Critical Analysis and Review of Current Mars Mission Scenarios for SpaceX Starship

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Critical Analysis and Review of Current Mars Mission Scenarios for SpaceX Starship

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Abstract

Human space exploration is currently aiming at the lunar environment in the frame of the ARTEMIS program, including the Lunar Orbital Platform Gateway and also lunar landings. In addition, there are mission plans by most prominently SpaceX for establishing a human exploration of Mars utilizing SpaceX Starship, a two-stage heavy launch vehicle and spacecraft for transfer to and landing on Mars. The currently discussed scenario includes landing on Mars, setting up of in-situ resource utilization (ISRU) for propellant generation and resupply of Starship for the return to Earth. Such a mission would not only be a huge step forward in human development, but would also require technological advances beyond what is currently possible. This paper analyses the currently available information about SpaceX mission plans for Mars based on Starship, extrapolates requirements, necessary technology developments and based on key figures evaluates the feasibility of these mission plans. Key figures are launch mass, payload mass and unloaded mass, technology readiness and costs. It is shown that two major parts of the mission scenarios, i.e. power supply and ISRU propellant production have low technology readiness, which is driving costs, mass and volume and timeframes expected to close technological gaps are not fitting SpaceX mission plans. System elements which require smaller technological advances, but are still critical include power supply for Starship during transfer and elevator technology to reach the ground after landing. Overall, the analysis shows that current plans are not feasible and therefore recommendations are made to achieve feasibility for Mars missions using Starship.

Keywords: Feasibility analysis, SpaceX Starship, Mars mission, human spaceflight

1. Introduction

SpaceX's Starship will bring the first humans to Mars, according to Elon Musk's vision [1]. This achievement would pale any human spaceflight mission that has occurred in the past six decades and is one of several plans for re-introducing the space environment beyond Low Earth Orbit (LEO) into humanity's theatre of activity. This leap forward in humanity's capabilities is ambitious, considering the fact that NASA's ARTEMIS program is still in its infancy as are all other plans for leaving LEO.

The mission to Mars is associated with several challenges, which have to be addressed. They range from human physiology and the health risks of spending prolonged time in a low-gravity environment to funding challenges and technical obstacles, e.g. a life-support system which can operated reliably for several years during a Mars mission – where replacement of parts, beyond what you took along for the ride, is not possible.

Mission scenarios for SpaceX's Starship involve refuelling on Mars with fuel obtained, resp. produced on the Martian surface [2]. This is one of the major challenges as the fuel has to be produced reliably if not for the crew to be stranded on Mars without a way home. The technology has not only to be reliable, but this huge infrastructure, larger than anything NASA brought to the Moon during the course of the Apollo-program, has to be transported to Mars.

These are just some challenges associated with SpaceX's Starship mission to Mars. This paper investigates the feasibility of Starship to be applied for the proposed Mars mission. For this purpose, first the currently available information is compiled and then weighed against the necessities of a Mars mission as given by the current mission scenario [2]. Data is extrapolated where necessary, based on existing technology of other entities, to paint an as complete picture as possible, involving in-situ-resource-utilization (ISRU) technologies for generating fuel on the Martian surface or nuclear reactors for power generation.

Subsequently, the feasibility is analysed and discussed e.g. considering the technology readiness level of the required technologies, available payload mass or Δv and thus propellant mass required.

2. Method

To review the feasibility of Starship's Mars mission as proposed by SpaceX, all relevant data for the spacecraft and mission components were compiled. This data was obtained from publications by SpaceX (e.g. [3] [4] [2])

or about SpaceX (e.g. [5] [6] [7]) were the former were not available. In case of contradicting information, the most recent one was selected, to consider possible updates on the design. Where no information was available about Starship, data was extrapolated from existing systems, e.g. based on ISS technology. The system design also includes ISRU-technology.

Since the topic of Starship is still new, the search was conducted purely via digital sources. Information also comes, for example, from videos in which Elon Musk is interviewed, in which he shows and explains the progress of Starbase, as well as from presentations he has given. In the search for further components and technologies for the Starship and ISRU, NASA and other space companies were frequently consulted for existing ones and those currently in development.

As a backdrop for the analysis a mission scenario has been formulated derived from information supplied by SpaceX, to evaluate how the above design is fitting that mission scenario. In addition, further requirements have been set for the Starship and the ISRU components that still have to be fulfilled. A possible launch window and trajectory including flight duration and the required speed difference were also selected (see Table 2).

With both in mind a system design has been set up as a compilation of information given about SpaceX Starship. The following steps were taken:

1) definition of the subsystems,
2) set-up of the respective system designs and requirements,
3) estimation of mass and power budgets where possible

With this compiled system design, the mission feasibility concerning the given mission scenario has been analysed and evaluated subsequently. For this feasibility analysis the most relevant key figures have been identified, which can be addressed with the available information. These key figures have been:

a. Launch mass
b. Unloaded mass (mass w/o crew supporting equipment)
c. Payload mass (mass w/ crew supporting equipment)
d. Technology Readiness Level
e. Costs

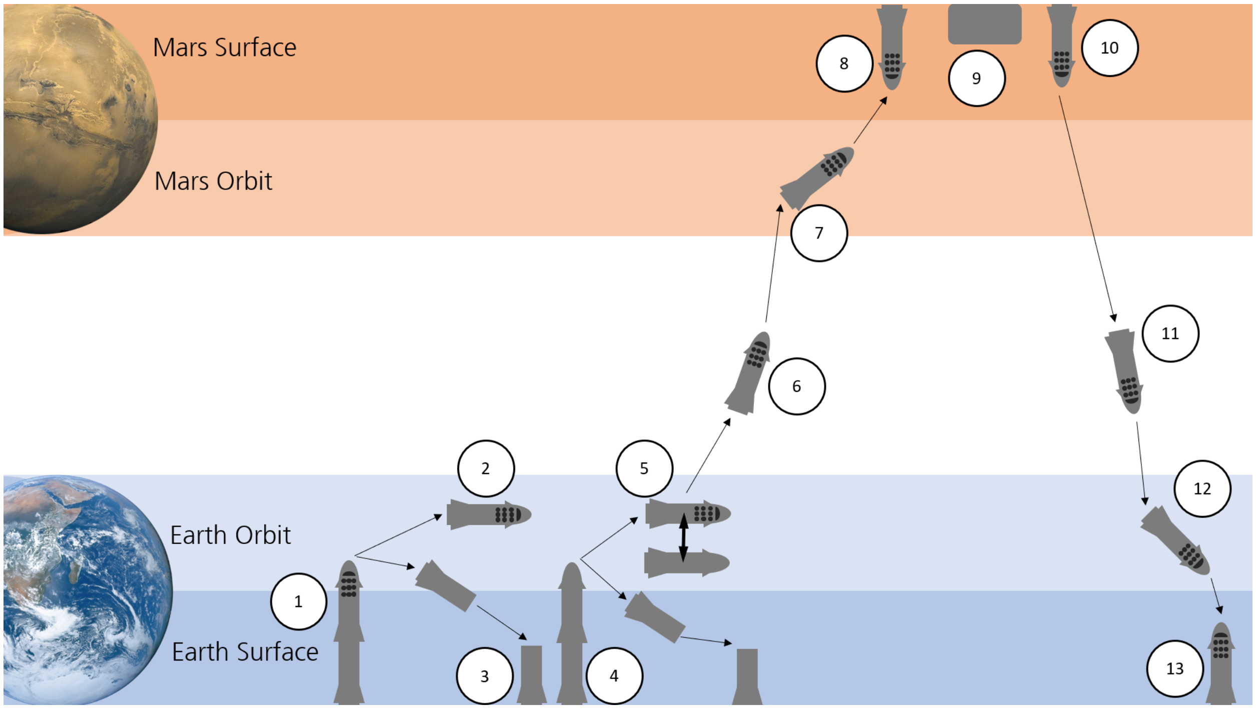

Figure 1: Mission scenario as described by SpaceX. First (1) the crewed Starship is transferred into orbit, where it separates into booster and upper stage (the actual Starship). The booster returns to Earth (3) and uncrewed transports launch into Earth orbit (4). There, the transports refuel the crewed Starship (5), before landing back on Earth. Once refuelled Starship makes the interplanetary transfer to Mars (6), where it conducts aerobreaking (7) and lands (8). ISRU is used to refuel Starship (9). Afterwards Starship can launch from Mars (10), transfers back to Earth (11), where it uses aerobreaking once more (12) to slow down and finally land (13). Source: [2], Mars and Earth images: NASA, public domain, overall image: own

3. Baseline Mission Scenario

Figure 1 shows the mission scenario compiled from information published by SpaceX for planned Mars missions using SpaceX Starship [2]. It relies on ISRU for generating fuel on Mars, which is a major element to be regarded for feasibility. Another major aspect is aerobreaking capability.

According to current planning, the first two uncrewed cargo Starships could use the next but one launch window in 2024 to make their first flight to Mars [8]. In the following launch window, two more cargo and two crewed Starships (10 to 20 people onboard) are set to be launched [9, p. 4]. For this work, it is assumed that the two crewed Starships will each have a crew of ten on the first mission and that a flight trajectory with a longer stay of 368 days on Mars [10] will be chosen, as the propellant for the return flight of both crewed Starships must be produced during this time.

According to mission plans [2], the crewed Starships will launch, (1) in Figure 1, from Boca Chica, Texas and/or from launch site LC-39A at the Kennedy Space Center (KSC) in Florida [11, p. 7 ff.]. The crewed Starship will remain on orbit (2), while the booster will return to Earth (3). Subsequently, transport variants of Starship will launch into orbit (4), where they refuel the crewed Starship and their booster will once more return to Earth. Once refuelled the crewed Starship will transfer to Mars (6), where it will use aerobreaking (7) to remove excess energy and land on the Martian surface (8). During the mission stay ISRU will be used to generate fuel and refuel Starship (9) for the return trip. Once the mission is over (and sufficient fuel has been generated) Starship will leave Mars (10) and go on its return trip to Earth (11). Again, using aerobreaking (12) Starship will eventually land on Earth and end the mission (13). [2]

4. Compiled System Design

The assumptions and designs made in this Chapter refer to the crewed version of Starship, because this is the version with the highest launch mass on the return flight from Mars. The cargo Starships would have a mass of 100 t less on a return flight (not on the first missions), as their payload would remain on Mars.

SpaceX's only design specifications for subsystems are for the main engines and tanks, and the stainless-steel structure. Therefore, the subsystem designs are mainly based on own assumptions made in this work or on existing systems such as the ISS or the Orion space capsule.

4.1 Starship

Structures

The structures subsystem comprises all structural elements, including protection against cosmic and solar radiation. To protect the most important areas, such as the crew's sleeping compartments and the control centre, these should be covered with polyethylene, as this is a well protective material [12]. For additional protection, water pipes, which are used to supply the crew and transport waste water, are to be laid in the spacecraft in a way that encloses as much habitable space as possible, as water is a well protective substance as well [12]. Since the mass of the radiation protection should be kept as low as necessary, materials that have to be onboard anyway should also be used as additional protection. These include for example equipment and food. Thus, in the event of a strong solar flare, a protective shelter could be built in which, in addition to covered walls made of polyethylene, the crew can surround themselves with food and equipment containers and wait it out. This increases the density of material around the crew, resulting in better protection. This process is also being pursued for the Orion capsule [13].

For micro-meteoroid protection, Starship, similar to the Columbus module of the ISS, is to have a protective layer reinforced with Kevlar and Nextel, a so-called Stuffed Whipple Shield (SWS), which bursts incoming objects with three layers of protective material and thus prevents them from penetrating [14]. The three layers should consist of two bumper shields (BS) and the back wall (BW), as shown in Figure 2.

Furthermore, Starship must be designed and built in such a way that its structure can carry the payload of up to 100 t with empty tanks, because they will be almost empty by the time it arrives on Mars. As with the current prototypes, 3 mm thick 304L stainless steel is assumed to be used for Starship's outer skin [15].

Environment Control and Life Support System

For Starship, the ECLSS is should be modelled after that of the ISS. For additional protection against strong solar storms, special vests are to be available onboard Starship, which should be worn when a solar flare occurs. One such vest is the AstroRad vest, which will be tested on

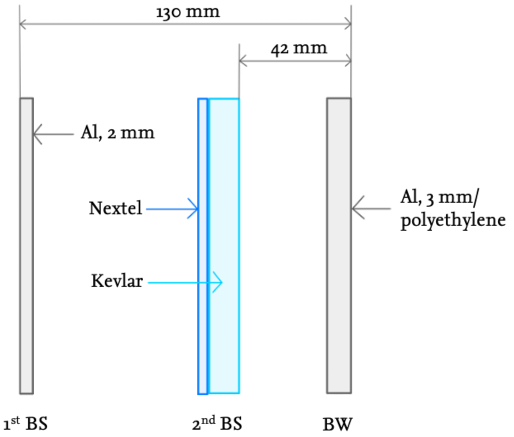

Figure 2: Stuffed Whipple Shield for Starship with two bumper shields (BS) and one back wall (BW), after [14]

the Artemis missions [16]. Furthermore, the ECLSS is to be expanded to include a radiation warning system that will warn the crew when solar storms occur and they have to seek shelter. The HERA (Hybrid Electronic Radiation Assessor) radiation warning system, which is used onboard the Orion capsule, is to be used for this purpose [13].

Communications System

Communication onboard Starship should be possible with a local network. For astronauts to communicate with each other at any time, there should be a panel in every room (including all living compartments) for audio transmission only, with which every other room and thus every other person can be contacted. In this way, other people can be quickly informed of problems or warned in case of emergencies. The transmission of video and data is also to be made possible via mobile devices and a wireless network.

Between Starship and the control centre on Earth, communication during the flight should be carried out via an optical communication system (laser communication system). One such system, NASA's Orion Artemis II Optical Communications System (O2O), will be tested on the Artemis II mission. It is supposed to deliver 10 to 100 times faster data transmission than conventional RF (radio frequency) systems, so that even videos in UHD can be received and sent on Mars. Furthermore, optical communication systems are smaller, lighter, more energy-efficient and more secure than RF systems. [17] However, as a back-up, Starship should also have a conventional RF antenna that can be used to communicate via the Deep Space Network (DNS), as it is the case with the Mars rovers and probes, for example.

Electrical Power System

The Electrical Power System (EPS) is responsible for the generation, conversion, distribution and storage of electrical power onboard Starship. Solar arrays, which are to be stowed in the engine section during launch and landing and to be deployed during the flight, allow electrical power generation during the flight. Therefore, they must not only be deployable but also retractable. Similar to the Orion capsule, the solar arrays are supposed to have a mechanism that allows them to constantly align themselves with the sun so that they can deliver full power.

Orion's four 7 m long and 2 m wide solar arrays, each consisting of three foldable panels, provide 11.2 kW of power for a crew of four people [18]. Therefore, Starship's solar arrays should have about ten times the power, 100 kW. In addition, the radiation intensity decreases by about half during the flight to Mars. In order for the solar arrays to deliver the required power near Mars, they need to deliver at least twice as much power near Earth, due to the reduced radiant energy on Mars of 590 W/m^2 compared to 1,36 kW/m^2 near Earth. [19, p. 19] With some margin for failing solar cells, for example, an output of around 250 kW (the power of 100 kW with the factor of two plus a margin of 50 kW) is required near Earth. One solar panel that should be able to deliver this amount of power is the MegaFlex from Northrop Grumman (formerly ATK), which is foldable and unfolds into a round panel by rotating 360°, as shown in Figure 3. The MegaFlex is a scalable system that is currently still being tested, but its smaller version – the UltraFlex – is already being used on, for example, the Cygnus spacecraft and the InSight lander on Mars. So, the technology is already proven and has a flight heritage. A system consisting of two MegaFlex arrays, each with a diameter of around 24 m, should be able to deliver this power according to Orbital ATK. Together, the two arrays have a mass about 2 t. [20]

Thermal Control System

The TCS should consist of two separate circuits – an internal (ITCS) and external (ETCS) system, which is to be based on that of ISS and Orion. Like them, the ITCS should have water as a coolant, as this is not dangerous to the crew in the event of a leak. Cold water is to be used to cool systems. Water heated by waste heat from systems is first used to heat certain areas before being cooled by the ETCS through an Interface Heat Exchanger (IFHX). The coolant of the external system absorbs the heat of the internal system and releases it into space via radiators. [21] HFE7200 is supposed to be used as the coolant for the ETCS because it has a low freezing point and low toxicity [22, p. 7]. For redundancy, there are to be two internal and two external TCS.

In addition, there should be electric heaters and Multi-Layer Insulation (MLI foil), which provides additional low radiation shielding.

Extravehicular Activities

Airlocks are needed to carry out extravehicular activities (EVAs). Similar to the concept of the HLS Starship, Starship should have two airlocks [23]. This way, several astronauts can go outside at the same time and redundancy is ensured.

Furthermore, elevators are needed, as seen in the HLS Starship concept, to bring the astronauts to the surface of Mars. The elevators are to be suspended from two extendable crane arms and have a platform with which

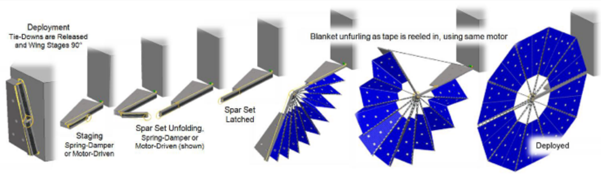

Figure 3: Deployment mechanism of the MegaFlex solar array [45]

the astronauts and the payload can be transported. In addition to low-maintenance operation, the elevators should also be able to function in strong winds so that outside work does not have to be interrupted for weeks due to dust storms.

Propulsion System

The propulsion system consists of the main engines, the control thrusters (RCS thrusters), the main tanks for liquid methane and liquid oxygen and the helium tanks for pressurizing the main tanks. The system for orbital refuelling of Starship is also included.

Since one engine has a mass about 2 t including the mounting structure [5], this results in about 12 t for the six main engines – three SL Raptor and three RVac engines.

Since Space Shuttle had 44 RCS thrusters [24], 50 RCS thrusters are assumed for the larger Starship. As a rough estimate for the mass of a thruster, the 220 N RCS thruster of the Orion capsule is used, which has a mass of approximately 2 kg [25]. This results in a mass of approximately 100 kg for Starship's RCS thrusters.

For the mass estimation of the main tanks, those of the Super Heavy booster are used. These currently have a mass of approx. 80 t [5] for a propellant mass of 3,600 t [5], but are still somewhat too heavy, which is why 70 t are assumed. Based on Starship and a propellant mass of 1,500 t [26], the mass of the main tanks is about 29 t. The helium tanks are assumed to have a mass of about 5 t.

Table 1 lists the assumptions made from the previous subsystem chapters. For the crew, the assumption is made that the ten people have a mass of around 80 kg each and are allowed to carry 40 kg of luggage, considering that it is a long mission duration. This results in 1.2 t for the crew and its luggage. Since no information is available on the masses of the remaining smaller subsystems (EVAs, robotics, heat shield etc.), it is assumed that these add up to 7 t. The total mass without propellant and payload is assumed to be 200 t. Masses of subsystems that are necessary for the crew or required for them to a greater extent are not counted as unloaded mass, but instead as payload mass. It is estimated in this work that half of the masses of the EPS, TCS and others margin are also needed for unmanned Starships such as the cargo version, as these require less power due to the lack of life support systems and thus also smaller solar panels and batteries as well as no such extensive TCS and, for example, no equipment for EVAs. Therefore, only the halves of the masses of the EPS, TCS and others margin as well as the masses of the structure, the meteoroid protection and the propulsion system are counted as unloaded mass. The unloaded mass of Starship is therefore around 125 t according to Table 1. Since Starship is supposed to be able to carry a payload of 100 t, a total dry mass of 225 t is assumed in the following. Therefore, in addition to the 200 t, an additional 25 t of payload, such as the rovers, can be carried.

Table 1: Total dry mass budget of a crewed Starship

		Mass (t)	**Total mass (t)**
Structures	Radiation shielding	40	101.3
	Meteoride shielding	21.3	
	Structure	40	
ECLSS	Radiation vests	0.27	20.27
	Margin	20	
EPS	Solar arrays	2	9
	Cables	1	
	Batteries	4	
	Components	2	
TCS	MLI	2.21	10.21
	Margin	8	
Propulsion	Main engines	12	51.1
	RCS thrusters	0.1	
	Main tanks	29	
	Helium tanks	5	
	Pipes etc.	5	
Margins	Crew + Luggage	1.2	8.2
	Other (EVAs, Robotics, Heat shield etc.)	7	
Total			200
Payload		25	25

In addition to the total mass, the Δv to be applied is required to calculate the propellant mass required for the flight to Mars and back, as this is also important for the propellant mass that needs to be produced on Mars. The Δv for the selected trajectory from NASA's Trajectory Browser refers to a launch from an Earth orbit at an altitude of 200 km, which can be assumed for Starship, because it still has to be refuelled. The assumed Δv for arrival at and departure from Mars refers to the escape velocity in a 200 km orbit around Mars. According to NASA's programme, landing on Earth will presumably take place with parachutes, because no Δv is specified for this. Table 2 shows the Δv's with these assumptions in the second column. For Starship's mission, however, the values for arrival at and departure from Mars must be adjusted, because Starship will not enter and leave a Mars orbit, but will land and launch directly on the surface of Mars. For the supersonic retropropulsive landing burn at an altitude of 2.5 km [27], a Δv of 1 km/s should be assumed, as well as for the landing on Earth.

Now the Δv for the launch from the Martian surface and the acceleration to the escape velocity in a 200 km Martian orbit is to be calculated, to which the value

Table 2: Total Δv for the planned mission

	Δv (km/s) NASA [10]	**Δv (km/s) modified**
Start Earth	3.63	3.63
Arrival Mars	0.623	1
Total Δv outbound flight	4.253	**4.63**
Start Mars	0.887	6.267
Arrival Earth		1
Total Δv return flight	0.887	**7.267**

already calculated by NASA for the return flight is then added. Including assumed velocity losses of 0.5 km/s at launch and the velocity change for injection to Earth of 0.887 km/s, the change of velocity at launch is as follows

$$\begin{aligned}\Delta v_{Start} &= v_{esc,200} + \Delta v_{Loss} + \Delta v_{Inj} \\ &= (4.88 + 0.5 + 0.887)\ \frac{\text{km}}{\text{s}} \\ &= 6.267\ \frac{\text{km}}{\text{s}}.\end{aligned} \tag{1}$$

With the simplified assumption that the Δv to be applied is burnt in one piece, the following can be calculated using the rearranged rocket equation:

$$m_0 = m_1 \cdot e^{\frac{\Delta v}{v_e}} \tag{2}$$

the mass m_0 before and the mass m_1 after burnout and thus the required propellant mass

$$m_f = m_0 - m_1 \tag{3}$$

can be calculated. The exhaust velocity can be calculated by the mean of the specific impulses of both engines [4] into

$$\begin{aligned}v_{e,S} = I_{sp} \cdot g_0 &= \frac{(3 \cdot 355 + 3 \cdot 380)\ \text{s}}{6} \cdot 9.81\ \frac{\text{m}}{\text{s}^2} \\ &= 3{,}605\ \frac{\text{m}}{\text{s}}\end{aligned} \tag{4}$$

Since the atmosphere of Mars is so thin and the pressure so low, the specific impulses under vacuum conditions are assumed for the launch on Mars. For the outbound flight (EM = Earth-Mars), it is assumed that m_1 corresponds to the total mass of Starship plus 10 t of propellant residuals (which is a bit more than the assumed 0,5 % by Elon Musk for the booster [5]), thus 235 t, resulting in the following values (included propellant residuals):

$$m_{0,EM} = 848.9\ \text{t} \tag{5}$$

$$m_{f,EM} = 623.9\ \text{t} \tag{6}$$

For the return flight (indexed ME), the assumption is made that with consumed food, no payload and 10 t of propellant residuals, m_1 is 200 t. This results in the following values (included propellant residuals):

$$m_{0,ME} = 1{,}501.4\ \text{t} \tag{7}$$

$$m_{f,ME} = 1{,}311.4\ \text{t} \tag{8}$$

For the outbound flight, 623.9 t of propellant are needed with a landing mass of 235 t, and for the return flight with a landing mass of 200 t, 1,311.4 t of propellant are needed.

4.2 In-Situ-Resource-Utilization

Propellant Production System

In order to produce the two propellants liquid methane (LCH_4) and liquid oxygen (LOX) on Mars, a propellant production plant is needed.

To produce methane and oxygen on Mars, different processes have to be used. Water and carbon dioxide are needed to produce methane and oxygen. The water is to be extracted from ice deposits located near the landing site just below the Martian surface or from those found on the surface. A suitable landing site with such deposits must be found beforehand, as this is essential for propellant production and thus also for the return flight to Earth. Electrolysis is then used to separate the water into its two components: hydrogen and oxygen [28]:

$$2\ H_2O \rightarrow 2\ H_2 + O_2 \tag{9}$$

The oxygen obtained is now in gaseous form and must be liquefied. The hydrogen is further used in another process, the Sabatier process [28]:

$$CO2 + 4\ H2 \rightarrow CH4 + 2\ H2O \tag{10}$$

In this, CO_2 extracted from the Martian atmosphere, of which the Martian atmosphere consists of 96 % [29], is converted into methane and water together with the hydrogen obtained from electrolysis. The methane, again gaseous, must also be liquefied and can be stored in tanks afterwards. The resulting water can either be fed to the water electrolysis system or provided to the ECLSS to supply the astronauts. Figure 4 schematically shows a possible process for propellant production on Mars.

To produce and pump the water, a drilling and pumping device is needed to melt the ice and bring water to the surface. In order to extract CO_2 from the atmosphere, a filter system is needed first to remove Martian dust from the air that is sucked in. Then the CO_2 must be separated from the other gases in the air in a separator. In addition, pumps, condensers, compressors, coolers and transport pipes are needed. [28] For the first missions, such a system could be transported completely onboard one Starship as a complete system for propellant production and would remain onboard. Thus, initially only pipes would have to be laid and the drilling, pumping and melting equipment for the ice and water would have to be set up.

For the estimation of the propellant production system (PPS), the 1,311.4 t of propellant calculated in equation (8) should be assumed, which will be needed for the return flight. However, since two crewed Starships are to fly back, 2,622.8 t are required. With a duration of 368 days (Chapter 3) on Mars and a 30-day safety buffer that the propellant should already be completely produced before the return flight, 338 days are available for production, resulting in a production rate of 7,760 kg/day.

A completely integrated propellant production system that has already been tested on Earth under Mars-like conditions is the Integrated Mars In-Situ Propellant Production System (IMISPPS) from Pioneer Astronautics. It has a single reactor that produces both propellants. The system has a production rate of

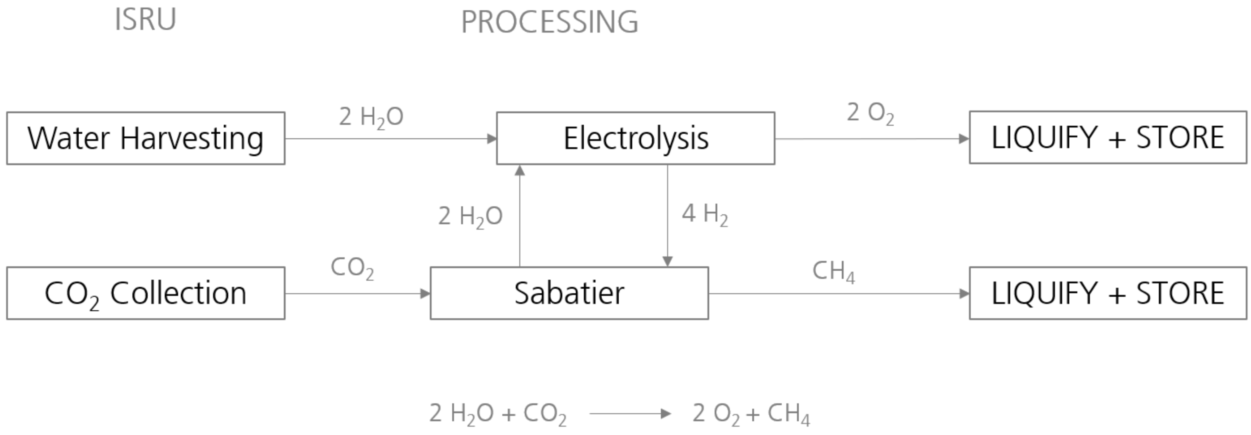

Figure 4: Process for propellant production on Mars, from harvested water and collected CO_2, after [43]

1 kg/day, a mass of 50 kg and requires 700 W of power. [30] Assuming technological progress over the next few years, the production rate of the system is estimated at 2 kg/day with a mass of 75 kg and a power of 1 kW. Based on the required production rate and therefore multiplied by 3,880, this results in a mass of 291 t and a power of 3.88 MW.

However, additional power and additional mass will be added for the water extraction, because in the IMISPPS the hydrogen for the Sabatier process was supplied from tanks and not extracted in advance [30]. Since no exact data is available for such a system, it is estimated that the mass and power of the water extraction system is one fifth of the propellant system, so that an additional 59 t and 776 kW are added, giving a total mass of 350 t and a power of 4.656 MW for the PPS.

In addition, LOX and LCH_4 tanks must be built for storage, whereby the tanks of the landed Starships are to be used for this during the first missions. Based on SpaceX’s mission plans, there should already be four unmanned Starships on Mars ready for LCH_4 and LOX storage when the first two crewed Starships arrive in 2026. Propellants can be loaded and unloaded via the ports that allow for orbital refuelling. This would allow space for other payloads on the first missions. For the transfer of propellants from the Starships converted into storage facilities to the crewed Starships that are to return to Earth, flexible transport pipes must be laid or refuellable rovers used. To prevent the pipes from becoming too long and to keep the distances as short as possible, the Starships must all land close to each other, which is possible thanks to the precise control system. The risk of damage from kicked-up dust and stones should be investigated beforehand.

Power Supply System

A power supply system (PSS) is needed for propellant production, Starships, rovers, future habitats and all other activities on Mars. Nuclear reactors are to be used as the primary power source, because the use of a solar system as the main power source comes with some disadvantages. For one thing, the received energy output on Mars is only half as much (590 W/m^2) as on Earth (1,361 W/m^2), due to the further distance from the sun. In addition, solar panels have an efficiency of only about 30 %, which further reduces the usable energy. [19, p. 19] The panels can also only provide power during the day and would be very limited during months of dust storms. Dust also accumulates on the panels over time, which also reduces power. Nuclear reactors operate independently of ambient conditions, provide power even at night and do not consume as much space in terms of area as comparably powerful solar systems.

For the first mission, in addition to two crewed Starships with ten people each, the propellant production plant and rovers must also be supplied by the power supply system. Assuming two Starships, each requiring 100 kW of power (Chapter 4.1), plus 4.656 MW (previous Chapter) for the propellant production plant and additional power for the rovers, it is assumed that the PSS must provide 5 MW of power.

The Kilopower system launched and demonstrated by NASA, whose follow-up project Fission Surface Power (FSP) is now being continued together with the Space Nuclear Power Corporation (SpaceNukes), is a scalable system in which a reactor core made of enriched uranium heats sodium in heat pipes, which in turn lead to Stirling engines that then convert the heat into electrical power [31] [32]. It is a small and light system for its power, very safe and four such reactors shown on the left in Figure 5 should be able to supply a base with four people [33]. The 10 kW system is expected to have a mass of about 1,500 kg and be able to produce electricity for up to ten years [34] [35].

In Figure 5, the reactor block (black) and the reactor casing (silver), in which the heat pipes are located, can be seen at the bottom with the Stirling engines above them. The shield above the FSP system, which is folded up

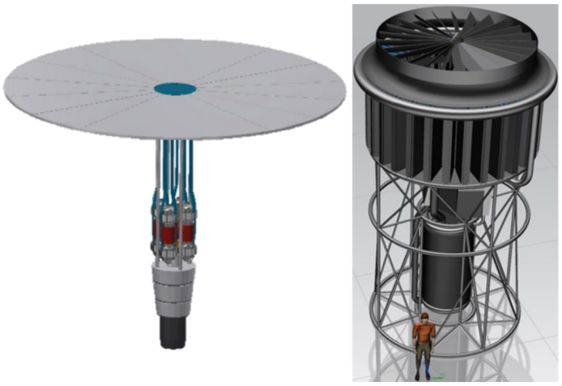

Figure 5: 10 kW (left) & 650 kW (right) FSP System [33]

during transport and only unfolded on Mars, is the radiator.

Two 2 MW systems, which are required for this power demand, will have a mass of approximately 32 t each. [34]. Such a system will look similar to the 650 kW system shown on the right in Figure 5, only larger. It can be seen that there is a fan at the top above the Stirling engines, which is intended to provide better cooling due to the increased heat generated. It should be ensured that this can dissipate sufficient heat given the low atmospheric density on Mars. For transport, the reactor block below the fan can be completely stowed away in the upper large casing. In addition to these two systems, a 1 MW system is needed to deliver the required 5 MW of power. Its mass is estimated at around 20 t.

To protect astronauts and surroundings from radioactive radiation, either the reactor must be surrounded by a protective shield or the reactor must be embedded in the Martian soil, whereby the second option saves additional mass and should therefore be preferred. The stated masses of the systems already include the protective shield. A 4.8 m deep hole is needed to bury the reactor block in the Martian soil [34]. With an estimated cylinder diameter of 2 m, the volume to be excavated is 15 m^3 and with a density of the Martian soil of 1,680 kg/m^3 [36], this corresponds to a mass of around 25 t. Furthermore, it must be ensured that in the event of a launch failure, the reactor remains switched off and will not be activated.

Solar panels could still serve as a back-up and additional power source. Solar panels such as the MegaFlex could be used again for this purpose. To ensure that the power does not decrease over time due to settled dust, a mechanism for removing Martian dust should be developed for solar panels on Mars. Lithium-ion batteries should be used for temporary storage and power supply at night, which can also provide a short-term back-up and ensure the power supply in the event of a power failure.

Transportation System

Unlike the robotics subsystem, which is responsible for transporting payloads onboard Starship, the transportation system is responsible for transport on the Martian surface. Different rovers are needed to transport astronauts and objects and to build infrastructure. To facilitate the construction of infrastructure, rovers are needed that can move the heavy and bulky payloads from the Starships on the Martian soil. Rovers with shovels and drills, like NASA's RASSOR rover, will help create flat surfaces for future habitats and the propellant production plant. Future habitat modules could also be covered with Martian regolith or built into rocks for extra radiation shielding. If transporting the two propellants from the production plant to the tanks or from the tanks to the Starships to be refuelled by means of transport pipes is too costly, for example because the distances are too long, there should be rovers with tanks that take over this task and constantly shuttle back and forth. For the construction of paved roads and landing zones for Starships, rovers with a printing head should be used. These melt the loose regolith and solidify it, creating a solid flat surface. With paved roads, rovers can travel faster and easier between different locations. The advantage of paved landing zones is that there is less dust when landing and it can be done on a flat surface. For the astronauts, there should be both rovers that, like the lunar rover of the Apollo missions, can be used with a spacesuit for short distances and ones in which the astronauts can travel longer distances without a spacesuit.

In order to avoid having to develop and build a completely new rover for each application, a simplified rover system such as the concept of the Modular Robotic Construction Autonomous System (MOROCAS), which is illustrated in Figure 6, is a suitable solution [37, p. 4]. As the name suggests, this concept is a modular autonomous rover system.

The basis is a chassis that can accommodate various modules and tools in a standardised dock and thus perform many different tasks. For example, it can hold a module with a tank, a shovel, a drill and one for crewed transportation. [37, p. 4] The shovel module must have

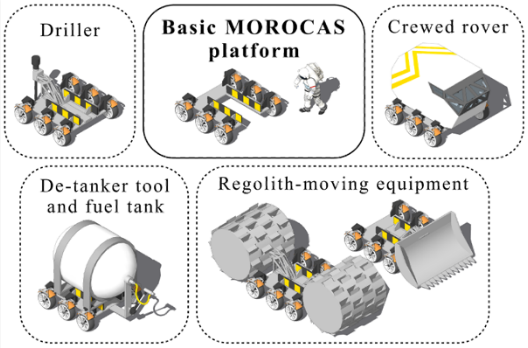

Figure 6: MOROCAS concept with different modules [36]

an excavator arm about 6 m long and be strong enough to dig the 4.8 m deep holes and 25 t of Martian soil for each of the reactors. In addition, there could also be modules with a printing head, a gripper arm and a cargo bed. Such a modular system saves costs and additional mass. In the report of the concept, it is estimated that a rover needs 10 kW/day of power [38, p. 18]. Unlike the concept, the rovers should be powered by batteries instead of with Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). Since the two Mars rovers Curiosity and Perseverance have a mass of around 1,000 kg [39], it is assumed for the MOROCAS concept that the base has a mass of 800 kg without scientific instruments, but with batteries. Five such rovers are to be transported. Including additional modules, a total mass of this subsystem of 10 t is assumed.

5. Feasibility

The feasibility analysis of the planned baseline scenario with regard to Starship and ISRU systems and the associated requirements is conducted on the basis of the following key figures: Launch mass, Unloaded mass, Payload mass, Technology Readiness and Costs.

5.1 Launch Mass

The payload to be transported and the Δv to be applied are decisive for the evaluation of the launch mass. The Δv required for a launch from the surface of Mars and the flight to Earth was already calculated in Chapter 4.1 at 7.267 km/s, as well as the resulting propellant mass of 1,311.4 t and launch mass of 1,501.4 t. So, there is still a buffer of 188.6 t until the maximum permitted launch mass of 1,690 t is reached. With these, if used purely for the propellant, for a landing mass of 200 t (see Chapter 4.1) an additional Δv of

$$\Delta v_{Start,M,add} = v_{e,S} \cdot \left(\ln\left(\frac{1{,}690\ \mathrm{t}}{200\ \mathrm{t}}\right) - \ln\left(\frac{1{,}501.4\ \mathrm{t}}{200\ \mathrm{t}}\right)\right) = 0.426\ \frac{\mathrm{km}}{\mathrm{s}} \quad (11)$$

could be generated.

Likewise, the launch from a 200 km Earth orbit has already been calculated, where only 623.9 t of propellant are required for a Δv of 4.63 km/s, since most of the Earth's gravity has already been overcome here. The launch mass from orbit after refuelling is 848.9 t. If the tanks were fully filled with the additional possible 876.1 t of propellant, with a landing mass of 235 t (see Chapter 4.1) an additional Δv of

$$\Delta v_{Start,EO,add} = v_{e,S} \cdot \left(\ln\left(\frac{1{,}725\ \mathrm{t}}{235\ \mathrm{t}}\right) - \ln\left(\frac{848.9\ \mathrm{t}}{235\ \mathrm{t}}\right)\right) = 2.556\ \frac{\mathrm{km}}{\mathrm{s}} \quad (12)$$

would be achievable. Thus, either a shorter travel time of only 192 instead of 304 days [40] or the transport of more payload could be realised. A shorter travel time in turn increases the length of stay on Mars, which in turn provides more time for propellant production, allowing a reduction of the PPS and PSS.

The only launch mass that remains to be verified is that of the entire Starship system during a launch from Earth into a 200 km Earth orbit. In the following, it will therefore be investigated whether the launch is possible. For this purpose, the launch mass and the required Δv are calculated. The launch mass results from a fully fuelled and fully loaded Starship (1,725 t) and a Super Heavy booster (3,760 t [5]), which is also fully fuelled, at 5,485 t. The required Δv is then calculated. Now the Δv to be expended must be calculated. With a special gravitational constant of the Earth of

$$\mu_E = 398{,}599\ \frac{\mathrm{km}^3}{\mathrm{s}^2} \quad (13)$$

the orbital velocity in a 200 km Earth orbit with a radius $r_{c,200}$ of 6,578 km can be calculated to be

$$v_{c,200} = \sqrt{\frac{\mu_E}{r_{c,200}}} = 7.78\ \frac{\mathrm{km}}{\mathrm{s}}. \quad (14)$$

Furthermore, the Earth's rotational velocity at launch latitude, in this example from Boca Chica in Texas ($\beta = 26°$), calculates to

$$\Delta v_{rot,BC} = \frac{2\pi r}{24\ \mathrm{h}} = \frac{2\pi R_E \cos\beta}{86400\ \mathrm{s}} = 0.42\ \frac{\mathrm{km}}{\mathrm{s}}. \quad (15)$$

When launching from Earth, losses for the steering angle (0.1 km/s), air drag (0.2 km/s) and gravity (1.5 km/s) must be overcome and added to the circular orbital velocity and the Earth's rotational velocity at launch latitude must be subtracted [41, p. 69]. In addition, a margin of roughly 5 % ($\Delta v_M = 0.42\ \mathrm{km/s}$) is to be added according to ESA [42, p. 7]:

$$\Delta v_{Start,E} = v_{c,200} + \Delta v_{Steering} + \Delta v_{Drag} + \Delta v_{Gravity} - \Delta v_{rot,BC} + \Delta v_M = 9.58\ \frac{\mathrm{km}}{\mathrm{s}} \quad (16)$$

According to equation (7) converted to Δv, the booster with the launch mass m_0, the mass m_1 after burnout of 1,925 t (1,725 t Starship + 160 t empty mass booster + 30 t propellant for booster landing + 10 t propellant residuals booster) and an exhaust velocity $v_{e,B}$ of 3,237.3 m/s according to equation (4) (330 s I_{sp}) produces a velocity change of

$$\Delta v_{Booster} = v_{e,B} \cdot \ln\left(\frac{m_0}{m_1}\right) = 3.390\ \frac{\mathrm{km}}{\mathrm{s}}. \quad (17)$$

After stage separation, Starship has to generate the remaining 6.19 km/s. If 1,725 t are used as the mass m_0 and the previously assumed exhaust velocity are inserted into equation (2) converted to m_1 and into equation (3), this results with added propellant residuals of 10 t already assumed in Chapter 4.1 in a propellant mass of

$$m_{f,Starship,Start} = 1{,}425.2\ \mathrm{t}. \quad (18)$$

This is less than the maximum propellant mass of 1,500 t, i.e. the launch is possible. Afterwards, 74.8 t of useful propellant remain onboard Starship, which requires correspondingly less mass to be refuelled. The limiting flight phase is therefore the launch from Earth, since 95 % of the maximum propellant mass is used for a payload of 100 t, whereas this is only 41.6 % for a launch from Earth orbit.

5.2 Unloaded Mass

For better comparability with other Starship variants and with the given data, as well as to determine the maximum possible additional payload, the masses of the subsystems of a crewed Starship, which are necessary or required to a greater extent for the crew, were not included in the unloaded mass but in the payload mass in Chapter 4.1. The unloaded mass of Starship was therefore about 125 t according to Table 1. With a stated unloaded mass of 100 t, this means a significant deviation of 25 %. Since current prototypes are presumably neither equipped with a TCS and EPS nor with meteoroid protection and have a mass of around 100 t, the estimated mass could nevertheless be realistic. Conversely, this means that either 25 t less payload can be transported in order not to exceed the 200 t (100 t unloaded mass + 100 t payload), or, as assumed in this work, a regular 100 t payload is added, which then increases the originally planned launch mass.

For a cargo Starship with an unloaded mass of 125 t and a payload of 100 t, this also results in a total dry mass of 225 t. What distinguishes a cargo Starship from the crewed version is that it will initially be fully loaded only on the outbound flight to Mars, and on the return flight it will be about 100 t lighter and therefore either the required Δv or the propellant mass would be lower. Since for both versions the propellant masses required for launch from the surface of Earth and Mars and from a 200 km Earth orbit are below the maximum possible 1,500 t, it follows that a 25 % increase in unloaded mass with an additional 100 t payload is feasible for both a cargo and crewed Starship and does not represent a critical condition.

5.3 Payload Mass

The payloads to be transported for the first Starships are the propellant production system, the power supply system and the rovers. A system mass of 350 t was assumed for the PPS. The total mass of the PSS, consisting of two 2 MW systems of 32 t each and one 1 MW system of 20 t, is 84 t. Five rovers of 800 kg each plus additional modules were estimated at 10 t. According to the baseline scenario, a total of four cargo Starships with a payload capacity of 100 t each and two crewed Starships with an available capacity of 25 t each for additional payload are available until 2026 to bring the required systems to Mars. Considering the mass alone, 444 t would have to be distributed among six Starships with a payload capacity of 450 t. This would be feasible, but it presupposes that the volumes of the payloads can also be distributed appropriately among the Starships as the payload volumes of the Starships are limited. Thus, the PPS, a 2 MW reactor and the 1 MW reactor could be distributed among the four cargo Starships. The rovers could then be transported onboard one of the two crewed Starships and the second 2 MW reactor onboard the other. Since the reactor would exceed the payload capacity of 25 t, the following examines how much additional payload mass could be transported if the maximum propellant mass of 876.1 t is utilised. Since the PPS should ideally remain onboard the Starships after landing in order to reduce the logistical effort, but it must be divided among four Starships, the Starships must be very close to each other so that pipes for connecting the individual units are as short as possible.

Both during the launch from Earth and from a 200 km Earth orbit, the maximum propellant mass was not yet fully utilised, as was shown in Chapter 5.1. Instead of using this additional possible propellant for a shorter travel duration, the maximum possible payload with an unchanged travel duration will be calculated in the following. Calculating the maximum possible payload mass now is an optimisation task, because with it the launch masses of the booster also change and thus also the velocity changes achieved. This is calculated for launch from Earth, as this is the limiting flight phase. Equation (19) is a combination of equations (2), (3) and (16).

$$\begin{aligned} m_{f,max,Starship,Start} &= (1{,}725 + x)\,\mathrm{t} \\ &\quad - \frac{(1{,}725 + x)\mathrm{t}}{e^{\frac{\Delta v_{Start,E} - v_{e,B} \cdot \ln\left(\frac{5{,}485+x}{1{,}925+x}\right)\mathrm{t}}{v_{e,S}}}} \\ &= 1{,}490\,\mathrm{t} \end{aligned} \tag{19}$$

Mass x includes not only the additional possible payload mass but also structural mass needed to support the additional payload mass. It is included in the total mass of Starship, the booster and the mass after the booster has burned out and was steadily increased in small steps until, with

$$x = 81.7 \tag{20}$$

the maximum useful propellant mass of 1,490 t (the maximum of 1,500 t minus the 10 t residuals) was almost reached at 1,489.96 t. SpaceX assumes that for every tonne of payload, another tonne of structure and propellant will be added [6]. The payload and structural mass of 81.7 t is therefore added to the propellant mass of 74.8 t from Chapter 5.1 and then divided, resulting in the maximum possible additional payload of

$$m_{P,max} = \frac{(81.7 + 74.8)\,\mathrm{t}}{2} = 78.25 \approx 78\,\mathrm{t}. \tag{21}$$

Assuming 10 t of propellant residuals after landing, the onward flight to Mars from a 200 km Earth orbit subsequently requires

$$m_{f,EM,Pmax} = 316.7\ \mathrm{t} \cdot e^{\frac{\Delta v_{EM}}{v_{e,S}}} - 316.7\ \mathrm{t} = 827.30\ \mathrm{t} \qquad (22)$$

of propellant according to equations (2) and (3).

With an additional payload capacity of 78 t per Starship, the total payload capacity of the four cargo and two crewed Starships would increase to 918 t. The payload volume remains of course unchanged, but if the volume is suitable, the PPS could be distributed over only two cargo Starships and the PSS into one Starship. This would create space for scientific instruments, more rovers, back-up solar arrays, a habitat module or similar.

Since the crewed Starships still have a large portion of their payload onboard when they are launched on Mars due to the systems needed for the crew, it must be ensured that a certain total dry mass is not exceeded. If the tanks of the crewed Starship on Mars were to be completely filled for a return flight with 1,500 t of propellant (1,490 t for the flight + 10 t of propellant residuals after landing), a maximum landing mass of 229 t including 10 t of propellant residuals and thus a total dry mass of 219 t would be possible at a required Δv of 7.267 km/s. With the assumption already made in Chapter 4.1 that 10 t of food were consumed at this point, 29 t of additional payload could be transported back to Earth. If the payload capacity of the crewed version were to be increased, the additional structural mass required for this would have to be subtracted from these 29 t.

According to Table 1, the mass of the subsystems required for the crew of a crewed Starship is around 75 t. The largest portion is accounted for by radiation shielding at 40 t and the ECLSS at just under 20 t. This should not be a problem for the first missions, but if up to 100 people are to be transported in later missions, the subsystems required for this would also have to be larger. A larger volume, which has to be surrounded by the heavy radiation shield, and ten times as many people, who have to be provided with recycled water and atmosphere, increase the respective subsystem masses by at least double, it is estimated. Even with 78 t of expanded payload capacity, but of which only 29 t of additional mass may be onboard Starship on the return flight, this scenario will be difficult to achieve.

Another problem besides the sheer mass is the power supply for 100 people. The power of 100 kW already required for Starship with a crew of ten, or 250 kW near Earth, would have to be between 2-2.5 MW for such a large crew. Solar panels that could deliver such power would probably have to be 60-80 m in diameter if a pair of two 40 m panels is to produce 700 kW and with a slightly exponential power-to-size ratio [20]. Such large panels not only entail the difficulty that they have to be retractable, but also that they are relatively long, estimated at 20-30 m when folded, and have to be stowed on or in Starship. No solar arrays can be seen in current renderings of Starship, only in the very first design of the ITS (Interplanetary Transportation System). This possibly indicates that SpaceX itself is moving away from solar arrays and wants to rely on nuclear reactors such as the FSP system. One of the advantages of these is that the system does not have to be designed to be twice as powerful near Earth in order to deliver the required power near Mars. But then there would be the problem of mass, which is estimated at around 20 t for a 1 MW system, and the question of the compatibility of a nuclear power supply and people onboard a spacecraft.

5.4 Technology Readiness

The radiation and meteoroid protection as well as the components of the ECLSS and TCS are technologies that have already been used on previous spacecraft or the ISS and therefore have a high degree of technology readiness.

The first technology currently being tested on many different missions is the optical communication system. In 2026, Deep Space Operational Services with multiple terminals forming a network are expected to commence and be available to missions from that date onwards [43]. Based on this described extensive testing over the next few years, it can be assumed that the technology readiness of an optical communication system will be high by 2026.

The MegaFlex solar arrays of the EPS are based on the UltraFlex, which has a flight heritage and, with TRL 9, the highest possible technology readiness level (TRL). A MegaFlex array with a diameter of 9.6 m has already been tested in the course of a TRL 5 demonstration, but it has not yet been tested in space or in the size required for Starship. As the technology is available but still needs to be scaled to the required size and a mechanism for retracting the solar arrays needs to be developed, it is quite possible that this could be operational by the planned launch date of 2026.

If NASA's xEMU are used as spacesuits for EVAs, then their technology readiness should have reached a TRL of 9, as they will already have been used on the first Artemis lunar missions beforehand and will therefore have flight heritage. It is considered feasible that the modifications that need to be made for a mission in the Martian atmosphere can be implemented by the time of the launch in 2026. In contrast, the required elevators must first be designed and tested.

The next new technology to be considered are Starship's main engines, the Raptor engines. At the time of writing, they have not yet been used in space, but will be from 2022 onwards during the orbital test flights. However, they have already been used in numerous test flights on Earth, so their level of technology readiness is high. For the RCS thrusters, for which no more precise specifications are yet available other than that they will probably be cold gas thrusters, it can be assumed that existing thrusters or similar to these will be used here, so that the technology readiness will also be given for these. The system for orbital refuelling, however, has not yet been developed. The feasibility of such a system must be demonstrated by the launch of the first two cargo Starships in 2024 and successfully tested during several tests, which is considered feasible due to the need to carry out all Mars missions on the scale SpaceX is planning.

The heat shield technology also still needs to be extensively tested during re-entries and possibly adapted, depending on what the tests reveal. However, it is believed that the heat shield tiles will meet their protection and reusability requirements by the first launch in 2024, especially since SpaceX already has experience designing a heat shield for the Dragon space capsule.

That the technology to produce liquid methane and oxygen would work on Mars has already been demonstrated with the IMISPPS presented in Chapter 4.2. However, this system has only a fraction of the propellant production rate needed to fuel two Starships. In addition, such a system without a water extraction plant requires with 3.88 MW a lot of power even with the assumptions of technological progress that have been made. Besides the mass and required power of such a system, the volume could also become a problem. It must be possible to distribute the system over several Starships. If it has to be distributed on more than four Starships because of the volume, the crewed mission is not feasible in 2026, as only four cargo Starships will be available by then. Therefore, it is seen as critical that such a system is operational and flight-ready by 2026. The current technology readiness and feasibility are therefore low.

The technology readiness of the Fission Surface Power System is also not yet very advanced. Technology demonstration has already taken place successfully on Earth with a smaller 1 kW reactor. The problem with the FSP, however, is the estimated time to operational capability. Systems with 10-20 kW are expected to be flight-ready in 3-5 years, the required 2 MW system only in probably ten years [34]. It can therefore be assumed that this technology will not be available for the planned 2026 mission.

The last new technology to be discussed that was proposed in the system designs is the MOROCAS rover concept. This is only a concept so far, but individual modules such as shovels and drills have been demonstrated on other rovers such as NASA's RASSOR or VIPER and will be used on future missions. The development of a common platform that can accommodate the various modules and the different modules is considered feasible, as technology from previous rovers can be used.

5.5 Costs

In order to be able to estimate the rough costs of Starship and booster Super Heavy, the costs that SpaceX forecast for the ITS concept in 2016 should be used as a reference. However, these values have to be scaled down because the ITS had a larger fuselage diameter of 12 m (instead of 9 m), thus larger tanks and consequently a higher payload capacity of 450 t. Furthermore, the primary structure was to be made of carbon fibre instead of stainless steel. [44] Table 4 shows the estimated costs of the ITS and next to it the costs related to the current Starship.

For the manufacturing and maintenance costs of the current Starship, those of the ITS concept are multiplied by the factor 0.5625, the ratio of the different fuselage cross-sectional areas, which takes into account the smaller volume of the current Starship. In addition, the different material must be taken into account in the manufacturing costs. For this purpose, the product of the structural mass of 40 t of Starship and 55 t of Super Heavy (analogous to Starship in Chapter 4.1) multiplied by the cost of carbon fibres, 130,000 US$/t, is subtracted from the already adjusted manufacturing costs and replaced by the product of the structural mass multiplied by the cost of stainless steel, 2,500 US$/t. [4] It is to be assumed that a Starship flying to Mars can complete ten flights and the booster and tanker 100, as these two only launch into near Earth orbit. The number of launches refers to a single crewed Starship from the baseline scenario, which has to be refuelled with 623.9 t in Earth orbit. However, there is still 84.8 t of propellant onboard (74.8 t + 10 t of residuals) if Starship is launched from Earth with full tanks as in Chapter 5.1 and assuming the 100 t of payload described in the baseline scenario. The tanker Starships therefore only have to provide 529.1 t of propellant, since 10 t of residuals are still onboard. It is assumed that the tanker Starships, like the booster, need 30 t of propellant for landing and 10 t of propellant residuals, so that according to equation (20) an $x = 49$ and thus a maximum extended payload capacity of 47 t results. The tanker Starships can therefore carry 147 t of propellant for refuelling, which minimises the number of refuelling flights, but does not quite match the 165 t [45,

Table 3: Cost comparison of different rockets

	Atlas V [46]	**Delta IV**	**SLS Block 1**	**Falcon 9** [47]	**Falcon Heavy** [47]	**Starship**
Costs (US$)	163 M	350 M [48]	876 M [49]	62 M	90 M	39 M
Payload to Mars (t)	5	8 [50]	20 [51]	4.02	16.8	100
Costs/tonne (US$/t)	32.6 M	43.8 M	43.8 M	15.4 M	5.4 M	0.39 M

Table 4: Costs ITS [43] and current Starship

		ITS			**Current**	
	Booster	**Tanker**	**Starship**	**Booster**	**Tanker**	**Starship**
Manufacturing costs (US$)	230 M	130 M	200 M	122.36 M	68 M	107.4 M
Lifetime launches	1,000	100	12	100	100	10
Starts/Mars trip	6	5	1	5	4	1
Average maintenance costs/flight)	0.2 M	0.5 M	10 M	0.11 M	0.28 M	5.63 M
Propellant costs/launch (US$)	1.13 M	0.42 M	0.33 M	0.6 M	0.28 M	0.25 M
Launch site costs/launch (US$)	0.2 M			0.2 M		
Total costs/Mars trip (US$)	11 M	8 M	43 M	13 M	6 M	20 M

p. 4]. Four tanker flights are thus needed to refuel the crewed Starship. The propellant costs are calculated from the price of the propellant of 168 US$/t and the propellant mass [44]. Maintaining Starship flying to Mars is more expensive, because after a long journey to Mars, all systems must be examined particularly thoroughly before it sets off on a new Mars journey. The reason why the tanker Starship is more expensive to maintain than the booster is that the heat shield, among other things, has to be inspected. The costs of 200,000 US$ per launch for the launch site are taken over by the ITS concept.

The total costs per Mars trip of the current Starship result from the manufacturing costs distributed over the number of expected launches during a lifetime, the maintenance, propellant and launch site costs multiplied by the number of required launches and a margin of 20 %. A trip to Mars thus costs 39 M US$, which corresponds to 390,000 US$/t for a 100 t payload. Table 3 compares the costs per tonne of payload of different rockets.

As can be seen in the comparison, the cost of Starship is only a fraction of the other rocket systems compared. It should be noted that the prices and payload capacities of the Falcon 9 and Falcon Heavy refer to a non-reusable version with the maximum possible payload. Even if their prices were to drop by half for a reusable rocket, the cost/tonne ratio would also drop by half but would still be significantly more than for Starship. Assuming that Starship's cost calculation is based on a single launch, rather than distributed over the number of expected launches over a lifetime, this would result in a cost of 12 M US$/t, which would still be at least a third of the other rocket systems, with the exception of SpaceX's rockets. In this case, the Falcon Heavy would even be 55 % cheaper.

The five boosters and four tanker Starships must therefore be reusable at least three times in order to undercut the Falcon Heavy's cost of around 5 M US$/t. The Starship flying to Mars does not even have to be reusable. Due to the low cost of Starship, even with a lower number of possible launches within the lifetime, the costs are seen as feasible.

For the technologies required, those with a low level of technology readiness generally require higher costs than those whose development is already more advanced. For example, the costs of the radiation vest, the optical communication system, the solar arrays, the space suits, the thrusters, the heat shield and the rovers, which unlike previous rovers do not have expensive scientific instruments, are likely to be within a feasible range, since they have either already been tested or will be tested in the near future, or can be based on similar existing technologies.

This is not the case for the nuclear reactors, the propellant production system and the elevators, which are very expensive to scale up or have to be designed in the first place. For example, the development and construction costs of the 2 MW reactor are estimated at one billion US dollars [34]. Similar costs could also apply to the PPS. Due to these high costs, it is not considered feasible to implement in the available time window.

6. Discussion

The biggest problems that have arisen in the analysis in this work are caused by the PSS, PPS and EPS and concern the mass, their required power and their produced power, respectively, and the technology readiness. With the currently available technology for propellant production, this system requires too much power for the size it needs for production for two Starships and is also too heavy. Technological progress was already assumed in the calculation of the PPS. Should this not occur, the required power and mass would increase by 40 % and 30 % respectively compared to the assumed values.

Distributing the PPS, PSS and rovers among the four cargo and two crewed Starships with a standard payload capacity of 100 t is feasible in terms of mass, but the volume of the individual components and the available volume of the Starships will probably be a problem, so that the 100 t might not be fully utilised. In the case that the payload volume is the problem, the possible extended payload capacity of 78 t is of no use, because the volume of the payload area of Starship does not change. However, if it is not the volume but the maximum payload capacity that is a problem, the possibility of the extended payload capacity could be used, which would increase the feasibility, because more space would be available and the additional payloads could be transported more easily.

As the main problem however, the high power requirement of the PPS of 4.656 MW is seen, which leads to heavy nuclear reactors with high power. In addition to the mass, these have the problem that their technology readiness is not yet very high, which in turn leads to high development and construction costs as well as a long time span until flight readiness of about ten years.

The fact that an elevator does not yet exist that has to bring astronauts and payloads to the surface of Mars even during dust storms is also problematic, as this is something that has not existed before and the requirements for this system are very high. This is because the elevators must be able to operate even during dust storms. The moving components, which are then particularly exposed to sand, must therefore be designed in such a way that sand cannot penetrate the system anywhere and lead to malfunctions.

For future flights to Mars with the planned 100 crew members, there is another problem – the power supply for Starship. Either huge solar panels would have to be used, a big leap in solar panel efficiency would have to happen by then, or reactors would have to be relied on, but this will again raise political questions of compatibility.

Starting the propellant production already two years earlier would drastically reduce the required power of the system. At 1,068 days, the production rate of the PPS would have to be only 2,456 kg/day, with a mass of 92.1 t and 1.23 MW of power, including the water extraction system, that is about 115 t and 1.54 MW. However, the feasibility of this idea is difficult because the system, which is distributed over several Starships, would have to be connected by robots to form one system. In addition, the Starships would have to land practically directly on an ice deposit so that it could be used directly for production. In addition, there is the connection of the PSS with the PPS and the transport of the produced propellant into the propellant tanks of the second cargo Starship for storage. All processes would therefore have to be executed automatically by robots, whose control cannot take place in real time either. If anything should go wrong and the system cannot produce any propellant, this can only be fixed when the crew lands two years later and then the propellant production system is designed too small to produce the required amount of propellant for the return flight in the remaining time span. Of course, such a problem can also occur during a crewed mission, but a human being is better able to solve an initially unknown problem. Another possibility would of course be to wait until production has started and is functioning and only then, when this has been achieved, to launch the crewed Starships. But here the difficulty remains that the system is distributed over several Starships and must be automatically assembled and made functional by robots. Starting propellant production only with the arrival of the crewed Starships may therefore seem risky at first and also definitely represent a risk factor, but in the end it is probably the safer way. Moreover, even with the extended production period, a 2 MW reactor is still needed, and its availability of ten years remains unchanged.

Due to the lack of alternatives for the problematic systems described above, these hurdles cannot be avoided more easily with other technologies. The use of solar panels instead of nuclear reactors represents too great a risk in dust storms, and there is no way around a propellant production system, since transporting 2,622.8 tonnes of propellant to Mars is also not practical and therefore not feasible. The problem with the elevator also cannot be solved in any other way due to the design and landing manoeuvre of Starship. For these reasons, it is concluded that SpaceX's expanded mission plans in the baseline scenario are not achievable and feasible at this scale and timeframe by 2024/2026.

If the time until the nuclear reactors of the PSS are actually ready for deployment is ten years, this would be deployable in 2032. This would also allow time for the development and scaling of the PPS, which in the best case can be made smaller, lighter and more power-efficient by then. If these hurdles can be overcome by then, the first cargo Starships could be launched in 2030 and the first crewed Starships in the following launch window in 2032. For these launch windows, a feasibility analysis must then be carried out again based on the required velocity changes, the duration of stay on Mars and thus the demands on the PPS. The issue of planetary protection should also be considered in detail in order to keep human contamination of Mars for scientific experiments as low as possible. However, this cannot be completely avoided when astronauts set foot on the surface.

7. Conclusion

This work analysed the feasibility of current plans for SpaceX's Starship. The analysis was based on the current system, the assumptions made and selected technologies, to give an overview of the subsystems and to identify existing problems, can be said to have been achieved. The final conclusion of the analysis, that the current mission plans are not feasible at this scale and timeframe, was made mainly due to the masses (350 & 84 t), volumes, required and produced power (5 MW) as well as the technology readiness of the propellant production system and power supply system. In addition, there is a lack of feasible alternatives. Even though the elevator and the larger electrical power system required for future missions with 100 crew members are major hurdles to overcome with Starship, the feasibility of the missions is significantly influenced by the required ISRU components. If these hurdles can be overcome, a Mars mission with Starship could be possible at a later time.

References

[1] C. Nwali, "Elon Musk Has Finally Predicted The Year Humans Will Land On Mars," May 2022. [Online]. Available: https://www.futurespaceworld.com/elon-musk-has-finally-predicted-the-year-humans-will-land-on-mars/. [Accessed 30. July 2022].

[2] SpaceX, "Making Life Multiplanetary," 28. September 2017. [Online]. Available: https://www.spacex.com/media/making_life_multiplanetary_transcript_2017.pdf. [Accessed 28. September 2021].

[3] SpaceX, "Starship," 2021. [Online]. Available: https://www.spacex.com/vehicles/starship/. [Accessed 1. September 2021].

[4] SpaceX, "Starship Update," 28. September 2019. [Online]. Available: https://youtu.be/sOpMrVnjYeY. [Accessed 8. September 2021].

[5] T. Dodd, "Starbase Tour with Elon Musk [PART 1]," Everyday Astronaut, 3. August 2021. [Online]. Available: https://youtu.be/t705r8ICkRw. [Accessed 13. September 2021].

[6] T. Dodd, "Starbase Tour with Elon Musk [PART 2]," Everyday Astronaut, 7. August 2021. [Online]. Available: https://youtu.be/SA8ZBJWo73E. [Accessed 13. September 2021].

[7] T. Dodd, "Starbase Launchpad Tour with Elon Musk [PART 3]," Everyday Astronaut, 11. August 2021. [Online]. Available: https://youtu.be/9Zlnbs-NBUI. [Accessed 13. September 2021].

[8] The Mars Society, "Elon Musk - 2020 Mars Society Virtual Convention," 16. October 2020. [Online]. Available: https://youtu.be/y5Aw6WG4Dww. [Accessed 12. October 2021].

[9] J. e. a. Heldmann, "Accelerating Martian and Lunar Science through SpaceX Starship Missions," *Planetary Science and Astrobiology Decadal Survey 2023-2032,* p. 518, Mai 2021.

[10] NASA Ames Research Center, "NASA Ames Research Center Trajectory Browser," 1. July 2019. [Online]. Available: https://trajbrowser.arc.nasa.gov/traj_browser.php?NEAs=on&NECs=on&chk_maxMag=on&maxMag=25&chk_maxOCC=on&maxOCC=4&chk_target_list=on&target_list=Mars&mission_class=roundtrip&mission_type=rendezvous&LD1=2020&LD2=2035&maxDT=2.5&DTunit=yrs&maxDV=20&min=DV&wdw. [Accessed 7. November 2021].

[11] NASA, "Draft Environmental Assessment for the SpaceX Starship and Super Heavy Launch Vehicle at Kennedy Space Center (KSC)," August 2019. [Online]. Available: https://netspublic.grc.nasa.gov/main/20190801_Final_DRAFT_EA_SpaceX_Starship.pdf. [Accessed 20. September 2021].

[12] S. Frazier, "Real Martians: How to Protect Astronauts from Space Radiation on Mars," 30. September 2015. [Online]. Available: https://www.nasa.gov/feature/goddard/real-martians-how-to-protect-astronauts-from-space-radiation-on-mars. [Accessed 15. November 2021].

[13] M. Garcia, "Scientists and Engineers Evaluate Orion Radiation Protection Plan," 22. September 2016. [Online]. Available: https://www.nasa.gov/feature/scientists-and-engineers-evaluate-orion-radiation-protection-plan. [Accessed 15. November 2021].

[14] R. Destefanis, E. Amerio, M. Briccarello, M. Belluco, M. Faraud, E. Tracino and C. Lobascio, "Space Environment Characterisation of Kevlar ®: Good for Bullets, Debris and Radiation too," 2009.

[15] L. Kanayama and A. Beil, "SpaceX continues forward progress with Starship on Starhopper anniversary," 28. August 2021. [Online]. Available: https://www.nasaspaceflight.com/2021/08/starship-starhopper/#more-79883. [Accessed 16. October 2021].

[16] A. Crane, "Orion "Passengers" on Artemis I to Test Radiation Vest for Deep Space Missions," 13. February 2020. [Online]. Available: https://www.nasa.gov/feature/orion-passengers-on-artemis-i-to-test-radiation-vest-for-deep-space-missions. [Accessed 16. November 2021].

[17] NASA Goddard Space Flight Center, "About ESC," 2021. [Online]. Available: https://esc.gsfc.nasa.gov/about?tab=technology. [Accessed 18. November 2021].

[18] ESA, "Power," [Online]. Available: https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Orion/Power. [Accessed 19. November 2021].

[19] B. e. a. Suścicka, "Evaluation of Mars Colonization Opportunities Depending on it's Conditions," in *Mars Society Convention 2020*, 2020.

[20] Orbital ATK, "UltraFlex Solar Array Systems," Goleta, 2015.

[21] X.-Y. J. Wang and J. R. Yuko, "Thermal Performance of Orion Active Thermal Control System With Seven-Panel Reduced-Curvature Radiator," in *Thermal and Fluids Analysis Workshop*, Houston, 2010.

[22] P. Oger, P. Vaccaneo, G. Loddoni and D. Schwaller, "Development of the thermal control system of the European Service Module of the Multi-Purpose Crew Vehicle," in *47th International Conference on Environmental Systems*, Charleston, 2017.

[23] NASA, "As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon," 16. April 2021. [Online]. Available: https://www.nasa.gov/press-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon. [Accessed 20. September 2021].

[24] J. Dumoulin, "NSTS Shuttle Reference Manual – Reaction Control System," 31. August 2000. [Online]. Available: https://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-rcs.html. [Accessed 18. December 2021].

[25] ArianeGroup GmbH, "200N Bipropellant Thruster," 2020. [Online]. Available: https://www.space-propulsion.com/spacecraft-propulsion/bipropellant-thrusters/200n-bipropellant-thrusters.html. [Accessed 19. November 2021].

[26] Federal Aviation Administration, "Draft Programmatic Environmental Assessment for the SpaceX Starship/Super Heavy Launch Vehicle Program at the SpaceX Boca Chica Launch Site in Cameron County, Texas," September 2021. [Online]. Available: https://www.faa.gov/space/stakeholder_engagement/spacex_starship/media/Draft_PEA_for_SpaceX_Starship_Super_Heavy_at_Boca_Chica.pdf. [Accessed 4. October 2021].

[27] SpaceX, "Vehicle Landing," 14. October 2017. [Online]. Available: https://youtu.be/5seefpjMQJI. [Accessed 1. December 2021].

[28] C. C. Pazar, "Resource Utilization on Mars," in *2020 Mars Society International Tele-Convention/Colorado School of Mines Review Paper*, 2020.

[29] ESA, “Comparing the atmospheres of Mars and Earth,” 9. April 2018. [Online]. Available: https://www.esa.int/ESA_Multimedia/Images/2018/04/Comparing_the_atmospheres_of_Mars_and_Earth. [Accessed 8. November 2021].

[30] R. Zubrin, A. Muscatello and M. Berggren, “Integrated Mars In Situ Propellant Production System,” *International Journal of Aerospace Engineering,* vol. 26, pp. 43-56, January 2013.

[31] Space Nuclear Power Corporation, “Basic Design Principles,” [Online]. Available: https://www.spacenukes.com/basic-design-principles. [Accessed 22. November 2021].

[32] Space Nuclear Power Corporation, “Power Systems,” [Online]. Available: https://www.spacenukes.com/products. [Accessed 22. November 2021].

[33] S. Potter, “Demonstration Proves Nuclear Fission System Can Provide Space Exploration Power,” 2. May 2018. [Online]. Available: https://www.nasa.gov/press-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power. [Accessed 22. November 2021].

[34] D. Poston, “Space Nuclear Power,” 14. October 2021. [Online]. Available: https://ce1193a9-12d2-4c0b-a989-4b1e5f59a75d.filesusr.com/ugd/a08fa5_29e9a58e48aa481da1b01e3db12e7d1c.pdf. [Accessed 22. November 2021].

[35] J. Harbaugh, “Fission Surface Power,” 7. May 2021. [Online]. Available: https://www.nasa.gov/mission_pages/tdm/fission-surface-power/index.html. [Accessed 22. November 2021].

[36] K. W. Lewis, S. Peters, K. Gonter, S. Morrison, N. Schmerr, A. R. Vasavada and T. Gabriel, “A surface gravity traverse on Mars indicates low bedrock density at Gale crater,” *Science,* vol. 363, no. 6426, pp. 535-537, 2019.

[37] A. e. a. Abdin, “Solutions for Construction of a Lunar Base: A Proposal to Use the SpaceX Starship as a Permanent Habitat,” in *72nd International Astronautical Congress (IAC)*, Dubai, 2021.

[38] A. e. a. Abdin, “Solutions for Construction of a Lunar Base – Final Report,” 2021.

[39] NASA, “Mars 2020/Perseverance,” March 2020. [Online]. Available: https://mars.nasa.gov/files/mars2020/Mars2020_Fact_Sheet.pdf. [Accessed 27. November 2021].

[40] NASA Ames Research Center, “NASA Ames Research Center Trajectory Browser,” 1. July 2019. [Online]. Available: https://trajbrowser.arc.nasa.gov/traj_browser.php?NEAs=on&NECs=on&chk_maxMag=on&maxMag=25&chk_maxOCC=on&maxOCC=4&chk_target_list=on&target_list=Mars&mission_class=oneway&mission_type=rendezvous&LD1=2014&LD2=2030&maxDT=2.5&DTunit=yrs&maxDV=7.1&min=DT&wdw_w. [Accessed 3. December 2021].

[41] E. Stoll, Raumfahrttechnische Grundlagen (Skript), Braunschweig: Institut für Raumfahrtsysteme – TU Braunschweig, 2017.

[42] ESA, “Margin philosophy for science assessment studies,” 15. June 2012. [Online]. Available: https://sci.esa.int/documents/34375/36249/1567260131067-Margin_philosophy_for_science_assessment_studies_1.3.pdf. [Accessed 3. August 2022].

[43] H. Monaghan, “Optical Communications Timeline,” 4. August 2021. [Online]. Available: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/timeline. [Accessed 7. December 2021].

[44] SpaceX, “Making Life Multiplanetary,” 27. September 2016. [Online]. Available: https://www.spacex.com/media/making_life_multiplanetary_2016.pdf. [Accessed 28. September 2021].

[45] G. e. a. Gargioni, “A feasibility analysis of a variable mass multiple asteroid retrieval mission.,” in *41th IEEE Aerospace Conference*, 2020.

[46] D. Murphy, “Megaflex - the scaling potential of ultraflex technology,” in *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Honolulu, Hawaii, 2012.

[47] M. D. Kaufman, “Whose is bigger? How all the Mars-bound rockets stack up,” 25. April 2017. [Online]. Available: https://www.popsci.com/mars-rockets-comparison/. [Accessed 10. December 2021].

[48] SpaceX, “Capabilities & Services,” 2021. [Online]. Available: https://www.spacex.com/media/Capabilities&Services.pdf. [Accessed 10. December 2021].

[49] T. Bruno, “Twitter,” 12. February 2018. [Online]. Available: https://twitter.com/torybruno/status/963109303291854848?s=20. [Accessed 10. December 2021].

[50] NASA Office of Inspector General, “Management of NASA's Europa Mission,” 2019.

[51] J. Ray, “The Heavy: Triple-sized Delta 4 rocket to debut,” 7. December 2004. [Online]. Available: https://web.archive.org/web/20041211171244/http://www.spaceflightnow.com/delta/d310/041207preview.html. [Accessed 10. December 2021].

[52] S. D. Creech, “NASA’s Space Launch System: Launch Capability for Lunar Exploration and Transformative Science,” in *2020 IEEE Aerospace Conference*, 2020.

[53] T. Sesnic, “Starbase Tour and Interview with Elon Musk,” Everyday Astronaut, 11. August 2021. [Online]. Available: https://everydayastronaut.com/starbase-tour-and-interview-with-elon-musk/. [Accessed 13. September 2021].

[54] SpaceX, “Starship Users Guide,” March 2020. [Online]. Available: https://www.spacex.com/media/starship_users_guide_v1.pdf. [Accessed 28. August 2021].