is extremely compressible, the requirement for the size of the gas tank would not be much.

D. Thermal control

Thermal insulation is important for keeping the crew warm. A good one can also greatly reduce the demand of active heating system to save some battery usage and also body heat could be sufficient for most of the time outside. Aerogel polymers is a flexible and strong thermal insulator. Its production is tricky to produce but its superb potential in space application was firmly proven [39]. A layer of aerogel polymer could be implemented as a form of passive thermal protection.

Furthermore, heating pads could be added for body parts that are sensitive to temperature drops in case that body heat is not enough. According to Human Aspect [21], such body parts include cheeks, back of the neck, and lower torso to thigh area. Gloves worn by the crews should provide active heating as well. Hands might not be sensitive to cooling, but cold hand affects the difficulty of any tasks that are handled by hands.

E. Radiation and physical protection

As mentioned previously, BNNT is proved to be an excellent material for radiation protection, especially when it is carrying hydrogen. According to Human Aspects [21], the career limit of radiation dosage for the different space agencies ranges between 600-1000 mSV. Moreover, it is above 1 000 mSV when recipients would experience acute radiation sickness. In figure 11, different materials with a thickness of 30 cm, were tested for their protection effectiveness against Galactic Cosmic Radiation (GCR) which ranges between 50 to 2 000 mSV. Although the test was done with high thickness, which would not be a feasible thickness when implemented to the Martian suit, higher hydrogen content could compensate for the loss in radiation protection effectiveness due to it being thinner for the Martian suit. With just 5 % hydrogen content, the dosage decreased by roughly 14 %. A base full-body BNNT+hydrogen layer could be worn. BNNT in itself is a very flexible material for its fiber structure [31]. This ensures the joints move freely even the body is covered with such a layer.

When exploring the rocky and desert surface of Mars, it is also important to have a durable and sturdy suit for physical protection. Aluminum could also be reinforced by BNNT (with hydrogen if necessary) [40] to inherit its radiation protection, but also increase material strength. An idea is that the Martian suits have BNNT reinforced aluminum armor plates designed similarly to the Stormtrooper suit from the Star Wars movies (see figure 12). This then also ensures physical protection for the crews while maintaining the free movement of the joints.

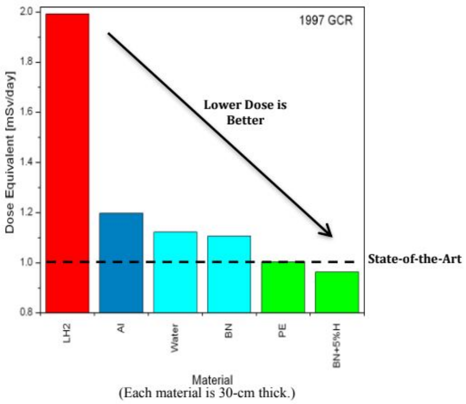

Figure 11: Different materials tested against the GCR [12]

Figure 12: Stormtrooper armor

F. Tools and equipment

As for the equipment, there will be no heavy-duty equipment. The mission design is to explore the surroundings of the landing site so the equipment they bring is supposed to have a low weight. The following equipment, which is listed in table II is going to be used.

Table II: Equipment for exploration missions and the estimated weight.

Equipment	Weight [kg]
Soil Sample Tubes x4	1.36
Hand pickaxe	0.70
Hand Shovel	1.20
Monitoring devices	0.50
Photo camera	1.80

G. Power

As the suit acts as a one-person life support system in the harsh mars environment it needs its own power bank to be able to power different kinds of subsystems for the human to survive. As for the battery a lithium-ion battery (LIB) has been chosen as they offer many advantages for space missions such as having the ability to be rechargeable. They have a high energy density and offer a wide temperature operation range which is critical on Mars [41].

Table III: Estimated Power for all the subsystems.

Subsystem	Power (W)
Communication	3
Information Display	1.64
O2 supply	10
CO2 removal	5
Cameras and lightning	11
Heating	85
Control system	5
Total:	120.64

The suit requires power for up to 8 hours. The total power for all the subsystems is 120 W, which can be seen in table III, therefore 965 Wh are required. The weight of the battery is then estimated to be 250 Wh/kg [42] so the weight is about 3.9 kg. For emergency purposes, an additional 1-hour worth of battery could be installed in case the main battery malfunctions. This means an extra 0.5 kg to the battery pack.

VII. RESULTS

A. Power generation

The source for power production has been chosen to be solar arrays, as it was the minimal system in terms of weight. For dimensioning the power systems, all the power requirements of Mars operations should be considered. These data, along with the masses, are shown in table V in section VII-C and then added together with the requirements from Human aspects and Logistics.

As subsystems like MOXIE, temperature regulation, and water recycling need to work also during the night, the use of some batteries should be considered, allowing these essential subsystems to work even when the Sun is not lighting the base, remembering that night conditions on Mars last approximately 14.5 hours. Moreover, power should be available also during sandstorms. Obviously, during this emergency situation, the power consumption should be kept to the strictly necessary, so it is assumed that all subsystems apart from MOXIE and temperature regulation are kept in standby. As stated in subsection II-D, major storms should not represent a problem. Some minor storms should be of course taken into account, it is however assumed that they won't last more than two days and that afterward, the astronauts will be able to clean the solar panels or that it would be possible to fold them during the storm. The use of lithium-ion batteries has been evaluated, as this solution allows for better performance, saving both mass and volume.

For finding out the required mass to be allocated with batteries, reasonable specific energies of a Li-ion battery have been found to be 250 Wh/kg and 700 Wh/L [42]. Then, assuming a storm duration of two days and only key components working, the total energy needed in this period would be 31 032 Wh. Given energy densities stated before, the mass and volume of batteries are respectively 124 kg and 44 L. This obviously is only the total mass, but several different batteries are considered in a way that even losing one of them would not be a major issue. Considering that they have been dimensioned analyzing the worst case of a storm lasting two days, they will of course be able also to provide power during the 14.5-hour-long night, both to the essential and the auxiliary subsystems. Then, the total mass of the solar panels should be estimated. As already stated, the solar flux on the surface of Mars accounts for 590 W/m^2. Moreover, the efficiency of the solar panels of 0.3 can be estimated [43]. From NASA report [44], the average weight per surface of a uni-facial solar array can be assumed to be ~2.4 kg/m^2. From the same paper, also the weight for all the remaining parts of the power system, i.e., everything is not the actual array, can be estimated. The following strategy was used: it was calculated the total energy consumed by all equipment working in a day together with the energy necessary to recharge half of the whole battery system. Then, it was assumed that the solar panels, working for 10 hours, should be able to provide this specific amount of energy. Like so, with two days without sandstorms, the batteries would be completely charged, and all equipment working. Data and assumptions stated before yielded a total surface of the solar panels of 19 m^2, corresponding, according to [44], to 56 kg, including both the panels and the remaining power systems. The height of the panel was assumed to be 10 cm for calculating the volume.

B. *Mission timeline*

The goal was to make a minimal mission, thus spending only a minimal number of days on mars to reduce the necessary masses and costs. The Table IV summarises a mission duration proposal. As the mission design proposed a 300 days orbit around Mars, only a small part of the time will actually be spent on Mars. The exact selected period will be chosen depending on sandstorms seasons and meteorological forecasts to minimize the risks. The mission will be cut into three different phases, the first one will be dedicated to the base creation, and is the one that most requires a good meteorological situation. After landing, the crew will only have a limited amount of time to first deploy the airlock, pressurise the base and activate the Moxie (day one on arrival). Since at least 2 days of batteries are landed on Mars, the solar panels deployment and electrical setup can be done in the following days, as it is also the longest task to execute (28 m^2 to deploy). The mission will then consist of exploration (main objective of the mission) and potentially brought experiments as specified in section V-B. 10 days are planned on this phase, as it will be enough to explore with drones and by foot the maximal area around the base (up to 15 km radius for the drones, and maximal out of the base mission of 8h outside as specified in section VI) Finally, before departure, a few days will consist of gathering and select all samples, preparing the base to leave it on Mars, and prepare the departure. Finally, a buffer of 3 days is planned to ensure enough supply in case of a departure report due to meteorological conditions, or if the exploration is longer than expected (in particular if some outside explorations are canceled due to sandstorms).

Table IV: Minimal mission timeline proposal

Base installation	4 days
Exploration and measurements	10 days
Departure preparation	3 days
Margin in case of sandstorms	3 days
Total duration	20 days

A typical exploration day like in figure 13 would allow for a phase of planning and preparation, usage of the drones from the base to do scouting and preparing point of interest to visit during the exploration, an outside time starting by maintenance (cleaning the solar panels, checking life support systems...) and then a few hours of exploration, collecting samples and doing measurements with the smaller drone. Finally, after going back to the base, the crew would first take a break and then focus on the data and samples collected, to either store them or send them, and to prepare for the next day. This schedule allows for a not too high workload to keep crew sanity, and would, of course, be adapted day by day depending on the outside events (no exploration during sandstorms, and more maintenance after them for example).

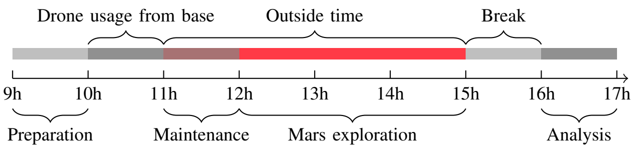

Figure 13: Typical schedule during the exploration phase in Mars hours

C. *Payload and energy consumption*

Table V: Power and masses of relevant subsystems for Mars operations

Subsystem	Power/Energy	Mass kg	Volume m^3
MOXIE	14316 Wh/day	35.0	0.022
Insulation	0 W	37.7	0.628
Heating	50 W	0.1	0.010
Drone 1	0.040 Wh/charge	0.6	0.001
Drone 2	0.024 Wh/charge	0.3	0.001
Beacon	25 W	1.5	0.009
Space suits (x4)	3860 Wh/charge	144.0	0.126
Solar panels	0 W	56.0	1.900
Batteries	0 W	124.0	0.044
Airlock	0 W	100.0	2.390
Pressurisation	0 W	35.0	2.000
Samples	0 W	10.0	0.004
Total (excl. astronauts)	19.98 kWh/day	544.2 kg	7.135 m^3

VIII. OFF-NOMINAL SCENARIOS AND RISKS

To avoid single-fault vulnerabilities the subsystems and the consumables should be distributed as much as possible across the base and habitat. All equipment masses, at least for the most critical ones, were computed including margins in order to take spare parts. Spare parts are also included for the drones, especially backup batteries and propellers, as part of their mass margin. Several off-nominal scenarios were considered, each of them corresponding to a specific level of probability and criticality. The results and the meaning of the probability and criticality levels are shown in table VI and VII for some of the identified scenarios. The risk is obtained by combining the probability and criticality of the event.

Table VI: Several different off-nominal scenarios before remediation

Risk	Probability	Criticity	Level of risk
Fire in the habitat	1	5	5
Drone breaks	3	1	3
Habitat leakage	2	4	8
Suit leakage outside	3	4	12
Life support system failure	2	4	8
Outside communication failure	2	2	4
Severe sandstorm (more than 2 days)	1	5	5
Critical module damaged during descent	2	4	8
Solar storm	1	4	4

Table VII: Legend of probabilities and criticities

Probability		Criticity	
Very low	1	Negligible	1
Low	2	Low	2
Moderate	3	Moderate	3
High	4	Severe	4
Very high	5	Catastrophic	5

The main off-nominal scenario considered in this report were sandstorms (previous to remediation it was the highest level of risk), that can last for several hours or even a few days. Thus, batteries to cover the most important life support system during this duration are used, and as long as the storm lasts two days or less, the crew would be perfectly able to survive. The fact that after the storm the panels could be covered with sand does not represent an issue either, as the crew would be able to clean them again from dust or even fold them during the storm, because as already stated in subsection II-B with the low pressure on Mars the wind of the storm does not represent a problem for humans by itself. In any case, spare parts for the solar panels are included as well to cover the potential issues after sandstorms, if maintenance and protection are not sufficient. However, if the storm lasts two days or more, the only option available for the crew would be taking off and returning to the transfer vehicle on orbit around Mars, as the ascent vehicle is always ready to lift up. However, storms lasting more than two days as already noted should not be common in Candor Chasma. Leaving Mars surface before planned should of course also be used in other critical off-nominal scenarios, such as base leakage, life support systems critical failure, or uncontrollable fire. In the case a sandstorm happens during outside time, a beacon is installed on the base to guide the crew back to safety as fast as possible. Moreover, the base can also be reconverted to an ascent vehicle to allow for a second ascent vehicle if necessary. The riskiest off-nominal scenario could then be that due to the rough terrain a crack or some kind of leakage occurs in the suit. The suit is divided into an elastic suit and a pressurised helmet. For leakage in the suit, a temporary fix would be some kind of duct tape or sealing wax. This temporary solution would give the crew enough time to return to the base and evaluate the leakage. If the suit gets irreversible damage, this would mean the end of the mission and return to the transfer vehicle. Therefore, two backup suits, one for each astronaut (total of 4), are carried.

IX. CONCLUSION

This report analysed a viable way to perform the Mars operations section of the mission proposed by Tom and Tina Sjögren, who are planning to be the first astronauts to walk on martian soil in the next few years. The choice of the landing site has been found to be quite particular, being quite different from the rest of the red planet surface. Landing in the bottom of a canyon, with harsh terrain, may make exploration on foot more difficult, but on the other hand, can also represent an advantage in terms of protection from major sandstorms, something that could make the difference at least for the first mission on a planet where humans never set foot and so where ways of dealing with this kind of storms may not be fully understood yet. The purpose of the crew is to have a minimal mission, hence everything has been designed keeping in mind the requirement of lowering the mass as much as possible. The choice of not having experiments or equipment of any sort, obviously apart from suits, is also going in this direction. The only exception is represented by the two drones, that in any case are representing an almost negligible fraction of the total mass and that could also be of vital importance if the landing site would then show to be impossible to explore even on foot, an option that of course should be taken into consideration.

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