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Review Article

Will SpaceX Send Humans to Mars in 2028?

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Abstract

In recent years, SpaceX posted several glossy websites claiming they would implement a very ambitious human mission to Mars as early as 2028. This is an innovative mission concept using several 100 MT "Starships" to transport multiple 100 MT payloads to the Mars surface and return the crew directly to Earth without a rendezvous. Although many details are not available, it has been revealed that it would utilize 1,200 MT of CH_4 and O_2 propellants in LEO, and an additional 1,200 MT of ISRU-generated CH_4 + O_2 propellants on Mars for the return flight. The landed crew would number 12. It would land about six Starships on Mars, requiring about 72 heavy lift launches to fuel the vehicles in LEO. The challenges include landing a 200 MT loaded Starship on Mars, a massive water-based ISRU system to provide propellants on Mars, and launching many vehicles within a launch window. While reducing mass was a central theme years ago, launch costs have decreased sharply, and reducing mass is no longer a priority. The SpaceX mission maximizes mass to reduce risk and maximize accomplishments. In this study, an attempt was made to determine whether mass allocations for such a mission are feasible. The results suggest that it might be theoretically possible for SpaceX to carry out a variety of such missions. However, the SpaceX mission faces herculean challenges and probably is at least three decades away. Nevertheless, the general approach is probably more relevant today than the NASA architectures generated so far. The claim of landing humans on Mars in 2028 seems overly ambitious.

1. Introduction

A human mission to Mars is widely regarded as the ultimate achievement of solar system exploration. Yet, such a mission remains a dream on paper because it embodies great technical challenges and a likely very high cost. Portree [1] and Platoff [2] described the history of NASA's planning for human missions to the Mars surface up to the year 2000. Portree claimed there were over 1,000 studies but he only reviewed 50 significant studies. Rapp [3] reviewed this work and updated the history to 2023.

The Mars mission concepts tend to divide into long-stay on the Mars surface (~500 days) vs. short-stay (up to ~ 30 days) on the surface. The long-stay mission is dictated by the fact that opportunities to efficiently depart for Mars are spaced at roughly 26-month intervals, and once arriving at Mars, the opportunity to return to Earth requires waiting roughly 500 days on the surface, while the Earth rotates faster about the Sun than Mars, until the relative positioning of the planets allows efficient return to Earth. The short-stay mission is considered more challenging because it requires nuclear propulsion to overcome the high Δv requirement and it requires a risky Venus flyby on the return trip. Furthermore, it is not clear that much can be achieved on the surface in this short mission as the crew recovers from the trip and carries out the setup in the short time available on the surface ("plant the flag and run").

NASA conducted several mission studies ("Design Reference Missions") of generic human missions to the Mars surface in the 1990s. These were not actually mission designs but rather, exploratory investigations into how such a mission might be implemented. In the 1990s, NASA developed a high-level overview (known as "DRM-1" and updated to "DRM-3") of an approach for a long-stay mission to Mars [3,4]. NASA introduced several important concepts. These included:

1. Split mission with delivery of surface infrastructure and ISRU 26 months prior to crew launch.
2. Nuclear thermal propulsion (NTP) for transport to Mars.
3. Aero assist for entry, descent, and landing (EDL).
4. Crew size = 6.
5. Use of ISRU to produce ascent propellants, bringing hydrogen from Earth.

6. Earth Return Vehicle (ERV) in Mars orbit – an ascent from Mars in a minimal capsule to rendezvous with a more massive ERV.

NASA reached a high level of optimism in a revision known as “DRM-4” that eliminated all nuclear power and ran entirely on solar power [3]. Fortunately, DRM-4 seems to have been discarded.

An important NASA study followed in 2009 (so-called “DRA-5”) that provided an updated and expanded analysis of a mission concept, and compared various mission alternatives [5]. This was a very extensive study that provided a conceptual design of an appropriate architecture. DRA-5 concluded that the cost should be spread over three consecutive missions with a crew of six in each mission. These missions would be preceded by several robotic missions to validate the various subsystems. The missions would use the “split-mission” approach adopted in DRM-3. Nuclear power would be used on the surface. DRA-5 noted that: “Current human health and support data indicate that it may take the crew a few weeks to acclimate to the partial gravity of Mars after landing.” That would make the short-stay mission impractical [5].

Mass and power requirements were estimated by DRA-5 for the cargo and crew landers. Final estimates were provided in terse tables. It is difficult to trace back to original calculations using “reverse engineering”. The writing style was difficult to follow and required repetitive reading to find information which was sometimes conflicting. Some topics were not given adequate coverage. For example, the term “propellant mass” occurs only once in the document. Some of the assumptions seem very optimistic to this writer. Nevertheless, DRA-5 is a major contribution with a wealth of information on how a human mission to Mars might be carried out. DRA-5 provides a starting point for further discussion of human missions to Mars [5].

DRA-5 concluded that the long-stay mission was greatly to be preferred [5]. This remained the NASA standard until about 2019. In parallel with the NASA studies, Zubrin’s “Mars Direct” also provided considerable detail on how a human mission to Mars might be carried out [3,6]. This mission concept utilized a very large ISRU system for a direct return from the Mars surface without the usual rendezvous with an Earth Return Vehicle in Mars orbit. I am not aware that Zubrin’s mission concept was ever mentioned by NASA, or referred to by NASA. It is notable that 25 years later, SpaceX utilized a very large ISRU system for direct return to Earth without rendezvous in Mars orbit.

The cost of a long-stay human mission to Mars is extremely difficult to estimate, but guesses on the Internet indicate that such a mission would be very expensive. McNutt and Delamere [7] suggested that a cost of one trillion dollars “is not unreasonable” for a simple “footprint” mission, implying that the cost of a full long-stay mission would be far greater. They did not actually cost the mission in any detail but made a very rough guess by analogy to the cost of the International Space Station (ISS). Cangi, et al. [8] found this estimate to be palatable as an order-of-magnitude estimate. Smith and Spudis [9] also reasoned roughly by comparison to the ISS and concluded that landing nine crews would cost 1.5 to 2 trillion dollars. Jones [10] cited several NASA sources that made guesses as to the cost of a human mission to Mars. One was $500 billion in 2014 dollars ($660 billion in 2024 dollars). None of these estimates are trustworthy because they lack specific details about the mission. Furthermore, they tend to rely upon very crude analogies to past missions in eras when launch costs were much higher than today. Nevertheless, the cost of a human mission to Mars is very likely to be measured in hundreds of billions of dollars.

In 2019, faced with the prospect that the cost of a long-stay human mission to Mars would be well beyond affordability, the NASA Administrator challenged the NASA Mars Architecture Team (MAT) to “develop a mission architecture capable of transporting humans to the surface of Mars and back as fast—and as soon—as practical”. This implied that a short-stay mission was requested. The MAT dutifully responded as ordered [11-13].

It was claimed that one of the motivations for pursuing a shorter roundtrip mission duration was to reduce crew health risks; however, health risks for short-stay and long-stay missions are somewhat comparable. At the heart of the new study of a short-stay mission is the use of nuclear propulsion. It is not clear from the very brief disclosures in the NASA papers exactly how they would deploy nuclear propulsion. Large amounts of liquid hydrogen would be stored in orbit, and the altitude at which the reactor would be started has a significant effect on the total propellant requirement [3]. Nuclear propulsion has been around since the 1960s, but there seem to be major political impediments. There was little discussion of the return trajectory, yet the return trajectory with a flyby around Venus is one of the major challenges in short-stay missions. Rapp [3] reviewed the mission plan in detail and concluded that it was likely to be almost as expensive as a long-stay mission with a very small exploration/science return.

The MAT provided this disclaimer: “It is important to note that NASA does not have a formal human Mars program and no decisions have been made; the architecture described here is intended to fill in an often-overlooked corner of the trade space, helping to complete the menu of options available to decision-makers as they chart the course for humans to Mars” [12,13].

That "corner of trade space" was likely "often-overlooked" because the challenges are great, the risk is high, and the return on investment is low.

As things stood around 2022, the latest NASA study was for a short-stay mission which is very unappealing, several approaches for a long-stay mission were previously documented, and DRA-5 set the standard for how a long-stay mission might be approached. The presumed cost of a human mission to Mars was far beyond any imaginable budget. Altogether, the prospects for a human mission to Mars in the coming decades were poor.

Despite all this objective evidence that a human mission to Mars will be very expensive and is unlikely to be feasible for many decades to come, the Internet is replete with claims that NASA will send humans to Mars in the 2030s. For example, Levine [14] posted a website entitled "NASA wants to send humans to Mars in the 2030s". According to Dr. Suzanne Bell, NASA is readying to send astronauts to Mars by the 2030s and the agency's "first, year-long simulated mission took one giant leap toward making that goal a reality" [15]. NASA claims to be developing the capabilities needed to send humans to an asteroid by 2025 and Mars in the 2030s [16]. NASA Administrator Jim Bridenstine said, "… as NASA presses ahead with plans to return humans to the Moon by 2024, he will not rule out a first human mission to Mars as soon as 2033" [17]. Explore Mars, Inc. is a non-profit organization that advocates for human exploration of Mars by the 2030s. Each year they hold a summit meeting in which a variety of speakers from NASA, academia, and private industry provide encouraging words for an upcoming human mission to Mars in the 2030s [18]. There are several reports on the Internet claiming that Space X will send a human mission to Mars as early as 2028, but it seems impossible to trace these back to an origin with details.

There are several such postings on the Internet that provide an optimistic view. The Internet is free and much of what is posted lacks credibility. But when NASA representatives post such misleading views, it is irresponsible. Cost and risk are two crucial aspects of any space mission. If the mission involves a human crew, the cost will be much higher than otherwise, and the requirements for risk will be more demanding, which in turn drives costs still higher. Yet, cost and risk are very difficult to estimate prior to the implementation of a mission, and experience suggests that we always underestimate both. We can be certain that a human mission to Mars will not take place in the 2030s.

An important change evolved since DRA-5 was published in 2009. As Rapp [19] discussed at length, in the 2009 era, launch costs were considered an important part of mission cost, and initial mass in LEO (IMLEO) was taken as a rough measure of mission cost. Mission design placed great emphasis on reducing IMLEO. Since then, thanks mainly to SpaceX, launch costs have dropped sharply. Now, new mission architectures can be considered with more launches and much higher mass delivered to space than had previously been considered affordable. Furthermore, the cost/risk balance between bringing resources from Earth vs. producing or recycling them on Mars might be tipping toward bringing resources for both ascent propellants as well as water supply ("take it or make it") [19].

A number of press releases on the Internet claim that SpaceX will send a human mission to Mars as early as 2028, but only very limited information is available [20]. Such a claim is difficult to appraise without further detail, and as far as we can tell the challenges appear to be overwhelming. Maiwald, et al. [21] reviewed the SpaceX plan for a large-scale human mission to Mars, making educated guesses about missing data, and they found significant problems with the mass balance for the mission. The SpaceX plan is extremely ambitious (and is likely to be very costly as well) with at least 72 heavy lift launches to land a crew of twelve and several hundred tons of infrastructure on a long-stay mission. Several unique architectural innovations were introduced, such as using a single vehicle for departure from LEO, landing on Mars, and returning directly from Mars without rendezvous. The propellants used throughout (transfer to Mars, ascent from Mars, and transfer to Earth ($CH_4 + O_2$) remain the same, thus simplifying the mission. The three major challenges are (1) landing a 200 MT vehicle on Mars (2) producing 1,200 MT of CH_4 and O_2 on Mars via ISRU, and (3) implementing many repeated heavy lift launches. Nevertheless, the SpaceX mission concept provides an interesting departure from previous mission scenarios that might provide a good basis for long-term planning of a human mission to Mars decades in the future.

It is now fifteen years since DRA-5 was published, and it is appropriate to review prospects for a human mission to Mars in the light of the SpaceX mission concept that introduces new concepts worth investigating as the basis for the next Design Reference Architecture. The goal of this manuscript is to review the mass balance for the SpaceX approach for a human mission to Mars to determine if the allocated Starship, payload, and propellant masses fit the laws of physics, and to emphasize the extreme demands implied in several critical technologies needed for such a mission. The SpaceX mission concept provides several innovative ideas for a future mission. The game is changing due to much lower launch costs. But the SpaceX timescale jumps the gun by at least thirty years.

2. Review of DRA-5

NASA published the 2009 study ("DRA-5") of human missions to Mars in two versions: the 80-page summary report and the 380-page "Addendum" [5]. These reports cover a very

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wide range of material. It is impossible to review all the many details in this extensive report. Here, we merely describe the end-to-end mission.

The sequence of the DRA-5 mission is illustrated in Figure 1, where the vertical height of any box is roughly scaled to the mass of each element. A series of steps is executed as follows:

1. Two cargo vehicles (mass ~ 246 MT) are assembled in LEO from deliveries by heavy lift launch vehicles. These are propelled toward Mars by Nuclear Thermal Propulsion (NTP) using LH2 propellant.
2. Both cargo vehicles are sent toward Mars and placed into Mars orbit using aerocapture. The orbit might be circular or elliptical. Rapp [3] discusses the pros and cons of the choice of orbit, related to the use of ISRU.
3. The power system, ISRU system, and ascent system are delivered to the Mars surface on one cargo delivery using aero-assisted EDL. The ISRU system begins filling propellant tanks of the ascent system over the next 14 months.
4. The surface habitat is retained in Mars orbit, pending the arrival of the crew at the next launch opportunity.
5. The crew launch vehicle (mass ~ 357 MT) is assembled in LEO. It includes the NTP propulsion system for trans-Mars injection, which also serves for return to Earth using an additional LH2 tank. A "transhab" houses a crew of six for transfers from LEO to Mars orbit, and from Mars orbit back to Earth.
6. When the propellant tanks of the ascent vehicle are full, and all systems are checked out, twenty-six months after the launch of the two cargo vehicles, the crew transfer vehicle is sent toward Mars – and injected into Mars orbit when it arrives.
7. The crew transfer vehicle links up to the surface habitat in Mars orbit, and the crew transfers to the surface habitat.
8. The crew in the surface habitat descends to the Mars surface using aero-assisted EDL.
9. The power system, previously used for ISRU production of ascent propellants, is now used mainly for life support of the crew and surface habitat.
10. The crew engages in surface operations for roughly 500 days.
11. The crew enters the ascent system and lifts off to rendezvous with the transhab in Mars orbit.
12. The crew and transhab depart Mars orbit toward Earth using NTP with the spare tank of LH2.
13. The crew and transhab enter Earth orbit.

3. NASA's Strategic Analysis Cycle 2021 (SAC21) human Mars architecture

DRA-5 determined that a short-stay (~30 sols on surface) mission is undesirable. The optimum approach is a long-stay

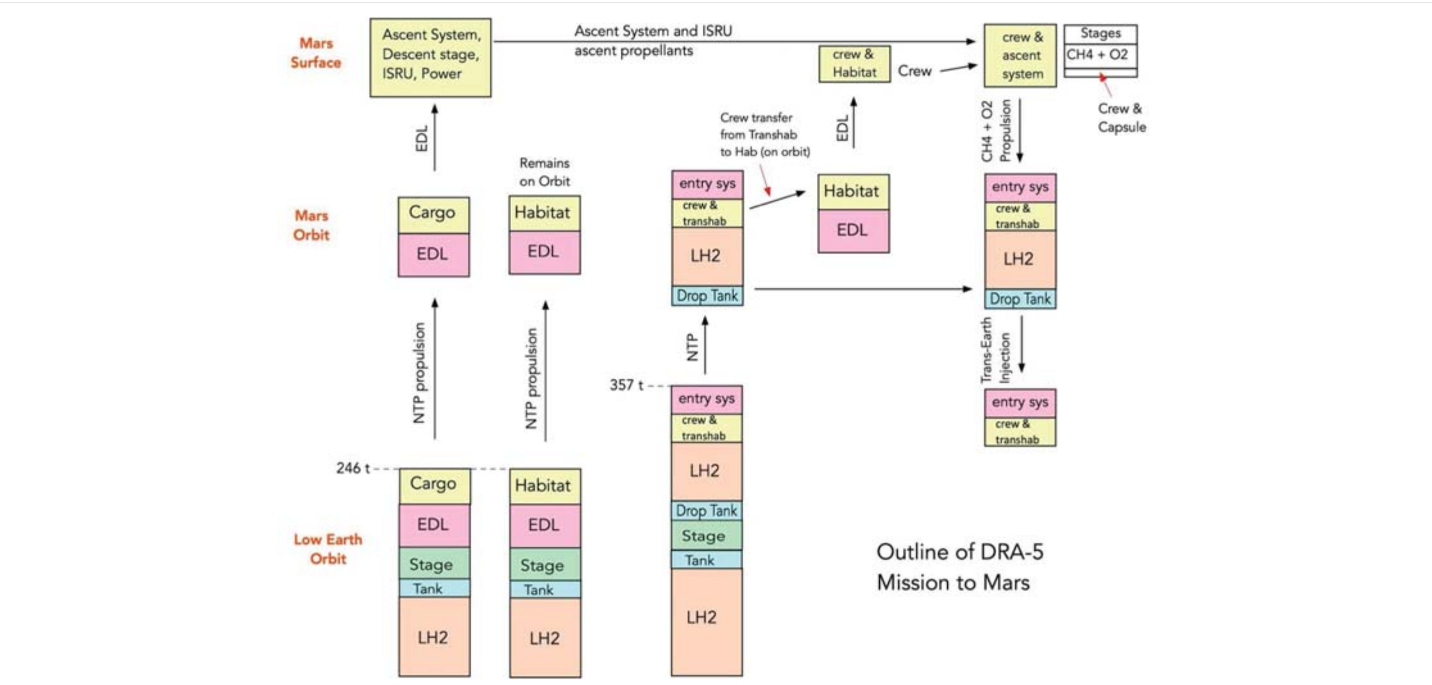

Figure 1: Schematic view of the DRA-5 mission to Mars [5].

mission (~500 sols on surface). However, such a mission appeared to be so expensive that it was far beyond the reach of affordability.

NASA's Mars Architecture Team (MAT) develops architectures and mission roadmaps for potential human missions to Mars. In 2019, the senior NASA leadership sought a lower-cost approach and challenged the MAT to develop a short-stay mission, with only a landed crew of 2, and no ISRU, for the first human mission. NASA Report HEOMD-415 [22] was the published response to this challenge [11-13]. This report is mainly concerned with crew activity in the ~ 30 sols that the crew is on the surface, to justify the short-stay mission. The description of the mission lacks detail. The mission is described in Figure 2. This figure (typical of NASA figures) is so terse and compressed that it is difficult to interpret in detail. It appears to convey the sequence of events shown in Table 1. No information on masses was provided.

The plan calls for the transfer of assets to cis-lunar space for refueling, prior to departure toward Mars. Rapp (2024A) analyzed this concept and concluded:

"Sending Mars-bound vehicles to cis-lunar space prior to trans-Mars injection saves little mass in LEO, unnecessarily includes lunar ISPP, which is costly, complex, and risky, and at the bottom line, has no benefits. The problem is that the amount of propellant needed to go from LEO to cis-lunar space is roughly comparable to the amount of propellant used for direct TMI from LEO, so the lunar-derived propellants only offset a small amount of propellant used to augment Mars Orbit Insertion and Entry, Descent, and Landing, and the amount of propellant required in LEO is almost the same in both cases. The Initial Mass in Low Earth Orbit (IMLEO) is not reduced much by utilizing lunar ISPP. At the bottom line, sending Mars-bound [vehicles] to cis-lunar space adds complexity, cost, and risk and provides essentially no benefits" [23].

This seems like a needless addition of complexity and cost. It is far less costly and more efficient for direct transfer from LEO toward Mars.

Rapp [3] concluded that it was likely to be almost as expensive as a long-stay mission with a minimal exploration/science return. This mission concept ought to be filed away and never brought forth again.

4. Review of SpaceX mission to Mars

4.1 SpaceX mission overview

There are several reports on the Internet claiming that Space X will send a human mission to Mars as early as 2028, but only a small amount of information was provided [20]. In addition, Maiwald, et al. [21] provided additional information in their review of the SpaceX plan. It is impossible at this time to know exactly what the SpaceX plan is in detail, but I attempted to piece together an approximate outline of a mission plan from the sparse data available. It seems likely that such a mission might not be feasible and affordable for many decades to come.

The SpaceX Mars mission is an ambitious enterprise involving many tens of heavy lift launches, several massive landers on Mars, a crew of twelve, and a very large in situ

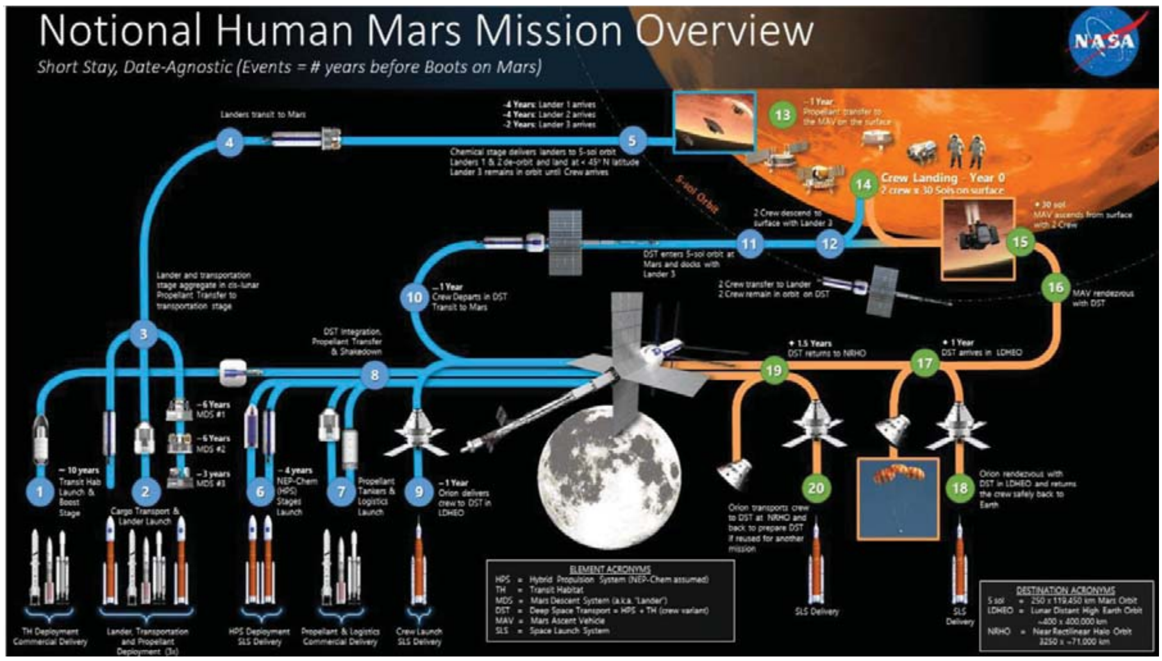

Figure 2: Mars Mission overview produced by the NASA MAT in 2021 [11-13].

Table 1: Approximate sequence of events in NASA short-stay mission.

Time (based on crew landing = Year 0)	Activity
−10 years	Transit Hab launched into LEO where it remains about 9 years. (The diagram shows multiple launch vehicles?)
−6 years	Launch two Mars descent systems (that carry cargo) to LEO
−6 years	Transport two Mars descent systems to cis-lunar space where they are fueled from an unspecified source but likely to be lunar ISRU? Send to Mars from cis-lunar space using chemical propulsion.
−4 years	Two Mars descent systems land on Mars
−4 years	Launch nuclear electric propulsion system to LEO
Unknown	Launch NEP propellants to LEO and integrate with NEP stage i
−3 years	Launch a third Mars descent system to LEO.
−3 years	Transport the third Mars descent system to cis-lunar space where it is fueled from an unspecified source but likely to be lunar ISRU? Send to Mars from cis-lunar space using chemical propulsion. Keep in Mars orbit until the crew arrives.
−3 years	Launch Earth Return Vehicle with a crew of 2 - Not clear why ERV needs to be populated?
−2 years	Third descent system reaches Mars orbit and remains in Mars orbit until the crew arrives.
−2 years	ERV is put into Mars orbit with a crew of 2
Unknown	Propellant for ascent delivered to Mars surface – This step is not clear.
−1 year	Propellant on the surface is transferred to the Mars Ascent Vehicle
−1 year	Crew of 4 is launched in an Earth Return Vehicle (ERV) and is transported to Mars orbit via the NEP stage.
0	Crew of 4 arrives in Mars orbit. 2 crewmembers transfer to the third descent system and two transfer to the ERV and remain in Mars orbit.
0	Crew of 2 lands on Mars at the same location as landed assets.
+30 sols	MAV ascends with a crew of 2 and makes rendezvous with ERV.
+ 1 year	ERV transfers to Earth using NEP.

resource system. It stirs the memory of Werner Von Braun's proposed flotilla of interplanetary vehicles carrying a crew of 70 humans [3].

The SpaceX Mars mission introduced three innovations: (1) instead of minimizing mass, use mass to reduce risk and complexity, (2) use a single vehicle through all phases of the mission, and (3) use the same propellants for all phases of the mission.

Three important factors are

(1) The mass of the Starship.

(2) The mass and contents of the payload.

(3) The total mass of the vehicle that ascends from Mars.

Three major challenges are

(1) Landing a 200 MT vehicle on Mars.

(2) producing 1,200 MT of CH_4 and O_2 on Mars via ISRU.

(3) Launching many heavy lift vehicles in a relatively short time.

The mass of the Starship was claimed to be 100 MT and 1,200 MT of propellant was provided in LEO for outbound TMI and EDL at Mars. Similarly, 1,200 MT of propellant is produced by ISRU on Mars for the return flight from the Mars surface. Going outbound, the transported mass is 200 MT (100 MT for Starship and 100 MT for outbound payload). For the return flight, the payload is less than 100 MT.

To put this in perspective, we can compare these figures to NASA's DRA-5. DRA-5 would have about 300 MT of LH2 propellant in LEO in 3 vehicles while SpaceX would have 1,200 MT of CH_4 and O_2 in LEO in each of about six vehicles. SpaceX generates 1,200 MT of propellants on Mars for the Starship direct return to Earth using ISRU, whereas DRA-5 would generate about 40 MT of propellants on Mars using ISRU for an ascent capsule to rendezvous with the Earth Return Vehicle in Mars orbit. SpaceX would land a 200 MT vehicle (100 MT Starship + 100 MT payload) on Mars while DRA-5 would land a ~40 MT payload on Mars. The current maximum payload landed on Mars is 1 MT.

The SpaceX mission introduced an innovative concept for a human mission to Mars. Figure 3 provides an outline of the full cycle of a crewed Starship, from LEO to Mars and return. In this chart, it was assumed that the payload for return from Mars was 75 MT. However, this is very uncertain.

The following steps are involved:

1. Build the mission around a massive vehicle called the "Starship" which is about 106 m long and 9 m in diameter. The back end of the Starship holds the thrusters and immediately forward of the thrusters are two tanks that hold up to 260 MT of liquid CH_4 and 940 MT of liquid O_2, for a total of 1,200 MT of propellants. Forward of that is a cargo storage chamber, a crew compartment (not included on cargo versions of the Starship?), and finally an exterior tiled thermal protection system for aero-assisted entry.
2. The Starship has a claimed mass of 100 MT, and using a booster stage, it can launch about 100 MT of either payload or propellants to LEO. Starships loaded with

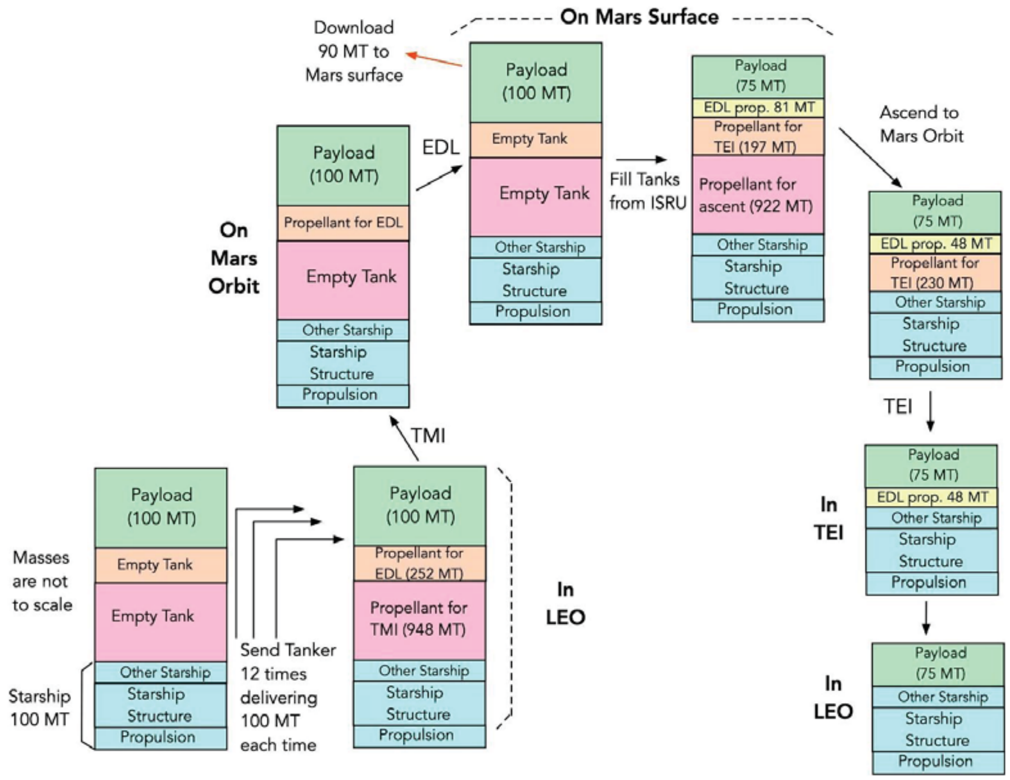

Figure 3: Outline of a crewed Starship assembly in LE, TMI, Mars orbit insertion, EDL to Mars surface, refueling on Mars, liftoff to Mars orbit, and TEI toward Earth [20,21].

propellants are used to repeatedly fuel a Starship that will ultimately be sent to Mars. After delivering propellants to LEO, the booster and refueling Starship drop back to Earth and are recovered.

3. Starships used to transfer cargo to Mars are designated here as "Starship-M". It is assumed that these do not have the crew compartment, and instead have a larger volume allocated to store cargo. Starships used to deliver propellants from Earth to a waiting Starship-M in Earth orbit are designated "Starship-P". Starships that deliver crew to LEO and then onto the Mars surface are designated "Starship-C".

4. The overall mission involves launches at two successive launch opportunities separated by 26 months.

5. Each Starship-M or Starship-C must be fueled in LEO by a series of twelve transfers from Earth. A series of Starship-P/booster launches is carried out with each one delivering 100 MT of propellants to Starship-M or Starship-C in LEO, and each Starship-P/booster is returned to Earth for reprocessing. A total of 1,200 MT of propellants fills the tanks of Starship-M or Starship-C in LEO. It is assumed that sufficient ground facilities are available for rapid repeated launches of Starship-P. SpaceX (unlike NASA) is not interested in assembling in cis-lunar space, which would only cost additional propellant and add complexity [23]. The 1,200 MT of propellants in a Starship are used for trans-Mars injection (TMI), and the remaining propellant after TMI is used for supporting aero-assisted orbit insertion, and Entry, Descent, and Landing (EDL) of the Starship to the Mars surface. Starships land on Mars with little remaining propellant.

6. At the first launch opportunity, two Starship-M are fueled in LEO, each using a dozen refills of propellant via Starship-P. These each land 100 MT of cargo on a precise site on Mars that establishes the power system, the ISRU system, and other infrastructure. The ISRU system verifies the availability of water at this stage but does not yet initiate the production of propellants. (This doesn't make sense to this writer. The verification of available water should be carried out long before sending Starships to Mars, and there is no good reason not to initiate propellant production at the first landing).

7. At the second opportunity, 26 months later, two additional Starship-M each delivered 100 MT of cargo to the Mars surface. This cargo is not defined. The same process of a dozen Starship-P flights is used to fuel each of these two Starship-M in LEO. In addition, two Starship-C are launched to LEO and fueled via the same

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process used for Starship-M. Each Starship-C carries a crew of six, producing a total landed crew of 12. The timing and procedure for sending crew to the fueled Starship-C is unclear.

8. The landed mass per delivery to Mars is estimated to be 200 MT – an unprecedented high mass to be landed in a single entry. (Currently, NASA can land 1 MT on Mars).
9. CH_4 + O_2 are used as propellants for all transfers, including trans-Mars injection (TMI), lift-off from Mars to Mars-orbit, and trans-Earth injection (TEI) from Mars orbit. That allows the same tanks and propulsion system to be used for both outbound and return flights.
10. Aero-assist supported by propulsion is used for entry to Mars orbit, entry, descent, and landing (EDL) at Mars, and entry to Earth orbit on the return flight.
11. CH_4 + O_2 propellants (about 1,200 MT) for ascent from Mars and TEI on Mars orbit are produced using a very large ISRU system, based on atmospheric CO_2 and presumed accessible water deposits, and stored in tanks used for TMI and Mars entry. Production begins after the second landing. The first landing only verifies available water. It is not known where SpaceX plans to land or what the prospects are for finding accessible water, and present data suggests this is a very long shot. Note that in NASA DRA-5, the crew does not launch until the propellant tanks of the ascent vehicle have been previously filled. Here, the tanks are planned to be filled while the crew is on Mars – a major risk.
12. Ascend from the surface to a circular Mars orbit, and then depart for Earth with a second burn.
13. The payload for the return flight from Mars was not specified. The payload is discussed in Section 4.3.3.

4.2 SpaceX mass balance

4.2.1 SpaceX starship and payload: We utilize the following nomenclature:

Payload:

M_{PL} = payload mass for trans-Mars injection from LEO toward Mars.

$M_{PL} = M_{PLS} + M_{PLR}$

M_{PLS} = payload mass off-loaded to the Mars surface.

M_{PLR} = payload retained on the Starship for return flight from Mars.

Starship:

M_S = Starship mass.

In LEO:

M_{PLEO} = Total propellant mass in LEO.

M_{PTMI} = Required propellant mass for TMI.

M_{PR1} = Propellant mass remaining in tanks after TMI.

$M_{PLEO} = M_{PTMI} + M_{PR1}$

On Mars:

M_{Pmars} = Total propellant mass on Mars prior to liftoff.

M_{PAM} = Required propellant mass for ascent from Mars and injection into Mars orbit.

M_{PR2} = Propellant mass remaining in tanks after injection in Mars orbit.

$M_{Pmars} = M_{PAM} + M_{PR2}$

On Mars Orbit:

M_{PMO} = Propellant mass in Mars orbit (This equals M_{PR2}).

M_{PTEI} = Propellant mass used for TEI.

M_{PR3} = Residual propellant mass after TEI for entry at LEO.

$M_{PMO} = M_{PTEI} + M_{PR3}$

According to SpaceX web postings, the Starship-M in LEO is assigned a mass of M_S = 100 MT, carries a payload of M_{PL} = 100 MT, and holds M_{PLEO} = 1,200 MT of propellants.

The basic questions that determine whether mass allocations in the SpaceX mission plan are viable are:

1. What is the mass breakdown for the Starship? Does it fit within the allocation of 100 MT made by SpaceX?
2. What is included in the payload in LEO? Does it include crew accommodations and crew support? What is included in the payload at departure from Mars?
3. What is the division of systems between payload and Starship?
4. Is the assigned propellant load of 1,200 MT adequate for transfers from LEO to Mars and from Mars to LEO?

The most important question is whether the propellant load assigned by SpaceX (1,200 MT) is adequate for transfers in both directions between LEO and the surface of Mars. This depends on the answers to the previous questions.

The propellant requirement for any transfer is primarily determined by the change in velocity imparted to the spacecraft. The value of $\Delta v \sim 4.0$ km/s for TMI is less than the sum of $\Delta v \sim 4.3$ km/s ascent to Mars orbit plus $\Delta v \sim 2.5$

km/s for TEI. Therefore, transport from Mars to TEI involves a greater change in velocity than transport from LEO to TMI, and the payload for the return trip must be less than the mass transported from Earth to Mars since both use the same amount of propellant. It is concluded that part of the payload delivered to Mars must be offloaded to the surface to reduce the return mass. Thus, the payload mass at TMI (M_{PL}) can be divided between that which remains for the return flight (M_{PLR}) and that which is offloaded to the surface (M_{PLS}).

$$M_{PL} = M_{PLS} + M_{PLR}$$

Lacking detail, further discussion requires making assumptions. Initially, we adopt SpaceX assignments of Starship mass = 100 MT and payload mass in LEO = 100 MT and attempt to fit the required subsystems into this framework. Then we independently make rough estimates of subsystem masses based partly on the analysis by Maiwald [21] to infer whether the SpaceX-assigned masses are viable.

4.2.2 SpaceX mass balance in LEO: According to SpaceX, the Starship-M in LEO has a mass of 100 MT, carries a payload of 100 MT, and holds 1,200 MT of propellants. Here, we adopt these values and examine how this might be implemented.

We first examine the masses in trans-Mars injection (TMI).

Consider the rocket equation for TMI:

$$q = \exp\{(\Delta v)/(g\, I_{SP})\}$$

$$I_{SP} = 360 \text{ sec}$$

$$\Delta v \sim 4.0 \text{ km/s}$$

$$q \sim 3.1$$

According to the usual rocket equation, a simplistic estimate for M_P would be: [3]

$$M_{PLEO}/(M_S + M_{PL}) = q - 1$$

$$M_{PLEO} = (q-1)\,(M_S + M_{PL}) = (2.1)\,(200) = 420 \text{ MT}$$

However, this is not correct. The usual rocket equation assumes that all the propellant is used up in the burn. Since only part of the propellant is used up for TMI (M_{PTMI}), the unused propellant (M_{PR1}) must be considered part of the system that is accelerated (along with the rocket and the payload) and must be added to ($M_S + M_{PL}$).

The proper rocket equation, taking account of unburned propellant is:

$$M_{PTMI}/(M_S + M_{PL} + M_{PR1}) = q - 1$$

This can be solved for M_{P1} and M_{P2} using:

$$M_{PTMI} + M_{PR1} = 1{,}200$$

Therefore:

$$M_{PR1} = \{1/q\}\{1{,}200 - (q-1)\,(M_S + M_{PL})\}$$

$$M_{PR1} = (1/3.1)\,\{1{,}200 - (2.1)\,(200)\}$$

M_{PR1} = 252 MT (residual propellant mass sent to Mars)

M_{PTMI} = 948 MT (propellant mass burned for TMI)

Thus, the burn for TMI utilizes 948 MT of $CH_4 + O_2$ propellants to send the 100 MT Starship, the 100 MT payload, and the residual 252 MT of propellants into TMI. The 252 MT of propellant is available to support mid-course corrections, aero-assisted orbit insertion, and entry, descent, and landing at Mars.

4.2.3 SpaceX mass balance: Departure from Mars: The Starship on Mars holds 1,200 MT of $CH_4 + O_2$ propellant. As we previously did for TMI, we use analogous formulas for liftoff and transfer to Mars orbit:

$$M_{PR2} = \{1/q\}\{1{,}200 - (q-1)\,(M_S + M_{PLR})\}$$

$$M_{PAM} + M_{PR2} = 1{,}200$$

with M_S = 100 and M_{PLR} = 75. Liftoff to a 500 km circular orbit requires $\Delta v \sim 4.3$ km/s so q = 3.38. [3] We find:

M_{PR2} = 278 MT (residual propellant remaining in Mars orbit)

M_{PAM} = 922 MT (propellant used to ascend from Mars surface to Mars orbit)

The Starship burns 922 MT to ascend from the surface to Mars orbit, leaving 278 MT in the tanks for Trans-Earth Injection (TEI) and EDL at Earth.

Rapp [3] showed that Δv for TEI depends on the specific year and the duration of the return flight. For a ~ 300-day flight, a rough estimate is v ~ 2.5 km/s so q = 2.03.

Using the method previously applied to TMI, we find:

$$M_{PR3} = \{1/q\}\{278 - (q-1)\,(M_S + M_{PLR})\}$$

$$M_{PR3} + M_{PTEI} = 278$$

$$M_{PR3} = (1/2.03)\,\{278 - (1.03)\,(175)\}$$

M_{PR3} = 48 MT (residual propellant to assist orbit insertion at LEO)

M_{PTEI} = 230 MT (propellant used for trans-Earth injection)

The estimate for propellant for TEI is 230 MT, leaving 48 MT to assist EDL into LEO. This estimate is based on the assumption that the payload for return from Mars is 75 MT which is discussed in Section 4.3.3.

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4.2.4 Trip time: According to Maiwald, et al. [21], SpaceX estimated the trip time between Earth and Mars to be 80 days, and possibly as low as 30 days. To put this in perspective, Rapp discusses trip time using H_2- O_2 propellants with Isp = 450 s, which compares favorably to CH_4-O_2 propellants used by SpaceX with Isp = 360 s, and it is difficult to find trajectories with trip times less than 150 days using H_2-O_2. Even these might only be available at some departure dates, and they require considerably more energy than trajectories with more usual 7-8 month trip times.

Maiwald, et al. [21] proceeded to carry out their own independent estimate of trip time. They found that the trip time depended on the launch date and assumptions about mass. Generally, they suggested a 180-day trip time going and returning should be possible, but these might be reduced at some launch dates. Meeting this trip time would be more difficult for the return trip than the outbound trip. The trip times suggested by SpaceX appear to be unattainable by a wide margin.

4.3 Starship and starship-C payload mass review

4.3.1 Overview: SpaceX provided essentially no information regarding a breakdown of subsystem masses on the Starship, or the content of the 100 MT payload on the Starship-C. The Internet posts do not reveal much about the detailed design of the Starship or the contents of its payload, other than the fact that 100 MT are allocated to the Starship and the payload. Some subsystems, such as crew accommodations might be attributed to either the Starship or the payload. In one sense, we are not so concerned with one or the other as much as whether it is possible to fit the sum of Starship mass and payload mass within the assigned limit of 200 MT in LEO. In that connection, there is a significant difference between the crewed Starship (Starship-C) and the cargo Starship (Starship-M). The Starship-C requires crew accommodations, crew supplies and suits, Environmental Control and Life Support Systems (ECLSS), radiation shielding, and food supply. These can be attributed to the payload, and not accounted for in the 100 MT Starship. The payload on the Starship-C can be divided into those elements that remain on the Starship-C for the return flight (M_{PLR}), and those that might be downloaded to the Mars surface (M_{PLS}). The initial payload in LEO is

$$M_{PL} = M_{PLR} + M_{PLS}.$$

4.3.2 Can the Starship Fit Within 100 MT Allocation?: Maiwald, et al. [21] carried out their own independent estimate of the Starship subsystem masses and concluded that the Starship would be considerably more massive than the allocated 100 MT. In doing this, they added a 20% margin, but we do not include a margin here. Maiwald, et al. [21] included a significant mass for radiation protection in the Starship mass but we include that in the payload mass of the Starship-C. In addition, they included ECLSS in the Starship mass, but we also included this in the payload mass. With these differences, a revised summary of Starship masses based on Maiwald, et al. [21] is given in Table 2. Although we reduced the Starship mass from the ~ 200 MT estimate by Maiwald, et al. [21], the net result still exceeds the 100 MT mass allocation by SpaceX. However, the estimate by Maiwald, et al. [21] is based on fragmentary inferences from SpaceX, and until SpaceX provides specific detailed data on the Starship, the results in Table 2 need further refinement, but they do provide a warning that the Starship as seemingly revealed in glossy websites might not fit within its mass allocation. It is also unclear whether 22.7 MT of meteorite shielding is necessary. Further changes in the Starship design are expected.

4.3.3 Can the payload Mass for starship-C fit within 100 MT allocation?

The payload includes:

- Crew accommodations
- Crew and crew supplies, clothing, suits, and equipment
- Radiation protection
- ECLSS – air supply
- ECLSS – water supply
- Food

The crew accommodations include the internal structures and facilities to house a crew of six for the outbound trip and the return trip. Based on Orion, a rough guess is 15 MT. Based on Maiwald, et al. [21], crew and crew supplies, clothing, suits, and equipment are guessed at 7 MT. They allocated 30 MT for radiation protection. Food is allocated 1.5 kg/CM/day and for a crew of six for 900 days, that amounts to 8.1 MT. In summary, except for ECLSS, the tentative requirement for payload is 60 MT, leaving 40 MT for ECLSS.

Life support includes supplying water, oxygen, buffer gas, food, and waste disposal materials, together with environmental control and recycling of air and water. We

Table 2: Breakdown of Starship subsystems, modified from the estimate by Maiwald, et al. [21].

Starship Subsystem	Modified Maiwald, et al. [21] Mass (MT)
Starship Structure	40.7
Meteorite shielding	22.7
Heat shield	11.0
Communications	0.6
Power	13.6
Propulsion	38.0
Harness	6.0
Total	132.6

assume an ECLSS system with a mass of 5 MT that recycles breathing air and water.

The requirement for breathing air is 1 kg/CM/day of oxygen and about 3 kg/CM/day of nitrogen. For a crew of six on a 900-day trip, the total air utilized is 21.6 MT, but assuming 95% of gases are recycled (as suggested by Maiwald, et al. [21]), the gas backup for a recycling system is 1.1 MT.

There is no NASA standard for the water requirement for long missions, but Ewert, et al. [24] provided a NASA report that suggested the minimal water requirement of 10 kg/CM/day and for long missions 15 kg/CM/day. The requirement for water per crewmember per day was discussed by Rapp [19]. Rapp suggested that a minimal "survival" level might be about 7 kg/CM/day, while Earth-like conditions could be provided with 27.6 kg/CM/day. For a crew of 6 over 900 days, the total water requirement is 37.8 MT for survival and 149 MT for Earth-like conditions.

A recycling system is now in use on the ISS. This system includes several subsystems. Some require periodic replenishment of resources; others break down occasionally and must be replaced by so-called "orbital replacement units". This system would not work on a mission to Mars [19]. The conventional view is that an upgraded recycling system for water could be developed in the future that could function reliably for the 900-day trip. Rapp was less optimistic regarding the reliability of a water cycling system over 900 days, and he suggested that to achieve essentially 100% reliability, the mission could bring 7 kg/CM/day from Earth as a secure minimal supply and use recycling to increase the water supply above that figure, perhaps even up to 27.6 kg/CM/day [19]. Here, we assume that water will be provided at 15 kg/CM/day for 900 days, implying total consumption is 81 MT.

We consider two options:

The first option follows Maiwald, et al. [21] in which we assume that there is a 5 MT ECLSS that can function reliably for 900 days providing 15 kg/CM/day. They assumed 90% recycling efficiency, so a backup of 8.1 MT of water is needed. The total mass of the system to provide water is 5 + 8.1 = 13.1 MT. The total mass for ECLSS including air and water is 14.2 MT. The total payload mass is 74.2 MT.

The second option would be to bring enough water from Earth to supply a survival level of 7 kg/CM/day for 900 days and use the 5 MT ECLSS to provide additional water of 8 kg/CM/day to achieve a total of 15 kg/CM/day with the assurance that survival level water does not depend on recycling [19]. In doing this, the water supply brought from Earth would be divided into two parts: one part would supply 7 kg/CM/day on the Starship-C for the 200-day outbound trip, and the second part would be delivered as cargo to the surface to supply 7 kg/CM/day for the 500-day surface stay and for the 200-day return flight to Earth. This is illustrated in Figure 4. That would require 8.4 MT of water to be carried on the Starship-C and 29.3 MT of water to be delivered to the Mars surface as part of the cargo by one of the Starship-M. In addition, the recycling system providing an additional 8 kg/CM/day would require a backup of 10%. For the outbound trip, this amounts to 1 MT, and for the surface and return trip, 3.4 MT.

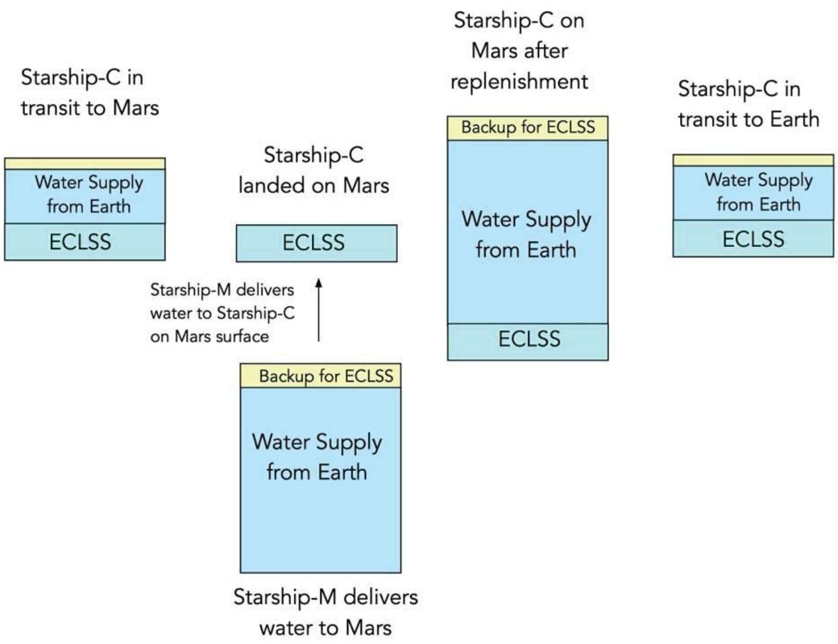

Figure 4: Sequence of water delivery [19].

In summary for Option 2:

Total water supply mass on outbound Starship-C = 5 + 8.4 + 1 = 14.4 MT

Total water supply mass delivered to surface via Starship-M: 5 + 29.3 + 3.4 = 38.7 MT

The total payload mass is then:

Option 1: 60 + 13.1 + 1.1 ~ 74 MT

Option 2: 60 + 14.4 + 1.1 ~ 75 MT

We suggest that Option 2 is to be preferred because it provides survival levels of water independent of the ECLSS, which implies far less risk.

Table 3 provides our rough estimate of payload mass for the return trip.

4.4 Major obstacles

4.4.1 Landing a two-hundred-ton vehicle on Mars: The lander proposed by SpaceX would have a landed mass of 200 MT. Exactly how they would land such a behemoth remains difficult to comprehend.

Current technology Entry, Descent, and Landing (EDL) technology is limited. The largest mass landed on Mars so far was about 1 MT.

Nevertheless, on paper, much greater loads are theorized to be possible to be landed on Mars. Studies carried out by NASA in the 1990s and DRA-5 modeled landing payloads of 40 MT or even 70 MT [5].

Rapp [3] reviewed various approaches for orbit insertion and EDL of high masses based on a series of studies carried out at JPL and Georgia Tech [3,25,26]. Many challenges were identified. From this review, he suggested that the maximum practical payload that might be landed on Mars would be 25 MT, with 100 MT approaching Mars (landed mass ~ 25% of approach mass). The ability to land is enhanced at landing spots with low altitudes because the "air" density profile is higher. More massive landers were viewed as beyond the state of current technology. Rucker, et al. [12] defined a short-stay mission for which they said:

Table 3: Estimated payload mass for the return trip from Mars.

Payload Element	Mass (MT)
Crew accommodations	15
Crew and crew supplies, clothing, suits, and equipment	7
Food	8.1
Radiation protection	30
ECLSS	5
Air backup	1.1
Water backup	1
Water from Earth	8.4
Total Payload	75

"... a useful payload envelope per lander, comfortably within the bounds of key entry, descent, and landing technologies is 25 MT. This payload envelope means that each major Mars cargo item must either be less than 25 MT or be divisible into smaller pieces, delivered on separate landers, and reassembled on the surface of Mars" [12,13].

Current research is exploring new ideas. In paper studies, it appears to be possible to land higher mass loads [27-29].

SpaceX proposes to land a 200 MT vehicle on Mars. Assuming that at least on paper, it might be technically feasible to precision-land a massive payload on Mars, a lengthy development and validation sequence would be required to establish the capability prior to carrying out a human mission to Mars. Manning [27] described a potential 20-year roadmap to validate EDL for a 40 MT payload [25]. A roadmap would begin with the analysis and optimization of designs (and atmospheres) via modeling. Scaled validation flights at Mars would begin in year 9. Full-scale development and Earth test during years 13 to 18, and full-scale validation at Mars around year 20.

An interesting question arises regarding validation tests at Mars. If one is going to land payloads on Mars to validate the technology, it seems wasteful to land a "dummy" payload. Therefore, in parallel with developing EDL over twenty years, it would be advisable to develop a generic infrastructure payload that would be landed as part of the EDL validation process. But that, in turn, requires that the landing site be known. It must be concluded:

One should not validate large-scale EDL at Mars without prior knowledge of the human landing site and the creation of a generic infrastructure payload.

4.4.2 Production of ascent propellants on Mars: Each Starship-C requires 1,200 MT of propellants and there are two Starship-C, so the total propellant requirement on the surface is 2,400 MT. Maiwald, et al. [21] concluded that a production rate of 5 MT per day would suffice. The mass of the ISRU system was estimated to be ~250 MT and the power requirement was estimated to be 3.4 MW.

Rapp [30] analyzed the mass flows and energy requirements for processing indigenous water and atmospheric CO_2 via the Sabatier/Electrolysis process. For a propellant production rate of 90 kg/day, the power requirement was estimated to be about 25 kW (including liquefaction). If we were to scale that up to 5,000 kg/day, the power requirement for processing would be 1.4 MW.

It is difficult to estimate the power requirement for vehicles to mine water and transport 2.3 MT of water per day. With that included the estimate of 3.4 MW by Maiwald, et al. [21] for the entire ISRU system is probably appropriate.

Maiwald, et al. [21] estimated the mass of the ISRU system to be 230 MT. Neither the Sabatier and electrolysis reactors nor the liquefaction systems are very massive. The mass of the water acquisition system is probably significant. We cannot hazard a guess for the mass of the ISRU system in this report, but we suspect it is likely to be far less than 230 MT.

Regardless of the mass and power requirements for this gigantic ISRU system, the prospects for its success are not encouraging. It seems almost certain that the ideal landing site would be in an equatorial area where water is very unlikely to be available. Even if a landing site were chosen to maximize chances of finding indigenous water, the program for prospecting and developing technology for obtaining the water would entail several major missions to Mars spread over several 26-month launch opportunities and might not be feasible in the end anyway [3,30].

4.4.3 Repeated, rapid, multiple launches: The SpaceX plan calls for as many as 72 heavy lift launches at a launch window. The required ground facilities, fuel supply, and environmental issues remain unknown. At first glance, this appears to be a significant challenge.

5. Summary and conclusion

Since about 2016, SpaceX released a series of various press releases, "tweets" and glossy websites making various claims that tax our credulity regarding sending humans to Mars. Most recently, it is widely reported on the Internet that on September 7, 2024, Elon Musk claimed via a "tweet" that humans could be on Mars in four years [31]. Because of Musk's fame and achievements, this claim was taken seriously in some quarters. We can state fairly certainly that humans will not reach the surface of Mars in four years. More likely at least thirty years from now.

The various announcements made by SpaceX since 2016 reveal some aspects of the SpaceX approach to a human mission to Mars. The mission is built around the "Starship" which is a 100 MT vehicle that can haul 100 MT of payload. Several Starships would deliver cargo to the Mars surface. Two Starships would each be fitted to carry a crew of six from LEO to Mars and back to LEO. All the Starships would be fueled in LEO by a dozen tankers, each delivering 100 MT of CH_4 + O_2 propellants, totaling 1,200 MT of propellants in LEO. The crewed Starships would refuel on Mars with 1,200 MT of CH_4 + O_2 propellants produced by ISRU utilizing supposed water resources on Mars. All told, there might be 72 (or more) heavy lift launches at one launch opportunity.

This sketchy outline does not provide much detail for analyzing and evaluating the feasibility of such a mission. Lacking such detail, Maiwald, et al. [21] independently modeled a hypothetical Starship based on established space engineering principles. They concluded that the Starship is likely to be considerably more massive than the 100 MT claimed by SpaceX. That would make the mission impossible to implement. Their (charitable) conclusion was: "With the information currently available a Mars mission with Starship is not feasible." They did not delve into the 100 MT payload.

In the current paper, we also independently analyzed the SpaceX mission using a different approach than that of Maiwald, et al. [21]. We joined the 100 MT Starship and 100 MT payload into a 200 MT combined system, and for the crewed Starship, shifted some subsystems into the payload. As a result, our estimate of the excess Starship mass was significantly reduced, although it remained greater than the claimed Starship mass of 100 MT. The payload mass for return from Mars was roughly estimated to be 75 MT. We also calculated the fraction of the 1,200 MT propellant load in LEO that is used for TMI, and the mass remaining to support orbit insertion and EDL at Mars. In addition, we calculated the fraction of the 1,200 MT propellant load on Mars used for ascent to Mars orbit, the propellant mass for TEI from Mars orbit, and the propellant mass remaining to assist orbit insertion into LEO for the return trip. These propellant allocations were found to be reasonable. Altogether, the mass allocation for the Starship vaguely defined by SpaceX is estimated to be optimistic but might become feasible with design updates. Our results regarding Starship mass indicate that significant challenges remain, but we are less pessimistic than Maiwald, et al. [21].

An important point alluded to by Maiwald, et al. [21] but expanded herein is the consideration of the lengthy technology development sequence that will be required for key technologies. The requirement to land a 200 MT vehicle represents a 200-fold increase over current technology and might not be technically feasible even after a twenty-year development and validation program costing tens of billions of dollars. The huge ISRU system envisaged by SpaceX requires access to available indigenous water at a desirable landing site, which is a low probability. Development and validation would also likely take twenty years at a cost of tens of billions. The need to launch 72 or more heavy lift launches at one launch opportunity introduces significant logistic and environmental challenges.

Our view is that the SpaceX mission to Mars introduces innovative ideas for a future human mission to Mars that might provide a very good approach for a human mission to Mars some thirty or more years in the future. The idea of SpaceX landing humans on Mars in 2028 seems overly optimistic.

The SpaceX Mars mission introduced three innovations:

1. Previous mission designs were preoccupied with reducing mass. This was partly to reduce launch costs,

but also more generally it was thought that the initial mass in LEO (IMLEO) was a rough indicator of mission cost. The object is no longer to reduce mass, but rather to reduce complexity and risk. The aim is to maximize mass to minimize complexity and risk, and maximize payoff, rather than minimize mass.

2. The SpaceX concept uses a single vehicle that travels from launch, through LEO, through Mars orbit, remains at the surface, and returns to Earth. As a result, there is no distinct separate Earth Return Vehicle, no ascent or descent capsules, no rendezvous maneuver, and no duplication of life support and consumables and habitats from vehicle to vehicle.

3. SpaceX uses the same propellants and the same engines for all phases of the mission, including transport to Mars, descent and ascent, and return from Mars. The propellants are cryogenic, but are far more easily storable than LH2, and are compatible with Mars ISRU. There is no need for different propulsion systems for different phases of the mission.

We regard the major contribution of the SpaceX concept as pointing the way toward a new approach to sending humans to Mars in an era of reduced launch costs. This might displace the prevailing obsolete NASA concepts such as DRA-5 or HEOMD-415.

6. Glossary

ECLSS: Environmental Control and Life Support System; ERV: Earth Return Vehicle; IMLEO: Initial Mass in Low Earth Orbit; ISPP: In Situ Propellant Production; ISRU: In Situ Resource Utilization; ISS: International Space Station; LEO: Low Earth Orbit; MAT: Mars Architecture Team (NASA); NTP: Nuclear Thermal Propulsion; Starship-C: Crew Version of Starship; Starship-M: Cargo Version of Starship; Starship-P: Propellant Tanker Version of Starship; TEI: Trans-Earth Injection; TMI: Trans-Mars Injection

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