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Mars Direct 2.0

How to Send Humans to Mars Using Starships

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Abstract

This paper examines potential mission modes for employing the SpaceX Starship to support the exploration and development of the Moon and Mars. It is shown that rather than employ it as a round trip transport taking crews all the way from Earth to the surface of the Moon or Mars and back, that significant advantages can be achieved by staging off of the Starship either in LEO or TLI orbits.

Keywords: (Starship, Mars Direct, ISRU, Human Mars Missions)

I. Introduction

At the International Astronautical Congress in Guadalajara Mexico September 2016, SpaceX CEO Elon Musk revealed a plan for his Interplanetary Transportation System (ITS) whose purpose would be to enable the human settlement of Mars, as well as to support large expeditions to various other destinations as far out as the moons of Jupiter. As portrayed by Musk, the ITS was a fully reusable two-stage to orbit spaceship using LOx/CH_4 propulsion in both stages which could deliver 500 tons of payload to LEO, and then be refueled on orbit by other ITS tanker flights, enabling it to fly to Mars. Landing on Mars it would unload its 500 ton payload along with 100 colonists and then be refueled with 2000 tons of LOx/CH_4 propellant produced on Mars allowing it to fly back to Earth. This ambitious proposal elicited considerable debate[1], and in view of valid considerations raised the design was subsequently scaled down by about a factor of three to a more achievable 150 ton to LEO system. This revised design, termed the BFR, was made public in 2017 by Musk at the IAC in Adelaide. In 2018 the BFR was renamed, with the system upper stage dubbed "Starship" and its lower stage named "Superheavy," and an aggressive effort has been initiated at SpaceX to develop it for flight.

While it has reduced the scale of the original ITS concept, in its public discussions so far SpaceX has stuck with the same basic plan of flying the entire Starship from LEO to the surface of Mars (or the Moon) and back. However, as pointed out in reference 1, alternative mission modes are possible, including simply using the Starship to lift payload spacecraft to various geocentric orbits ranging from LEO to Trans-Lunar Injection (TLI). The spacecraft could then perform the lunar or Mars mission, allowing the much larger Starship upper stage to swiftly return to Earth to support another flight.

In this paper we will compare the merits of such alternative approaches. Three options will be considered. 1. The SpaceX baseline using the Starship to perform the full interplanetary mission. 2. Using the Starship to deliver a spacecraft to TLI. 3. Using the Starship to deliver a spacecraft to LEO. To limit the number of variations to a manageable level, as well as to maintain consistency, all options considered will be fully reusable and employ LOx/CH_4 propulsion for all phases of the mission.

II. The Starship

The Starship system is a two stage to orbit system employing LOx/CH_4 propulsion in both stages. The first stage, or "Superheavy," returns to land at the launch site in the same manner that SpaceX has demonstrated in its Falcon 9 and Falcon Heavy launch systems. The second stage, or Starship proper, proceeds to orbit, where it can be refueled by additional Starship tanker flights, allowing it to fly to the Moon, Mars, or destinations beyond. As near as can be determined from SpaceX's September 2019 update, the relevant characteristics of the Starship system are described in Table 1. All masses are in metric tons.

Table 1. The Starship System

Stage 1 (aka "Superheavy.)	
Gross mass	3,065 tons
Ascent propellant	2728 tons
Dry mass and landing Propellant	355 tons
Specific Impulse	330 s
ΔV	3.1 km/s
Stage 2 ("Starship," proper.)	
Gross Mass	1335 tons
Propellant	1100 tons
Dry mass	120 tons
Payload to LEO	115 tons
Specific Impulse	375 s
ΔV	6.4 km/s
Ground Lift Off Mass	4400 tons

III. Alternative Mission Plans to the Moon and Mars

We choose the baseline ΔVs for missions to the Moon and Mars shown below.

Table 2. ΔVs for Missions to the Moon and Mars

LEO to TLI	3.1 km/s
LEO to TMI	4.2 km/s
TLI to TMI	1.1 km/s
TLI to Lunar landing	3.0 km/s
Lunar surface to TEI	3.0 km/s
TMI to Mars landing	0.4 km/s
Mars surface to TEI	6.5 km/s
TEI to LEO	0.1 km/s

In Table 2, the ΔV chosen for the Mars mission is the medium energy 4.2 km/s orbit. This is the preferred orbit for a human Mars mission because it offers a two-year free return trajectory, as well as a reasonable average one way flight time to Mars of 180 days. It is possible to go to Mars slower with less propellant using a ΔV as low as 3.8 km/s from LEO, or somewhat faster at the expense of reduce and/or more propellant using trajectories with ΔVs greater than 4.2 km/s, but these would not offer free return. It is assumed that a Starship returning to LEO from TEI aerocaptures into orbit, and thus requires only a small ΔV of 0.1 km/s to raise its perigee to complete the maneuver.

3.1 The SpaceX baseline plan for Missions to Mars.

In the SpaceX plan, the entire Starship is refueled on orbit and flown to Mars along with its 115 ton payload. It is thus necessary to put 235 tons of dry mass through a ΔV of 4.6 km/s using 375 s Isp propulsion. The mass ratio resulting is 3.5, so 587 tons or propellant needs to be delivered to LEO to refuel the Starship to enable the mission. This could be done using 5 tanker flights. So a total of 6 Starship launches are required to enable the mission. After unloading the cargo, the remaining 115 ton vehicle needs to be put through a ΔV of 6.6 km/s to return it to LEO. This entails a mass ratio of 6.03. Therefore 602 tons of LOx/CH4 propellant needs to be produced on Mars to enable the return flight. Assuming 2 kg/day or propellant produced per kWe, producing this much propellant in 500 days will require 602 kWe.

Fig. 1. The SpaceX baseline plan involves sending the Starship all the way to Mars, where it will be refuelded on the surface with in-situ produced LOX/CH$_4$. The large mass of the Starship entails excessive propellant production power requirements.

3.2 The SpaceX baseline plan for Missions to the Moon

In the SpaceX plan, the entire Starship is refueled on orbit and flown to the Moon, landed on the Moon, and flown back from the Moon. This is a total roundtrip ΔV of 9.2 km/s. The mass ratio for this mission is 12.22. For the Starship to do this with no payload would require 1345 tons or propellant. Assuming enlarged tankage, could be done with 11 tanker flights, given that the moon-flight Starship could take some propellant itself, in place much of its nominal 115 ton payload. Payload delivery capability would be zero.

Once lunar oxygen production is available, 94 tons of oxygen supporting the return flight from the lunar surface can be supplied locally. This would increase the cargo capability by from 0 to 94 tons. Assuming 100 days to produce the propellant at a cost of 500 W/kg-day, 568 kWe would be required.

It may be noted that in both of these scenarios, the Starship is fully committed for the duration of the mission, that is 2.5 years for the Mars mission and possibly several months or more for the lunar mission.

3.3 Using the Starship to Deliver the Mars Mission Spacecraft to TLI.

In this scenario, the Starship restricts its activity to deliver the Mars mission spacecraft to TLI, and then itself return to LEO, making it available for use again less than a week after LEO departure. The Mars mission spacecraft, which is considered to be the 115 ton payload, then continues the rest of the way on its own. In this case, the Starship (which is considered to mass 122 tons because of the 2 tons of propellant needed for LEO capture from TLI) needs to put 237 tons of inert mass through a ΔV of 3.1 km/s. The mass ratio for this is 2.32. So 313 tons of propellant needs to be delivered to LEO to support the mission, or approximately 2.7 Starship tanker flights. The Mars spacecraft then needs to do a ΔV of 1.5 km/s to send itself on TMI and land. This will require a mass ratio of 1.5. So of the 115 ton Mars spacecraft, 38 tons is propellant, and 77 tons are landed on Mars. We assume that 57 tons of this is cargo to be delivered one way, while 20 tons is spacecraft dry mass. This will need to be sent through a ΔV of 6.6 km/s to return it to Earth, entailing a mass ratio of 6.03. So 101 tons of propellant will be needed, requiring 101 kWe for its production in 500 days.

3.4 Using the Starship to Deliver the Moon Mission Spacecraft to TLI.

In this scenario, the Starship restricts its activity to deliver the Moon mission spacecraft to TLI, and then itself returns to LEO, making it available for use again less than a week after LEO departure. The Moon mission spacecraft, which is considered to be the 115 ton payload, then continues the rest of the way on its own. In this case, the Starship (which is considered to mass 122 tons because of the 2 tons of propellant needed for LEO capture from TLI) needs to put 237 tons of inert mass through a ΔV of 3.1 km/s. The mass ratio for this is 2.32. So 313 tons of propellant needs to be delivered to LEO to support the mission, or approximately 2.7 Starship tanker flights. The Moon spacecraft then needs to do a ΔV of 3.0 km/s to land. This will require a mass ratio of 2.26. So of the 115 ton payload spacecraft, 64 tons is lunar orbit capture and landing propellant, and 51 tons are landed on the Moon. If 20 tons of this is spacecraft dry mass, 25 tons of propellant will be needed to return it to Earth through the ΔV of 3.0 km/s. This leaves 6 tons of payload to be delivered one way to the Moon. We note that this 20 ton dry mass spacecraft will need to have a total propellant capacity of 25 + 64 = 89 tons, roughly the same as the 101 tons needed to return it from Mars. So a common return spacecraft design is possible. With LOX/CH4 propulsion, a propulsion stage mass fraction of 8% is reasonable, meaning that of the 20 ton drymass return spacecraft 8 tons will be tanks and engines and 12 tons will be habitation.

It may be noted that once lunar oxygen production becomes available, 78% of the return propellant will come from the Moon. As a result, cargo payload to the lunar surface will be increased by 19 tons, from 6 tons to 25 tons. Assuming a 100 day lunar mission stay, and a propellant production power requirement of 500 W per kg/day, 95 kWe will be required.

3.5. Using the Starship to Deliver the Mars Spacecraft to LEO

In this scenario, the Starship is used simply as a fully reusable Earth to LEO delivery system with a payload capacity of 115 tons, and so, in principle any Mars or Moon mission plan could be employed. For example, if could be used to support the Mars Direct[2] plan, with high capability. However in this paper I will restrict mission plans to those based on fully reusable LOX/CH4 transportation systems. In all of these plans, no on orbit refueling of the Starship is required.

To go from LEO to Mars landing is a ΔV of 4.6 km/s, entailing a mass ratio of 3.5. So of the 115 tons lifted to orbit, 33 tons can be the drymass of the payload landed on Mars, while 82 tons is required for TMI and Mars landing. Of the 33 ton payload, 13 is cargo, and 20 is the drymass spacecraft that will return to Earth using 101 tons of LOX/CH4 payload produced in situ, requiring 101 kWe.

Fig. 2. As an alternative mission mode, the Starship could be used as fully reusable Earth to LEO heavy lift vehicle, staging off payloads to Trans-Mars injection. Propellant production power needs are greatly reduced.

3.6 Using the Starship to Deliver a Moon Spacecraft to LEO

In this scenario, the Starship delivers a 115 ton spacecraft to LEO. The ΔV from LEO to the Lunar surface is 6.1 km/s, requiring a mass ratio of 5.26. So of the 115 tons lifted to orbit 93.5 tons will be needed to be used as propellant to deliver the remaining 21.5 to the lunar surface. If this is a one-way cargo mission, about 7.5 tons will need to be spacecraft propulsion systems with 14 tons of cargo delivered. If it is a piloted mission, the 21.5 tons can be divided between 12.5 tons of return spacecraft and 9 tons of propellant. This could be a problem because 7.5 tons of the 12.5 tons of spacecraft would be propulsion. This could be resolved if lunar oxygen were available in advance of the mission, in which case a 16.5 ton drymass spacecraft could be sent to the Moon, along with 5 tons of methane fuel. Combined with 19 tons of lunar oxygen the 5 tons of methane would be sufficient to send the return vehicle home. Until lunar oxygen production is operational, cargos of LOx and methane could be delivered to the Moon in advance of the crew by the cargo landers. In this case, the 20 ton return vehicle used for Mars mission return could also be used for the Moon.

IV. Summary of Results

A summary of the results of the analysis of the six scenarios considered is presented in Table 3. The * signifies that the option is employing ISRU and it is the piloted mission that is being considered. Without ISRU the LEO/Moon option would use a separate cargo delivery of 19 tons per flight. In that case 2 Starships would be required per piloted mission, one for the cargo and the other for the crewed flight. All Mars mission considered use ISRU.

Table 3. Summary of Mission Options Considered

Starship Destination	Mars	Moon	TLI/Mars	TLI/Moon	LEO/Mars	LEO/Moon
# Tanker Flights	5	11	2.7	2.7	0	0
Cargo delivered	115	0/94*	57	5/24*	13	5*
Return ship mass	120	120	20	20	20	20*
ISRU Power (kWe)	602	0/568*	101	0/95*	101	95*
Cargo/Starship launch	19	0/7.8	15.4	1.6/6.8*	13	5*
Ship reuse time(days)	1000	100	10	10	10	10

Examining the results in Table 3, we see strong reasons to prefer the mission modes in which the Starship goes to LEO or TLI over that where it goes all the way (ATW) to either the Moon or Mars. The ATW Mars mission requires 602 kWe to enable return, and a very large ISRU capability in place before the first mission, which is practically a show stopper. The ATW Moon mission requires 12 Starship launches per flight, compared to 4 for the TLI option and 1 (with ISRU) or 2 (without ISRU) for the LEO option. While the ATW Moon mission would benefit a great deal from ISRU, the 568 kWe power requirement to do it is quite formidable. In the case of an exploration mission, there seems little reason to prefer the TLI Mars option over the LEO Mars option, as the latter is quite adequate and does not requirement any on orbit refueling. If we shift from exploration to settlement, the TLI Mars option does become preferable, as its payload delivery capability is much larger. The same relationship holds true for the TLI and LEO staged Moon missions; in the exploration phase the LEO staged mission gets the job done well enough, but once we move to development staging at TLI offers cargo delivery advantages that justify the added complexity of on-orbit refueling.

The impact of the large power requirement entailed by adopting the ATW mission plan bears discussion. Large scale space nuclear power reactors do not currently exist, nor is there a NASA program in place to create them. Private development of space nuclear power reactors is unlikely, given the restrictions in place on access to highly enriched uranium. This means that a privately developed human Mars mission will most likely need to employ photovoltaics for power generation. The solar flux on Mars is about 400 W/m^2. If we assume non tracking panels with an efficiency of 20%, the total average day/night power generation will be 20 We/m^2. The 602 kWe power system required by the ATW mission would thus entail 30,100 square meters of photovoltaics, or about 6 football fields. At 4 kg/m^2, the array would have a mass of 120 metric tons. Adopting either the TLI/Mars or LEO/Mars mission modes would cut this formidable requirement by a factor of six.

It should also be observed that the ATW/Mars option commits a Starship to a single mission for 2.5 years, while either the TLI/Mars or LEO/Mars options allows it to be used continually. For example, the Starship could be used to support Mars missions during the two months every two years that Mars launch windows are open, while supporting lunar or asteroid missions on an ongoing basis during the 26 months between Mars mission launch windows. This represents an order of magnitude increase in the productivity of a given Starship.

The one disadvantage the TLI/LEO staging options pose compared to the ATW options is that they require the development of a 20 ton-class flight vehicle, essentially a miniature version of the Starship upper stage. However in view of the tremendous reductions in mission logistics and power requirements enabled by such a development, as well as the order of magnitude increase in efficiency of Starship utilization that it allows, it would appear to be more than justified. Furthermore, such a mini-Starship would be a match for the Falcon-9 lower stage, transforming the current SpaceX workhorse into a fully reusable medium lift launch system which could have broad commercial application.[3]

V. Conclusion

We find that the Starship could offer tremendous capabilities to enable the exploration, development and settlement of the Moon and Mars. This is particularly the case if the suboptimal mode of using it to fly all the way to the lunar or Mars surface and back is replaced by flight plans which stage off of it either in LEO or TLI orbits. By employing such staging, the ISRU requirements, including critical power requirements, needed to support operations would be reduced by a factor of 6. In addition, the number of missions each Starship could fly within a given time period would be greatly increased, with a concomitant multiplication of persons and payload delivered by each Starship vehicle. Furthermore, the development of a mini-Starship for use as a Earth return vehicle to enable such mission modes would be readily justified as it could also be used as the upper stage of a Falcon-9, creating a fully reusable medium lift launch system with broad commercial application.

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VI. References

1. R. Zubrin, “Colonizing Mars: A Critique of the SpaceX Interplanetary Transportation System,” The New Atlantis, October 21, 2016 https://www.thenewatlantis.com/publications/colonizing-mars
2. R. Zubrin with R. Wagner, “The Case for Mars: The Plan to Settle the Red Planet and Why We Must.” Simon and Schuster, New York, 1996, 2011.
3. R. Zubrin, “The Case for Space: How the Revolution in Spaceflight Opens Up a Future of Limitless Possibilities.” Prometheus Books, Amherst, NY, 2019.