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Perspective

Human Missions to Mars Using the Starship

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Abstract

A human mission to Mars has been widely regarded as the ultimate goal for space exploration in our time. Exploration of Mars has been limited to observations from orbit and a few rover expeditions that each cover about 20 km. The vast amount of Mars surface remains to be explored in situ. These limitations were mainly due to the cost of launching high mass payloads to Mars. After 100 years and a thousand studies, human missions to Mars remain in an early concept stage. The advent of the SpaceX Starship with its putative capability to affordably land a 100 MT payload on Mars enables new, more ambitious approaches for exploring Mars at a grander scale. Here, we outline a mission to scientifically explore a wide swath of Mars utilizing the SpaceX Starship to deliver unprecedented amounts of materiel to Mars. A main landing site provides the command-and-control hub for distributed assets across Mars. A pair of communication satellites enables almost instantaneous command, control, and data retrieval. While SpaceX viewed this mission as an early step in establishing a settlement on Mars, we view it as an opportunity to scientifically explore the planet. Two variations of the mission employ different approaches for returning from Mars. The Mars Leviathan mission utilizes a Starship to leave LEO, land on Mars, and return from Mars to LEO. The major challenge in the "Mars Leviathan" mission is to produce a large mass of propellants via ISRU to ascend the crew of 12 in a Starship from Mars and return to Earth. Alternatively, we propose a "DRA-6" mission that uses a Starship to leave LEO and land on Mars, but for return, it uses a small capsule to lift a crew of six from Mars and rendezvous with an Earth Return Vehicle waiting in Mars orbit. The added capability of Starship enables the avoidance of the challenges involved in utilizing indigenous water on Mars by bringing water from Earth. In addition, water for life support is brought from Earth.

Background

Human missions to mars

A human mission to Mars has been widely regarded as the ultimate goal for space exploration in our time. Zubrin provided the arguments for such a mission [1]:

"Of all the planetary destinations currently within reach, Mars offers the most—scientifically, socially, and in terms of what it portends for the human future" [1].

He also said: "There are real and vital reasons why we should venture to Mars. It is the secret to unlocking the secrets of the universe. It is the challenge to adventure that will inspire millions of young people to enter science and engineering, and whose acceptance will reaffirm the nature of our society as pioneers. It is the door to an open future, a new frontier on a new world, a planet that can be settled, the beginning of humanity's career as a spacefaring species ..." [1].

NASA investigated options for a human mission to Mars in a series of so-called "Design Reference Missions". NASA Design Reference Mission "DRM-1" provided these rationales for a human mission to Mars [2]:

- Human Evolution – Mars is the most accessible planetary body beyond the Earth-Moon system where sustained human presence is believed to be possible. The technical objectives of Mars exploration should be to understand what would be required to sustain a permanent human presence beyond Earth.
- Comparative Planetology – The scientific objectives of Mars exploration should be to understand the planet and its history to better understand Earth.
- International Cooperation – The political environment at the end of the Cold War may be conducive to a concerted international effort that is appropriate, and may be required, for a sustained program.
- Technology Advancement – The human exploration of Mars currently lies at the ragged edge of achievability. Some of the technology required to achieve this mission is either available or on the horizon. Other technologies

will be pulled into being by the needs of this mission. The new technologies or the new uses of existing technologies will not only benefit humans exploring Mars but will also enhance the lives of people on Earth.

- Inspiration – The goals of Mars exploration are bold, grand, and stretch the imagination. Such goals will challenge the collective skill of the populace mobilized to accomplish this feat, will motivate our youth, will drive technical education goals, and will excite the people and nations of the world.

Mars is the planet most like Earth, and might have resembled Earth even more in its early history, when liquid water might have been present.

Platoff (2001) wrote a history covering 1952 to 1970 [3]. Portree (2001) wrote a history of mission planning for sending humans to Mars by the year 2000 [4]. Rapp (2023) extended that history to 2023 [5].

According to Portree:

More than 1,000 piloted Mars mission studies were conducted inside and outside NASA between about 1950 and 2000. Many were the product of NASA and industry study teams, while others were the work of committed individuals or private organizations.

Despite all this ingenious planning for a human mission to Mars, NASA never seriously contemplated a human mission to Mars because of the cost [6] and the technical challenges, particularly the difficulty in landing large payloads on Mars, the production of propellants for the return trip by processing Martian materials, and the recycling of waste products [5].

Current NASA plans for human mission to mars

Historically, NASA missions were limited by the cost to launch materiel into space, and NASA missions were limited in scope and extent. The robotic missions to Mars explored a small area with a range up to perhaps 20 km. Today, almost all the surface of Mars remains unexplored in situ. Even orbital observations, though synoptic, are limited by resolution. For example, the very important gamma-ray observations of near-surface hydrogen from the Odyssey spacecraft had pixel dimensions of about 550 km [7].

After the great success of the Apollo missions, human exploration of space searched for an identity for fifty years and marked time building around the Shuttle and the Space Station. NASA is now returning to the Moon because it is far less demanding than a human mission to Mars; yet the payoff from a lunar mission is minimal compared to a human mission to Mars. According to NASA:

"We're going back to the Moon for scientific discovery, economic benefits, and inspiration for a new generation of explorers: the Artemis Generation. While maintaining American leadership in exploration, we will build a global alliance and explore deep space for the benefit of all" [8].

NASA did not elaborate on "scientific discovery," and it is not clear what the landing team would do and accomplish on the Moon, but the opportunities for scientific discovery appear to be limited. An important theme of the NASA lunar initiative is limiting launch mass, and NASA currently plans a complex, challenging, risky plan to mine putative water ice at the Lunar South Pole to avoid transporting propellants from Earth. Yet, it has been argued that it is "faster, cheaper, better" to simply bring propellants to the Moon using new low-cost, high payload launch systems [9-12]. NASA appears to be operating according to the old mass-limited paradigm. With the advent of new, lower-cost launch systems, the lunar mission reduces to a tautology: "We go to the Moon to produce propellants. We produce propellants on the Moon so we can go to the Moon" [10].

By contrast, the potential scientific return from exploration of Mars appears to be much greater. NASA's last serious paper study of potential human missions to Mars was carried out in 2009 [13].

In 2021, the senior NASA leadership challenged NASA's Mars Architecture Team (MAT) to develop a lower-cost approach. The MAT proposed a short-stay mission, with a landed crew of 2, while 2 others remained in orbit for no apparent purpose except to be bored [14-16]. Rapp (2024) concluded that the return on investment for this hypothetical mission was minimal ("plant the flag and run") [17]. Fortunately, this mission concept seems to have been discarded.

NASA maintains a "Moon to Mars" strategy [18]. While some mission aspects overlap, particularly life support and habitats, human missions to the Moon and Mars differ in major fundamental ways. These include the fact that Mars is infinitely more interesting, landing on Mars and departing Mars provide very different challenges, there is a significant time delay in communicating with Mars, and once committed to Mars, return requires waiting for the next 26-month opportunity when Mars and Earth are properly phased. As things stand in 2025, NASA's plans for human exploration of Mars remain a distant chimera, only hazily outlined.

Advent of the Starship – Making Human Exploration of Mars Possible

Jones (2024) pointed out that historically, launch cost was a major impediment to exploring and exploiting space [19,20]. High launch costs led to high investment in space hardware development, which led to high space mission costs. As Jones put it: “Spacecraft designers and space mission planners are mass misers”. Engineers shun “brute force” approaches and seek creative methods to reduce mass. We are now entering a new era where much lower launch costs and evolution of the Starship assure that launch costs no longer have an impact on mission design that would have prevailed decades ago. However, NASA does not seem to have fully adapted to the new reality and continues to think in terms of reducing mass, despite the greater opportunities opened by affordable, larger mass missions. Jones provided the allegory of a poor person who suddenly becomes rich but continues to live frugally.

The advent of the Starship by SpaceX with a putative affordable payload of up to 100 MT changes the rules for space exploration. SpaceX is thinking in far more extensive and grander terms than NASA [21,22]. However, while SpaceX claims that it will implement human missions on the Mars surface in the next few years, independent analysis argues that these claims are overly optimistic [17,23]. There is a great deal of preparatory work required before SpaceX can safely land a human crew and return them from Mars. Nevertheless, if the Starship can deliver a 100 MT payload to the Mars surface affordably (while the largest payload yet landed was about 1 MT), that requires a new frame of reference for planning future Mars missions.

The so-called “Design Reference Architecture (DRA-5)” in 2009 was NASA’s last serious analysis of options for a long-stay human mission to Mars. Three major challenges in proposed human missions to Mars were identified as (1) precision landing of heavy masses on Mars, (2) providing propellants for the return flight to Earth, and (3) providing water for life support [13]. At that time, the cost of launching mass to LEO was an important factor in mission design, and landing large masses (up to 40 MT) on Mars was an unproven conjecture for mission plans. As a result, the main theme of the mission design was minimizing mass, both in LEO as well as on the Mars surface. In DRA-5, NASA proposed a development to increase capability for landing greater masses on Mars, tapping indigenous Mars resources to produce ascent propellants (ISRU), using a minimal ascent capsule requiring minimum ascent propellants, ascent to rendezvous the crew with an Earth Return Vehicle (ERV) waiting in Mars orbit, relying on robust, long-life water recycling, and scheduling the ERV to depart from Mars orbit rather than the Mars surface. Departure from LEO utilized a nuclear thermal rocket (NTR) to minimize mass requirements in LEO and reduce trip time, and a minimal ascent capsule limited the ascent propellant load to about 40 MT. This was the outline of a human mission to Mars (DRA-5) in a mass-limited era [13].

The advent of the SpaceX Starship with its much lower cost per MT and putative 100 MT payload provides new capabilities not imagined in previous Mars mission studies. The Starship changes the rules and requires revamping planning for human missions to Mars. Instead of minimizing mass, the appropriate approach now is to use mass to simplify and expedite the mission, reduce risk, and broaden the accomplishments of the mission [17,23].

The SpaceX Mission

Overview

In a series of postings and press releases on the Internet, SpaceX provided a rough outline of a human mission to Mars that was viewed as a first step toward the establishment of a settlement on Mars. While many bold claims were made, details were piecemeal and inadequate. Independent reviewers analyzed this description of the mission and provided doubts regarding some aspects and additional insights as to how such a mission might be conducted [17,23].

Building on these previous studies, we propose a human mission to Mars (the Mars Leviathan Mission) to scientifically explore a much wider swath of the planet than was heretofore possible. This mission resembles the SpaceX mission except that exploration is our theme, rather than preparing for a settlement. The mission utilizes the SpaceX Starship to deliver cargo and crew to Mars for a long-stay mission of roughly 500 days on Mars. The initial crew delivery could be extended a second or third time, building infrastructure at each stage.

A main landing site would be the headquarters for the crew, where a very advanced laboratory would carry out deep analysis of Martian samples. The crew would manage, operate, and control remote resources on the surface of Mars. Robotic rovers would be emplaced at strategic locations on Mars that will explore locally and send data back to the main landing site via a global communication system, including two communication satellites around Mars. The main landing site would manage the remote rovers with almost no time delay.

If a means can be developed to transport samples long distances across Mars, Martian samples would be sent back to the main landing site for analysis via the newly developed transportation scheme. Alternatively, robots in long-distance rovers might operate out of the main landing site to bring back samples to the main landing site.

We allow a lengthy, multi-year pre-project period for design, development, demonstration, and validation on Mars, covering numerous sequential 26-month spaced launch opportunities. This is followed by the mission, which might include 1, 2, or 3 successive crew landings.

Getting to mars

The plan for getting to Mars follows the plan outlined by SpaceX in a series of Internet postings. This plan was analyzed in some detail by Rapp (2024) [17]. The Starship is fueled in LEO by repeated deliveries of cryogenic propellants by tankers, each delivering 100 MT of propellants to the Starship tanks. After a dozen such fueling steps, the Starship is laden with 1,200 MT of CH_4 + O_2 propellants (roughly ¼ CH_4 and ¾ O_2 by mass). The Starship payload of about 100 MT is delivered to the Starship in LEO. The loaded Starship in LEO includes 100 MT of Starship, 100 MT of payload, and 1,200 MT of propellants. (Note that Kingdon (2025) assumed 1,500 MT of propellants) [24].

It was estimated that the Starship burns about 950 MT of propellant for trans-Mars injection, leaving about 250 MT of propellant in the Starship for mid-course correction and assisting aero-braking in entry, descent, and landing (EDL) at Mars [17].

SpaceX did not discuss the process for EDL in any detail. According to SpaceX, "From interplanetary space, the ship enters the atmosphere, either capturing into orbit or proceeding directly to landing. Aerodynamic forces provide the majority of the deceleration, then the 3 center Raptor engines perform the final landing burn." Rapp (2024) estimated that the Starship burns about 950 MT of propellant for trans-Mars injection, so that of the 1,200 MT of propellant the Starship holds in LEO, about 250 MT remain during TMI. Perhaps 30 MT are used for mid-course corrections, so theoretically, about 220 MT would be available either to assist aero EDL, or for shortening the trip time.

It is not clear whether the 200 MT Starship (including payload) is inserted into Mars orbit before EDL, or (more likely) whether the Starship goes directly into EDL. Beyond that, we lack detail on the EDL process. If SpaceX can land a Starship (with or without much payload) in 2026, as claimed by SpaceX, that should clarify more details on the EDL process. We suspect that they will encounter significant delays. SpaceX did not distinguish between landing an empty Starship vs. a Starship loaded with up to 100 MT of payload – a significant difference.

Landing site, prospecting, and propellant production in Mars Leviathan

The most critical early decision needed in the Mars Leviathan project is where to locate the main landing site. This decision is contingent on finding a location that provides thousands of MT of accessible indigenous H_2O, is sufficiently low in elevation to facilitate landings, and would provide a relatively benign climate (the closer to the equator, the better). Other subordinate criteria included slope limitation, strength of soil, and radar reflectivity. In addition, a room must be available for multiple landings. It is not clear at the outset that such a site exists. The choice of landing site needs to be made as early as possible in the mission because each landing over the multi-year pre-mission period would provide assets at the chosen site, and any landings at other sites prior to final selection of the main landing site would be peripheral and far less valuable.

A study of potential landing sites provided a list of seven possible sites for a human mission to Mars based on Starship [25]. Faced with the problem of satisfying the various criteria, the main difficulty was finding sites with accessible ice at low latitudes. Lacking definitive information on the availability of accessible ice, they took the optimistic view based on various radar and geomorphic observations from orbit suggested that accessible ice might be available near 40°N latitude [26]. They identified several sites near 40°N latitude where the elevation was ideal (typically ~ -3 km relative to MOLA) in regions where various observations from orbit suggested the possibility of accessible ice being present. However, the radar observations do not prove that accessible ice exists, and the latitude is likely to be too high for a benign human mission. Considering the uncertainties in ice availability and adoption of latitude outside the equatorial zone, it is too early to select a landing site pending far more exploration of Mars for accessible H_2O.

Because accessible, near-surface H_2O would have to be validated – both the existence of the resource and the ability to process the resource ("ground truth"), several 26-month sequences of launch opportunities would likely be required. Recent observations from orbit, including ice ejected from impact craters, radar probing of the subsurface, and geomorphological interpretation of surface structures, indicate that subsurface ice is far more prevalent than had previously been thought [26]. This led to widespread optimism that accessible ice might be widely distributed on Mars. However, Rapp and Inglevakis (2025) provide a very extensive review of the data, and they concluded that the putative accessible ice implied by these observations is mainly restricted to latitudes around 40°N and above [26]. Whether accessible H_2O at a suitable site can be found at all, and if found, whether as near-surface ice or mineral hydrates, remains unclear at this time.

The greatest weakness in the Mars Leviathan mission is the uncertainty in the accessibility of H_2O at an acceptable latitude and elevation. That is why we put forth the DEA-6 mission, which avoids the use of Martian H_2O altogether.

Global exploration

Because of limitations in launch capabilities, all in situ exploration of Mars has heretofore been highly local. Rovers traverse a small local area surrounding their landing sites. The range of rovers is limited by slow control due to the lengthy time delay in commands from Earth to Mars. The vast areas of Mars remain unexplored. The advent of the SpaceX Starship enables far more ambitious mission plans. The Mars Leviathan Mission would utilize a main landing base where the crew is housed and an Earth-equivalent laboratory is set up to analyze samples of Martian materials. The large investment required for this mission would only provide a commensurate return if it were able to explore much larger areas of Mars.

In addition to the main landing base, various instrumented robotic rovers would be deployed across the surface of Mars at key locations to observe the surface and atmosphere, and send daily reports of data and observations to the main base. The rovers will be controlled by operators at the main landing site with essentially instantaneous response aided by a pair of communication satellites, thus avoiding the lengthy time delay in controlling rovers from Earth. This will enable each rover to traverse a significantly greater range than rovers controlled from Earth. Lag-free remote science would be accomplished using a global communication system in place (a pair of relay satellites) with emplaced robotic explorers spread across the planet, and the command center would control the remote rovers with almost instantaneous response, rather than our once-a-day communications on Earth-controlled missions.

In addition, it is hoped that a technology can be developed to transfer small Martian samples from distributed rovers across the planet to the main base (on occasion). The rovers would be equipped to take samples of local rock. Development of such a transportation capability presents significant challenges. The literature on long-range transportation on the Mars surface is sparse. If such a system proves to be problematic, an alternative would be to employ long-range rovers from the main base, operated most likely by robots. They would not be able to cover as much land area as the dispersed rovers, but they would greatly amplify the discovery area compared to previous missions.

Thus, we have presented a variant of the human mission to Mars posted on the Internet by SpaceX [17,21,22]. However, instead of thinking of this mission as a preliminary step toward a settlement, we plan it as a mission to scientifically explore a vast area of Mars in situ.

In this mission concept, various robotic Mars rovers would be deployed across the landscape of Mars and would be controlled by operators at the main landing site using almost instantaneous data transfer via two communication satellites placed in orbit around Mars. By eliminating the time delay involved in controlling operations from Earth, navigation and activity of the rovers would be sped up immensely.

In addition to sending data to the main landing site, it is intended that the rovers would be capable of occasionally sending samples to the main landing site. That would require development of a system for surface or near-surface transportation, entailing validation on Mars, and that would be very challenging (if at all possible) and likely require at least three 26-month sequences of launch opportunities to validate the technology on Mars.

Long-range transportation on Mars has rarely been investigated, and typically only at a very preliminary level. Perusing the literature, progress appears to be slow, whether on balloons, aircraft, rovers, hoppers, or whatever. Power, propulsion, guidance, control, and navigation present challenges. A major effort would be required to develop a system for transporting samples very long distances across Mars. If a means can be developed to transport samples long distances, Martian samples will be sent back to the main landing site for analysis via the newly developed transportation scheme. If the development of such a system proves problematic, an alternative is to send long-distance rovers from the main landing site to bring back samples.

Getting back from mars

Following the SpaceX mission design, we employ direct transfer from the Mars surface to LEO. We refer to this as the “Mars Leviathan” approach. The virtue of the Mars Leviathan approach is that the same vehicle, the same propellants, and the same propulsion system are used for trans-Mars injection, EDL, and direct return from the Mars surface to LEO, introducing uniformity, simplicity, and reduced risk. The propellant requirement to lift a Starship with limited payload from the Mars surface into Trans-Earth injection (TEI) was estimated to be about 920 MT of $CH_4 + O_2$. The plan would be to use ISRU to produce 1,200 MT of propellants, leaving about 280 MT of propellants to assist entry to LEO (assuming the entire crew of 12 could return in one Starship). If two crewed Starships are required for return, the total propellant requirement would be 2,400 MT. It is prohibitive to imagine bringing 2,400 MT of propellants from Earth. Therefore, the propellants would have to be produced from indigenous Mars water and CO_2. Utilizing this approach imposes serious limitations on the choice of landing site and requires a lengthy, challenging program to prospect, develop, and validate H_2O acquisition and processing in situ. Several exploratory flights to Mars would be required to validate this capability.

SpaceX regards this mission as a first step towards the establishment of a “settlement”, but we think this mission could better serve as a giant step forward in Mars science exploration.

However, there are several major problems with such a mission.

This mission involves at least five Starship landings on Mars, and each Starship launch from LEO requires a dozen launches to fuel the Starship in LEO with 100 MT of propellants at each turn, which makes the enterprise very extended and prone to problems. Nor is it clear that ground launch facilities could handle 60 or more heavy-lift launches.

The requirement for 1,200 or 2,400 MT of $CH_4 + O_2$ propellants for ascent of two Starships from Mars and return to Earth is a very demanding one. An early, extensive synoptic search for accessible H_2O would be required in temperate zones, along with requirements for low elevation to enhance landing. The process to extract the H_2O, produce propellants, and store them would need to be demonstrated in situ.

The landing site would be chosen based on available H_2O at a lower elevation to enhance landing dynamics. Search for an appropriate landing site will be a major endeavor based on in situ observations. It is important to select a landing site as early as possible in the pre-project because every landing there during the pre-project will leave assets there to accumulate. See Section 2.3 for a discussion of landing sites.

In addition, some analyses indicate that SpaceX was overly optimistic in its claims for the performance of the Starship, as well as in aspects of the Leviathan mission [23].

Trip time

Trip times between Earth and Mars are not easily generalized. Each launch opportunity provides several possible trajectories. Propellants with higher specific impulse produce significant reductions in trip time. Traditionally, H_2–O_2 propellants were considered with Isp = 450 s^{-1}, and lower energy trajectories were chosen to minimize the mass of propellants. Trip times were envisaged for a cargo of about 9 months, and higher energy trajectories for a human crew achieved perhaps six months. NASA proposed the use of nuclear thermal propulsion with Isp around 900 s^{-1}, which allowed a reduction of trip time to as low as 3 months in some cases [13]. All the above had the intent to limit propellant mass for transfers between Earth and Mars.

With the advent of the Starship, the whole culture of space mission design changes from minimizing mission mass to using large amounts of mass to accomplish more ambitious missions. The availability of extra mass also allows consideration of much higher energy trajectories that significantly reduce trip time with chemical propellants, even though $CH_4 + O_2$ propellants have a lower Isp. Maiwald, et al. (2024) found trajectories with transfer times down to about four months [27]. Kingdon (2025) found trajectories that allowed transfer to Mars in 3 months [24]. However, he assumed the Starship held 1,500 tons of propellant, whereas we are under the impression it is 1,200 tons. Furthermore, he used a specific impulse of 370 s^{-1} and pointed out that Elon Musk claimed SpaceX can achieve 380 s^{-1}, whereas smaller values were found by Thunnissen, et al. (2004) and Hurlbert, et al. (2016) [24,28]. The extra load of propellants in the Starship allows short trip times despite the lower Isp.

A minimized human mission to mars using the starship

Introduction

We imagine two versions of the mission that differ widely in size and scope. The greater mission ("Mars Leviathan") follows the SpaceX concept more closely, using a crew of 12 delivered by two Starships, and each Starship departs LEO, lands on Mars, and lifts off from Mars to return to LEO. This is the simplest conceivable architecture for the mission. However, it entails a crew of 12, requiring a very extensive life support system, and depends on the ability to produce more than 1,000 MT of ascent propellants from putative Mars water resources – at this point, an unknown capability. Even if a source of Mars water can be found, it is likely to be at a higher latitude than would be desirable for the mission. Here, we propose a scaled-down mission that has the great advantage that no indigenous Mars water is required, and all recycling of liquid waste would likely be eliminated.

In some ways, the lesser mission is patterned after NASA's "DRA-5". A Starship delivers a crew of 6 to the Mars surface. For return, a small ascent capsule lifts off with the crew to rendezvous with a separate Earth Return Vehicle (ERV). In this mission, two additional vehicles are needed in addition to the Starship, and a rendezvous crew transfer maneuver is introduced. We call this "DRA-6". The difference in scope can be seen by the difference in propellant mass for ascent from Mars; the Leviathan mission requires either 2,400 MT of propellants on Mars to send two Starships back to Earth, or possibly 1,200 MT of propellants if one Starship can return a crew of 12, while the DRA-6 mission requires only 40 MT of ascent propellants for a crew of 6. That represents a huge advantage.

Use of ascent capsule and rendezvous to earth return vehicle

The DRA-6 approach for returning from Mars utilizes a minimal ascent capsule (about 9 MT) capable of supporting a crew of six for several days that requires ~40 MT of ascent propellants to ascend to rendezvous with an Earth Return Vehicle (ERV) waiting in Mars orbit. This was the plan for a human mission to Mars in a mass-limited era when the DRA-5 study was carried out [13]. In previous mission plans, the required 40 MT of ascent propellants were typically thought to be produced by Mars from indigenous H_2O and CO_2 resources to minimize mass brought from Earth.

Here, we propose to use the same system for return from Mars, but instead of relying on indigenous H_2O from Mars, we utilize the high payload capacity of the Starship to bring water from Earth to produce propellants without use of water from Mars, thus avoiding the risky, time-consuming, expensive search for H_2O on Mars, and allowing landing at many potential sites at low elevation independent of putative endowment with near-surface H_2O. That is a major advantage. We also supply water for life support from Earth.

This variant of the mission is called “DRA-6”.

Water for ascent propellants and life support in DRA-6

The ascent propellant requirement for DRA-6 is about 8 MT of CH_4 and 32 MT of O_2 (total of ~ 40 MT). The propellants contain 6 MT of carbon, 2MT of hydrogen, and 32 mT of oxygen.

In DRA-6, the 2 MT of hydrogen is supplied by bringing 18 MT of water from Earth. The 18 MT of H_2O is electrolyzed to produce 2 MT of H_2 and 16 MT of O_2.

Four MT of hydrogen is reacted with 22 MT of indigenous Martian CO_2 via the proven Sabatier reaction:

$$CO_2 + 4H_2 = CH_4 + 2H_2O$$

The 4 MT of H_2 is provided by 2MT from the 18 MT of water brought from Earth, plus 2 MT from electrolysis of the water produced by the Sabatier reaction.

The products are 8 MT of CH_4 and 18 MT of H_2O.

The 18 MT product H_2O from the Sabatier reaction is electrolyzed to produce 2 MT of H_2 and 16 MT of O_2.

The overall reaction is:

$$CO_2 + 2H_2O = CH_4 + 2O_2$$

All told, 18 MT of water plus 22 MT of CO_2 are reacted to produce 8 MT of CH_4 and 32 MT of O_2 (total of ~ 40 MT).

The water requirement for life support is given in units of kg/CM/day. There are no firm guidelines for how much water is needed to support a crew in deep space for long periods of time. This was discussed in some detail by Rapp (2024), who suggested two extreme levels [29]:

Bare survival level: 7 kg/CM/day

Earth-equivalent conditions: 27 kg/CM/day

Here, we adopt a level of 20 kg/CM/day as a comfortable compromise.

For a crew of 6 for 500 days on Mars, the total requirement is 6 x 500 x 20 kg = 60 MT.

Two approaches can be considered to supply the 60 MT of water. In one approach, the entire 60 MT is brought from Earth. If this approach were adopted, the total water brought from Earth for propellants and life support would be 78 MT.

It seems almost certain that a recycling system to recover potable water from liquid waste would be developed for the Starship delivering crew to Mars, and for the ERV or Starship delivering crew from Mars to LEO. Since this technology would be available for use on Mars as well, it could be applied to reduce the requirement to bring water from Earth. Thus, a second approach that cuts the mass requirement from Earth in half is to supply water for life support to the crew on Mars at two levels. Water would be brought from Earth at the survival level. The total water would be 7 kg/CM/day x 6 crewmembers x 500 days = 21 MT. This 21 MT would be brought from Earth as part of a 100-MT Starship payload to provide survival water in case of problems with recycling. The plan is to provide the crew with water at 20 kg/CM/day. The additional 13 kg/CM/day above the survival level would be provided by recycling liquid waste at 90% recovery. The total water supplied by cycling would be 39 MT, including 4 MT as backup brought from Earth and 35 MT obtained by cycling. In addition, the mass of the cycling plant (~5 MT?) would be brought from Earth. The total additional mass for the cycling system would be 9 MT. The total mass brought from Earth would be about 21 + 9 = 30 MT as part of a Starship payload.

In providing ascent propellants plus water for life support, about 18 + 30 = 48 MT of water would be transferred from Earth to Mars if cycling were used, and about 78 MT of water would be transferred from Earth to Mars if cycling is not utilized.

The mission concept is built around the supposition that a means can be found to transport samples from a wide swath of the Mars surface to an advanced laboratory at the main landing site. At this time, no such technology exists. It would have to be developed, and that presents great challenges due to the thin atmosphere and the rocky terrain. The alternative would be the use of long-range rovers based at the main landing site, probably operated by robots using AI, but controlled from the main base.

Discussion

Human missions to Mars have been under study for about 100 years. During that time, about 1,000 mission studies were carried out by various groups and organizations. This history was described and discussed by various references [3-5]. As we entered the 21st century, the prospects for a human mission to Mars were dim due to perceived cost, the difficulty in delivering large masses to Mars, and the challenge to obtain large amounts of water. One recent estimate is that a human mission to Mars might cost “half a trillion dollars” [6].

Exploration of Mars has been limited to observations from orbit, and a few rover expeditions that each cover about 20 km. The vast amount of Mars surface remains to be explored in situ. These limitations were mainly due to the cost of launching high mass payloads to Mars. After 100 years and a thousand studies, human missions to Mars remain in an early concept stage [3-5]. The advent of the SpaceX Starship promises to enable affordable delivery of massive payloads to Mars, thus enabling human crews to carry out much wider synoptic exploration of Mars than was conceivable 15 years ago.

In the era of the 20th century, the total mass of materiel delivered to LEO was viewed as a rough measure of relative mission cost. The term "initial mass in low Earth orbit" (IMLEO) became a common term in Mars mission planning, and minimizing IMLEO became an important part of mission planning [5]. As we entered the 21st century, the space establishment was driven by the need to reduce mass as a primary objective of space mission design.

In the 21st Century, SpaceX developed several new launch vehicles that significantly reduced launch costs, changing the equation for the design of space missions by reducing the importance of IMLEO in mission design [30]. SpaceX is now developing the Starship, a very large launch vehicle that is claimed to be capable of affordably delivering a payload of 100 MT to TMI. The advent of the Starship by SpaceX changes the rules for space exploration. SpaceX is planning Mars missions in far more extensive and grander terms than NASA [21,22] However, while SpaceX claims that they will implement human missions on the Mars surface in the next few years, independent analysis argues that these claims are optimistic and will take longer [17,23]. There is a great deal of preparatory work required before SpaceX can safely land a human crew and return them from Mars. Nevertheless, if the Starship can deliver a 100 MT payload to the Mars surface affordably (while the largest payload yet landed was about 1 MT), that requires a new frame of reference for planning future Mars missions.

The Mars Leviathan Mission – Adopting the SpaceX Mission to Exploration

We described the Mars Leviathan Mission in which we adopted the mission to Mars outlined by SpaceX, but we set the mission goal as a scientific exploration of a large swath of the planet, enabled by near-instantaneous control of remote assets from a main landing site using communication satellites (rather than preparation for a "settlement". The mission concept is built around the supposition that a means can be found to transport samples from a wide swath of the Mars surface to an advanced laboratory at the main landing site. At this time, no such technology exists. It would have to be developed, and that presents great challenges due to the thin atmosphere and the rocky terrain. The alternative would be the use of long-range rovers based at the main landing site, probably operated by robots using AI, but controlled from the main base.

Nevertheless, utilizing the Starship introduces several issues:

- The evolution of the Starship has been marred by a series of catastrophic failures. While such setbacks are common in the development of launch vehicles, the Starship seems to have experienced perhaps more than its share [30,31]. Nevertheless, one must believe that eventually, SpaceX will solve these problems, and a reliable Starship will become part of the launch inventory.
- The mass of the Starship was independently analyzed according to basic engineering principles, and the mass of a Starship was estimated to be greater than that indicated by SpaceX – and it is not clear that a payload of 100 MT is feasible [23]. This will remain a source of doubt until SpaceX comes forth with more detailed data.
- Despite the problems in testing prototype Starships, SpaceX continues to make bold predictions of the timing of future accomplishments by the Starship that tax our credulity. Claims that they will land a Starship in 2026 and land a human crew in 2028 are well beyond belief.
- Each launch of a Starship headed to land on Mars requires that the tanks of the Starship be fueled twelve times by tankers, each carrying 100 MT of cryogenic propellants. Whether it is possible to repeatedly launch tankers and transfer propellants to the Mars-bound Starship remains to be demonstrated.
- Return from Mars requires at least 1,200 MT of ascent propellants produced from a large amount of indigenous Mars water. Including water for life support, more than 1,000 MT of Mars water is needed. Whether such a source of accessible water can be found at an acceptable latitude and elevation remains uncertain, and the search for, and validation of such a source would be challenging.
- Imagine a Starship loaded with 1,200 MT of propellants exploding after launch due to a mishap? Safety is a major issue.

SpaceX envisions the first human landings as precursors to the establishment of a "settlement," but it is not clear what the purpose of a settlement is. Do settlers sit around and "settle" while their bodies slowly degenerate?

While SpaceX claims that it will land a human crew on Mars in the next few years, we believe that preparation for a human mission to Mars with validation at Mars will take considerably longer.

Use of the Starship to transport crew and cargo to Mars greatly reduces launch costs and enables much larger masses to be transported to Mars, enabling far more ambitious exploration of Mars than had previously been envisaged. However, such expanded missions become very challenging and costly due to the expanded mission elements other than launch. It is not clear how to fund such a mission.

The DRA-6 Mission – Using the Starship While Avoiding Use of Indigenous Mars Water

We propose a scaled-down human mission to Mars using the Starship (DRA-6), where the use of putative Mars water is avoided, and recycling of liquid waste can also be avoided – two major simplifications.

Relying on obtaining H_2O from Mars adds considerable time, cost, and risk to a mission. It is not even clear that accessible indigenous water can be found at a suitable location for a human landing. On the other hand, use of an ascent capsule and separate ERV introduces the need for creating two additional vehicles (not needed in the Mars Leviathan concept) and the risk entailed in a rendezvous maneuver.

The major difference between the risks in the Mars Leviathan approach and the DRA-6 approach is that the Mars Leviathan depends on obtaining large quantities of Martian water, while the DRA-6 mission depends on adding an ascent capsule, an Earth Return Vehicle, and a rendezvous maneuver.

In previous mission concepts, NASA had assumed that a small capsule carrying the crew would lift off and rendezvous with a waiting ERV in Mars orbit for return to LEO. This permits a relatively small mass of ascent propellants (~ 40 MT for a crew of 6). But it entails two additional vehicles and a risky rendezvous/crew transfer. By contrast, SpaceX utilizes a single Starship to land on Mars and return from Mars. For direct return from Mars to LEO, it was estimated that a Starship requires about 1,200 MT of propellants on the Mars surface [17]. That must be produced from indigenous Mars resources. SpaceX adopted the approach of a single Starship leaving LEO, landing on Mars, and returning from the Mars surface to LEO. It is not clear at this point whether a suitable landing site can be found that could supply the required quantity of propellants. Therefore, we provided an alternative for which ascent propellants can be produced with a mere 18 MT of water brought from Earth.

Further study is required to determine which approach provides the more robust mission, taking into account cost, risk, scientific return, and a springboard for future exploration. How to return from Mars is the main pivot point in going forward with a human mission to Mars based on the use of the Starship: How to return the crew from Mars?

The perception of future space exploration and exploitation depends on one's viewpoint. Elon Musk and SpaceX look beyond the near-term and envisage a "settlement" on Mars with thousands of people. In this manuscript, I am concerned with the first human mission to Mars, which appears to be extremely costly and technically difficult. While SpaceX has made bold claims about landing on Mars in a couple of years, these claims have been delayed several times and don't hold up under scrutiny. The difficulty in the search for accessible water at a suitable landing location on Mars seems to have been underestimated. We have proposed DRA-6, a scaled-down version of the SpaceX mission that seems more appropriate for the first human mission to Mars.

Conclusion

1. A human mission to Mars has been widely viewed as the apex and culmination of solar system exploration for eighty years. More than 1,000 piloted Mars mission studies were conducted inside and outside NASA between about 1950 and 2000. Many were the product of NASA and industry study teams, while others were the work of committed individuals or private organizations. Despite all this ingenious planning for a human mission to Mars, NASA never seriously contemplated a human mission to Mars because of the cost and the technical challenges, particularly the difficulty in landing large payloads on Mars, the production of propellants for the return trip by processing Martian materials, and the recycling of waste products.

2. SpaceX is now developing the Starship, which is claimed to have the capability to land 100 MT of payload on Mars. When the Starship becomes operational, the potential impact on space missions will be enormous. The ability to affordably launch much larger masses to space will enable more ambitious space missions. The biggest initial impact will be to enable crewed missions to Mars.

3. SpaceX experienced a series of setbacks in developing the Starship. They have yet to demonstrate reliable launching and have not even begun to validate on-orbit refueling. Despite that, they made several bold predictions, such as claiming they will land on Mars in 2026 and will send humans to Mars in 2028, which appear to be impossible to fulfill. Nevertheless, it seems likely that the Starship will eventually become operational, it will land unprecedentedly large payloads on Mars, and the question is how best to use it for a human mission to Mars.

4. SpaceX envisages the early human mission to Mars as a stepping stone toward the establishment of a settlement. We doubt that a settlement is a desirable goal, and instead propose adapting the SpaceX human mission to Mars for scientific exploration of a wide swath of Mars, managing remote assets on Mars at a main landing site via communication satellites.

5. The Leviathan mission concept follows the SpaceX architecture with each crewed Starship leaving LEO, landing on Mars, and returning from Mars directly to LEO. This necessitates a massive Mars H_2O project to produce 1,200 to 2,400 MT of propellants to send two crewed Starships from the Mars surface to LEO. This seems beyond the cost and capability of a first human mission to Mars.

6. Instead, we propose a simpler, far less challenging, and far less costly mission that we call "DRA-6". In this mission concept, we land on Mars using a Starship, but use a small ascent capsule to lift the crew from the Mars surface to rendezvous with a waiting ERV in Mars orbit for the trip to LEO. By bringing a mere 18 MT of water to Mars, we avoid the need for indigenous Mars water for propellant production. This avoids the use of Mars H_2O altogether but adds some complexity to the mission. In addition, it should be possible to avoid the risky recycling of liquid waste.

7. A lengthy development period must precede the actual mission in which the various technologies must be developed and validated. The greatest challenges are to find a suitable landing site and to develop a system to transport samples from remote sites on Mars to the main landing site, where a very capable laboratory will be established.

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