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Research Article

Preparing for SpaceX Mission to Mars

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Abstract

SpaceX announced a plan for a bold, innovative, new approach to land a human crew on Mars. Unlike traditional space missions that minimize mass, the SpaceX approach utilizes many lower-cost launches to create a simplified, robust mission concept utilizing large amounts of mass.

SpaceX claims it will land a crew on Mars in the next several years.

A great deal of development and validation *in situ* of critical elements of the mission must be demonstrated prior to carrying out the mission. The *in situ* production of 1,200 MT of cryogenic propellants and the entry descent and landing of a 200 MT vehicle represent the greatest challenges. Locating an accessible source of H2O at a suitable landing site will require a series of launches of prospecting missions at increasing resolution at 26-month launch intervals.

The preparation for the ultimate SpaceX mission will require at least ten years and most likely twenty years of development and demonstration at a cost of several tens of billions of dollars. It is not clear why SpaceX continues to make bold claims for timing that is not possible.

Introduction

In a series of Internet postings over the past few years, SpaceX claimed they would implement a near-term human mission to Mars in the late 2020s.

An AI overview on the Internet said:

"In 2016, Elon Musk said that SpaceX could begin sending humans to Mars as early as 2022. However, SpaceX's current plans are for uncrewed missions to Mars in 2026, followed by crewed missions two to four years later."

Since then, Musk and SpaceX have continued to claim that they are just a few years away from landing humans on Mars.

In 2020, Musk was quoted as saying:

"… 'highly confident' that the company will land humans on Mars in "about six years from now."

In 2024 Musk was quoted as saying:

"… humans could land on Mars within four years and be living there in a self-sustaining city in 20 years."

The scale of the initial mission is unprecedented, with a landed crew of twelve, and several thousand tons of propellants used for transfers between LEO and the Mars surface, compared to previous mission designs with crews of 2, 4, or 6, and propellant loads of several tens of tons [1]. Unlike previous mission designs, the SpaceX mission utilizes a single space vehicle to go from LEO to Mars and back, eliminating a rendezvous with a second vehicle on the return flight.

While the SpaceX vision for a human mission to Mars is replete with major challenges, the outline of the mission provides some valuable new insights and approaches. As pointed out by Rapp [2], and originally by Jones [3] a major element of the traditional approach to designing space missions was to reduce mass in LEO. Thus, historically, the "initial mass in LEO" (IMLEO) was considered to be an indicator of mission cost and was an important factor to be minimized by clever design. With the great reduction in launch costs produced by SpaceX in recent years, reducing IMLEO no longer has great leverage. Instead, SpaceX apparently takes the opposite view and increases mass (hopefully at an acceptable cost) to simplify, reduce risk, and increase reliability. In this mission design, IMLEO is less relevant.

The SpaceX mission to Mars simplifies the mission by utilizing a single vehicle from LEO to the Mars surface and

back to Earth, using the same engines and propellants for all legs of the round-trip journey. The return flight goes directly from Mars to LEO without a rendezvous, as Zubrin suggested thirty years ago [4].

However, only a few details of the mission were presented. The various posted details of the SpaceX mission were reviewed by Maiwald, et al. [5] and by Rapp [6]. These reviews discussed the challenges involved, and they concluded that the mission is unlikely to be feasible as briefly described by SpaceX. Aside from several glossy brochures posted on the Internet by SpaceX that contain limited descriptive data for the proposed SpaceX mission, the Maiwald and Rapp publications represent the only serious quantitative analyses of the mission feasibility.

The lander proposed by SpaceX would have a landed mass of 200 MT, comprised of a 100 MT Starship and a 100 MT payload. That is 200 times greater than the largest payload so far landed on Mars. Exactly how such a behemoth would be landed on Mars remains difficult to comprehend. Assuming that it might eventually become technically feasible to precision-land such a massive payload on Mars, a 20-year development and validation sequence would likely be required to establish the viability of this capability prior to carrying out a human mission to Mars. Furthermore, Maiwald, et al. [5] performed a detailed analysis of the SpaceX mission, and they estimated that the mass of the Starship would exceed the claimed value of 100 MT by a considerable amount [5].

A Starship that carries a crew of six requires 1,200 MT of propellants and there are two crewed Starships, so the total propellant requirement on the Mars surface for the return trip from Mars is 2,400 MT. SpaceX proposes to produce this propellant load from indigenous Mars resources using ISRU. That would entail finding a suitable source of H_2O at a suitable landing site, which at best would be very challenging, and at worst, might not be possible. A search for suitable near-surface resources would be needed in preliminary exploratory missions. The process would have to be validated *in situ* on Mars. It seems likely that the landing site would be in an equatorial area where near-surface H_2O has been detected from space in a few locations – most likely hydrated minerals. The program for prospecting and developing autonomous technology for obtaining water from regolith would be a lengthy arduous process, entailing several major missions to the Mars surface spread over several 26-month launch opportunities [6].

Each Starship requires 1,200 MT of propellants in LEO. The SpaceX plan calls for tankers to deliver propellants to a Starship in LEO, 100 MT at a time, so 12 round-trip tanker launches would be required to fuel each Starship in LEO. Including cargo, as many as 72 heavy lift launches might be required at each launch window. The required ground facilities, fuel supply, and environmental issues remain unknown, and launching 72 massive vehicles might not be feasible [7]. A Reddit forum on the SpaceX Mars mission suggested that initially, propellants for the return trip could be brought from Earth instead of using ISRU [8]. That would require sending 2,400 MT of cryogenic propellants to Mars. Each 100 MT of payload sent to Mars requires 12 launches to LEO. Therefore, the proposal to bring 2,400 MT to Mars requires an additional 24 x 12 = 288 launches. The Reddit forums are replete with a good deal of misconception regarding the SpaceX mission to Mars.

Additional insights were provided by Saumya, et al. [9] who presented their interpretation of how a Mars mission based on Starship might be carried out.

Aside from the several major technical and financial challenges in the SpaceX mission to Mars, the aspect that seems most underplayed, yet absolutely necessary prior to launching humans, is developing critical technologies and demonstrating them on Mars prior to the actual mission. Because of the 26-month spacing of launch opportunities, this will likely require a minimum of twenty years and a large investment. Perhaps the greatest challenge in preparing for the proposed SpaceX Mars mission is that the choice of the landing site is dependent on the availability of H_2O, so prospecting for H_2O and validating precision entry, descent, and landing at sites are intimately entwined and one can't proceed without the other in unison. As different sites are investigated, major power systems will be needed at each site.

Methodology

The mission planned by SpaceX is far greater in span, dimension, ambition, and cost than any space mission planned by NASA. The preparation for this mission will encompass several technologies to be developed and demonstrated at Mars, and preparation for the SpaceX mission will be greater in scope and cost than preparation for any space mission carried out previously.

This paper applies space system engineering principles to the proposed SpaceX human mission to Mars to analyze several technologies and subsystems that need to be demonstrated as viable in advance of such a mission. [5,6,10] Space system engineering is the process of defining the capabilities needed, and potential approaches for fulfilling these needs, identifying constraints and limitations that must be overcome in each case, and suggesting steps and a timeline for validation. The procedure mainly utilizes the author's 50 years of experience in space system engineering, as well as key references from the literature, to analyze requirements and opportunities in each aspect of preparing for a SpaceX human mission to Mars. In this paper, an attempt to provide overviews of a rational plan was made to prepare for the SpaceX mission. Implementation

of the actual SpaceX mission, a gigantic enterprise, will not be covered in this paper and is so extensive that it could hardly be described by one person.

Results

The water requirement

Water is required in large quantities for the proposed SpaceX mission. Water is required mainly to produce propellants for ascent and the return flight from Mars to LEO, and for life support while the crew is on the surface and during the return flight. Water for the outbound flight from LEO would be part of the outbound payload.

SpaceX indicated that 1,200 MT of CH_4 + O_2 propellants would be required on Mars for each return flight, and there would be two return flights for a total of 2,400 MT on Mars. The hydrogen requirement to produce propellants defines how much indigenous water would be required to be processed.

Assuming that CH_4 constitutes 24% of the total propellant mass load, the hydrogen requirement is (0.24)(2,400)(0.25) = 144 tons, which implies that 1,296 MT of water would have to be acquired and processed if the Sabatier/electrolysis process went to completion with no losses. Allowing for incomplete reaction and losses, the actual requirement might be at least 1,350 MT of indigenous water acquired on Mars.

The requirement for water for life support was discussed by Rapp [2] and Heldman, et al. [11]. Rapp suggested that a survival level was 7 kg/CM/day and an Earth-like environment could be achieved with 27.6 kg/CM/day. Heldman, et al. [11] suggested 14.4 kg/CM/day, which would probably be a good choice in a mass-constrained mission, but for the SpaceX mission where mass is relatively abundant, we choose a less constrained value of 20 kg/CM/day. For a crew of 12 spending 550 days on Mars and 210 days on the return trip, the total water requirement is (760)(20)(12) = 182,400 kg = 182 MT.

Allowing for inefficiencies and losses, the total water requirement for propellants and life support is estimated to be roughly 1,600 MT.

It is not clear if the purity of the water is a consideration for propellant production. Purity is important for life support. If the water is obtained from indigenous hydrated minerals, it is distilled, so purity might not be an issue. If water is obtained from indigenous ground ice, purity will have to be addressed, especially since perchlorates are known to be widely prevalent on Mars.

Heldmann, et al. [11] addressed supplying the required water as follows:

"There are multiple options for obtaining water to support return flights to Earth for the first few crews on Mars. Water can be transported to Mars from Earth within Starship cargo vehicles to ensure the availability of necessary water for life support and propellant production. This approach will be especially important for ensuring life support needs for the first few human crews on Mars before the ISRU of water ice is fully functional and reliable. Bringing water from the Earth for propellant production is also likely possible in an emergency situation but is challenging, requiring the expensive delivery of water from Earth. Ultimately, the required water will be mined as a natural resource on Mars to support the expanding base and provide propellant for routine return trips to the Earth" [11].

Since the Starship payload is 100 MT, bringing 182 MT of water from Earth for life support would entail two additional Starship launches. Bringing 1,600 MT of water to Mars for propellant production and life support would entail an additional 16 Starship launches without return. Each Starship launch is supported by twelve tanker launches to fuel departure from LEO. To send 18 additional Starships to Mars, 216 tanker launches would be required. The logistics of adding all these launches taxes one's credulity, not to mention cost and timeline. Clearly, ISRU must be a fundamental part of the SpaceX strategy.

Locating and verifying accessible H_2O on Mars

Butcher [12] reviewed observations of ice on Mars at "mid-latitudes" (30° to 60°). At various locations, ice in regolith, as well as thick buried layers has been found, with greater preponderance at the higher latitudes. He said that most of the known subsurface ice deposits in Mars' mid-latitudes are within hundreds of meters of the surface. However, the major observations from space sensed hydrogen in the top one meter of the surface. These observations typically have poor resolution and require assumptions to interpret the data as possible quantitative hydrogen. Butcher mentions "happenstance" excavations of small local ice deposits by fresh impact craters. Ground penetrating radar found evidence of widespread layers that might be interpreted as deeply buried ice. Butcher said: "A valuable addition to the datasets available to study Mars' mid-latitude ice deposits would be an orbital ground-penetrating radar capable of resolving the properties of the 1–20 m deep layer of the subsurface." He pointed out that current instrumentation is poorly suited to explore these depths, and interpretations of data at these depths are quite subjective. Butcher's summary suggests caution regarding assumptions about the availability of ice at equatorial latitudes.

There is evidence of considerable optimism in the NASA community with some publications seeming to suggest widespread accessible ice occurs in equatorial regions. Golombek, et al. [13] said "The landing site must be close to significant deposits of water/ice" and then listed a few

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references to observations of ice on Mars without elaboration or discussion, as if that provided an optimistic outlook for widespread ice. The remainder of their study was dedicated to finding sites at low elevations to enhance entry, descent, and landing, and a brief sentence was added, suggesting the need for further study of "the extent and characteristics of the ice deposits" – as if near-surface ice would be at most locations and the choice of landing site would rest mainly on elevation and other factors [13]. Heldmann, et al. [11] said: "The most valuable resource on Mars for ISRU is the vast deposits of Martian water ice" even though almost all (if not all) of that ice is unlikely to be accessible to a human crew. They said: "Characterization of the ice resource is a top priority for near-term robotic flights to Mars in preparation for human exploration", improving upon SpaceX who made the unimaginable claim that ISRU would be implemented while the crew was on Mars, they emphasized the need to locate accessible ice at potential landing altitudes using "robots and rovers" long prior to the actual human mission [11]. These quotes leave out a great deal. The words "hydrated minerals" do not occur in these papers, and it is possible that hydrated minerals might be more readily available than ice at equatorial landing sites. In fact, there might not be any accessible ice at equatorial landing sites. However, both papers appear to be certain that ice will be available at the landing site. Heldmann, et al. [11] describe a rover to seek ground truth that can travel over distances of kilometers. They claimed this would be delivered by a Starship, which is like using a sledgehammer to drive in a tack because the Starship can carry a payload of 100 MT and a rover is likely to have a mass around 1-2 MT. But before sending a rover, or more likely several rovers to Mars, a great deal more must be done to further refine our knowledge of the distribution of near-surface H_2O, especially in equatorial regions. Heldmann, et al. [11] did not discuss where the proposed rovers would be deployed. Considering the currently poor resolution of observations, a great deal of work will be needed prior to landing rovers for prospecting. Further synoptic observations are needed with much higher resolution than was obtained by the Odyssey orbiter with its 300 km pixels. The gamma-ray spectrometer aboard the Odyssey orbiter provided data for the schematic shown in Figure 1 [14]. There are several equatorial areas of interest, particularly the one in the center of Figure 1.

To actually locate and verify significant H_2O sources in equatorial regions would require a dedicated campaign. One can imagine a two-pronged approach consisting of improvement of global synoptic observations. The first part of this campaign would require developing a technology to allow higher resolution synoptic detection of hydrogen across the broad swath of equatorial regions.

A variety of possibilities exist for improved resolution, including a slowly descending lander that takes synoptic views as it descends, airplanes, helicopters, gliders, balloons, networks of small, fixed landers, orbiters that temporarily dip down toward the top of the atmosphere, tumbleweeds, hoppers, and probably more, but regardless of the method, Initial study might be focused on the central light blue area in Figure 1 that represents an attractive area to explore further for H_2O, and is likely to contain significant amounts of hydrated minerals. Several other equatorial areas would also provide good initial opportunities for further refinement of observations. If the observational pixel could be reduced from the present 300 km to say, 15 km, we would have data across the central light blue area in Figure 1 as shown in Figure 2.

NASA carried out very little development of methods to improve upon detecting H_2O on Mars with higher resolution. We are at a stage of infancy in this regard. Heldmann, et al. [11] suggested use of rovers for ground truth, but they didn't (and couldn't) know where to land those rovers, and until we further refine synoptic observations from orbit, we won't know where to land rovers for ground truth. Since rovers probably have a range of 1 km per week, the probable location of H_2O deposits would have to be pinned down to a ~ 15 km pixel before rovers would be deployed to crisscross a 15 km pixel. Considering the 26-month spacing of launch opportunities, and the need to test and validate procedures at Mars, it seems likely that fulfillment of synoptic high-resolution observations would take a considerable investment of money and time.

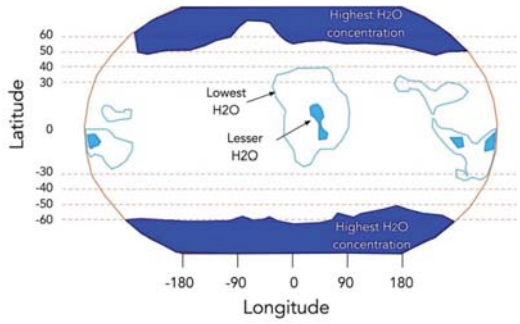

Figure 1: Map of water content in the upper 1 m of the Mars surface as estimated from modeled measurements taken by the gamma ray spectrometer on the Odessey orbiter. Light blue areas have significantly less hydrogen than dark blue areas [14]. This figure is modified from Butcher (2022) [12].

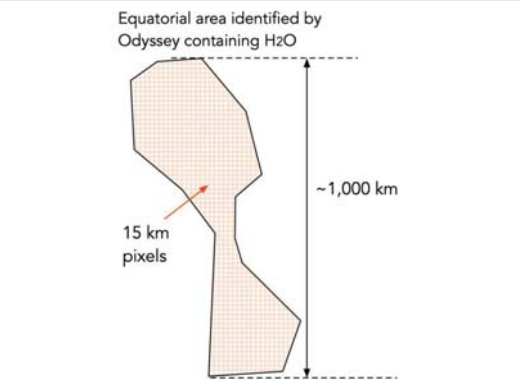

Figure 2: The central area with H_2O detected by Odyssey is subdivided into 15 km pixels.

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After a significant source of equatorial H_2O is located at about 15 km, ground truth would be established by landing rovers with instrumentation and digging/excavation/drilling capability to pinpoint the best locations, observe if they are constituted of ice or mineral hydrates, and determine the requirements for obtaining water or regolith containing H_2O from this source. This would be followed by the establishment of a pilot plant to verify a method of production and purification of water in quantity. All told the entire sequence of prospecting and validation would take at least 10 years, and more probably 20 years. However, SpaceX seemed to claim that they would use ISRU to produce water while the crew is on Mars – probably based on the fantastic view that near-surface ice is readily available almost everywhere – and an exaggerated view of what could be accomplished in real-time on Mars.

We infer from all our readings of several press releases and occasional papers that recent observations of ice ejected from impacts and other incidental exposures of ice, typically at mid-latitudes have created a spirit of over-optimism regarding widespread, accessible ice at most locations. We retain a more conservative view that accessible equatorial ice is at best rare, and mineral hydrates are more likely. Hopefully, future observations will provide greater clarity, although NASA's priorities favor sample return and search for evidence of life, and the search for water on Mars appears to be on the "backburner" while the lunar initiative continues.

Finding an appropriate landing site

The choice of landing site on Mars for the SpaceX mission will be driven primarily by several factors: (1) the primary requirement of a suitable near-surface supply of H_2O that can efficiently supply several thousand MT of H_2O and (2) the desire for a relatively benign climate limiting the choice to an equatorial location, possibly ± 20° latitude. In addition, (3) sites at low elevations are important to facilitate entry, descent, and landing, and (4) sites with interesting science opportunities would be an added bonus. There will not be a mission without a water supply, so that requirement must be taken as central and uncompromising. However, there is no precedent for the entry, descent, and landing (EDL) of a 200 MT vehicle on Mars, and since lower elevations enhance the EDL process, that is also a very important consideration.

Golombek, et al. [13] reported on a JPL study in cooperation with SpaceX "to consider landing sites for initial Starship Mars missions in the 2020s". However, Rapp (2024A) argued that crewed Starship Mars missions in the 2020s are an impossible goal [6]. The JPL study placed primary emphasis on locations at low elevations in the latitude range 35° to 40° as summarized in Table 1, but implied optimism for accessible water ice, based on brief mention of a few orbital observations of near-surface hydrogen or ice-ejected by impacts on Mars, which leave a great deal of doubt about prospects for obtaining H_2O at the proposed landing sites in their Table 1. There seems to be considerable unwarranted optimism in the NASA community about the availability of H_2O in the latitude range 35° to 40°. Furthermore, these latitudes might not be acceptable for a landing site for other reasons.

The prevailing optimism about near-surface ice at moderate latitudes was also expressed by Heldmann, et al. [11] who described "vast deposits of Martian water ice", most of which is not accessible at equatorial landing sites. The backup for this claim was a brief mention of various observations from orbit in their references 15 to 23 which are interesting but inadequate to assure accessible ice is available at prospective landing sites. They said: "The location and ease of access of water ice are key drivers for the landing site selection" which omits the possibility of obtaining water from hydrated minerals – and these mineral hydrates are likely to be far more available than ice at lower latitudes. The better statement would be *location and ease of access of H_2O (in whatever form) are key drivers for the landing site selection*.

The availability of H_2O at low-elevation equatorial sites is the key factor in determining the best choice of landing site. It is not clear at this juncture exactly how important low elevation is for EDL, but there will be no missions without a very substantial source of water. As of today, no information has been revealed by SpaceX on how they plan to land a 200 MT vehicle on Mars. If it turns out that the sites with equatorial water are not at low elevation, and if low elevation is critical for EDL, that might dictate that the landing site would have to be chosen at a higher latitude where perhaps low elevation and water might be available at the same location. Therefore, the search for available water should not be carried out independently but must be carried out jointly with the refinement of the SpaceX EDL process which presently has zero content. Until the importance of low elevation is established, the search for accessible H_2O cannot be begun. If it turns out that low elevation is helpful but not crucial, the search for equatorial water can begin. If low elevation turns out to be enabled, then the search for accessible H_2O would have to be restricted to locations at low elevation, and that would severely reduce the probability of finding accessible H_2O (perhaps to zero).

Entry, descent, and landing

Along with locating and acquiring water on Mars, Entry, Descent and Landing (EDL) of the 200 MT Starship (including payload) presents a major challenge for the SpaceX mission. EDL on Mars involves applying forces to a spacecraft to oppose the acceleration toward the surface by the gravitational attraction of Mars. Without opposing forces, the spacecraft would be attracted by the gravity of Mars, hit the surface at a velocity of about 4.3 km/s, and be destroyed at impact. The

three methods for opposing this downward force that has been applied to Mars landers so far include (1) retro-propulsion, (2) using aeroshells that convert energy into heat using high-temperature aeroshells at entry, and (3) parachutes at lower altitudes in the final stage of landing.

It has been shown that the mass of high-temperature resistant shields for entry is typically considerably less than the mass of propellants required for retro-propulsion. Therefore, NASA plans for future human missions always utilize aeroshells as the primary factor for entry, assisted (as necessary) by retro-propulsion.

The greatest mass landed on Mars so far was about 1 MT. Various paper studies by NASA and the Georgia Tech group investigated the possibility of landing much greater masses on Mars. Rapp [1] reviewed these investigations and concluded that a 25 MT payload ought to be feasible. Nevertheless, the current NASA plan for a short-stay Mars mission limits the planned landed payload mass to 25 MT [15]. In a recent description of NASA's plans for a human mission to Mars, one of the major goals was stated as "20-25 MT payload to Mars surface delivery (EDL)" [16].

Manning proposed a 20-year development period to validate EDL for a 40 MT payload [17]. On the other hand, if SpaceX can land a Starship on Earth from LEO, that would provide some evidence of the possibility it might land on Mars, although the two atmospheres are very different, and Mars provides far less resistance to an aeroshell.

Rapp (2024B) provided estimates of propellant requirements for various SpaceX mission maneuvers [6]. Of the 1,200 MT of propellants available in LEO, 948 MT are used for trans-Mars injection and 252 MT of propellants remain as the 200 MT Starship approaches the Mars atmosphere. If EDL were carried out entirely by retro propulsion, the required mass of propellants is estimated to be 1,054 MT. Therefore, the propellant available for EDL is far less than that required for a completely retro propulsion EDL. The front end of the Starship is covered with aeroshell tiles. It is not clear whether the available area of aeroshell tiles plus the 252 MT of propellants is sufficient to act as a suitable thermal barrier. The onus is on SpaceX to show that a viable EDL process is feasible. They can do this in steps by landing successively higher masses on Mars, or possibly simply landing a loaded Starship on Mars without precursors – if they are capable of doing that. At some point before that, they have to quantitatively describe the end-to-end EDL procedure.

If they are going to land a fully loaded Starship on Mars to demonstrate they have that capability, they might as well land it at the ultimate site to be used for crew landing and begin installing 100 MT of infrastructure. This implies that an adequate supply of water has been demonstrated at that site. The demonstration of EDL, selection of landing site, and demonstration of ISRU are all closely entwined and cannot be done separately.

In situ resource utilization

In situ resource utilization on Mars has been discussed in the literature mainly at the scale of tens of MT in a mass-constrained mission [18]. The SpaceX system deals in thousands of MT where mass is far less constrained. This opens up a totally new regime for ISRU and this requires rethinking about a system 100 times larger in magnitude than most of the systems contemplated previously.

The major uncertainties are (1) how to prospect for large accessible deposits of H_2O, (2) what preliminary steps are needed to validate processes and procedures for acquiring H_2O from such sources, and (3) whether actual implementation is carried out prior to crew landing or while the crew is on Mars. This will determine whether the whole process must be carried out autonomously or under the control of the crew. The usual NASA plan calls for autonomous processing and loading the ascent tanks with propellants prior to crew departure from Earth; however, SpaceX indicated that they would do the actual ISRU processing under crew supervision. The risk that the process might encounter obstacles was not discussed by SpaceX. Their plan appears to be naïve and extremely risky.

Prospecting for H_2O, EDL, and selection of a landing site are intimately entwined as previously discussed in this paper. A lengthy development and demonstration program will be required. Significant machinery will be required to excavate or otherwise obtain putative H_2O from the resource, the form of which is presently unknown. The whole system includes electrolysis of the H_2O to obtain H_2, acquisition of pressurized CO_2 from the atmosphere, and reaction of CO_2 with hydrogen according to the well-known Sabatier reaction [18]:

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

and electrolysis of the product H_2O, so the entire reaction is:

$$CO_2 + 2H_2 = CH_4 + O_2$$

Maiwald, et al. [5] concluded that a production rate of 5 MT of propellants per day would be required and the power requirement was roughly estimated to be 3.4 MW. The actual system for accomplishing all that remains to be imagined, so this is a very preliminary estimate. Depending on the location (especially the altitude), the water source might be mineral hydrates or ice embedded in regolith. For example, if the source provided water at say 15% water, 85% regolith, the system would have to excavate and process 33 MT of Mars surface material per day. This system should be demonstrated and validated prior to crew departure from Earth. That would likely require a development and demonstration plan that

would span about four 26-month launch opportunities and many billions of dollars.

Large-scale power would be needed to carry out prospecting, yet it seems likely that the final choice of landing site would require investigating several sites for ground truth, implying several large power systems at different sites.

Long-range travel and exploration

One topic that has not received enough attention in planning human missions to Mars is long-range travel and exploration. The challenges in going to Mars, living on Mars, and returning from Mars have dominated the discussion. However, the main site where habitats and power are available presents only a microcosm of opportunity for exploration. Without long-range transport, a human mission to Mars might not return adequate results.

Currently, NASA is trying to find a way to implement an affordable Mars Sample Return mission [19]. The current view is that an immense amount of information can be derived from the analysis of a few samples from Mars in a vast array of suitably equipped laboratories at various universities and research centers on Earth.

Prior to the SpaceX mission plan, bringing such laboratory facilities to Mars was regarded as prohibitive, but if the SpaceX scheme could actually be implemented, there does not seem to be any reason why a fully functional laboratory could not be installed on Mars. With long-range transportation on the surface, a far more complete set of samples for analysis could be obtained and analysis carried out *in situ*.

Unfortunately, technology for the mobility of a human crew on Mars has received little more than a "bullet" or two in NASA PowerPoint presentations, and the development of capabilities for long-range exploration would be starting essentially from scratch with almost no background. One might imagine open rovers for moderate distances where crew wear suits, or they might be teleoperated without crew. Pressurized rovers have been mentioned but serious work appears to be scarce. A brief study did not go very far [20].

The development of appropriate surface transportation vehicles is heavily dependent on power systems. The Perseverance Rover presently operating on Mars is powered by a ~ 100 W RTG. It uses batteries to store energy for higher power consumption for a limited duration. That would be grossly inadequate for a crewed rover. Furthermore, RTGs are in short supply and are likely to remain so because they require Plutonium. Providing energy to a long-distance rover remains a challenge. There do not seem to be any serious designs or performance estimates for crewed pressurized rovers, and power for such rovers is a major question mark.

Power systems

Maiwald, et al. [5] estimated that the required power for ISRU would be about 3.4 MW. Power would also have to be provided during the demonstration and validation stages prior to the actual crewed mission. This includes the power to validate ISRU, propellant storage, long-distance travel, and life support systems. Therefore, several power systems with increasing power levels would likely be deployed as technology is advanced on Mars. Eventually, when the crew lands, most of the power used for ISRU would be transferred to life support for the crew. However, if SpaceX persists in claiming they would carry out ISRU while the crew is on Mars, the total power would be the sum of that used for ISRU and that used for life support.

The power system would be located at a distance from the main landing site and a berm created to avoid direct line of sight radiation from reaching the crew. A cable would connect to the landing site.

This power system would be landed and autonomously deployed and connected at an earlier launch opportunity.

Power for long-distance transportation remains a question mark. The Perseverance Rover, now on Mars has a 0.1 kW RTG for power. McClure, et al. [21] reported that NASA has small "kilopower" nuclear reactors under development for lunar and Mars missions. These fission power systems range from 1 kWe to 10 kWe and can be used in a modular fashion for any desired capability in that range.

Oleson, et al. [22] explored 10 kWe and 40 kWe fission power systems. While the 10 kWe fission power system (FPS) could be deployed as a single unit, the 40 kWe system was too large and had to be deployed in multiple trips. Their systems employed several subordinate technologies now under development.

The power system planned for the SpaceX mission is about 100 times larger than the ones currently being developed by NASA.

Discussion

There are many admirable aspects of the SpaceX mission to Mars. As Rapp pointed out, the traditional approach to designing space missions is to place emphasis on reducing mass to save launch costs. The great reduction in launch costs projected by SpaceX makes that approach obsolete, and SpaceX proposes quite the opposite: Utilize large amounts of mass to facilitate a more ambitious, more robust, and less risky mission design [6]. 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. 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.

However, the timeline for the implementation of this grand concept is not credible.

As a recent review showed, the timeline for the hypothetical SpaceX Mars mission has been delayed several times [23]. In 2016, the target date for the human mission was 2024. By 2020, the target date slipped to 2026. Then, it was extended to 2029. Based on press releases made by SpaceX and by Elon Musk, a speculative timeline for the SpaceX human mission to Mars was posted to the Internet as [23]:

- 2024-2026: Starship's first orbital and cargo flights test the key components for long-duration spaceflight.
- 2028-2030: Possible uncrewed cargo mission to Mars during the Mars window in 2028. This mission would focus on delivering supplies and equipment. (Note that this presumes that a final landing site had been selected prior to 2028).
- 2031-2033: Manned flight to Mars could happen in the 2031 window but only after progress is achieved on cargo flights and preparedness for life support and habitat. (This demonstrates the simplicity and naivete of those who comment on the SpaceX Mars mission).

It seems clear that nobody involved in this scheme, whether at SpaceX or reported on the Internet based on SpaceX announcements, has much understanding of the challenges involved or a rational conception of the required timeline for development and validation. Our opinion is that there will not be a manned flight to Mars in 2028, nor in 2031, and probably not for twenty years after that. Even the cargo mission landing on Mars is very unlikely pending the development and demonstration of a system for landing a 200 MT vehicle. And a landing site would have to be chosen prior to that. And ISRU would be required to be proven before that. Even making an unsupportable assumption that the crew can land safely, the crew cannot get back home without having access to 2,400 MT of propellants produced from indigenous Mars resources. We project that it will take at least ten years, and far more likely twenty years, involving multiple landings and synoptic exploration, to develop, validate, and demonstrate a system for producing, liquefying, and storing 2,400 MT of liquid CH_4 and O_2 on Mars at an appropriate landing site – if possible.

Aside from the problem of producing propellants for the return trip, several other important subsystems need to be developed over a significant timeline. It seems likely that a series of missions would be required to validate that a 200 MT loaded Starship could safely land on Mars. In the very unlikely possibility that SpaceX could achieve an incredible and unprecedented engineering breakthrough by simply landing a Starship on Mars in the short run based on what they know at this time, that would still not allow them to return without producing 2,400 MT of propellants *in situ*.

As we discussed previously, an early estimate of a ~ 3.4 MW power system would be needed to drive the ISRU system for propellant production, which is 100 times larger than the power systems now under development by NASA. Exploration requires long-range transportation on Mars; these must also be developed – essentially from scratch.

For all these reasons, and more (we have not discussed radiation, zero-g and low-g, human factors, difficulty performing 72 Starship launches in a single launch window, risks, dealing with emergencies, and more) we believe that at least a decade and far more likely two decades of dedicated, costly development would be required prior to sending a crew to Mars with a reasonable probability of success.

SpaceX posted glossy brochures that make bold claims not backed up by anything substantial or credible [24]. Elon Musk is a much-admired person for his accomplishments and when he makes a declaration, the whole world of the press tends to believe his words verbatim. For example, one news posting said:

"SpaceX will start launching Starships to Mars in 2026. These will be uncrewed to test the reliability of landing intact on Mars. If those landings go well, then the first crewed flights to Mars will be in 4 years" [25].

The Internet is replete with reports that SpaceX will land a crew on Mars in a few years. However, it is not as easy as it sounds and it is essential to recognize that designing a viable space mission would involve far more complex processes and require extensive expertise and resources.

Here, we are faced with a conundrum. The published papers by Maiwald, et al. [5] and Rapp [6] claim that the information provided by SpaceX on the Internet does not lead to a viable mission in the near term. The present paper argues that a lengthy, expensive development, demonstration, and *in situ* validation program would have to precede such a SpaceX mission. However, SpaceX continues to make claims for implementing the mission in a few years. We must acknowledge that Elon Musk possesses sufficient intelligence and has substantial support from the engineers at SpaceX to comprehend these matters. There are seemingly two possibilities: either Maiwald, et al. and Rapp misunderstood the SpaceX mission, and their criticisms are not valid, or Musk and SpaceX have a different agenda requiring them to make

bold claims beyond what is feasible in the short term. If the latter, one can only conjecture their motive. The SpaceX vision is bold and grand. It dwarfs anything NASA could imagine. NASA is bogged down with science missions, climate missions, and supporting constituencies at NASA Centers. NASA has not yet adopted the new regime of low launch costs and using large amounts of mass for ambitious projects. In the current political climate where outsourcing government agencies is viewed favorably, perhaps SpaceX is positioning itself to be the entity that someday replaces NASA.

Conclusion

SpaceX announced a plan for a bold, innovative, new approach to land a human crew on Mars. Unlike traditional space missions that minimize mass to reduce launch costs, the SpaceX approach utilizes many low-cost launches to create a simplified, robust mission concept utilizing large amounts of mass.

However, the timeline for implementation of the SpaceX manned mission to Mars is unachievable. A great deal of development and validation *in situ* of critical elements of the mission must be demonstrated prior to carrying out the mission. The most important of these include:

- Production and storage of 2,400 MT of cryogenic CH_4 and O_2 propellants for the return trip
- Deciding on a landing site compatible with EDL and ISRU
- Entry, descent, and landing (EDL) of a 200 MT vehicle on Mars
- Long-range travel from the Mars base
- Carrying out 72 launches in a launch window
- 3.4 MW power system

We predict that validation and demonstration of the production of propellants and EDL will require at least ten years, and more likely twenty years, including multiple launches to Mars. The other systems will also require multiple years of development. These pre-mission activities will require multiple prospecting and demonstration missions on Mars at several locations where high levels of power will be required. These activities will certainly cost in the billions, but how many billion cannot be estimated at this time.

It is our contention that the SpaceX mission concept is innovative and attractive, but the claims of imminent implementation appear to be "mission impossible". Either the claims made in this paper are mistaken, or SpaceX has a reason for making claims that are unachievable. The future will reveal which.

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