Low Mass Human Mission to Mars Blue Team - Transfer Vehicle Report

Christophe Segretin, Kaibin Wen, Oscar Malm, Thomas Holmboe, Stephan Weißenböck and Léa Wullschleger
All authors are MSc students at KTH Royal Institute of Technology, Stockholm, Sweden
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***Abstract*—The goal of this study is to conceptualize a transfer vehicle for a complete Mars mission from LEO to LMO and with a return to Earth. This mission was given to our Team CRIMSON by the startup Pythomspace, where Tina and Tom Sjögren, two experienced adventurers, are the crew members. The main goal is to provide a vehicle as simple and light as possible. The transfer vehicle contains several big modules of which a CAD model has been made. At the front there is the Node, where is attached an Earth return capsule, one MAV and MDV and an airlock allowing EVAs. It is linked with an inflatable habitat with all storage and life support system needed for the journey. Then a power module which supports $700\mathrm{m}^2$ of solar panel and $84\mathrm{m}^2$ of radiators is able to regulate the temperature of the vehicle and provide it 11.4 kW. Finally, there is a propulsion system with 5 Asterex engine providing 1000 kN of thrust in total and a mix of propellant of HNO3 : Furfuryl with a ratio 2:1. The whole transfer vehicle has a total wet mass of 380.1 tonnes and a total dry mass of 73.3 tonnes. The most of it is divided in components of 3 tonnes in order to be launched by the launcher Kang. But the inflatable module, MAV, MDV and the whole amount of propellant will be launched by Falcon Heavy.**

***Index Terms*—Interplanetary travel, Human Spaceflight, Mars, Transfer vehicle, Mass Budget, CAD Design**

I. Introduction

A. Mission Goal

The startup Pythomspace has the vision to make a human mission to Mars within the next 5-6 years. The founders and driving minds of Pythomspace are the two explorers and adventurers Tina and Tom Sjögren. During their expeditions to Mount Everest and skiing to the two Poles they have learnt how to survive with minimum gear and how to design their own lightweight equipment. Thus, their idea is to make the mission as simple and low-mass as possible.

The goal of this project was thus to design a minimum mass human mission to Mars based on Pythomspace´s general ideas with keeping the total mass to LEO as low as possible being the prime goal.

To cover all aspects of the mission C.R.I.M.S.O.N (Crewed Return Interplanetary Mission for Surface Observation and New research) see Figure 1, the C.R.I.M.S.O.N Team was divided into smaller teams, which includes project management, logistics, transfer vehicle, mars operation, mission design and human aspects. This report presents the concepts developed by the transfer vehicle team.

Fig. 1. Logo of the C.R.I.M.S.O.N mission

After presenting the scope of work of this team and the assumptions, an overview of the mass budget will be presented. The solutions for the propulsion system will also be detailed. Finally, an overall description of the design of the space vessel as well as a focus on the different modules complete this paper.

B. Scope of the Transfer Vehicle work

The Transfer Vehicle team had the responsibility to design a transfer vehicle enabling the trip from LEO to LMO as well as the trip back.

In order to do so, the following tasks were defined:

- Mass budget of the transfer vehicle and partition of mass in the vehicle
- Characteristics of the propulsion system
- CAD model and design of the transfer vehicle
- Iteration with the other teams (Logistics for the sizing of the power system and discussion on the design; Mission Design for the ΔV; Human aspects and Mars operations for the mass)

C. Assumptions

Some assumptions were considered as a starting point. An important aspect considered was the feasibility of the transfer vehicle and the technologies used. Indeed, as the mission is set for the near future, the technologies considered should be usable in a few years (some extrapolations were made and justified but in an acceptable range).

Launcher: The bigger launcher of Pythomspace, 'Kang', which will be ready in a couple of years is assumed to be able to launch 3 tons to LEO and have a diameter of 2.5 m [1]. One of the goals was to use Kang as much as possible to deliver the majority of the equipment to LEO where the transfer vehicle will be assembled. But since the payload mass is limited, launches using Falcon 9 and Falcon Heavy from SpaceX have also been considered [2], especially for the propellant. This also offers more flexibility for the design of the tanks as these launchers are bigger (Falcon 9 can launch 22.8 t to LEO, Falcon Heavy can launch 63.8 tons to LEO and the payload bay has a diameter D=5.2m and length L=13.1m) [3].

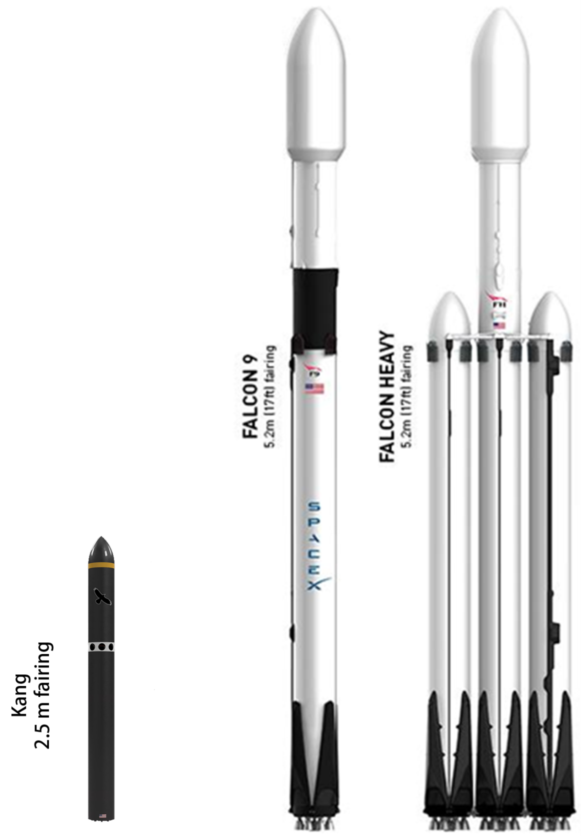

Fig. 2. Three different launchers used in this mission [1], [3]

Propulsion System: As will be further explained in III. Propulsion System, it was decided to keep the Pythomspace Asterex engines for the transfer vehicle in order to reduce cost (no need to buy engines from other companies) and use as many technologies developed by PythomSpace as possible. However, as they only have a thrust of 12kN, an upscaled version was considered.

Mars Descent and Ascent Vehicle: The transfer vehicle will carry two Mars landers. From LMO the first of two landers (Mars Descent Vehicle, MDV) with ascent propellants and supplies descends. If the first landing is successful, the second lander with the people will follow. One of the landers will function as a MAV (Mars Ascent Vehicle), bringing the crew back to the spaceship and transfer back to Earth. Pythomspace has preliminary values for the MAV and MDV: The MAV is expected to be 4190kg wet and 710kg dry (including crew). The MAV is unpressurized. Each MDV is expected to be 4750 kg in atmospheric entry. However, due to the trajectory chosen by the Mission Design team, more propellant will be needed for the landers and the mass used

Fig. 3. Full skeleton of Asterex engine of Pythomspace [1], including the engine and the feed system.

for the mass budget is detailed in II.

Radiation and Solar Particles Event: After some discussion with the Human Logistics team, it was deemed that the radiation levels were in the acceptable range, all the more as the habitat does provide some sort of radiation insulation (see V.D) so no other mitigation methods were considered. In the case of a Solar Particle Event, the two astronauts can stay in the Earth Return capsule or the Mars Landers which might offer more protection than the other parts of the vehicle since they are constructed for reentry.

Risks: The mission should have an estimated chance of success (i.e. a human stepping on Mars) of at least 75% and the risk for death should not be higher than 3%. This can be compared with the space shuttle flights which had an estimated risk of total loss of 1/70: this is a high-risk mission but enables the design to be more minimalistic.

II. Mass budget

In order to compute the required propellant, make a plan of the launch periods and design the transfer vehicle, the first step is to set up a mass estimation. The goal of the mission is to keep the cost and therefore the mass as low as possible. To start off, the vehicle is divided up into 7 main systems.

First is the node which has 6 docking ports and connects to multiple segments. The 2 MDVs, an airlock, and an Earth return capsule are all attached to the docking ports on the main structure of the node. The node also connects to the habitat so the crew can enter the different segments on the node easily when they need to. Two sets of EVA equipment are stored inside the node.

Then there is the habitat system which is made up by an inflatable module and contains the ECLSS (Environmental Control and Life Support System). The ECLSS mainly consists of some basic substance to keep human alive such as water, oxygen, and nitrogen. It also includes the water recovery system which can achieve a recovery rate of up to 90%, and the air revitalisation system that can remove carbon dioxide and maintain the air quality in the habitat. There is also a toilet and waste management system. Furthermore, there are also many miscellaneous devices such as exercise equipment, fire extinguishers, etc. Due to safety considerations, there are 2 spare systems for each critical system which can cause fatal accidents if malfunctioning, which are the water recovery system and air revitalisation system. The mass and volume of the whole ECLSS mainly comes from the Human Aspect team [4]. Other consumables such as cloth, food, and hygiene kits are also contained in the habitat system.

The power system consists of the solar panels and a power management and distribution (PMAD) device. For the thermal control system, it consists of 2 radiators and some other thermal equipment such as the pumps and fluids. Details of the power system and the thermal control system can be found in Section IV.

The electronics system includes some fundamental electronic devices needed through out the mission. First are the communication devices, which includes some antennas, both high gain and low gain, and some transponders. Some computers on board are also included. Then there is the Data Handling System (DHS), which includes 3 computers and some memory units. Three computers ensures that the malfunctions of one or two computers will not jeopardise the mission. This is also the configuration on the ISS [5].

Then there is the Attitude and Orbit Control System (AOCS). Several thrusters with corresponding fuel and tanks are distributed throughout the whole spacecraft to perform the attitude and orbit corrections needed during the mission. There are some sensors such as the star tracker and the sun sensors that can help determine the position of the spacecraft. It is fully autonomous since the communication delay with Earth will make remote control impossible. The design of our AOCS is simplified from the AutoNav system of Deep Space 1 mission [6].

Finally there is the propulsion system which is made up of 5 Asterex engines and their fuel tanks. Details of the propulsion system are elaborated in SectionIII.

Each system consists of smaller components that can be seen in Table I. Of course, one cannot consider every single component of the transfer vehicle for a first conceptual study, so this table only includes the most important and heaviest parts.

TABLE I
SYSTEMS, THEIR COMPONENTS AND INDIVIDUAL MASSES

System	Components	Mass [kg]
Node	Airlock	2500
	Docking ports	500
	MDV 1	16950
	MDV 2	16950
	EVA	478
	Earth Return Capsule	2860
Habitat	Inflatable Module	11000
	ECLSS & Consumables	13629
Power	Solar array	1782
	PMAD	517
Thermal Control	Radiators	715
	Thermal equipment	357
Electronics	Communications	120
	DHS	45
AOCS	Thrusters	20
	Fules and Tanks	3470
	Sensors	10
Propulsion	Asterex Engines	200
	Structures	300
	Fuel	306850
	Tanks	950

For the mass budget, different methods were used in order to compute the values seen in Table II: While some were gathered from literature on conceptual designs of Mars transfer vehicles [7] [8], some were down/up-scaled from existing technologies or computed just for this mission based on data from other groups.

TABLE II
THE SYSTEMS AND EACH MASSES OF THE TRANSFER VEHICLE

System	Mass [t]	Volume [m^3]
Node	40.2	35
Habitat	24.6	174
Power System	2.23	12
Thermal Control System	1.07	11
Electronics System	0.17	6
AOCS	3.5	36
Propulsion System	308.3	250
Total Dry	**73.3**	**280**
Total Wet	**380.1**	**532**

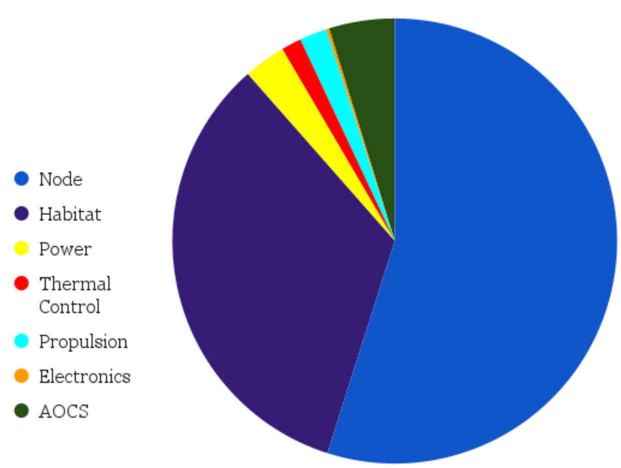

Fig. 4. Mass distribution

The key value from Table II is the total dry mass of 73.4 t, which is lighter than the values found in the references, but makes sense for this mission since it only consists of two crew members and should be as light as possible. The following Figure 4 shows the mass distribution excluding *Fuel*, which amounts for about 80 % of the total mass. It can be observed that the *Node System* takes up more than half of the total mass because it includes heavy components like the MDV and the MAV which each have a mass of about 17 t individually. Following that is the *Habitat*, which contributes to about one third of the total mass. It consists of the inflatable module (11 t) and the ECLSS and consumables (13.6 t) for both crew members for the full mission duration. Finally, the remaining systems only make up less than 10 % of the total mass.

III. Propulsion System

The mass of the required propellant was estimated with the rocket equation

$$\Delta V = -I_{sp} \cdot g_0 \cdot ln\left(\frac{m_f}{m_0}\right) \tag{1}$$

where ΔV is the required change in velocity, m_f is the final mass at the end of the burn and m_0 is the inital mass. Since the initial mass includes the propellant mass that is used during the burn, the total mass of propellant m_p required will be; with m_s the dry mass:

$$m_p = m_s \frac{1 - e^{\frac{-\Delta V}{I_{sp} \cdot g_0}}}{e^{\frac{-\Delta V}{I_{sp} \cdot g_0}}} \tag{2}$$

In reality, the mass of the vehicle is not constant during the whole transfer as water, food and propellant are consumed but it was deemed reasonable to make that approximation to get an upper estimate of the propellant mass needed.

A. Assumed values and hypotheses

The results from the Mission Design [9] and mass budget are reported in Table III.

TABLE III
Propulsion system parameters

Parameter	Value
ΔV	4.84[km/s]
m_s	72.8×10^3[kg]

It was decided to use the propulsion technologies developed by Pythomspace as it is a Pythomspace mission, and to reduce cost. The engine developed by Pythomspace is called Asterex, and runs on what Pythomspace refers to as Green Propellant (see table V). The existing version of the Asterex engine however only has a thrust of 12kN (Table IV), and thus an upscaling of the thrust was assumed, bringing total thrust per engine to 200 kN. Five engines are used, giving a total thrust of 1000 kN. This is sufficient to accelerate the transfer vehicle about 3.9 km/s during the initial transition to Mars in approximately 24 minutes (not accounting for the vehicle getting lighter during the burn due to consummation of propellant).

TABLE IV
Asterex Engines

Current Asterex Engine		Upscaled version
Thrust	12 kN	200 kN
Isp	300s	300s

TABLE V
Green propellant

Fuel:	Furfuryl alcohol ($C_5H_6O_2$)	$\rho = 1.1296 g/cm^3$ [10]
Oxidiser:	Fuming nitric acid (HNO_3)	$\rho = 1.5 g/cm^3$ [11]

The total propellant mass required is 306 850kg.

B. Propellant tanks

To keep the vehicle as light as possible, aluminium-lithium alloy 2195 [12] is used for the tank structure. 2195 was chosen as it is a lightweight material that has previously been used in the SpaceX Falcon 9 [12]. The driving dimensioning factor for the tanks was that they should fit within a Falcon Heavy launcher, in regards to both diameter and weight, since the tanks are launched fully loaded with fuel.

The wall thickness of the tanks was chosen as $e = 2mm$, as the material is quite strong (the Atlas rocket tanks had the same thickness).

No information on the propellant pressure in the tanks was available, so it was assumed to be at atmospheric condition to have an upper estimate of the tank mass (some pressure is needed for the fuel to reach the combustion chamber. For instance Ariane 5 tanks have a pressure of around 3 bars [13]). Moreover, no service temperature was found so standard temperature (T=293.15 K) and density were assumed. This might not correspond to reality but enabled a rough estimation of the tank mass.

The mixture ratio of oxidiser and fuel is HNO_3 : Furfuryl = 2:1. Thus 102,280kg of furfuryl alcohol and 204,560kg of nitric acid are required.

The tanks are assumed to be cylindrical with radius R and length h.

$$V_{tank} = \pi R^2 h \tag{3}$$

$$m_{tank} = \rho_{tank} \pi ((R + e)^2 - R^2) h \tag{4}$$

TABLE VI
Tank parameters

Material	aluminium-lithium alloy 2195
Density	2700 $[kg/m^3]$
Volume	54.95 $[m^3]$
Thickness	2 [mm]
Diameter	5 [m]
Length	2.8 [m] (2.1m for nitric acid
Structural mass	237 [kg]
Mass of furfuryl per tank	62.1 [t]
Mass of acid per tank	61.8 [t]

Thus three tanks of furfuryl alcohol and six tanks of nitric acid are required.

C. Discussion

The technology used for the propulsion system is deemed to be largely feasible. The greatest uncertainty comes from the upscaling of the Asterex engine, with assumed thrust levels almost 17 times larger than their current capability. Higher thrust engines running on alcohol as fuel are in development, for example from Copenhagen Suborbital whose Spica engine will have 100 kN of thrust [14]. This indicates that the fuel combination should allow for higher thrust engines, and 200 kN of thrust should be entirely possible.

Even if this higher thrust cannot quite be achieved, the mission should not be in immediate jeopardy. The problem with lower thrust levels is the time it will take to accelerate. As the Hohmann transfer method uses theoretical instant bursts of speed, lower acceleration could cause complications with the trajectory. If the vehicle is in the upper parts of LEO, meaning orbital periods of up to about 2 hours [15], and the burn itself takes up to 24 minutes, the vehicle will have travelled about 20 % of its orbit before the burn is complete. This should be acceptable, but might require further analysis. However such an analysis was deemed outside the scope of this project.

Other possible solutions are to either increase the number of engines, or to put the transfer vehicle into a higher orbit prior to the transfer burn, meaning that the orbital period will be extended and the burn time to orbital period ratio will decrease. Naturally this first maneuvre would consume propellant as well, but that could ostensibly be solved by another craft using its propulsion system to boost the vehicle, similar to how the orbit of the ISS is boosted.

An entirely different propulsion system, using for example methane or kerosene as fuel, could also be a viable alternative. This would probably increase costs, as the engines couldn't be manufactured in-house by Pythomspace, but it might allow for a system with higher I_{sp}, meaning higher efficiency and therefore less required propellant.

Another challenge will be the docking of the fuel tanks and especially the connection of fuel lines between the tanks during assembly. The seals must be sufficiently tight to avoid pressure drops and leakage of fuel. Since furfuryl alcohol and nitric acid form a hypergolic propellant, it is vital that the two substances do not come into contact with each other anywhere but in the combustion chamber.

Furthermore, the structural mass of the tanks do not include any inner structure such as dividing walls between the fuel and oxidiser. It is assumed that these would be constructed in a lightweight material and that the mass would not increase drastically. This is another area where further studies would be required. On the other hand, the preliminary calculations of the tanks mass might be overestimated as no pressurisation was considered.

Propellant sloshing is of course another difficulty which must be solved. During burns it shouldn't pose much of a problem since the acceleration will force propellant toward the bottom of the tanks, but before ignition ullage motors might be required to settle the propellant. These motors aren't considered in the general design, but would probably not add too much weight nor complexity.

IV. Power and Thermal Control Systems

A. Power system

A power system is needed to supply power to the whole transfer vehicle. It mainly consists of 4 large solar panels and a Power Management and Distribution (PMAD) device. The function of the PMAD is to store, regulate, and distribute power. The design is mainly based on the power system on the ISS [5] and the one presented in [7]. The Logistics team gave a total mass of the solar panels as $1722\,\mathrm{kg}$ and an area of $700\,\mathrm{m}^2$. This allows to produce an energy of $11.4\,\mathrm{kW}$ needed to run the total transfer vehicle. The mass includes both the solar cells and some supporting structures. The mass of PMAD is typically estimated to be 30% of the total mass of the solar panels [5], which leads to a mass of 517 kg. The solar panels are mounted on the service module, which lies between the inflatable habitat and the propulsion system. This is the core module of the whole spacecraft and it should be launched first.

B. Thermal control system

The thermal control system is to regulate the temperature of the spacecraft to prevent some components from overheating, especially for the habitat module. The temperature of the habitat should be maintained between 18°C to 26°C [5] for the comfort of the crew. So an active thermal control method should be used.

The heat of the spacecraft has 2 main sources, one is the irradiance of the sun and the other is the heat generated by the equipment on board. For our mission, the solar irradiance at the apogee $S_a = 1452$ W/m^2 and at the perigee $S_p = 508$ W/m^2. For this heat source, some passive control methods such as thermal coatings and white paints that have a large emissivity ϵ and a relatively small absorbance α is enough to reach thermal equilibrium [5], [16].

The second source, heat generated from internal equipment, is assumed to be constant throughout the whole mission. For this heat, a 2-sided radiator is used to transfer the heat from the spacecraft to outer space. The radiator is also mounted on the service module perpendicular to the solar panels to minimize the solar radiation on the radiator fins. The area of the radiator is estimated with the following equation:

$$A_{rad} = \frac{Q}{\sigma\epsilon\eta(T_r^4 - T_e^4)} \tag{5}$$

where Q is the constant heat load, $\sigma = 5.67\times10^{-8}$ W/(m^{2}K^4) is the Stefan–Boltzmann constant, $\epsilon = 0.9$ is the emissivity of the radiator, $\eta = 0.8$ is the radiator fin efficiency. T_e is the mean effective thermal environment temperature and it is estimated to be 233 K [5], [7]. T_r is the mean radiator temperature. We assume that all the energy generated by the power system will eventually convert to waste heat, so here $Q = 11.4$ kW. With $T_r = 280$ K, the total radiator area $A_{rad} = 87$ m^2. Using an area density of 8.2 kg/m^2, the total mass of the radiator is 715 kg.

The service module that includes the power system, thermal control system and the main electronic system, is described in Table VII.

TABLE VII
SERVICE MODULE

Components	Mass [kg]
Solar panels	1722
PMAD	517
Radiator	715
Thermal equipment	357
Communications	120
AOCS sensors	10
Total mass	3441

Note : Radiators will be launched in a second launch as the total mass exceeds the maximum mass of 3 tonnes.

V. DESIGN OF THE TRANSFER VEHICLE

A. Descent and Ascent vehicle

The design of the Mars descent and ascent vehicles (MDV & MAV) is provided by Pythomspace as seen in Figure 5. The two MDVs will land on Mars separately. The crew members will land in the second one if the first has landed successfully. After their mission on Mars, only one of the MDVs will be transformed into a MAV to get the crew back on board.

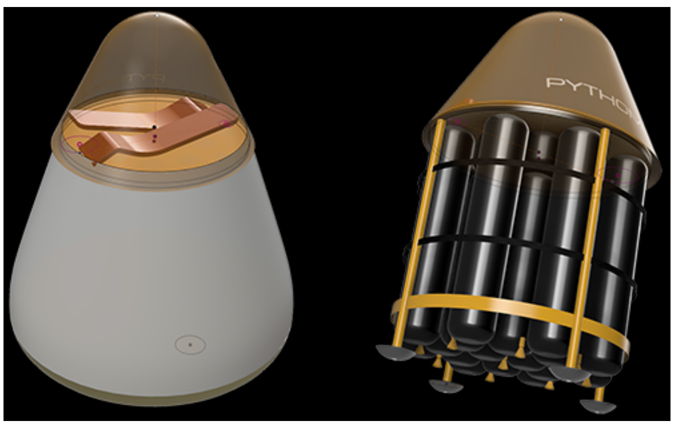

Fig. 5. Mars Descent Vehicle (left) and Mars Ascent Vehicle (right) as designed by Pythomspace [1]

It should be noted that from the mission design team, the mass of the 2 MDVs and the MAV will be different from the original data provided by Pythomspace. The original wet mass of the MDV is 4750 kg. This is changed to 16950 kg as more fuel is needed in the powered descent phase on Mars. For the MAV, the wet mass changes from 4190 kg to 6220 kg. The size of the MDV and MAV should change accordingly.

B. Earth return vehicle

When the transfer vehicle returns to the earth it will not perform a capture burn due to ΔV constraints, and as such will fly by the earth on a hyperbolic trajectory. To get the crew safely to the ground, they will have to descend to the earth surface in a small descent capsule. The capsule will do a skip reentry before landing in the ocean. This is very similar to how the Apollo crews returned to earth after going to the moon, so the plan is to develop and use a capsule of a similar design, see Figure 6. This would be a conic capsule that fits the two crew members and is protected by a heat shield on the bottom.

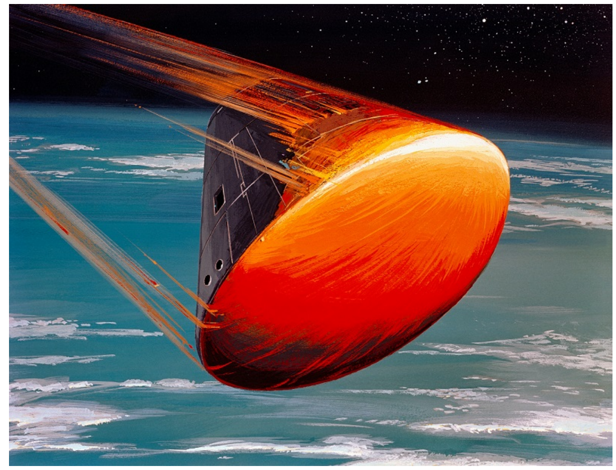

Fig. 6. An illustration of the Apollo return capsule. A similar but smaller design would be used for the C.R.I.M.S.O.N. mission.

C. Docking and EVA

The docking system consists of a node and several modules with a total mass of 40.2 tonnes. There are 6 docking ports on the node. Five of them are used and there is a free one for resupply needed in the parking orbit. The node with the airlock system weights 3 tonnes and they can be launched together in one launch. The node is pressurised and attached to the habitat. There are 2 MDVs attached on the node opposite each other. Moreover, the return capsule of 2.86 tonnes is also attached at the front and will be used exclusively to return to earth. A preliminary view of the node with its components can be seen Figure 7. The main purpose of the node is to join every module attached to it in a simple way through the entire mission. Plus, the airlock is used in order to be depressurised and allow EVA missions such as repairing broken components outside of the transfer vehicle. It can be found, stored in the airlock, 2 space suits for EVAs. Finally, a 360° observation windows is situated in the airlock to let the crew members see space.

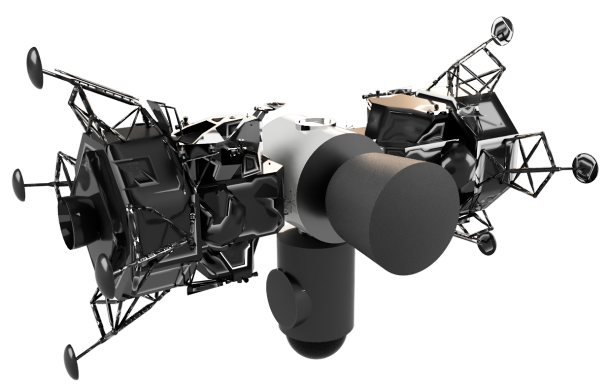

Fig. 7. CAD model of the node. On each side is a Mars descent vehicle (a model of the Apollo lunar lander is used as a placeholder). In the front is the earth descent capsule, and on the bottom is the EVA hatch and observation window.

D. Habitat

The design of the main living area is inspired by the inflatable module on the ISS: The Bigelow Expandable Activity Module (BEAM) developed by Bigelow company and their larger B330 habitat [17], [18], which is still under development. The success of BEAM increased the TRL (Technology Readiness Level) of inflatable habitat to 9 (The system has been tested in an operational environment). So it can be expected to use this technology in our transfer vehicle.

There is a minimum habitable volume needed for a person to stay mentally healthy during a spaceflight [7], [19]. It is a function of mission time and amount of crew members, and is given by the expression:

$$V_{hab,min} = n\left(6.67\ln\left(\tau_{mission}\right) - 7.79\right), \tag{6}$$

where n is the amount of crew members, $\tau_{mission}$ is the the mission duration in days, and the result, $V_{hab,min}$, is the minimum habitable volume needed given in cubic meters. For this mission, the whole duration is 1007 days, of which they will spend 23 days on Mars surface. So the time they spend in the transfer vehicle habitat is 984 days, which is $\tau_{mission}$ here. Therefore, the resultant minimum living space for two crew members is $76.4\,\mathrm{m}^3$. By adding $98\,\mathrm{m}^3$ needed to store the ECLSS, food, etc., the total volume needed for the habitat module is $174\,\mathrm{m}^3$. The Bigelow company has their research program B330, which has a total pressurized volume of $330\,\mathrm{m}^3$ after being fully expanded. So our $174\,\mathrm{m}^3$ inflatable habitat is feasible in the near future.

Fig. 8. Bigelow B330 inflatable habitat prototype [18].

Based on the dimensions and mass of B330, we scale it down to obtain the parameters of our habitat. The diameter of B330 is 6.7 m and the length is 16.88 m [18]. Our habitat will have a similar shape with a 5 m diameter and a 9 m length. As for the mass, there is no precise mass distribution information for the B330. The whole B330 is around 23 t, which includes the propulsion system, power system, and many other that are not needed in our design. So we scale it down to around 11 t for our habitat. But since there is no precise mass information of B330, the mass of our habitat is just a rough estimation.

The habitat is placed between the service module and the node. So when performing maneuvers, the force applied on the habitat could become a possible problem. But the structure of the inflatable habitat has a certain level of structural rigidity to withstand the force. And if in the future investigations show that the force due to maneuvers becomes too large for the habitat to bear, it is also possible to place the habitat in front of the node.

E. Overview of the transfer vehicle

The transfer vehicle is designed so that all the different modules will dock with each other in a long line. In the back are the nine tanks which are mated axially, with the five Asterex engines on the aftmost tank. After that comes the power module where both the solar panels and radiators are mounted. In front of this module is the service module, which houses among other things important life support systems and electronics. Next is the inflatable habitation module, and after this the node, where the landers, the earth descent capsule, and the EVA hatch are docked. All of this can be seen in Figure 9.

VI. Off-nominal Case

An off-nominal case was also considered, namely the vehicle getting hit by micrometeoroids and the possible impact that could have on the vehicle. The impact was considered on a per-module basis.

Habitat: The habitat is based on the Bigelow Beam module which has proven to be resilient to micrometeoroid strikes [17], but if the habitat is so severely damaged that a hole appears in the wall it could lead to catastrophic failure. The module is inflatable and thus needs to be pressurised to keep its form, and since it is the primary living space a depressurisation event would leave the crew extremely vulnerable.

The solution in this event would be obvious, namely to patch the hole. The patching itself would likely be easy and could probably even be hastily done with duct tape in the worst case before a more permanent solution is found. Locating the leak might be more difficult since the hole would likely be minuscule. As such, time would be the essential factor here.

Mars landers & return capsule : The MAV and MDV are quite resilient to micrometeoroid strikes as they are unpressurised and thus a breach in the hull wouldn't cause any immediate problems. Should an impact be found on either vehicle that could cause problems during landing or ascent, the Mars landing would probably have to be aborted as repairs would probably be very hard to perform.

If the crew return capsule is damaged beyond usability, a rescue mission would have to be set in motion to rescue the crew from the transfer vehicle once they return to Earth's system.

Propulsion system: It is unlikely that a micrometeoroid would cause so much damage that the entire propulsion system breaks down. Should something happen there is some redundancy built into the system as there are five engines available.

Power System: The solar arrays should keep working even if they are hit, albeit with slightly reduced power output. Therefore the estimated total power output from the solar panels at the beginning of the mission has a margin accounting

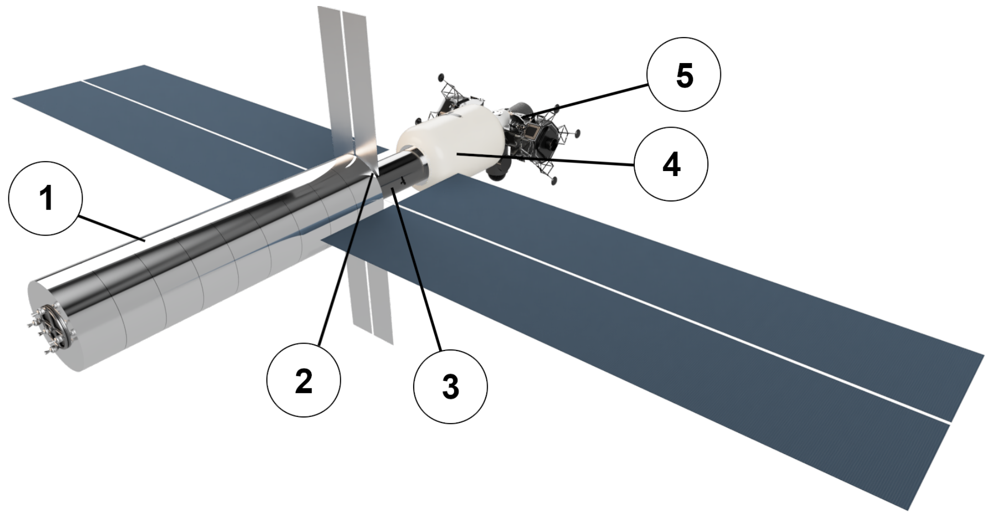

Fig. 9. CAD mock-up of the transfer vehicle, with the different parts labelled. (1) Tanks and engines (2) Power module with radiators (grey) and solar panels (blue) (3) Service module (4) Inflatable habitation module (5) Node with airlock, EVA hatch, earth descent capsule and two mars descent vehicles.

for efficiency decrease during the mission. If a strike hits some vital part of the electronics, repairs would have to be performed.

In conclusion, the impact of micrometeoroids could in theory cause major problems. However the risk of total mission loss from this is deemed to be very small.

VII. Conclusions

In this article, a conceptual design of a transfer vehicle for a Mars expedition of two crew members is provided. The design goal is to achieve a minimal mass budget but still make it safe enough to maintain at least a 75% chance of success and the chance of a fatal accident is less than 3%. According to the estimate from Project Management team, the mission success probability is 80% and the probability of a fatal accident is 2% [20]. So the transfer vehicle only includes the most crucial components.

In our design, there is a node, which connects to an airlock for EVAs, an Earth descent capsule for the crew to return to Earth, and two MDVs that will land on Mars. The node takes up more than half of the total dry mass of the spacecraft, which is mainly due to the mass of the 2 MDVs.

The node is then connected to the main inflatable habitat, which is the living space for the crew members and stores the ECLSS and consumables such as food, hygiene kits, etc. The design of the inflatable module comes from the B330 project of Bigelow Aerospace company. The total pressurized volume is $174\,\mathrm{m}^3$ with $76.4\,\mathrm{m}^3$ for the crew to live in, which considered the comfort and mental health of the crew for such a long mission.

The other end of the habitat is connected to the service module, which contains the electronics such as data handling system, communication system, and PMAD system. The solar panels and radiators are mounted on the service module. The solar panels has a total area of $700\,\mathrm{m}^2$ and can provide a total power of $11.4\,\mathrm{kW}$. The radiators can dissipate the heat generated inside the spacecraft.

At the end of the spacecraft is the propulsion system, which consists of the fuel tanks and the engines. In our design, an upscaled version of the Asterex engine is used and 5 engines are integrated together to provide a total thrust of 1000 kN. The oxidizer and fuel used for the engine are fuming nitric acid and furfuryl alcohol, and the ratio is 2:1. The total mass of propellant is 306,850kg to provide a total $\Delta V = 4.84$ km/s.

With everything built as simple as possible, the total dry mass of the transfer vehicle is 73.4 t and the wet mass which includes the fuel is 380.3 t. Different components will be launched separately by the Kang launcher provided by Pythom Space or by Falcon 9 and Falcon Heavy of SpaceX depending on the mass and volume. Then the transfer vehicle will be assembled in the parking orbit before it sets off for Mars.

VIII. Workload Breakdown

- Christophe Segretin
  - Mass budget, Habitat, Overview of the transfer vehicle, Abstract
- Kaibin Wen
  - Mass budget, habitat, power system, and thermal control system
- Oscar Malm
  - Propulsion system, off-nominal case
- Thomas Holmboe
  - Earth return vehicle, Overview of the transfer vehicle
- Stephan Weißenböck
  - Mass Budget, Descent and Ascent vehicle
- Léa Wullschleger
  - Propulsion System, Introduction

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