Transplanetary Vehicle for Human Mars Mission

Rasmus Bergström
Mathilde Brizon
Lasse Larsson
Sina Poetzsch
Jonas Thunmarker

SD2905 Human Spaceflight
Royal Institute of Technology
Stockholm, Sweden

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Abstract

In this paper aspects of an interplanetary vehicle for going to Mars are investigated. The mission to Mars consists in total of three vehicles, one for the crew, one for the Mars habitat and one for cargo and lander. Certain important aspects on the effect of the space environment on the human body and psyche are investigated and related mitigation options are presented. Regarding the vehicle itself the crew habitat consists mainly of a Bigelow BA330 module with a life support system consisting of the experimental new NASA technology called Water Walls, which also provides radiation protection. A artificial gravity system will be used to mitigate the effects of microgravity on the astronauts. The propulsion system used for all vehicles is a nuclear-thermal rocket engine which will also be used as the main source of power for the vehicle. A brief risk register shows that most associated risks can be mitigated in a reasonable manner and that only limited considerations must be taken to allow for a potential mid-transfer abort.

1 Introduction

This paper will investigate the requirements and the conceptual design of a manned transplanetary transport vehicle travelling between Earth and Mars. This paper is part of a larger project where 4 groups work together with the objective to plan a human Mars mission.

A good way to start the adventure of going to mars is designing an interplanetary transport vehicle. This work is part of the red teams project A mission to Mars as an outcome of the course Human Spaceflight at The Royal Institute of Technology in Stockholm. The paper deals with the design of an transplanetary crew vehicle going to and from Mars, the cargo transport to Mars and the needed propulsion systems. The mission aim is to travel to and from Mars with six astronauts. The journey to Mars will last 176 days, with a return trip lasting 198 days. In addition, two cargo vehicles will be launched on trajectories lasting 320 days each. Starting with how humans are affected during such a long time mission, the needed life support systems are determined. Then the transplanetary vehicle design is considered in detail containing the power system, radiation shielding, structure design, artificial gravity and finally the total mass of the vehicle. The requirements for the propulsion system are then calculated and a system is chosen. Finally it is investigated what the risks of the mission during the transfer phase are and what the probability of these risks are.

2 Effects on humans in space

2.1 Human body in space

A space mission is a challenge for the human body perfected over thousands of years for life on earth. In space it has to sustain microgravity or even the complete lack of gravity, radiation, absent sunlight and a narrow habitat. An introduction about effects on the body in space and how to handle them during the transplanetary mission is given in this section.

2.1.1 Effects on human body in space

The mass of bones and muscles is reduced in weightlessness and the sense of balance is disturbed. As a result of radiation short time effects like sickness can occur. Those are probably caused by intense SPE (solar particle events). Long time effects are caused by exposure to GCR (galactic cosmic rays) over a long period [1]. Especially in the beginning of a mission astronauts tend to suffer from sleep disorder due to noise, excitement of the flight or the abnormal day night cycle. Indicators like schedules, waking up by other crew members, clocks or machines have to be used to define a sleep-wake cycle. Darkness stimulates a higher production of the hormone melatonin which can cause fatigue and depressive mood. The desire to sleep increases with duration of the space mission. The strongest physiological effects appear during the first three month [2]

2.1.2 Physical training

Physical training of two and a half hours a day is intended as a countermeasure to effects on the body in space. To ensure a vigorous exercise the daily training unit will be divided in two or more shorter subunits. Sport equipment like treadmills is considered. It has to be durable, easy to repair and there have to be redundant exercise possibilities. On board will be artifical gravity [1] [3]. The astronauts need to be fit when arriving Mars to act as best as possible in the new and uncertain environment. The body has to be adapted to stand gravity again. Therefore an intensive preparation is needed. The physical training will be increased during the month before landing, especially for the leg muscles. Around three and a half hours of training a day is reasonable.

2.2 Human behaviour during ling-time missions

This section mentions difficult circumstances during the mission which influences the human psyche. Furthermore needed psychological design aspects of the crew vehicle habitat are considered to provide a pleasant living environment.

2.2.1 Psychology effects on humans during long-time mission

The communication to earth will be restricted. There will be a significant time delay and the communication can also be interrupted for long times. Therefore the crew will be trained to act autonomously in case the connection to the control center on earth is lost.

Boredom is most probable during the long mission, especially on the way back to earth when the most exciting event of the mission, the time on mars and the preparation for it, is over. Consequences can be emotional instability, hypersensitivity, depressive reactions and a reduced impetus. [?]

Even with training and evaluation in advance it cannot be predicted how people will react during a long-term mission. Large individual differences on how astronauts respond to isolation have occurred in former experiments [4]. For such a long mission one has to be aware that conflicts between the crew members will occur. By providing a good crew habitat and by training the astronauts in conflict management one aims to solve conflicts quickly and reduce their impact on the mission.

2.2.2 Providing a pleasant living environment and minimize conflict potential

diversity to counteract monotony and boredom. Variety is increased by offering diverse food and multiple activities. Virtual reality, books, movies, board and card games and brainteasers entertain the group but are also able to increase the group cohesiveness and mental fitness. For a long mission 50 kg books, 50 kg of digital data storage as DVDs are recommended [3]. Equipment and tools are necessary to repair broken equipment, and to give the astronauts the possibility to become active and creative and change their living environment as far as the safety of the habitat is not reduced. For the crew it can be very important to live traditions that they used to have on earth, e.g. celebrating Christmas and rebuilding a Christmas tree can improve satisfaction and cohesiveness of the people on board [4]. Additionally one has to consider private areas for the crew members to separate from each other. Especially in case of conflicts retreats will become an important element of the transplanetary vehicle. Each crew member will have a small private area and there is the possibility to move the sleeping berth to another place. Before the mission and during the mission the astronauts have to be trained to be aware of situations that might lead to conflicts and how to act to prevent them or to solve arguments quickly. Windows for a visual link to earth and Mars and into space are provided. A particularly important aspect to stabilize the psyche is the communication to earth with family and friends. Email transfer will be the main choice for this communication. Via email also the emotional condition of the astronauts can be measured by the ground staff and if necessary countermeasures are initiated to avoid conflicts and depressions [?]. In advance prepared video sequences from family and friends are also an useful feature. The astronauts have to keep their belief in the meaningfulness of mission over a very long time. A great value to achieve that is the emotional support from earth.

3 Life-support systems

A life support system is essentially the various systems that keep astronauts alive in the vacuum of space. Without it there could be no human exploration of space, no moon landings and no space stations. As such it is of paramount importance that these systems are well designed, durable and that there are fail-safes in place in case of eventual failure.

Previous missions, such as Apollo, Mir and the ISS have relied on large, expensive and failure prone systems for generating a liveable environment for the astronauts. For missions beyond lunar orbit lighter and more reliable systems are needed.

3.1 Prerequisites

The life-support system has to be able to handle the needs of six astronauts. This includes supplying them with oxygen to breath, water to drink, and a reasonable temperature. Furthermore it needs to be able to handle all the waste the astronauts will produce during their voyage, this includes both organic and inorganic (such as food wrappers) waste. A life support system needs to be able to provide,Adequate oxygen supply, Water purification, Food supply plus contingency, Temperature regulation system, Waste removal system, Fire Detection & suppression and finally Radiation protection. In addition to this the system needs a certain amount of redundancy in case of any one system failing. For example, if the oxygen supply fail for some reason the consequences would be disastrous.

3.2 Current solutions

The only current mission that could be comparable to a Mars mission is the International Space Station. This station uses a number of different systems to provide a breathable atmosphere, adequate temperature, and radiation protection. If the transplanetary habitat was equipped with these systems a failure could prove catastrophic due to the fact that no adequate help could be provided from earth.

3.3 Technology used

Due to this the habitat is to be equipped with a new technology developed by NASA called Water Walls. This is referred to as being massively redundant and highly reliable, especially suited for long duration missions. The system uses a series of bags located on the walls of the spacecraft as this is the perfect place for radiation protection. These bags can come in various shapes and sizes all depending on the mission and shape of the craft they are attached to. As each bag is used up the crew removes it, turns on the next one and either empties the removed bag so that it may be reused or discards it. These bags can essentially be split into four different blocks based upon their purpose. These are known as Climate Control, Contaminant Control, Air Revitalization, and Power and Waste. In addition to the Water Wall technology a separate fire detection and suppression system have to be used.

3.3.1 Climate control

The Climate Control block is divided into Humidity Control and Thermal Control. These subsystem both consume salt and brine while producing condensate that will later be used in the Power and Waste block. The input for the block is air circulation over the membranes covering their surfaces.

3.3.2 Contaminate control

This block is made up of the Volatile Organic Destruction and Semi-Volatile Organic Destruction units. The primary purpose of this block is to break down Volatile Organic Compounds (VOCs). The Volatile Organic Destruction unit accomplishes this using titanium dioxide and ultraviolet light, though ambient cabin light also works but at a slower pace. The Semi-Volatile Organic Destruction unit utilizes the solubility of semi-volatiles in water as well as the organic decomposition of these volatiles.

3.3.3 Air revitalization

The Air Revitalization unit uses algae and cyanobacteria to absorb CO2 from the air. The algae then store carbon whilst releasing oxygen which can be returned to the cabin atmosphere. The algae used in this process can also be eaten if the need ever arises.

3.3.4 Power and waste

The Power and Waste process block is made up of the Urine and Graywater Processing, Blackwater and Solid Waste Processing, and the Microbial Fuel Cell. The Blackwater and Solid Waste unit feeds the Microbial Fuel Cell with partially treated waste. The Fuel Cell then produces electricity for nearby low power appliances, eliminating need for wiring. The Urine and Graywater unit process converts its inputs into ammonium and also water for drinking.

3.3.5 Fire detection

Fire detection and suppression can be performed in the same way as it is done today on the ISS, i.e. using smoke detectors to discover fires and putting out the flames using portable fire extinguishers. Portable Breathing Apparatuses will probably also be needed in case there are particular heavy fires onboard.

4 Interplanetary vehicle design

4.1 Power system

The power system of the spacecraft is one of the most important parts. Indeed, this system must not fail because it supplies the electricity for all the other systems (such as communication system, computer equipment, life support system etc.). This system must be redundant.

There are many different types of systems [6] that can provide electricity, e.g. batteries, solar panels, Nuclear thermal generator (coupled with the propulsion system) etc.

But we cannot choose only one type of power system. Depending on the flight phase, different types of power system will be used. It sounds obvious that solar panels cannot provide the energy required for the equipment during the launch for example.

4.1.1 Battery

The rocket has to have some kind of batteries on-board in order to provide energy during the launch and re-entry. This is the most reliable source of energy.

4.1.2 Radioisotope thermoelectric generator (RTG, RITEG)

This system is the most efficient and is probably the ideal system. However, it has some disadvantages such as the public reaction about using nuclear power, or the effects of the radiation emissions for the crew. In spite of these disadvantages our choice of propulsion system is nuclear thermal. Thus, it becomes obvious that we will use the nuclear thermal generator as primary electrical source during the transplanetary journey.

4.1.3 Solar panels

Due to the need for the power system to be redundant, a backup system is necessary. For that, the solar panels seem like a good choice. They can be deployed during the transplanetary journey (this mission is not too far into deep space, so the sun can provide enough energy).

4.1.4 Choice of power system

The three systems will all be chosen. Indeed, the principal source of energy will be the RTG but during critical operations like launch and landing the batteries will be used and the solar panels will be there as redundancy for the rest of the mission.

4.2 Artificial gravity

In their travel to Mars, the astronauts will live in a weightless environment. This kind of environment has a lot of effects on the human body, mostly when people are exposed to these conditions for a long time. As the travel to Mars will last about six months the negative effects of weightlessness must be taken into account. These negative effects include; Bone loss, weaker blood circulation, muscle loss, disturbance of the balance system as well as many minor effects

On the return trip this is not really a problem because the astronauts will have time to rest on Earth after their mission. But on the way to Mars, the physical incapacity caused by these negative effects is a major issue. Indeed, the astronauts must be able to work as soon as they will land on Mars as they need to construct their habitat. The best solution will be to recreate Earth's gravity on the spacecraft. Studies are still trying to determine if the two following solutions can counteract the effects of weightlessness on health.

- To create a permanent low gravity on the spaceship
- To create an intermittent high gravity on the spaceship (only during short periods of time)

4.2.1 How to create artificial gravity

There are several ways to create artificial gravity [7].

High mass. The most obvious, with a high density object. As the Earths gravity, a mass can be on-board and attract other masses. However, to create a sufficient gravity, the mass needs to be very big. Obviously, a rocket launch cannot afford such a mass, the density of the material is too high and the major issue of a spaceship is still its weight.

Magnetism. It is possible to create artificial gravity by using magnetism. However, superconductors must be used for the powerful magnetic fields needed. These kinds of magnets are also very heavy and they need to be kept at a very low temperature. It is too big constraints compared to the very low efficiency. Indeed, a thousand-kilogram magnet is needed to recreate the Earths gravity.

Linear acceleration. A linear acceleration on the way to Mars can be a solution. Actual rockets can accelerate until they reach 1g or even more. The only problem is the required fuel, and then, the extra mass needed for the fuel. The advantage with this solution, the travel to Mars would be reduced to around 5 days. But the engine must have a really high specific impulse. The two systems: Hall effect thrusters (electric propulsion by accelerating ions) and Variable Specific Impulse Magnetoplasma Rockets (VASIMR) (electromagnetic propulsion using radio waves to ionize the propellant into plasma and magnetic fields to accelerate it) could probably supply this solution but it is still in study.

Rotation. Finally, it is possible to spin the spaceship. Indeed, by rotating the spacecraft, it is possible to create artificial gravity. This time, the problem is the dimensions of the transplanetary vehicle needed. The rotation can also have negative effects on people. To avoid any kind of sickness due to the rotation, the rotation must be around 2 rpm. Then, at $\omega_{rpm} = 2\ rpm$, to recreate the Earths gravity, the diameter of the vehicle must be:

$$R = \frac{9.81n}{\left(\frac{\pi\omega_{rpm}}{30}\right)^2} \tag{1}$$

Where R is the radius of the rotation, n is the percent of gravity and omega is the rotational speed. Due to equation 1 the radius needed to achieve 1g is 22 m. A faster rotation than $\omega_{rpm} = 7\ rpm$ and people will not be able to stand it. And with this value, the radius R needed is reduced to 18 meters. But, to create a low artificial gravity, like 10% of the Earths gravity, this solution is feasible. With the constraint of 2 rpm, the radius R needs to be at least 22 meters.

The best advantage of the rotating spacecraft solution is that there is no extra mass needed (Except for a propulsion system to make the spacecraft rotate).

The solution that was chosen is the last one, i.e. a rotating spaceship with a rotation speed around 4.5 rpm giving a radius of 16.6 m. This means that the astronauts will be subjected to roughly Mars gravity.

4.3 Structure design

A Bigelow 330 will be used as the habitat for the crew vehicle. This structure provides 330 m^3 of living space for the astronauts [8]. While it does have its own ECLSS it is not adequate for a long term transplanetary mission which is why it will be exchanged for another one. This new life support system will be explain later in the paper.

The Bigelow 330 is an inflatable habitat which means that its launch volume, and mass if you want to launch the gasses at a later time, is much smaller than for example the modules used on the ISS.

4.4 Radiation shielding

On Earth, the atmosphere provides us a natural solar and cosmic radiation shielding. However, as soon as a craft is in space, it no longer have that protection. The types of radiation that exists outside of earth atmosphere can be essentially classified into three categories; Galactic cosmic rays (GCR), Solar energetic particles (SEP) and Trapped particles (Van Allen Belts).

Which all influence the design of the spacecraft as well as the duration of the mission. Without something to protect the astronauts from this radiation that would surely die due to radiation poisoning before reaching Mars. Thus, they need something to shield them from this radiation.

4.4.1 Technologies for radiation shielding

To overcome the problem of radiation, some solutions that exist are; Put tanks all around the spacecraft, Electrostatic radiation shield, Use of the plastic material RXF1 (based on polyethyl), Water walls.

Vehicle configuration : tank disposition. The most basic idea of the radiation shielding is to put the most thickness of material between the radiation and the crew. But, without adding extra mass, this can be a challenge. To modify the design of the spacecraft in order to put the tanks around the crew compartment is a possibility. However, the tanks will become more and more empty, thus reducing their efficiency. This means that this is not the best solution.

Electrostatic radiation shield. This is an active shielding. Indeed, it generates positive and negative charges in order to interact with any charged particle which comes close to the electrostatic field.

Plastic RXF1. The plastic material RXF1 is composed of hydrogen and carbon atoms. Because the mass of these atoms are lighter than aluminium or other heavy materials used to make radiation shielding, the interaction with the radiation leads to less secondary radiations. The more hydrogen there is, the more the material will absorb the radiation.

Water Walls. A new technology is currently being studied at NASA. It is called Water Walls and the aim of this technology is to replace a big part of the whole life support system of the spacecraft. Indeed, the Water Walls can allow to control and regulate a lot of parameters in addition to protect the spacecraft from radiation. This is thanks to a water layer included in the wall all around the habitat.

The Water Walls system is a passive system. So, it relies on biological processes. That makes it more reliable than some mechanical or electrical systems which can fail.

4.4.2 Choice of radiation protection

In order to add the minimum of single function extra mass, the choice of the Water Wall has a lot of advantages including a very high reliability because of the massive redundancy of the system. This system will be further explained later in the report.

4.5 Masses of transplanetary vehicles

When all the components had been chosen the final mass of the transplanetary vehicle could be calculated. The masses for the various components are presented in Appendix A. The final of the crew habitat was calculated to a total of 45 tons. Together with the lander of 11 tons [10] this yields a final mass of the crew vehicle of 56 tons. The masses of the cargo vehicles, called Mars habitat vehicle and Mars support vehicle, are 53.1 tons and 66.8 tons. These values are given[11] and will not have to be calculated.

5 Propulsion systems

5.1 Trajectories

From the planned mission structure[9] it was given that two different kinds of trajectories would be used. One fast trajectory which will be used to transport the crew vehicle so that the astronauts will be exposed to the hazardous radiation of space for such a small time as possible. The downside of this is that it requires more energy. The second trajectory used is a slow trajectory which will be used to transport the cargo vehicle as it requires less fuel.

The vehicles will be designed to be able to launch on all of the launch windows for the next 23 years (until 2037). This will require a bit more ΔV capability but instead it will give a more useful and adaptable vehicle.

5.1.1 Trajectories for crew vehicle

Earth-Mars Transfer (EMT) The required[12] ΔV to do a fast trajectory to Mars, that is having a transfer time of less or equal to 180 days, is 4.08 km/s. It is worth noticing that a slower transfer does not necessarily provide a lower ΔV.

Mars Orbit Capture (MOC) The crew vehicle will be parked in a parking orbit around Mars. The required ΔV delivered from the engines during this phase can be heavily reduced by performing an aero capture manoeuvre. When the crew vehicle reaches Mars the engines will perform a ΔV burn to put it into a highly elliptical orbit around Mars.

The aero capture manoeuvre is then performed by letting the vehicle pass through the upper parts of the Mars atmosphere at the perigee. Due to atmospheric drag the spacecraft will slow down and therefore the apogee will be lowered. When the apogee is at the desired altitude a last burn is made to put the spacecraft into a circular orbit around Mars. The total ΔV burn for the Mars Orbit Capture is approximated to be around 0.7 km/s [**?**].

Even though aero captures manoeuvres has been performed on previous unmanned Mars missions [**?**] they are deemed to be very hard to perform. For this paper it is assumed that the manoeuvre is possible and will not require any special equipment,

Mars-Earth Transfer (MET) The return trip back to Earth will be at the launch window that is 2 years after the launch date. For some launch windows and transfer times this ΔV could be as low as 2 km/s. But by increasing the allowed ΔV to 3.0 km/s all launch windows until 2037 can be used with a transfer time of 180 days ore less.

Earth Orbit Capture (EOC) An elliptical Earth Orbit Capture would require an dΔV capability of around 0.4 km/s. This will place the vehicle in an elliptical grave yard orbit whit a suitable perigee so that it will allow the lander to safely descend to Earth.

5.1.2 Trajectories for cargo vehicle

The cargo and Mars habitat will go directly from an interplanetary trajectory to the surface of Mars by breaking in the Mars atmosphere which means that it will not require any orbit capture burns.

Earth-Mars Transfer (EMT).

The most energy efficient trajectory that can be done is a Hohmann trajectory. This means that the spacecraft reaches Mars exactly when it has rotated 180° around the sun. In this case the cargo vehicle uses a so called type II trajectory which means that it will travel more than these 180°. This will not effect the ΔV [13], it will still be as effective as a Hohmann transfer, instead it will yield in a slower approach speed to Mars. For a transfer between Earth and Mars this gives a ΔV of 3.98 [km/s]. [**?**]

5.2 Requirements

As the mission is planned to be executed in 2033 only technologies that is realistic to have available at that time have been taken into consideration. As the planned trajectories all are calculated for a high thrust and fast impulse propulsion system other systems that have a low thrust where deemed not feasible and was therefore neglected.

Another requirement for the propulsion system is that it should be capable of delivering multiple burns as this is required to inject the crew vehicle into orbits around Mars and Earth as well as put the vehicle into the transplanetary trajectory between the planets.

The ΔV-budget for the crew and cargo vehicles can be seen in table 3 in Appendix B.

5.2.1 Possible propulsion systems

By looking at the requirements and ΔV-budget it was concluded that there was two different propulsion technologies that would be suitable for this mission., liquid propellant propulsion and nuclear thermal propulsion.

Liquid propellant propulsion. Is the most common of all spacecraft propulsion and has been used for almost every Mars mission to this day. It is a proven technology but its performance is limited by the amount of energy that can be stored in a chemical compound. Depending on the fuel mixture different specific impulses can be reached where the highest is for a bi-propellant rocket that uses liquid oxygen/hydrogen which can reach an specific impulse (I_{sp}) of up to 455 [s].

Nuclear thermal propulsion. Uses a nuclear reaction to heat the propellant the create a large pressure. The propellant is then accelerated and exhausted through a nozzle like an ordinary rocket. The advantage of this propulsion system is that it is dependent on the energy of the nuclear reactor and not the chemical energy stored in the propellant. As nuclear energy can generate energies of several orders of magnitudes larger the propellant can be accelerated to higher velocities, which in turn yields a higher I_{sp}. Experimental rockets that as an approximate I_{sp} of around 1000 [s] has been tested[14].

The current problem with nuclear thermal propulsion is the risk of a nuclear accident that nuclear reactors create. In this paper the political effects and restraints of using such a technology has been neglected.

5.3 Mass-budget

As the ΔV requirements is given the required starting mass, that is the mass of the propellant, can be calculated by using the rocket equation. By using MATLAB the lowest starting mass was found by an iteration of the rocket equation. This was done for each propulsion technology, including the approximate mass of each propulsion system. The result is presented in table 1.

Propulsion system	I_{sp}	**Engine mass [kg]**	**Payload mass [kg]**	**ΔV [km/s]**	**Propellant mass [kg]**	**LEO mass [kg]**	**Number of launches**
Mars habitat							
LOX/LH2	455	3400	53100	3.98	78680	133430	2.52
Nuclear/LH2	1000	1650	53100	3.98	27370	82120	1.55
Support module							
LOX/LH2	455	3400	66800	3.98	98370	166820	3.15
Nuclear/LH2	1000	1650	66800	3.98	34210	102660	1.94
Crew module							
LOX/LH2	455	3400	56000	8.18	311180	370580	6.99
Nuclear/LH2	1000	1650	56000	8.18	74960	132610	2.5

Table 1: Comparison of final masses in LEO for different propulsion systems.

The engine mass is an approximated value for the mass of that engine type, the mass of the tanks was neglected. The LEO mass is the starting mass when the spacecraft is in Low Earth Orbit. The number of launches is approximated by taking the maximum payload mass to LEO of a heavy lifter (Falcon Heavy) and calculate how many launches has to be made to assemble that specific propulsion setup in space.

5.4 Choice of propulsion system

By looking at table 1 it is clear that a crew vehicle that uses chemical propulsion is not an option, as it requires more than 6 launches to get into LEO. Also there will be problems with storing these large amounts of propellant in space for a longer extent of time. For the crew vehicle the best option seems to be the nuclear thermal propulsion system. A trip to Mars and back to Earth would require just over two launches, this value could probably be lowered down to two launches by cutting some mass of the vehicle.

This in turn means that the best propulsion system to use for the cargo vehicle also will be the nuclear thermal propulsion system. Even though it is more feasible to use liquid propellant for the cargo vehicle it will probably be much better from a construction and economical point of view to just focus on developing one propulsion system instead of two separate. With this in mind the choice was made to use the nuclear thermal propulsion system for both types of vehicles.

6 Risk, Safety & Emergencies

During the 178 day transfer from Earth to Mars and the subsequent 198 day transfer back again from Mars to Earth there are several risks involved for the vehicle and the crew. Some risks can mean a complete loss of the vehicle and crew whilst other risks might only pose a slight inconvenience. A simple risk register table is given in Appendix C. Below two selected scenarios are more thoroughly discussed.

6.1 Medical emergencies

During the crew transfer there is the risk of medical emergencies. There are naturally many different medical emergencies that can befall the crew, much like happens to people on Earth, although some risks are specific for manned space flight. The problem in this case is that the crew would be completely isolated from all types of medical facilities and would need to be completely self-reliable when it comes to curing any type of medical ailment. On earth the risk per person for injury or disease requiring evaluation or hospitalization is 6-7 % per year and for intensive care this number is 1-2 % per year. This would mean that for the six man crew the average time between someone requiring intensive care would be around 7.6 years, meaning that for the total 2.6 year mission the probability of someone requiring intensive care would be 21 %. [25] This would of course be unacceptable for a Mars mission due to the limited ability of medical attention.

The available options in order to handle this risk is to either take pre-emptive measures to assure that the probability of someone requiring intensive care during the trip will be low enough to be acceptable (i.e. to make the vehicle and subsequent landing safer than any regular year on earth) or to make sure that the crew habitat has the capability of treating such ailments. Of course the best course of action would most likely be a combination of both these countermeasures.

NASA has several procedures for how to treat different minor medical problems on-board ISS [16][17][18] (summarized in [19]). If any medical problems were to occur the crew habitat should have basic capabilities of dealing with these kinds of problems.

Pre-emptive measures, in order to avoid any more serious medical problems, could be to pick crew members that are healthy and fit in order to make sure that they will not get any diseases during the trip. This is already standard procedure during astronaut selection. [28] Also the crew habitat should be designed to be very safe and clean in order to avoid diseases and accidents.

Still, if any complicated medical procedures would have to be carried out, for example surgery, the issue is somewhat more complex. There are however interesting solutions to this problem as well, for example in-orbit surgery [20] . The possibility of an orbital, microgravity environment surgery is currently being investigated but the possibility has shown some success already. Common problems such as bodily fluids not being contained in the same way within the body cavity might not be such a large problem as could have been expected [21] . Surgery on Mars could also be an option and would to some degree be more reminding of regular surgery [22] . The surgery could also be performed via remote control by surgeons on earth using robotic surgery tools controlled from earth by a skilled surgery. This would eliminate the need to bring a surgeon along for the mission. This approach has already proven successful, however due to the long distance between the spacecraft and the surgeon during a Mars mission this might be significantly more difficult to implement [23][24] .

6.2 Mission abort scenario

There are several different things that could go wrong in a space mission (as mentioned in the risk analysis section above) but it would be impossible to analyse all of these in detail in this paper. Below one interesting scenario is discussed. The scenario doesn't necessarily specify however the exact malfunction but rather the consequences and subsequent solutions to this problem. The scenario can easily be connected to any of the above mentioned risks and their associated consequences.

Scenario description The scenario considered is the eventuality of a forced mission abort during mid-transfer from Earth to Mars. This could for example be caused by a faulty habitat meaning that the option of landing on Mars is unavailable or one or several of the crew members falling ill. Another possible scenario could also be some form of malfunction with the propulsion leading to a severely reduced V available for the vehicle. This would mean that the vehicle would possibly have to skip to circularize the orbit upon arrival to Mars in order to have enough fuel for the return trip. This would however lead to other problems, because in the most efficient setup of the mission the resources required for the return trip would be sent to Mars before the crew vehicle is sent. The crew vehicle would then dock with one of the cargo vehicles and the required return trip resources would be transferred to the crew vehicle. There is also the possibility of the cargo vehicle being lost during the transfer from Earth to Mars. This would also lead to the crew vehicle not being able to resupply for the return trip. Considering this the crew vehicle should be designed to bring all resources required for the return trip as well to ensure that any failure disabling a docking in Mars orbit will not be fatal for the crew. As the vehicle will be travelling on a faster trajectory than the slower cargo vehicles (which are sent beforehand) the option of transferring the crew to another vehicle in case of an emergency is not available. This means that the vehicle in which they will be travelling will need to be reliable enough alone to provide an acceptable probability of survival for the crew. There are several ways of designing the crew vehicle in order to provide this order of reliability. Some examples would be redundancy in key subsystems, no single-fault failure systems and the entire system also being two-fault tolerant. [26] Since the crew vehicle is manned repairs can also be performed during the mission meaning that easily repairable components would be an advantage. Therefore the crew vehicle should naturally have a capacity to support EVAs. The total abort V required varies between 0 and 2.7 km/s, depending on which trajectory is chosen. [27] The vehicle should reasonably be designed to have the capacity to abort even if using the most demanding trajectory meaning that after injection into transmartian trajectory the vehicle should have a minimum of 2.7 km/s of V remaining. However the circularization around Mars takes a maximum of 3.5 km/s of V if aero braking is employed, also depending on trajectory, meaning that no extra fuel actually needs to be carried to allow for full mission abort capability. [27] In the case of a full propulsion failure however the only trajectory that would assure return of the crew would be a free return trajectory. The choice of trajectory is however a question suitable for larger mission planning. In summary the specific actions required to allow for this certain non-nominal situation would be to bring enough supplies in the crew vehicle to keep the crew alive for the trip to Mars and also during the return trip as well as to design the crew vehicle to be very robust, redundant and also easily maintainable. However, no specific actions need to be taken to allow for sufficient abort V as long as the vehicle is designed to allow for circularization around Mars for all possible trajectories.

7 Conclusions & Discussion

There will be three different vehicles travelling to Mars, one of which is a crew vehicle. This seems to be the best solution to the problems at hand. The crew vehicle have a mass of 132610 [kg] in LEO and is capable of making the trip from Earth to Mars in less than 180 days. The cargo vehicles has masses of 82120 [kg] for the Mars habitat module and 102660 [kg] for the Support module and are designed to make the trip to Mars in more then 270 days. Both the crew and the cargo vehicle are using nuclear thermal rockets for propulsion and power generation. For life support and radiation shielding NASA:s new Water Wall technology is used. This has all been done at a top down level, meaning that the paper does not go into much detail about every component or solution chosen. No consideration have been made about what to do with the radioactive reactor after it has ended its service.

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A Masses of crew vehicle

Structure	Mass [1000 kg]
Bigelow 330	15
Life Support System	17.5
Equipment	5
Consumables	7
Astronauts	5
Total	45

Table 2: Summation of masses for crew vehicle.

B ΔV-budget

Crew vehicle		
Stage	**Max. dV [km/s]**	**Max. Transfer time [days]**
EMT	4.08	≤ 180
MOC	0.7	-
MET	3.0	≤ 180
EOC	0.4	-
Total	8.18	≤ 360
Cargo vehicle		
Stage	**Max. dV [km/s]**	**Max. Transfer time [days]**
EMT	3.98	≥ 270
Total	3.98	≥ 270

Table 3: ΔV-budget for crew and cargo vehicles.

C Risk Analysis/Risk Register

Risk	Description	Mitigation
Critical risks		
Failure of life support	The life support systems are made up of several different subsystems such as heating, water recycling, food, air, waste management etc. [A]	Backup and redundancy. A long mission such as this would probably require a large and complex life support system. There is no real way of using a simpler system as a backup in this case however since there is nowhere to escape in case of emergency.
Crew ailment	Radiation poisoning, effects of zero gravity or any other form a disease. (Psychological ailments)	Proper shielding from radiation, artificial gravity and exercise, careful crew health monitoring, plenty of on board drugs, sterile environment, medically educated crew etc.
Power System Failure	Power generation insufficient, power not properly stored or transmitted etc.	Backup and redundancy. Design for a certain excess of power generation in order to allow for unexpected power consumption peaks or power generation shortages.
Propulsion system failure	Failure of engine itself, the fuel system, piping & tanks etc. leading to the crew being stranded in orbit or never being able to enter Mars orbit. Would eventually lead to the crew dying from the life support running out.	Backup and redundancy in the propulsion system. Use of a free return trajectory would ensure the crew returns to earth even in the case of total propulsion failure.
Collision with space debris	Collision with any form of space debris could	Micrometeoroid shields, such as Whipple shields, offer good

	potentially lead to a complete loss of the vehicle.	protection against smaller objects most probably found in interplanetary space. Collision avoidance maneuvering can deal with any larger objects.
Significant risks		
Failure of Lander	Leading to the crew not being able to land on Mars. This would lead to a failure (or at least partial) failure of the mission.	Robust (i.e. redundant) lander and ascent vehicle.
Failure of propulsion (for one of the vehicles) leading to failure of transfer	Same probability as for failure of propulsion for the crew vehicle but the severity would not be as large. If the habitat or the Lander cannot reach Mars the mission cannot be performed.	Ability to send a new cargo vehicle together with the crew vehicle in case the first cargo vehicle is lost. The cargo vehicle should naturally also be robust and redundant.
Failure of any major system for the cargo vehicles leading to failure of transfer	Same severity as for failure of propulsion for the cargo vehicle but the probability is the added probabilities of any of the major systems failing.	Same as above.
Failure of any major system for the cargo vehicles leading to broken equipment	Systems such as temperature control or similar could fail leading to damaged equipment, but not a completely failed transfer of the cargo vehicle. Severity not as high but the probability is most likely larger.	Important equipment should be double redundant and securely stored. In case most of the equipment is unusable the same mitigation option as above can be used.

Partial failure of life support	Could potentially lead to a mid-transfer abort being required.	Due to the length of the mission any partial failure of the life support system would most likely lead to a life-threatening critical failure. Mitigation same as above for the critical risk situation.
Failure of artificial gravity	Could lead to the crew not being able to land or perform their required tasks upon arrival to Mars. (Due to the physiological effects of microgravity)	Failure of the artificial gravity system could potentially be critical. Potential backup systems could be exercise equipment. The system could also be made double redundant or easily repairable.
Minor risks		
Failure of scientific equipment	Could lead to inability to perform certain parts of the scientific mission.	Secure storage of equipment. Important equipment should be double redundant.
Failure of minor life support	Could lead to uncomfortable living conditions but not forcing a complete mission abort.	Backup and redundancy. Due to the length of the mission the full life support system would probably have to be double redundant either case. Also, uncomfortable living conditions might become critical if not handled.
Psychological problems (faulty psychological countermeasures)	Psychological problems could potentially be caused by uncomfortable living conditions for the crew. The psychological problems might even reach a point severe enough to force a mission abort.	Careful preemptive countermeasures, such as choosing physiologically stable crew members, designing the crew vehicle in a pleasant way and bringing many recreational items for the crew. The crew should also be carefully monitored during the flight and

		be kept in constant contact with earth.
General technical issues leading to time waste for maintenance	All technical issues will of course imply a waste of time for the crew, having to spend time repairing faulty equipment.	General robustness and simplicity of the on board systems. This can be difficult to achieve however due to the sheer complexity of the required vehicle.