Low Mass Human Mission to Mars
Blue Team - Mars Operations Report

Mathias Dahlman, Renato Franzè, Nannaphat Kusolphisarnsut, Meredith Moore, Naoki Moriya, Ina Taxis
All authors are MSc students at KTH Royal Institute of Technology, Stockholm, Sweden

Submitted March 20, 2022

***Abstract*—Human exploration of Mars is becoming an increasingly near reality. Pythom Space and the Crewed Return Interplanetary Mission for Surface Observation and New research (C.R.I.M.S.O.N.) plan on having astronauts on the surface of the Red Planet in the next six years, taking as little mass as is feasible. This report details the requirements and procedures for the crew of C.R.I.M.S.O.N.'s visit to Mars, during which two people will remain on the surface for 23 days. The schedule of the mission is explained first, with evidence to support why certain decisions about the timeline were made. Communication with Earth, along with its challenges, are discussed. The crew will descend to Mars immediately upon reaching orbit using two Mars descent vehicles. The specifications of the space suits and habitat on Mars will be examined with respect to requirements such as thermal control, radiation shielding, dust protection, mobility, pressurisation versus non-pressurisation, and mass. Transportation vehicles and daily life on Mars will be discussed along with the goals of the crew's research and experiments involving the planet. The method of sample collection used and everything else brought to space was carefully selected to add the lowest possible amount of mass to the mission.**

***Index Terms*—Interplanetary, Human Spaceflight, Mars, Martian expedition**

***Supervisors*—Christer Fuglesang, Erik Clacey**

I. INTRODUCTION

The Crewed Return Interplanetary Mission for Surface Observation and New Research is a privately funded collaborative mission with Pythom Space, a SpaceTech company founded by Tina and Tom Sjögren. In the next six years, two astronauts will spend 23 days on the surface of Mars, a feat that has never before been done. During a year-long stay in Mars orbit, the crew of C.R.I.M.S.O.N. will perform groundbreaking research regarding the existence of life on Mars, characteristics of climate and geology, and the possibility of human survival on a foreign planet. Moreover to investigate how and why the climate of the Red Planet has evolved in the past years, how Earth and Mars differ in climate, and the geological and structural history of Mars. Samples will be taken from the surface of Mars back to Earth for analysis. The human body's reaction to being on another planet will also be studied for future missions. The goal of C.R.I.M.S.O.N. was to make this mission simple and attainable while taking the lowest possible mass into space. The mission requires the chance of success to be greater than 75% and risk of death to be smaller than 3%.

To accomplish the mission, small teams were allocated specific roles such as mission design, transfer vehicle, human aspects, overall coordination, and logistics. The Mars Operations team is comprised of six people whose responsibilities were to prepare and plan for the astronauts' stay on Mars. This included studying the environment on Mars and its potential for supporting human life, determining a landing site, establishing a timeline for the mission, and researching aspects that are necessary on the surface of Mars such as communication with Earth, space suits and habitat, planetary vehicles and other equipment. The specifications of these are covered in this report.

At times, the Mars Operations team worked with Mission Design [1] to determine the length of the stay. In order to minimise the risk of death, as well as the amount of equipment required on the mission, it was decided that the astronauts would only spend 23 days on the surface of Mars. The orientation of Mars, Earth, and the Sun will pose several issues with communication. These complications are addressed, as are the dangers of radiation and exposure on Mars. The harsh environment will require the astronauts' space suits and habitat to be both highly efficient and protective, with thermal regulation, radiation shielding, life support, and dust protection, while being as lightweight and flexible as possible. Mars Operations and Human Aspects [2] worked together to determine how much mass will be allocated for consumables. Two Mars Descent Vehicles (MDVs) will be used, both unpressurised to save mass. With these measures, C.R.I.M.S.O.N. will be able to complete its mission to the Red Planet carrying the least mass possible.

A. *Mars environment*

Mars is the fourth planet in terms of the distance from the Sun, one after the Earth. Also, Mars is the second smallest planet in the Solar System and is known as the Red Planet which is caused by a thin film of hydrated iron oxide called limonite and gives its surface a rusty red color [3]. Thus, reddish, fine-grained dust which is smaller than 5 μm is ubiquitous on the surface of Mars. Mars is also known to have a basaltic crust [4].

TABLE I
CHARACTERISTIC PARAMETERS OF MARS

Characteristic parameter	Mars	Ratio (Mars/Earth)
Mass [10^{23} kg]	6.42	0.107
Equatorial radius [km]	3 396.2	0.532
Surface gravity [$\mathrm{m/s^2}$]	3.71	0.379
Surface pressure [Pa]	636	0.006
Average temperature [°C]	-63	-
Length of day [hours]	24.7	1.03

Some characteristic parameters of Mars and the ratio compared to the Earth are shown in Tab. I [5]. Note that, the temperature of Mars is very wide range from -130°C to 20 °C. Moreover, the surface pressure listed on Tab. I is at the mean radius, therefore it can also vary depending on the altitude of Mars. Since the mission plans to land at a deeper altitude on Mars, the pressure on the surface of Mars is expected to be greater than the value listed in Tab. I. The possible constraints regarding the landing site are discussed later.

From Tab. I, it can be seen that the gravity of Mars is much smaller than that of the Earth due to the lower mass of Mars. This property makes everything lighter on Mars, which means that the movement can be more flexible than on Earth. On the other hand, there is a drawback as well especially for the human body which will be explained in more details later. Since the length of the Martian day is approximately the same as that of the Earth, it might be helpful for the future manned long-stay mission, as humans do not need to adapt to a different day-night cycle.

The atmosphere of Mars is composed of 95% of carbon dioxide, 2.8% of nitrogen, and 2% of argon [6]. Here, the amount of oxygen is small enough to be negligible. Furthermore, the Martian atmosphere is too thin to protect against ionizing radiation and ultraviolet radiation. Also, there is no planetary-scale magnetic field to block ionizing radiation. Therefore, high levels of radiation can reach the Martian surface [7]. Note here that, due to the presence of a thin atmosphere on Mars, radiation doses compared to that in outer space are expected to be lower at around 0.67 mSv/day while 1.84 mSv/day in outer space [8].

B. Landing site

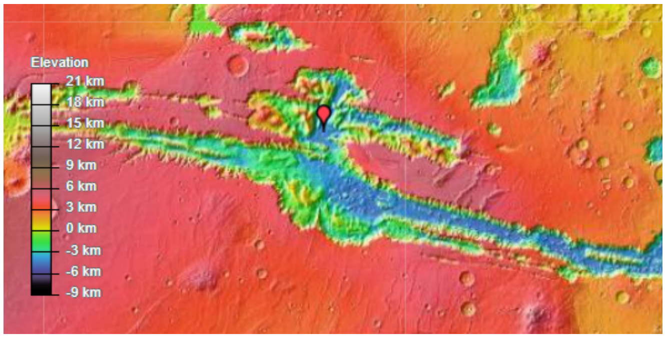


Fig. 1. Geologic map of the Valles Marineris region. The red point is the location of the Candor Chaos.

In C.R.I.M.S.O.N. mission, the landing site on Mars is set at Candor Chaos at the altitude of −4500 m with 7.25 degree south latitude, and 72.25 degrees west longitude as shown in Fig. 1. Candor Chaos is located at one of the largest canyons in the Valleys Marineris canyon system called Candor Chasma. The surface of Candor Chasma has various landforms, such as layered deposits and sand dunes [9]. Many forms of erosion, such as wind and water erosion are seen on the surface. In addition, there are traces of large-scale landslides caused by gravity. Therefore, the environment of the landing site is interesting for Mars exploration.

C. Environmental constraints

The environment of Mars is adequately harsh to add many constraints as mentioned above. The following is a general list of constrains that needs to be taken into account for the manned Mars mission.

- Lower atmospheric pressure
- Lower temperature
- Lower gravity
- Radiational effect
- Location of the landing site

There is much lower atmospheric pressure on the surface of Mars. Therefore, when landing on Mars, there is less air friction, so the rocket engines need to reverse thrust and use parachute for greater deceleration. In addition, the wind makes dust particles very miserable, therefore an efficient system to remove them will be needed for the equipment, such as the space suits. The Martian environment is not only cooler than the Earth, but also temperature changes are expected to be more severe, therefore more durable materials must be used.

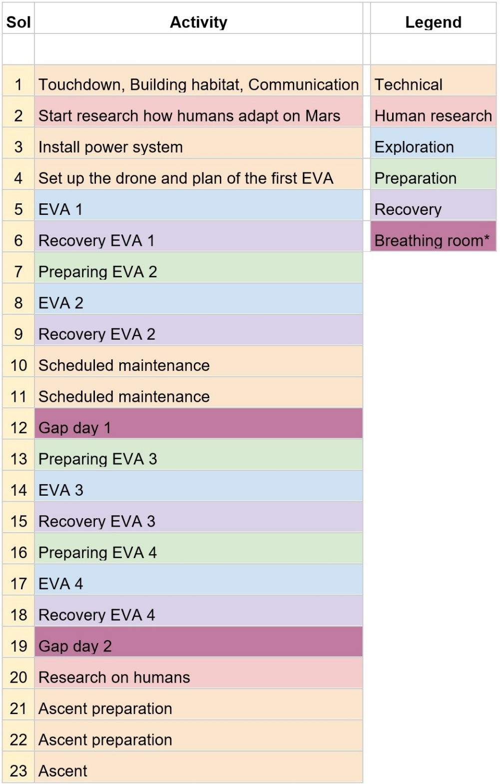
In the low-gravity environment on Mars, human muscles will not be used as much as the environment on the Earth, so muscle atrophy will be expected, especially for the long-duration mission [10]. Note that this effect can be expected to be small for the mission because the duration of stay on Mars is relatively short at 23 days. Bone and muscle atrophy are also much more severe in microgravity during the transfer.

Higher radiation levels on the surface are an additional point of difficulty for the survival of life and this can be especially dangerous for long-duration missions. Note here again that, this effect can also be expected to be small enough for humans to stay safely on the surface of Mars.

Lastly, because the landing site is at the deeper part of the valley, difficulties of communication during the stay on the surface of Mars would be expected.

D. Mission timeline

The decision of the Mission Design group was to go on a long duration Mission. According to that the orbiter will stay one year in Mars Orbit. The final decision was to stay 23 days out of this year on Mars surface. The decision was made considering the time needed on Mars surface to collect as much information as possible, but also keeping the risk of death on Mars surface as low as possible. Since no other human was on Mars before, the environment is unfamiliar and there is no way to predict exactly what will happen to the human body. Moreover, as already mentioned, although the radiation levels on Mars are lower than in outer space due to a thin atmosphere, this danger needs to be considered for the stay on Mars. Furthermore, on Mars's surface, the crew's life depends on the habitat and the Mars suits to create a safe environment. The longer the stay on surface the higher is the risk of some of the used materials for protection is suffering overuse by the rough environment (dust, extreme temperatures etc.). Also since the mission should be as lightweight as possible the mass of materials and support systems on Mars surface is limited. Connected to this the ability for power supplies on Mars surface is also limited. Since energy is also an important factor to ensure survival on surface, this was a main reason to plan a shorter mission. In Fig. 2 the exact mission plan is presented. The mission includes 4 Extravehicular Activities (EVAs) together with one preparing and one recap day. For the ascent from Mars' surface with preparations for the stay (building habitat, power supply and communication systems).



Sol	Activity
1	Touchdown, Building habitat, Communication
2	Start research how humans adapt on Mars
3	Install power system
4	Set up the drone and plan of the first EVA
5	EVA 1
6	Recovery EVA 1
7	Preparing EVA 2
8	EVA 2
9	Recovery EVA 2
10	Scheduled maintenance
11	Scheduled maintenance
12	Gap day 1
13	Preparing EVA 3
14	EVA 3
15	Recovery EVA 3
16	Preparing EVA 4
17	EVA 4
18	Recovery EVA 4
19	Gap day 2
20	Research on humans
21	Ascent preparation
22	Ascent preparation
23	Ascent

Legend
Technical
Human research
Exploration
Preparation
Recovery
Breathing room*

Fig. 2. Mars operations schedule

To begin operations on Mars, the the first descent vehicle will land on the surface of the planet bringing the habitat, the communication system, the drones, the research equipment and the propellant necessary for the ascent. If the landing is successful, the second MDV will descend carrying the crew in their space suits and the Environmental Control and Life Support System.

The tasks of the crew on sol 21 and 22 are mainly focused on the preparation of the ascent. This includes transferring the fuel from the first MDV to the second one, which will cover the role of Mars Ascent Vehicle (MAV). The MAV will host the crew wearing spacesuits, along with the LSS and consumables needed during the ascent and the collected samples.

II. COMMUNICATION

A. *Communication to Earth*

Communicating between Mars and Earth will always have a time gap with an average of 20 minutes. Caused by the constellation of Mars, Earth, and Sun, there are also specific times when communication between Mars and Earth is not possible. This is caused by the fact, that Earth and Mars regularly (every 780 days) line up with the sun in between. Then every signal communication link is blocked [11]. Considering the timeline of the Mars-Mission, this will be the case approximately after half a year in Mars Orbit (one reason why it was chosen to ascend to Mars during the fist time in Mars orbit). However, it was decided not to rely on a direct communication link between Mars surface and Earth. Instead, communication over a cubesat system in the parking orbit of Mars will be used. The cubesat system will be part of the descent vehicle and launched into a circular parking orbit around Mars at an altitude of 3120 km (Mission Design). Therefore, the crew on Mars surface can communicate approximately every 4.43h for 1.44h with the cubesat system [12] (Mission Design [1]). During that time, Tom and Tina on Mars surface can upload research data in the orbit or receive important information from Earth. The cubesat system in the parking orbit will communicate with the transfer vehicle, which will be equipped with larger antennas to transfer the data back to the DSN (Deep Space Network) on Earth. Using this setup, a smaller High Frequency Antenna (with 400 megahertz) on Mars surface is enough (similar one is used by the rover Perseverance) [13]. Furthermore they will be able to transfer larger data-rates over this ”multi pitch” communication link (up to 2 megabits per second from the surface in the Mars parking orbit).

In case of the mission, the launch site has to be considered as well. Staying inside a Canyon will cause signal reflections by the rock walls [14]. It can be assumed that there is a good communication link during the time the cubesat system is approximately directly above the canyon. Taking all this into account, another antenna (X-Band Low-Gain Antenna) will be provided for a back-up communication way to Earth. This is considered for emergency cases only. The data rate is between 10 and 30 bits per second (to low to transfer a big amount of research information), depending on the used DSN antenna on Earth [13] [15].

B. *Communication on Mars Surface*

For communication during EVAs on Mars surface, a communication system integrated in the helmets will be provided. It will be based on the new technology from NASA which is used for EVAs on ISS. This includes speakers in the inside area of the helmet and furthermore some embedded voice activated microphones. They are able to activate on voice recognition of the astronaut. This is an upgrade compared to the old “snoopy caps” which are used before since the astronaut does not need to wear a cap under the helmet. The speakers' headphones are connected over a local radio frequency. Receivers and Senders are included on the backside of the suits and charged within storage batteries [16].

III. SPACE SUITS

Space suits are one of the core aspects of manned spaceflight and their design plays an important role in this mission. A wide variety of requirements need to be taken into account when designing a space suit that allows to complete EVAs on the surface of Mars, having to deal with the harsh conditions of the Martian environment. When compared to the suits being currently used on EVAs outside the ISS, Martian suits need to satisfy additional requirements to fulfil their roles. This said, given the very long duration of the mission, it is expected that the astronauts might need to conduct maintenance operations outside of the spacecraft. Therefore, in accordance with the Logistics group [17], the suit that is being designed for this mission needs to be able to fulfil both the requirements of EVAs on Mars and the requirements given by EVAs in space. This hybrid design is being named the H.E.R.O. suit (Hybrid Exploration and Repair Operations suit). The design of the various aspects of the suit is primarily focused on its use on Mars, as it represents its nominal application and it is the most critical in terms of requirements.

A. Thermal Regulation

First, given that temperatures on Mars range from +20 °C to -130 °C [5], a proper temperature regulation system represents a fundamental requirement. The thermal regulation system needs to take into account the sources of heat intake, i.e. solar radiation, Mars radiation, suit electronics, metabolic functions, and the heat loss, i.e. radiation and convection. The thermal environment of the space suit can be modelled as shown in Fig. 3.

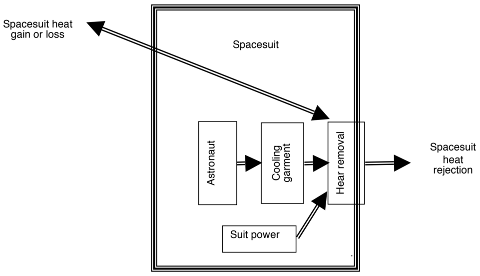


Fig. 3. Thermal environment of the space suit [18]

The extreme hot and cold temperatures are considered to size the thermal control system, although temperatures are expected to lie in the middle of the aforementioned temperature range during daytime near the landing location of the mission. Given the solar radiation on Mars of $q_{\text{Sun}} = 600$ W/m^2, assuming the coldest temperature of Mars surface of -130°C (143 K) and considering the sky to be 50 K cooler than the surface, the external temperature of the suit can be calculated with a balance of the heat flow ($Q_{\text{in}} = Q_{\text{out}}$), using equation (1). The calculation assumes equal surface area being exposed to the sky and to the martian ground. Note that solar heat radiation involves only the projected area of the suit, while heat radiated from the suit involves the area in its entirety. The space suit is covered by a white coating to reduce the solar heat load, with absorptivity $\alpha = 0.25$. Given the presence of martian dust, this value is expected to increase to 0.4. On the contrary, the emissivity of the white coating is very high, i.e. 0.85; this value is considered to be reduced to 0.7 for the same reason. The emissivity of Mars surface is 0.82 [19].

$$\begin{aligned}\alpha_{\text{suit}} q_{\text{Sun}} A/4 + \alpha_{\text{suit}} \varepsilon_{\text{Mars}} T_{\text{Mars}}^4 A/2 + \alpha_{\text{suit}} \sigma T_{\text{sky}}^4 A/2 \\ = \varepsilon_{\text{suit}} \sigma T_{\text{suit}}^4 A\end{aligned} \tag{1}$$

This calculation yields an external temperature of the suit of 201.6 K. As the suit is using advanced insulating material, its heat transfer coefficient is $k = 0.62$ W/(m^2 K) [18]; assuming the internal temperature of the suit to be 20°C (293 K) and considering a total surface area of 1.92 m^2, the conductive heat through the suit can be calculated using equation (2).

$$Q_{\text{cond}} = kA(T_{\text{int}} - T_{\text{ext}}) \tag{2}$$

The same calculations can be repeated considering the maximum temperature of the Martian surface of 20°C, obtaining a conductive heat loss of 38.6 W. The metabolic heat production of an astronaut during an Apollo EVA on the Moon averaged at 267 W, with a minimum of 140 W and a maximum of 465 W [18]; given the obvious lack of data, the same values are assumed for a Martian EVA. The overall heat production of the systems and the electronics of the suit is assumed to be 60 W. Considering the maximum possible heat intake from metabolic activity and from suit conduction, the holistic heat balance of the space suit results in a net maximum heat intake of 486.4 W. Given this heat load requirement, the heat removal system of choice is a radiator with heat pumps, with an overall heat capacity per unit mass of 160 Wh/kg [18]. Given the maximum duration of an EVA of 7 hours, this results in a mass of the cooling system of 21 kg. It is important to note that this cooling solution differs from the one adopted for EVAs on the ISS, which requires the evaporation of water in order to regulate the temperature of the space suit. This choice limits the overall requirements in terms of water and therefore mass. The cooling system can be regulated to different levels of heat loads in case an EVA outside of the orbiter needs to be performed.

B. Radiation Shielding

Radiations are vastly known to represent a menace for human health and the absence on Mars of a natural defence such as Earth's magnetic field requires the implementation of artificial means of protection against space radiation. A solution similar to the FLARE suit, described by Sèbastien Ruhlmann [20], was taken into consideration for shielding against solar radiation given its effectiveness, but was ultimately discarded as it does not pair well with the requirements of the missions, given its high mass and water requirement. Instead, radiation shielding in the suits is provided by a layer of material called Demron, a non-toxic polymer developed by Radiation Shield Technologies [21]. The material is lightweight and flexible and it therefore does not pose a limit in the manoeuvrability of the suit. In order to provide sufficient radiation shielding, a 0.8 mm layer is required [22]; given the density of the material of 3.14 g/cm^3, the mass requirement for radiation protection is 4.8 kg.

C. Dust Protection

Martian dust is known to represent a threat to human health and its damage is enhanced by the frequent winds that occur on the surface of the Red Planet. Mars dust is currently known to contain Hexavalent Chromium, which can cause cancer, a high concentration of Perclorates, which can cause problems to the thyroid, and highly oxidative particles, that negatively impact the respiratory and cardio-pulmonary systems [23]. For these reasons, counter measurements need to be adopted in order to remove dust from the space suit. The tendency of the dust to stick to surfaces not only causes it to enter the habitat, but it can also alter the thermal balance of the suit itself and impair mobility. For this reason an electron beam like the one developed by B. Farr et al. is adopted for the suits and the habitat [24] [25]. The work has shown promising results where the electron beam removed 83-92% of the dust on a space suit sample in 100 s. An electron beam will be permanently available in the habitat, while a portable version is meant to by carried by the astronauts during EVAs on the surface of Mars.

D. Mobility

The H.E.R.O. suit needs to allow a wide range of motions in order for the astronauts to be able to efficiently and effectively complete tasks in EVAs outside of the spacecraft and, most importantly, on the surface of Mars. In the first iteration of the design of the suit an exoskeleton was considered, in order to sustain the walk and enhance physical capabilities. These advantages though were not considered worth the significant increase of mass, and given also the fact that the assembly of the habitat does not require high levels of strength, the adaptation of an exoskeleton was discarded. In order to allow a full range of motions, rotational bearings (Fig. 4) are incorporated inside the suit, thus granting improved flexibility while also sustaining part of the loads [22].

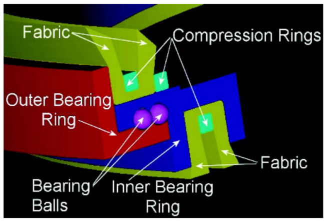


Fig. 4. Bearing apparatus

Gravity on Mars' surface is about 38% of Earth's; research found that the optimal walking speed on Mars is 3.4 km/h, while the optimal speed on Earth is 5.5 km/h [26]. While boots do not play an important role when it comes to EVAs in space, their design is key in order to allow the astronauts to properly walk on the surface of Mars. They need to provide a good balance between strength and flexibility, and the non-slip soles grant optimal balance on the impervious terrains of the Red Planet. A helmet that provides high visibility while also being durable enough to withstand Mars' sandstorms is also part of the design of the suit.

E. Material Choices

The suit is composed of a series of layers, each one absolving a different function. Other than the aforementioned layer of Demron for radiation protection, the layers of the suit are designed as follows:

Internal pressure layer. It functions as a barrier to eliminate the loss of gas and moisture and resists the permeation of contaminants (such as CO_2). This role is fulfilled by a layer of Ethylene vinyl alcohol (EVOH). It is a copolymer of ethylene and vinyl alcohol with excellent resistance to permeation of gases. This material is commercially available from Kuraray America Inc, thus it does not require any research and development costs [27].

Dampening layer. It absorbs and dissipates the energy from the impact of micrometeoroids and dust storms. The material chosen for this purpose is silicon elastomer, produced by Dow Corning under the name of Polysiloxane [28].

Structural layer. It provides backbone for the pressure garment and it stops the inner layers from expanding. This function is accomplished with the use of Polymide.

Insulation layer. It minimises the heat loss and ensures dimensional stability through the large temperature gradients. Polyethylene therephlalate (PET) was found to be the best material to minimize the heat lost due to thermal conduction. This material provides an effective barrier to moisture and oxygen and it can be used in a wide range of temperatures. It is used in combination with a thin layer of aluminium, that grants insulation from radiated heat. A thin layer of nylon is located between the insulating layers in order to permit relative movement and allow layers to shift and slip to avoid thermal stresses caused by the temperature gradient.

Impact, puncture and fire protection layer. Polyphenylene benzobioxazole (PBZO) is the rigid-rod polymer that efficiently accomplishes the functions of this layer. It is made by the Japanese manufacturer Toyobo and it is sold under the commercial name Zylon [29].

The overall mass of the different layers and the mobility bearings adds up to 20.9 kg.

F. Portable Life Support System

The Portable Life Support System (PLSS) of the H.E.R.O. suit needs to contain everything that is required in order to sustain a 7 hours EVA. Given the aforementioned walking speed of 3.4 km/h, the astronauts can explore the Martian environment in a radius of about 10 km from the habitat, with 1 hour of operational margin. According to the data provided by the Human Aspects group [2], the mass of oxygen requirement for 7 hours is 0.25 kg. In order to have a valuable safety margin, the PLSS includes 0.4 kg of oxygen. In order to remove CO_2 from the suit environment, adopting disposable LiOH cartridges would be too demanding in terms of mass. Instead, a modern regenerative system based on the absorption of CO_2 by a metal oxide is implemented, thus saving mass and providing additional oxygen [30]. To overcome the significant loss of water caused by long and physically demanding EVAs, the suit includes 1 kg of drinking water. Hygiene needs are met with the use of a Maximum Absorbency Garment.

G. Equipment

Several instruments and tools are needed in order for the astronauts to complete their mission, both when conducting an EVA in orbit and on the surface of Mars. The tools that equip the suit can be interchanged, therefore making the suit adaptable to the needs of the EVA. The equipment needed to conduct scientific research on the the Red Planet is covered in section V. Additionally, the suit requires microphones and cameras in order to record footage during operations and proper LED lights in order for the astronauts to effectively operate in different lighting conditions, while maintaining low power consumption.

During operations, various parameters need to be monitored, both regarding the suit and its user. Similarly to the system implemented in the ISS space suits, the space suit caution and warning system keeps under control a series of parameters that assure the safety of the astronaut and the correct progress of the mission. The values that are monitored include the oxygen pressure, the suit pressure, the ventilation flow, the CO_2 level, the temperature of the cooling system and the flow of its pump, battery discharge current and voltage [30].

The active systems that require power in order to operate are the cooling pumps, the ventilation loop of the Life Support System, the monitoring and control system, the communication equipment, the control electronics, the integrated cameras and LED lights. The overall maximum power consumption is estimated at around 90 W. Given the energy density of modern Li-ion batteries of 270 Wh/kg [ref], the suit requires a battery of 2.5 kg for a 7 hours EVA, considering a safety margin.

The overall mass breakdown of the space suit is shown in Tab. II (the mass of the research equipment is to be added depending on the EVA).

TABLE II
MASS BREAKDOWN OF THE SPACE SUIT

Component	**Mass [kg]**
Layers of materials	20.9
Cooling system	21.0
PLSS and consumables	10.3
Electronics and monitoring	0.4
Battery	2.5
Total	*55.1*

IV. VEHICLES

In this section, space exploration vehicles are discussed. Instead of using traditional autonomous rovers alone which is significantly time-consuming as well as making the exploration slow and inefficient as some obstacles may be in the path of the rovers; thus, the exploration can become faster and more efficient by using the aerial vehicle, drone. Drones can take images, survey things on a larger scale, scout ahead and get images of places that is not able to reach on the ground. Also, drones would allow seeing over that hill and scouting the terrain that is otherwise masked by other topography. While it is controversial in the past about how a drone can fly in the thin or nearly vacuum atmosphere on Mars, NASA has successfully sent the first aircraft in history to make a powered, controlled flight on another planet on 18th of February [31].

The Mars helicopter, Ingenuity, is the first successful helicopter from NASA to fly on a planet other than Earth, Mars. Due to its low mass of 1.8 kg, Ingenuity satisfies the mission requirement that is lightweight. The number of drones brought to the Martian surface is set to be 2 for redundancy. The illustration and the anatomy of the Mars Helicopter are shown in Fig. 5 [31].

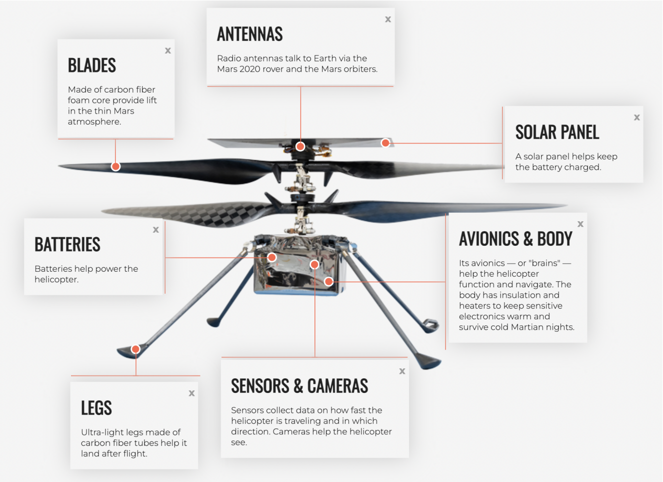


Fig. 5. Ingenuity components

The overall structure is not complex, and it only has 6 main components. The drone itself is operated by solar-charged Lithium-ion batteries that power dual counter-rotating rotors mounted one above the other. The blades are made of carbon fibre foam core and have a span of 1.2 meters from tip to tip. The radio antennas are equipped at the top for communication. Its avionics or brains helps the helicopter to fly autonomously, without human control. Sensors collect data on how fast the helicopter is travelling and in which direction, and two cameras which are black and white navigation camera and a colour camera for terrain images are also attached. Then, the last component is the legs which help the helicopter land after flight. Ingenuity is attached to the belly of the Perseverance rover in order to travel to the interesting exploring location and must safely detach to begin the flight. However, the rover is considered too heavy for the mission since its mass is approximately 1000 kg [32]. Also, the astronauts can carry the drone with them to scout the terrain once considered out of sight and reach or it can be used at the habitat for reconnaissance before doing some EVAs on the Martian surface [31].

Currently, the helicopter was designed to fly for up to 90 seconds, to distances of almost 300 meters at a time and up to 5 meters from the ground. Although the flight duration, flight altitude, and flight range are short, it is a significant achievement for the Human race. The knowledge can now be applied to many other planets and moons that humanity might aspire to explore. In the next few years, many other flying drones are expected to follow, but first Ingenuity has to prove that it can fly and survive the harsh Martian environment. The next generation of a rotorcraft could be in the range between 5 and 30 kg with science payloads between 0.5 and 5 kg.

Six-rotor might be implemented to increase flight range and endurance [33].

V. RESEARCH

Research exploration over the past decade has provided more detailed information about Mars and its history. It has been achieved through three main factors: (a) a focused effort to acquire compositional data, which offers a new lens through which to decipher the history of the planet and complements photographic morphologic data available since the Mariner and Viking missions; (b) observations of the surface at increasingly high spatial and spectral resolution, provided by the ever-increasing capabilities of orbital instruments; and (c) in situ exploration and small-scale measurements by rovers and landers [4]. It is very important to utilize the information obtained from these efforts to conduct further research and exploration through the manned missions. In general, there are mainly four goals: (1) Life, (2) Climate, (3) Geology, (4) Human [34]. First goal; life is an important issue for exploring whether Mars could have been similar to the Earth and whether it had life or the environment for life to survive. The origin of life is said to be the greatest scientific question of our time [35]. Thus, investigating whether life can survive in non-terrestrial environments is of interest. Second goal; climate is based on the fundamental question of how the climate of Mars has changed over time to its present state, and what causes it to change. It is also important to understand the similarities and differences that emerge when comparing the climates of Mars and the Earth. Third goal; geology is to gain insight into the composition, structure and history of Mars as a planet. This leads to understand the origin and evolution of Mars as a geological system. Last goal; human aims to explore the potential for the possibilities if humans can survive on Mars and the risks during operations in further manned missions and gain insight into the future manned mission design.

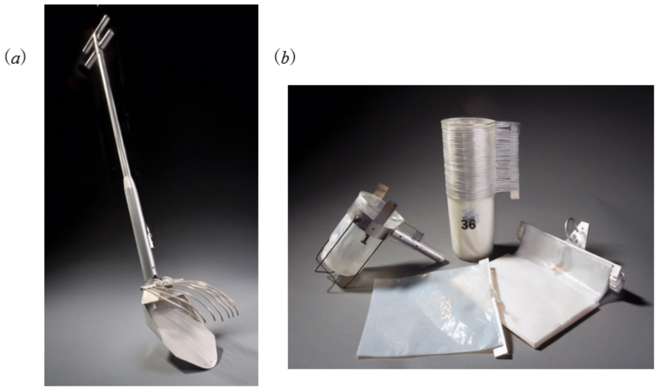


Fig. 6. Sample collecting tools. (a) Conbined scoop and tong tool (Scong), (b) Sample bags.

In the Mars mission, samples from the Mars surface will be collected through EVAs and brought back to Earth in order to achieve the above goals as much as possible. For collecting samples, there are several possible ways, such as using the hands, using tools, and using drones equipped with a sample collecting system. However, there is concern about damages to the space suit if the sample has sharp edges caused by using hands to collect samples. Furthermore, while mounting the sample collecting system on the drone would allow for us to collect samples at farther distances, it force a more complex structure of the drone, which leads to increased mass. Thus, a combined scoop and tong tool will be used for sample collection. The collected samples are stored in the sample bags as shown in Fig. 6 [36].

It would also be valuable to investigate the effects on human bodies in the Mars environment. The interest here is how human bodies react on other planets. The risks to be considered for human bodies can be summarized with the acronym “RIDGE,” short for Space Radiation, Isolation and Confinement, Distance from Earth, Gravity fields, and Hostile/Closed Environments [37]. By understanding these risks in depth, one can learn keys for future manned missions toward longer-duration mission. In addition, as explained previously, the use of drones will also be a great help to explore Mars.

Humans will likely undertake long-duration missions to Mars within the next few decades. In that case, since it costs more to transport all resources from Earth, local resources should be used on Mars [38]. Also, further use of space exploration vehicles, such as drones and rovers will allow more exploration for longer distances, which helps collecting a wide variety of samples and to build a Mars space base.

When considering a long-duration mission, taking into account the effects of radiation will be more important. In recent years, the possibility of radiation shielding in Martian cavities and their entrances has been investigated by simulations [39]. Exploration of such sites will allow further geological investigations and may lead to the discovery of suitable habitats for living organisms.

VI. MARS HABITAT

The habitat for the crew needs to contend with the harsh conditions on the surface of Mars. It must provide all the necessary environmental control and life support systems (ECLSS). The structure of the habitat need to maintain the internal pressure, allow EVAs to be performed, and be strong enough to protect the crew from other potential hazards. From the requirements and constraints of the mission, it ought to be low mass and easy to use.

A. Environmental control and life support systems

The habitats ECLSS need to maintain the atmosphere, provide thermal control, remove excessive carbon dioxide and toxic particles. An open loop system will be used for the ECLSS on the surface, rather than a regenerative system, since the duration is relatively short.

Breathing pure oxygen for an extended duration can be harmful to the human body. The habitat should therefore contain a combination of oxygen and nitrogen. The Earth’s atmosphere is composed of about 78% nitrogen and 21% oxygen. The standard atmospheric pressure on the Earth is 101.3 kPa. The Skylab space station had an atmosphere containing 74% oxygen and 26% nitrogen, at a total pressure of 34 kPa [40]. A similar atmosphere will be used inside the

Mars habitat. Lower pressure implies less mass, which is one of the mission's primary objectives.

A regenerative carbon dioxide scrubbing system is not suitable to bring to the surface of Mars due to the short stay. ISS uses a lithium hydroxide-based (LiOH) system to complement the regenerative scrubbing system [41]. The canisters on ISS has 3 kg of LiOH pellets and a total mass of 4 kg. 1.5 kg of LiOH pellets is required per person and day. Consequently, one canister is needed per day for the crew, which brings the total mass to 92 kg for the entire stay on the surface.

The habitat should contain both a passive and an active thermal control system. The passive system will be composed of a multi-layer insulation of appropriate materials, which will retain the heat. The active thermal control system will be composed of a sublimator/evaporator and a heater connected to the habitat.

A big concern exists about the potential damage to the human body Marsian soil can cause. A lot of the dust on the surface is magnetic and will stick to the space suits when the crew perform EVAs. An electron beam will be used before entering the habitat to mitigate most of the dust from the space suits. However, dust will inevitably still enter the habitat. Therefore, the habitat also needs a dust removal system. An air filter inside the habitat will remove some of the dust, but another option is also necessary. NASA has suggested to use a magnetic wand or something similar to mitigate lunar dust [42]. This could be used to mitigate dust inside the Mars habitat.

1) Consumables: An average human needs 0.84 kg of oxygen per day. A stay of twenty-three days on the surface means that 38.64 kg of oxygen is required solely for breathing. If the launch window for the ascent is missed due to an unexpected event, they might have to stay for up to three more days. Therefore 5.04 kg of extra oxygen should be brought, giving a total of 43.68 kg oxygen for breathing.

Each crew member will be allowed to consume 4.4 litres of water per day on the surface. This amount will be used for drinking, dehydrating food, and hygiene. The crew will consume 202.4 litres of water on the surface. 26.4 litres of extra drinking water should be brought if an unexpected event would occur, giving a total of 228.8 litres for water consumption.

The Human Aspects group stated that each crew member consumes 2.49 kg of food each day. A stay of 23 days gives a total food consumption of 114.54 kg. A three-day safety margin gives 129.48 kg for the total food mass.

The total mass of consumables for the 23 days on the surface, with a three-day margin, was estimated to be about 402 kg.

B. *Habitat alternatives*

A permanent habitat would not suit the mission due to the short stay on the surface. The objective is to make the Mars mission as low-mass and straightforward as possible. A permanent habitat would be too complicated to build in the limited amount of time, and it would be too heavy for this mission. Two different alternatives of a temporary Mars habitat was analysed. The first option was to have one MDV pressurised and used as a habitat. The second option was to bring an inflatable habitat to the surface. The two alternatives are discussed in the upcoming sections.

C. *Pressurised Mars descent vehicle*

Using landers as habitats is a concept used before. The Lunar Module (LM) functioned as the habitat during the Apollo Lunar landing [43]. The concept of using the MDV as a habitat on Mars has been in discussion for many years. NASA had a proposal in the 1960s to use the MDV as a short stay habitat on Mars, called Mars Excursion Module (MEM) [44] [45]. The MEM would function as the MDV, habitat, and MAV. Although the project did not get past the conceptual stage due to a lack of funds, the concept was promising.

The C.R.I.M.S.O.N. mission will use two MDVs. The first MDV to descend from LMO to the surface will contain supplies and propellant for the ascent. If the landing is successful, the second MDV with the crew will descend. The second MDV that brings the crews to the surface could be pressurised and used as the habitat. The first MDV would be unpressurised to save mass.

Since one of the primary objectives of the project is to minimise mass the MDV will be as small as possible. The Kang rocket used for launches from Earth to LEO has a maximum diameter of 2.5 m, which puts a constraint on the MDV. The mission plan is to stay 23 days on the surface. The main concern of using one of the MDVs as the habitat is the vehicle size. The limited size would make it rather difficult to live in for that amount of time. Consequently, an inflatable habitat concept was also analysed.

D. *Inflatable habitat*

The concept of inflatable habitats was considered by NASA as early as the 1960s. A wide variety of designs have been made since then, e.g. NASA's TransHab concept in 1999 [46]. Inflatable or expendable modules offer great potential for mass and volume savings for space missions. Expendable modules have been tested and used in space before, e.g. the Bigelow Expandable Activity Module (BEAM) that was attached to the International Space Station in April 2016 [47]. Inflatable habitats have potential to meet the requirements of a Mars habitats. A few advantages of inflatable habitats over rigid habitats are packaging efficiency, flexibility, and psychological benefits for the crew [48]. An inflatable habitat can offer low mass, be portable, and have a sizeable packaged-to-inflatable volume ratio. The main concerns of using the MDV as a habitat is the size and mass. Minimising the mass implies that the MDV should be small. Thus, an inflatable habitat could be a practical option for the C.R.I.M.S.O.N. mission.

Samuel S. Schreiner et al. designed an inflatable habitat for Lunar exploration [49]. The intention is to increase range and safety for Lunar explorations that use an unpressurised rover. The designed system is composed of an inflatable habitat, ECLSS, a solar shield, and a solar power array. The system would allow the crew to rest for eight hours away from the

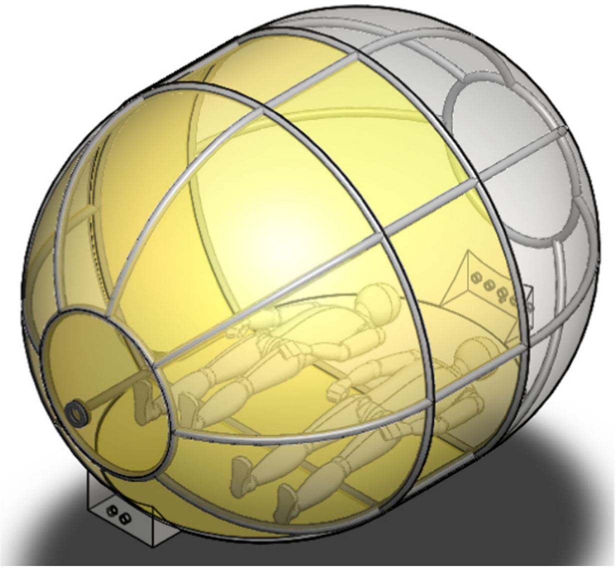


Fig. 7. Inflatable habitat for a crew of two astronauts [49]

primary habitat. The concept of the inflatable habitat is shown in Fig. 7.

The inflatable habitat designed by Schreiner et al. is intended for the Lunar surface, and the ECLSS on the unpressurised rover can maintain an atmosphere for eight hours. The circumstances for the C.R.I.M.S.O.N. mission in this paper is considerably different. However, the same concept can be used with a few adjustments. No rover will be brought to Mars to minimise mass, and the ELCSS need to maintain an atmosphere for the entire duration on the surface. The solar shield and solar power array will not be used.

1) Material and structure: The atmospheric pressure on the surface of Mars is around 6.5 millibars at ground level. When the interior is not entirely pressurised, the habitat requires support structures to sustain its shape. The support structure will consist of inflatable ribbings. Similar ribbings are used in multiple constructions on Earth, e.g. the NASA polar habitat developed by ILC Dover, Inc [50], the military STAT tent [51], and commercially used inflatable tents. The inflatable ribbings can sustain the habitat's shape when the inside is unpressurised. A fibre-reinforced elastomeric composite material will allow the ribbings to contain high pressure and strengthen the structure.

The walls and ceiling will consist of multiple layers of fabric-like material covering the air bladder. The construction will consist of a urethane-coated bladder, followed by a nylon liner layer, and finally, a few layers of woven Vectran fabric restraint. The Vectran fabric provides strength to withstand the pressure. The urethane bladder is used to maintain the atmosphere without leakage. The nylon liner intends to provide a soft layer to protect the air bladder. The LIFE habitat currently being tested by Sierra Nevada [52] is using the same materials. Another option than Vectran could be Kevlar, which possesses similar tensile strength. However, Vectran is much more flexible than Kevlar and might be more suitable for an inflatable habitat.

Tab. III presents the optimised geometry of the inflatable habitat designed by Schreiner et al.. The total mass of solely the inflatable habitat was estimated to 35 kg.

TABLE III
INFLATABLE HABITAT GEOMETRY [49]

Optimised geometry	
Cylinder radius	1.29 m
Cylinder flat side length	0.75 m
Maximum floor width	1.80 m
Maximum floor length	2.55 m
Maximum height	2.21 m
Interior volume	12.00 m^3
Door height	1.84 m

2) Airlock: The habitat will have an airlock system integrated. Schreiner et al. designed a low mass, airtight, flexible membrane. With the membrane attached inside the habitat, the internal volume can function both as the habitat and airlock. Fig. 8 illustrates how the flexible membrane is used. The crew will first pressurise the inflatable ribbings. Then they can enter on the airlock side, pressurise the internal volume, remove the suits, and finally move into the habitat side. A valve is attached to allow airflow between both sides of the membrane. It would be possible to open the hatch without wasting the entire atmosphere with the membrane. It was estimated that 40% of the internal atmosphere would need to be vented when opening the hatch.

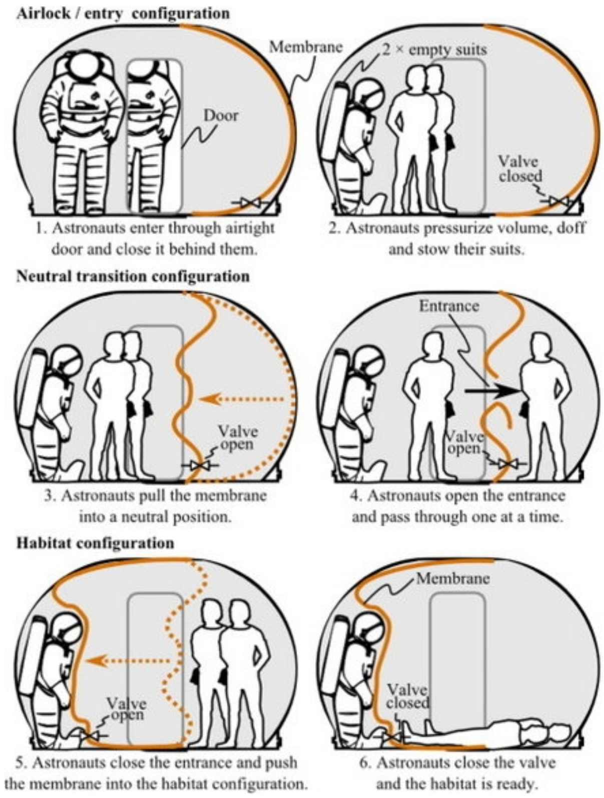


Fig. 8. Airlock system with a flexible membrane [49]

3) Environmental control and life support system: The habitat will use two thermal control systems, a passive and an active. Multi-layer insulation made of appropriate materials will retain heat and function as the passive system. The mutli-layer insulation will be made of beta cloth. It is a woven fibreglass cloth that is impregnated with Teflon [53]. Although a good material choice and an appropriate number of layers would provide reasonable thermal control, an active system is necessary. The active thermal control unit will be composed of a sublimator/evaporator and a heater connected to the habitat via umbilical cables.

The internal pressure in the habitat will be similar to what the NASA Skylab space station used. That is 74% oxygen and 26% nitrogen at a pressure of 34 kPa. The ideal gas law (3) was used to approximate the mass needed for inflating the habitat.

$$pV = nRT, \tag{3}$$

where p is the internal pressure, V is the internal volume, n is the number of moles, R is the gas constant, and T is the internal temperature. Assuming pure oxygen at 34 kPa and a temperature of 295 K, the required oxygen mass for pressurising the habitat is approximately 5.32 kg. The crew needs 43.68 kg of oxygen for breathing on the surface. Assuming the inflatable ribbings need 1.5 kg of gas, that 40% of the internal atmosphere escapes when opening the hatch and that the hatch will be opened eight times, the mass was estimated to be 66 kg for pressurising the habitat and breathing. It was decided to bring 70 kg to the surface for an extra safety margin and to compensate for leakage and ullage of gas.

Each crew member will be allowed to use 4.4 kg of water per day for drinking, dehydration food, and hygiene. 228.8 kg of water will be brought for consumables. The thermal control unit uses water to maintain a comfortable temperature. Using data from Schreiner et al. it was estimated that the systems need approximately 37 kg of water during the stay on the surface. A total of 266 kg of water will be brought to the surface.

The total mass of the ECLSS system, including the hardware and consumables, was estimated to be around 575 kg. The total mass, including the habitat, is approximately 610 kg.

It was estimated that 300 W would be required when using the ECLSS and recharging the space suits. Solar arrays would not be efficient on the landing site. Therefore, it was decided to use fuel cells. The Logistics group calculated that 62 kg of fuel cells would be required for the stay on the surface.

4) Radiation protection: The lack of magnetosphere around Mars means radiation is a significant concern on the surface. According to the paper ”New Results from the MSL-RAD Experiment on Curiosity” [54] the equivalent dose rate from GCR is 0.64 mSv/day on the surface. A stay of 23 days would give a dose of nearly 15 mSv. The habitat will have multiple layers of Vectran, beta cloth, and nylon liner. These layers would give the crew a little radiation protection from GCR and SPE. Due to the short duration on the surface, passive shielding should provide ample radiation protection.

VII. OFF-NOMINAL CASE

One off-nominal case considered was habitat failure. The habitat is a critical part of Mars operations and the crew's survival. Since it is inflatable, the risk of failure might increase, such as incapability of inflating, leaks, or other damages. More minor damages can be repaired on the surface. However, severe failures that are impossible to repair quickly will require the crew to leave the surface prematurely.

Leaving earlier than intended introduces a few additional problems. First, the crew has to prepare the vehicle for the ascent. Two days are allocated for ascent preparations, but they might need to do it in less time. They also need to wait for a launch window. The transfer vehicle will be in a large orbit around Mars, as decided by the Mission Design group. The worst-case scenario is a waiting time of three days.

One solution is to bring a small extra inflatable. It can be placed inside the MAV and be connected to the ECLSS. This will allow the crew to survive without the primary habitat for a few days. Furthermore, the crew must leave some of the consumables on Mars in case of a premature leave. The MAV propulsion system and fuel mass are designed for the nominal ascent mass. This requires that the transfer vehicle in orbit has extra consumables stored.

VIII. CONCLUSIONS

Designing a Mars mission scheduled for launch in a few years is challenging. The primary goals for Mars Operations were to design the space suits, the habitat, life support systems and decide what operations to conduct on the surface. Minimising the mass while ensuring the safety of the crew was the primary objective of the project. This puts a lot of constraints on the mission and limits the possibilities on Mars. It was decided to not use a rover, which restricts the area of exploration. Instead, drones will be used to allow some further exploration of the surrounding, while being low mass. They are operated by solar-charged lithium-ion batteries, thus avoiding the need to bring extra batteries. In order to conduct the scientific research on Mars, samples will be collected using tools on the surface through EVAs and bring them back to Earth.

To save as much mass as possible, the weight of the communication system on Mars surface was also limited. Due to the fact that the connection delay to Earth is around 20 minutes (no chance of immediately response), the crew has to face the reality to be on their own and solve possible problems without further help. It was decided to bring a high gain antenna (similar to the one used by rover perseverance) to Mars surface. Since this antenna only needs to communicate with the cubesat launched by the mission in Mars' orbit, it can be much smaller and lighter then the antennas on the transfer vehicle which have to send signals all the way back to the DSN on Earth. Although a perfect communication is not possible (considering the landing side in the canyon) it is a good compromise between budget, weight and still being able to guarantee to send/receive signals to/from Earth most of the time.

In addition, it was also decided that an inflatable habitat would be used. A permanent habitat would be more time consuming and less mass efficient to bring. Using a pressurised MDV as the habitat would require more mass than the inflatable habitat. One disadvantage of the inflatable habitat is the uncertainty in TRL. It must be analysed and tested before launch. It might require more than four years until it is ready. The environmental control and life support systems for the habitat was solely analysed at a conceptual state with rough estimates from different sources. It was deemed out of the scope of this project to design a complete ECLSS. Therefore, it needs a lot more thorough analysis and testing before launch.

The dust mitigation technologies are at a conceptual state and need more research. One idea could be to use similar technology as the Artemis project will use on the lunar surface, which most likely will launch before the C.R.I.M.S.O.N. mission. Moreover, long-duration Mars mission will likely be carried out within a few decades, where further dangers such as radiation need to be considered. It will be another giant leap for mankind.

Lastly, a mass breakdown of all subsystems for the surface is presented in Tab. IV.

TABLE IV
MASS BREAKDOWN FOR THE DESCENT.

System	Mass [kg]
Crew	140
Space suits (2)	110
Habitat	35
ECLSS for the habitat	575
Drones (2)	3.6
Power supply	62
Research equipment & tools	30
Communication system	10
Total	966

IX. WORKLOAD BREAKDOWN

A. Ina Taxis

Ina focused mainly on the communication possibilities between Mars surface and Earth but also for communication between the crew members during EVAs. Moreover collected some intel on Drones.

B. Nannaphat Kusolphisarnsut

Nannaphat mostly focused on the vehicle that works on Mars, and discussed about the schedule on the Martian surface with the team members.

C. Naoki Moriya

Naoki mainly worked on the research on Mars, and also covered fundamental information of Mars, landing site, and environmental constraints.

D. Mathias Dahlman

Mainly worked with the habitat and its environmental control and life support systems. Also conducted some research about dust mitigation strategies and the off-nominal case.

E. Meredith Moore

Worked on general research and compiling information for the abstract and introduction.

F. Renato Franzè

Mainly worked on the research and design of the space suits and their various subsystems and components.

REFERENCES

[1] B. Günay B. Sosa H. Venkatesan J. Götz L. Byrne, K. Seidel. Low mass human mission to mars blue team - mission design report.

[2] L. Murphy. M. Chillet W. Widyatmoko K. Persson, K. Nordström. Low mass human mission to mars blue team - human aspects. March 2022.

[3] Edward Clinton Ezell and Linda Neuman Ezell. *On Mars: Exploration of the Red Planet, 1958-1978*, volume 4212. Scientific and Technical Information Branch, National Aeronautics and Space ..., 1984.

[4] Bethany L Ehlmann and Christopher S Edwards. Mineralogy of the martian surface. *Annual Review of Earth and Planetary Sciences*, 42:291–315, 2014.

[5] Dr. David R. Williams. Mars fact sheet. 2020.

[6] Heather B Franz, Melissa G Trainer, Charles A Malespin, Paul R Mahaffy, Sushil K Atreya, Richard H Becker, Mehdi Benna, Pamela G Conrad, Jennifer L Eigenbrode, Caroline Freissinet, et al. Initial sam calibration gas experiments on mars: Quadrupole mass spectrometer results and implications. *Planetary and Space Science*, 138:44–54, 2017.

[7] Lewis R Dartnell. Ionizing radiation and life. *Astrobiology*, 11(6):551–582, 2011.

[8] L. Murphy. M. Chillet W. Widyatmoko K. Persson, K. Nordström. Low mass human mission to mars blue team - human aspects. March 2022.

[9] NASA. Investigating mars: Candor chasma. https://mars.nasa.gov/resources/21432/investigating-mars-candor-chasma/.

[10] NASA. Muscle atrophy. https://www.nasa.gov/pdf/64249main_ffs_factsheets_hbp_atrophy.pdf.

[11] esa. New concept may enhance earth-mars communication. https://www.esa.int/Enabling_Support/Operations/New_concept_may_enhance_Earth-Mars_communication, 2009.

[12] Lubab A. Salman Ayman N. Mohi, Jabir S. Aziz. Cubesat communication system, a new design approach, 2015.

[13] NASA. Mars 2020 mission perseverance rover : Communications. https://mars.nasa.gov/mars2020/spacecraft/rover/communications/.

[14] unauthored. Propagation issues for communication between earth and mars. https://descanso.jpl.nasa.gov/propagation/mars/MarsPub_sec7.pdf.

[15] 'NASA'. The mars relay network connects us to nasa's martian explorers. https://mars.nasa.gov/news/8861/the-mars-relay-network-connects-us-to-nasas-martian-explorers/.

[16] unauthored. The space suit. https://www.hq.nasa.gov/office/pao/History/SP-4026/noord47.html.

[17] L. Messmer S. Stenberg W. Josefsson Rudberg G. Dal Toso, J. Salminen. Low mass human mission to mars blue team - logistics report.

[18] Harry Jones. Spacesuit cooling on the moon and mars. 07 2009.

[19] C. Chase. The temperature of mars. https://rdcu.be/cIx0Q.

[20] Sébastien Ruhlmann. The flare suit: A protection against solar radiation in space. Master's thesis, KTH, Space Technology, 2019.

[21] Demron, radiation shield technologies. https://radshield.com/.

[22] J. Marcy, A. Shalanski, M. Yarmuch, and B. Patchett. Material choices for mars. *Journal of Materials Engineering and Performance*, 13:208–217, 04 2004.

[23] Robert W Moses, Dennis Bushnell, David R Komar, Sang Choi, Ronald Litchford, Franklin Chang-Diaz, and Mark Carter. Maintaining human health for humans-mars. In *2018 AIAA SPACE and Astronautics Forum and Exposition*, page 5360, 2018.

[24] B. Farr, X. Wang, J. Goree, I. Hahn, U. Israelsson, and M. Horányi. Dust mitigation technology for lunar exploration utilizing an electron beam. *Acta Astronautica*, 177:405–409, 2020.

[25] B. Farr, X. Wang, J. Goree, I. Hahn, U. Israelsson, and M. Horányi. Improvement of the electron beam (e-beam) lunar dust mitigation technology with varying the beam incident angle. *Acta Astronautica*, 188:362–366, 2021.

[26] Giovanni Cavagna, Patrick Willems, and N Heglund. Walking on mars. *Nature*, 393:636, 07 1998.

[27] Eval, kuraray america inc. https://eval.kuraray.com/products/eval-resin/.

[28] Polysiloxane, dow corning. .

[29] Zylon, toyobo co., ltd. https://www.toyobo-global.com/seihin/kc/pbo/.

[30] C. Norberg. *Human Spaceflight and Exploration*. 01 2013.

[31] NASA. Mars helicopter tech demo. https://mars.nasa.gov/technology/helicopter/#.

[32] NASA. Nasa's ingenuity mars helicopter succeeds in historic first flight. https://www.nasa.gov/press-release/nasa-s-ingenuity-mars-helicopter-succeeds-in-historic-first-flight.

[33] Wikipedia. Ingenuity(hellicopter). https://en.wikipedia.org/wiki/Ingenuity_(helicopter).
[34] Don Banfield, Jennifer Stern, Alfonso Davila, Sarah Stewart Johnson, David Brain, Robin Wordsworth, Briony Horgan, Rebecca ME Williams, Paul Niles, Michelle Rucker, et al. Mars science goals, objectives, investigations, and priorities: 2020 version. *Mars Exploration Program Analysis Group (MEPAG)*, 2020.
[35] Elizabeth Howell and Nicholas Booth. *The Search for Life on Mars: The Greatest Scientific Detective Story of All Time*. Arcade Publishing, 2020.
[36] Smithsonian National Air and Space Museum. Apollo to the moon: Sampling the moon. https://airandspace.si.edu/exhibitions/apollo-to-the-moon/online/science/sampling-the-moon.cfm.
[37] NASA. The human body in space. https://www.nasa.gov/hrp/bodyinspace.
[38] David Karl, Kevin M Cannon, and Aleksander Gurlo. Review of space resources processing for mars missions: Martian simulants, regolith bonding concepts and additive manufacturing. *Open Ceramics*, page 100216, 2021.
[39] D Viúdez-Moreiras. The ultraviolet radiation environment and shielding in pit craters and cave skylights on mars. *Icarus*, 370:114658, 2021.
[40] Leland. F. Belew. Skylab, our first space station. ed. (1977). NASA Scientific and Technical Information Office. OCLC 2644423. SP-400.
[41] John T. James and Ariel V. Macatangay. Carbon dioxide - our common ”enemy”. 2009.
[42] Juan H. Agui and Dennis P. Stocker. Nasa lunar dust filtration and separations workshop report. 2009.
[43] T.E. Ford. The apollo lunar module: A description of the construction of the lunar module used to make the first manned landing of a space vehicle on another planet. Aircraft Engineering and Aerospace Technology, Vol. 41 No. 10, pp. 26-28. (1669). Accessed 16 February, 2022.
[44] Project deimos. Astronautix. Retrieved 16 February 2022.
[45] G. R. Woodcock. An initial concept of a manned mars excursion vehicle for a tenuous mars atmosphere. NASA.(7 June 1966). Retrieved 10 February 2022.
[46] Kim Dismukes (curator). Transhab concept. NASA.gov. Archived from the original on 2006-06-27. Retrieved 2022-02-19.
[47] Spacex crs-8 mission overview. NASA. Retrieved 19 February 2022.
[48] M. Roberts. Inflatable habitation for the lunar base. The Second Conference on Lunar Bases and Space Activities of the 21st Century, Volume 1. (September 1, 1992). Bibliographic Code: 1992lbsa.conf..249R. Accessed 18 February 2022.
[49] Samuel S. Schreiner, Timothy P. Setterfield, Daniel Richard Roberson, Benjamin Putbrese, Kyle Kotowick, Morris Vanegas, Mike Curry, Lynn M. Geiger, David Barmore, Jordan J. Foley, P Latour, Jeffrey A. Hoffman, and James W. Head. An overnight habitat for expanding lunar surface exploration. *Acta Astronautica*, 112:158–170, 2015.
[50] David P. Cadogan and Craig R. Scheir. Expandable habitat technology demonstration for lunar and antarctic applications. 2008.
[51] K. Cowing. Using a planetary analog to test a prototype inflated habitat for nasa. NASA.(7 June 1966). Retrieved 24 February 2022.
[52] B. Evans. Uv. AmericaSpace.com. Retrieved 24 February 2022.
[53] Rachel R. Kamenetzky and Miria M. Finckenor. Msfc investigations of beta cloth darkening due to ultraviolet radiation interactions. NASA. (1999).
[54] Zeitlin C. et al.. New results from the msl-rad experiment on curiosity. NASA. Eighth International Conference on Mars (2014).
[55] F. Ohlson R. Sitthinuncharoen J. Carra, K. Ketsumpan and L. Stoppa. Low mass mission to mars blue team - project management report.
[56] O. Malm T. Holmboe S. Weißenböck L. Wullschleger C. Segretin, K. Wen. Low mass mission to mars blue team - transfer vehicle report.
[57] Rob Garner. How to protect astronauts from space radiation on mars. NASA. Archived from the original on March 6, 2016. Accessed 15 February, 2022.
[58] et al. James T.F. Wise. Comparative toxicity of lunar, martian dust simulants, and urban dust in human skin fibroblast cells. *Gravitational and Space Research*, 3(1):51–58, 2015.
[59] Pedro Lopez, Eric Schultz, Bryan Mattfeld, Chel Stromgren, and Kandyce Goodliff. Logistics needs for potential deep space mission scenarios post asteroid redirect crewed mission. In *2015 IEEE Aerospace Conference*, pages 1–10, 2015.
[60] Georgina Torbet. Cosmic comms: How the first humans on mars will communicate with earth, 2021.