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Energy and Resource Analysis of a Large-Scale Earth-Mars Human Transport System

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Abstract

Spurred by recent interest both within and outside of NASA focusing on human spaceflight beyond low Earth orbit, we perform the first comprehensive assessment of energy and resource requirements of a large-scale human transport system between Earth and Mars. We model SpaceX's Mars Colonial Transporter (MCT) plans as closely as possible, based on publicly available information, including their announced goal of building and maintaining a one million-person settlement on Mars. We develop credible estimates of a reusable, multi-stage spacecraft for moving humans and cargo between Earth and Mars each 26-month synodic period, as well as additional spacecraft for moving CH_4/O_2 propellant from either Earth's surface or the Moon to a LEO depot. Additional propellant is produced on Mars for spacecraft returning to Earth. Consumables, passenger cargo and crew are included, but other infrastructure requirements (including the more significant and technologically challenging Mars surface infrastructure needs) are not examined. We assume 10 cargo trips per passenger trip, resulting in 16 t/passenger of cargo to provide physical infrastructure for the Mars settlement. We develop a scenario starting in 2042 to achieve a Mars settlement population of one million after ~90 years, taking into account finite ship lifetimes, transport capacity growth, population growth and attrition from those returning to Earth. Cumulative fleet mass is estimated at 21 million tonnes (Mt), while cumulative propellant mass is ~270 times as large (~5,600 Mt). Cumulative shipped cargo is 22 Mt. We find that very significant mass and energy savings are available in shifting propellant production for the LEO refuelling depot from Earth to the Moon, resulting in 77 percent less cumulative propellant or ~1,260 Mt. However, a source of lunar carbon is required, which may need to be supplied from the Earth or asteroids, and raises concerns about depletion of limited lunar water resources. We also considered shifting from CH_4/O_2 to H_2/O_2 propellant, but it results in approximately the same lunar water demand. Therefore, entirely asteroid-derived propellant may be necessary in the long term. SpaceX's proposed plan provides 5 m^3/person habitable volume, which is very cramped compared with the International Space Station (~65 m^3/person); we estimate that increasing this habitable volume to a more reasonable 20 m^3/person would increase mass and energy requirements by 2.4 times, however. We consider reductions in shipped cargo mass, human hibernation to reduce spacecraft and consumables mass, and space elevators as possible long-term strategies to reduce cumulative mass and energy requirements.

Keywords: Mars settlement, human spaceflight, SpaceX, Mars Colonial Transporter (MCT), in-situ resource utilization, life-cycle energy analysis, Moon resources, Mars resources

Acronyms/Abbreviations

Base Case (BC); Design Reference Architecture (DRA); Earth transfer orbit (ETO); entry, descent and landing (EDL); International Space Station (ISS); low Earth orbit (LEO); low Mars orbit (LMO); Mars Colonial Transporter (MCT); Mars transfer orbit (MTO); million tonnes (Mt); National Aeronautics and Space Administration (NASA); specific impulse (I_{sp}).

1 Introduction

Plans to send humans to Mars have been in development at NASA for over 40 years [1], but recently several private institutions, including Mars One [2], Inspiration Mars [3], Explore Mars [4], Mars Foundation [5], and SpaceX [6], as well as individuals including Robert Zubrin [7] and Buzz Aldrin [8], have advocated to send people to the Red Planet. Most prominent among these is SpaceX, who has announced plans to build a one million-person settlement [9] to serve as a "safety net" for humanity, should disaster strike on Earth. Popular movies and books such as *The Martian,* design competitions such as Mars City Design [10], and funding organizations like SpaceVault [11] are also engaging the wider public and helping make the idea of going to Mars a palpable reality.

With such large-scale plans in play, we wanted to explore the impact of a million-person Mars settlement on energy and resource demands on Earth, Mars and other celestial objects (e.g., Moon or asteroids) utilized to support the effort. To that end, we developed a high-level model of an Earth-Mars human transport system, based on preliminary work in Greenblatt [12], drawing on many sources of data detailed in that reference. The current work modifies this model to resemble SpaceX's envisioned Mars Colonial Transporter (MCT) system (hereafter "SpaceX system") as much as possible, utilizing publicly available information. We focus on spacecraft mass, quantities and source locations of propellant and human life support resources (water, air, food), and the required energy to produce these materials. Our motivation is to identify system design choices that could have negative consequences at large scale, including wasteful or inefficient resource use, depletion of non-renewable resources (especially on the Moon) and detrimental human health impacts. To avoid undesirable outcomes, we propose alternative approaches that could be phased in over time, as space capabilities mature.

2 Material and methods

The model originally described in Greenblatt [12] consisted of fleets of four types of reusable spacecraft (denoted H-1 through H-4) to move humans between Earth and Mars every synodic period (~26 months), and four other types of reusable spacecraft (denoted P-1 through P-4) for moving propellant (H_2/O_2 and CH_4/O_2) from the Moon and Mars to in-orbit depots. Some human consumables (water, O_2) were also provided from these sources, whereas N_2 and food consumables were provided from Earth and Mars. Cargo mass estimates were included in the analysis. A Monte Carlo simulation was performed to explore parameter variability, as confidence bounds were large for many key variables. In addition to estimating the mass flows and energy consumption of producing consumable resources, the model also estimated the energy needed to construct spacecraft on Earth or in other space locations. The study was, to our knowledge, the first comprehensive assessment of the energy, resource and infrastructure requirements of a large-scale Earth-Mars transport system.

2.1 SpaceX Base Case (BC)

For modeling the SpaceX system, we modified the model to represent a single type of reusable spacecraft, rather than four separate spacecraft, in keeping with SpaceX's announced plans. (In the original model, only the H-3 spacecraft travel between Earth and Mars and remain in orbit around both planets; the other, smaller spacecraft shuttle passengers between H-3 and the planet surfaces.) The Moon was also omitted as a source of propellant, except as a sensitivity. A single type of propellant transport spacecraft was modeled for supplying propellant to a depot in LEO.

Other major design changes include a much lower mass (and volume) per person for the human transport spacecraft, limited transported cargo, and all propellant assumed to be CH_4/O_2, chilled to just above the freezing points of these gases (91 and 54 K, respectively) [13][14], and a vacuum engine I_{sp} of 380 s [15][16][17]. Additional cooling energy is included in our embodied energy calculations, but represents a modest increase.

In a given synodic period (~26 months), the assumed sequence of events is as follows:

1. One or more spacecraft depart Earth with 100 passengers each [9][17][18], and first stages are returned to the surface, while the second stages are replenished in LEO with Earth-supplied propellant [13].
2. The spacecraft enter a fast (~3-4 month) transfer orbit to Mars [19][20][21]. While this requires more propellant than a Hohmann-type minimum energy transfer, it minimizes passenger exposure to deep space conditions, and saves propellant on the return journey (see Section 3.1).
3. Once at Mars, the spacecraft perform an aerocapture maneuver and descend to the surface via aerobraking, using a minimal amount of propellant.
4. After off-loading on the Mars surface, >80% of payload capacity is replaced by additional propellant capacity [22], and spacecraft are replenished from an in-situ propellant production plant on Mars [13].
5. The spacecraft depart Mars and enter another fast transfer orbit, passing inside the orbit of Venus (or under some conditions, Mercury) to reach the Earth.
6. Upon Earth rendezvous, the spacecraft perform aerocapture and aerobraking maneuvers, and ultimately land propulsively on the surface.

Total journey is less than one synodic period [20], and each spacecraft is reused several times. Spacecraft engine, propellant tank, heat shielding and habitat mass are estimated, together with consumables and propellant. We utilize published performance data for the SpaceX Falcon 9 rocket and Merlin 4D engines [6][23][24][25] to inform many of our spacecraft assumptions.

2.2 Sensitivity scenarios

In addition to the BC, we include several additional scenarios to explore parameter sensitivities:

1. Different departure and return trajectories (Table 1)
2. Larger spacecraft mass (sections 3.2 and 3.3)
3. Use of H_2/O_2 for all propellant
4. Propellant supplied to LEO from Moon
5. Different cumulative shipped cargo mass
6. No aerocapture or aerobraking at Mars
7. Induced torpor (human hibernation) [26]
8. Space elevator on the Moon, Mars or Earth

3 Calculations

3.1 Earth-Mars orbits

We used simple trajectory assumptions (e.g., circular planetary orbits) to represent average conditions, and estimated duration and hyperbolic velocity requirements for various combinations of outbound and return trajectories that returned the spacecraft to Earth within the same synodic period [20], e.g., ~400 to ~520 days total duration, including a short surface stay on Mars (≤35 days). An example scenario is shown in Fig. 1.

Table 1 shows a number of trajectory combinations illustrating the range of options available. (Because of Mars' eccentricity, not all trajectories are possible each synodic period, but these illustrate average conditions.)

Essentially, there is a trade-off between duration and velocity for each leg of the journey, and further trade-offs between outbound and return velocities, indicating an optimum where velocity, and hence required propellant mass, is minimized. This point occurs close to the conditions for Scenario 4, with a ~4 month outbound duration, which is strongly preferable over lower-energy trajectories (with ~6-9 month duration) to minimize human exposure to weightlessness and space radiation. Moreover, the faster outbound scenarios also result in lower reentry velocity for Earth capture (e.g., ≤12 km/s vs. ≥14 km/s), which significantly reduces thermal shielding requirements.

Significant velocity savings can be achieved by sending spacecraft beyond Mars' orbit, returning them to Earth with a total duration just shy of the synodic period (e.g., Scenarios 7-8). However, this results in a very long return journey (~600 days), and a narrow window for preparing spacecraft for the next launch.

Alternatively, by abandoning the requirement that spacecraft return to Earth during the same synodic period (e.g., Scenarios 9-10), return journey velocities can be reduced by 3.6 to 6.5 km/s relative to Scenarios 4 and 2, respectively. However, this requires extending the surface stay to >450 days, and results in double the required spacecraft fleet—a strong disincentive.

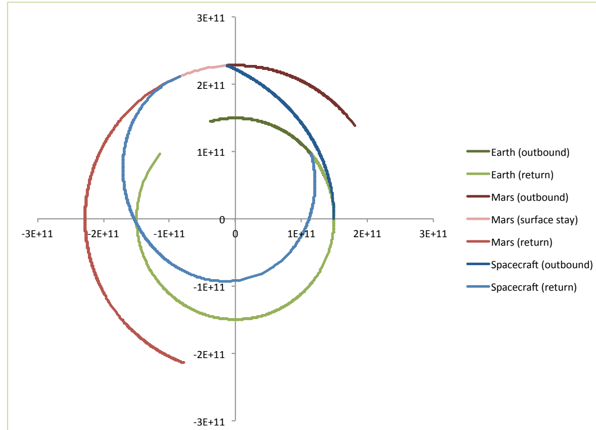

Fig. 1. Example of an Earth-Mars round trip trajectory

For Scenarios 1-6, surface stay duration is a potentially important variable, but we have not explored it thoroughly here, aside from noting that it could strongly affect the required return delta-v (e.g., Scenario 1 vs. 2). Since payload off-loading and propellant transfer would presumably be relatively fast processes (a few days at most), the main time-consuming tasks in turning around a spacecraft for launch would be inspection and maintenance, which during the early years of settlement could require many weeks or months, but in the long term could probably be reduced to a few days as well. Therefore, our BC assumption of 35 days strikes a balance between these two extremes, and indicates an important sensitivity to explore in the future.

Table 1. Orbital parameters for Earth-Mars outbound and return trajectory scenarios

	Scenario									
Parameter	1	2	3	4	5	6	7	8	9	10
Orbital period (years)										
Outbound	1.417[a]	1.417[a]	1.500	2.000	2.500	3.000	2.000	2.500	2.000	1.417[a]
Return	0.956	0.918	1.008	1.074	1.092	1.101	1.958	1.974	1.417[a]	1.417[a]
Semi-major axis (M km)										
Outbound	188.8	188.8	196.0	237.5	275.6	311.2	237.5	275.6	237.5	188.8
Return	145.1	141.3	150.4	156.9	158.6	159.5	234.1	235.4	188.8	188.8
Perihelion - Return (M km)	62.4[b]	54.7[b]	72.8[c]	85.8[c]	89.3[c]	91.1[c]	149.6	149.6	149.6	149.6
Duration (days)										
Outbound	259	259	188	127	110	102	127	110	127	259
Surface stay	5	35	35	35	35	35	35	35	575	455
Return	233	224	246	260	264	265	586	592	259	259
Total	497	518	469	422	409	402	748	738	961	972
Hyperbolic velocity (km/s)										
Outbound departure	2.94	2.94	3.34	5.08	6.17	6.93	5.08	6.17	5.08	2.94
Outbound arrival	2.65	2.65	2.05	0.48	2.00	3.04	0.48	2.00	0.48	2.65
Return departure	8.31	9.12	7.34	6.28	6.03	5.89	0.32	0.38	2.65	2.65
Return arrival	13.97	14.78	13.00	11.94	11.68	11.55	5.34	5.27	8.30	8.30

[a]Hohmann minimum-energy transfer orbit. [b]Perihelion located inside orbit of Mercury. [c]Perihelion located inside orbit of Venus.

3.2 Spacecraft habitable volume

Musk has stated that the transport spacecraft would have an interior volume per person of a "large SUV" (sport utility vehicle) [27]. However, it was unclear if this volume referred to the habitable or pressurized volume, with the latter often being more than twice as large as the former for a given spacecraft design.

We investigated the interior volumes of SUVs on the U.S. market and found them to be slightly less than 5 m^3. This is similar to the habitable volume per person of the NASA Mars Design Reference Architecture (DRA) 5.0 [28], or the pressurized volume per person of NASA's Orion capsule [29], but significantly smaller than the International Space Station (ISS) (65 m^3/person habitable volume and 153 m^3/person pressurized volume) [30].

For durations of several months, research indicates that habitable volume should be at least 20 m^3/person [31]. Regardless of whether the SpaceX system refers to habitable or pressurized volume, it is probably inadequate on a per person basis. However, considering that the spacecraft is designed to accommodate 100 people, there could be a reasonable compromise between cramped personal quarters and much larger common spaces. We assumed a habitable volume of 5 m^3 (and a corresponding pressurized volume of 12.5 m^3) for our BC, but explored larger volumes in sensitivity scenario 2. (We had assumed a habitable volume of 30 m^3/person in [12], about half that of the ISS.)

3.3 Spacecraft mass budget

SpaceX has indicated on several occasions that its spacecraft will be designed to transport ~100 people with a total payload mass of ~100 t [9][17][18], or ~1 t/person. This compares to ~2 t/person for the SpaceX Dragon capsule, ~4 t/person for NASA's Orion capsule, ~7 t/person for DRA 5.0, and ~70 t/person for the ISS. None of these designs come anywhere close to the SpaceX target. However, the Bigelow Expandable Activity Module (BEAM) currently flying on the ISS has a 16 m^3 pressurized volume and 1.4 t mass [32], and would deliver this required mass ratio if the habitable-to-pressurized volume ratio is no smaller than 44% (similar to Orion and ISS but larger than DRA 5.0).

The much larger Bigelow B330 [33], with 330 m^3 pressurized volume and 20 t mass, would deliver this required mass ratio even with a 30% habitable-to-pressurized volume ratio (about the same as DRA 5.0). It also includes life-support equipment, thermal management and avionics/communications [33][34]. For the BC, we assume a B330-type habitat with a habitable volume ratio of 40%. With a human mass allowance of 100 kg, this yields 0.86 t/person.

However, other than propellant, several additional mass elements will increase the total per person mass ratio:

1. Consumables (water, air, food)
2. Passenger cargo
3. Non-habitation equipment including solar power, engines, thermal protection, and storage containers for propellant, consumables and cargo
4. Professionally-trained crew handling spacecraft operations, including command, communications, maintenance, security, etc. (see [12] for discussion of these items).

3.3.1 Consumables

We estimate a per person daily consumables demand of 0.7 kg dry and 2.4 kg whole (wet) food, 1.4 kg of potable water, 30.0 kg of wash water, and 2.5 kg of air (20% O_2 in N_2) [7][28][29][35][36][37]. With 95% reclamation of water and N_2, the net total demand is 5.3 kg. Therefore, consumables will increase the per person mass by 0.64 t for a 120-day supply.

We also estimate an additional contingency supply of 1.32 t (assuming all dry food and less total water) sufficient for an additional ~630 days in space, or just over two years, in the event that the outbound spacecraft is not able to intercept Mars and must return to Earth. However, we do not include these contingency supplies in the BC, positing that they are only needed initially when human transport is more risky. With many spacecraft transiting between Earth and Mars each synodic period, the possibility of rescue ships becomes much more likely.

3.3.2 Passenger cargo

Cargo was assumed to be 50 kg per person in the BC, consistent with baggage limits for commercial aviation. Lower mass limits, down to literally the clothes on one's back, could be imposed, reducing this mass to a negligible level. (We had assumed 100 kg/person in [12].)

3.3.3 Non-habitation equipment

The mass of non-habitation equipment was estimated to be 0.60 t/person, including engine (0.06 t/person), thermal protection (0.20 t/person), and propellant storage (0.24 t/person, or 2.8% of propellant mass based on empirical relationships for large liquid H_2/O_2 tanks [40] and the ~2.2× bulk density ratio with CH_4/O_2). While the DRA 5.0 estimates a significant mass for power (0.97 t/person), solar power ultra-lightweighting efforts currently underway [38][39] suggest this mass could fall to almost negligible levels. We assume a modest ~0.1 t/person in our BC.

These four factors yield a total additional mass of 1.28 t/person for the outbound journey, or 2.20 t/person including people and habitation structures.

3.3.4 Crew

Finally, we estimate a crew size of 10 per 100 passengers, leading to an additional 10% increase in mass, or 0.22 t/passenger in the BC. While this could conceivably be reduced to almost zero, we felt that 10% provided a reasonable safety margin for ensuring survival in various emergency situations. (We had assumed a 15% crew-to-passenger ratio in [12].)

3.3.5 Total spacecraft mass without propellant

We conclude that the total spacecraft mass is 2.41 t/passenger (not including propellant mass). Including contingency consumables nearly doubles this mass to 4.52 t/passenger, so omitting this safety margin is a critical, but initially somewhat risky, mass reducing strategy.

3.4 Delta-v budget

Table 2 lists assumed delta-v's between Earth and Mars, where all burns are assumed to be performed impulsively at perigee to maximize the Oberth effect. In the BC, we assume that EDL at Mars and Earth comprise a total of 1.10 [22] and 0.55 km/s of delta-v, respectively, including contingency (we assume that Earth's thicker atmosphere requires less propulsive deceleration than Mars'). Delta-v's for propulsive deceleration in lieu of aerocapture and/or aerobraking are also shown ("No aero" column), though the lack of any aerobraking at Earth return is not realistic, since this is an established approach and propellant requirements would otherwise be exceedingly large. The BC uses parameters from Table 1, Scenario 5.

Table 2. Delta-v assumptions (including contingency)

Transit segment	BC	No aero
Earth surface to LEO (Stage 1)	4.10	4.10
Earth surface to LEO (Stage 2)	5.88	5.88
Earth surface to LEO subtotal	*9.98*	*9.98*
LEO to MTO	4.83	4.83
MTO to Mars capture	1.10	0.39
Mars capture to Mars surface		5.53
LEO to Mars surface subtotal	*5.94*	*10.76*
Mars to LMO	4.10	4.10
LMO to ETO	4.30	4.30
ETO to Earth capture	0.55	5.04
Earth capture to Earth surface		11.02
Mars to Earth surface subtotal	*8.95*	*24.45*

For the return journey, with an additional delta-v requirement of 3.01 km/s, the total ship mass without propellant (but including extra propellant tank mass) must be reduced by 55%. As other non-habitation equipment mass is fixed, this results in a 77% decrease in payload to 41 t, sufficient for ~17 people including crew (note that ~275 days of consumables are required for the return journey in the BC, which affects passenger capacity). We believe that this capacity is sufficient in the early years of settlement, when crews will travel back and forth and few passengers will be returning to Earth. In later years, however, it is likely that nearly equal numbers of people will travel in each direction (see Section 3.9).

3.5 Comparison to existing Falcon Heavy

The total estimated spacecraft mass (excluding propellant) for 100 passengers is 241 t, of which 67 t is non-habitation equipment (the second stage rocket), and 175 t is payload (habitation equipment, people, consumables and cargo). This payload is ~3× the size of the current Falcon Heavy payload of 54 t in LEO [6], or about the same as the engine thrust ratio of the envisioned MCT to the Falcon Heavy [15].

It is assumed that the entire payload will be delivered to the Mars surface, in order to supply valuable wastes, which can be utilized as fertilizer for growing food, to the Mars settlement. (If contingency consumables are included, they would be valuable as additional supplies.) If these items (70 t in the BC) are jettisoned prior to Mars entry, descent and landing (EDL), the landed payload mass could be reduced to 95 t, resulting in a notable savings in EDL propellant (24 t). However, relative to the total required propellant mass (~950 t), these savings are almost negligible.

3.6 Artificial gravity

The use of artificial gravity, e.g., via ship rotation, can greatly improve human health during long space voyages [41]. While more sophisticated arrangements are possible (e.g., ring), we assume a simple dumbbell arrangement, whereby the ship mass is split into two equal portions, connected by a high tensile strength tether (<0.4% of non-propellant spacecraft mass) deployed once en route to Mars [12]. Each portion would include life-support equipment, consumables, avionics, communications, engines and propellant, and would therefore be self-sufficient in the event that the tether was severed.

Assuming Mars gravity (0.38*g*) and a 150 m rotational radius to avoid negative physiological effects [42], we calculate that the additional propellant to spin and later de-spin the spacecraft requires an extra 0.05 km/s of delta-v, or a 1.7% increase in total mass. This modest increase could be accommodated with a 2-person reduction in passenger capacity, or a ~4% reduction in habitable volume. While not assumed in the BC, it would be worthwhile for the SpaceX system design to include the ability to provide artificial gravity.

Given that many spacecraft would be heading to Mars simultaneously once settlement is underway, it may be possible to combine multiple spacecraft to form a ring, held together by tethers and connected via airlocks to provide a larger, more spacious spacecraft of many hundreds or even thousands of passengers. Each spacecraft would be self-contained, however, and would individually land on Mars.

3.7 Settlement cargo

To provide necessary equipment for a growing human settlement, we assume 10 cargo trips for every human trip [9], which could be accomplished either by sending less people per trip, or building dedicated cargo transport ships. In the BC, we assume identical ships and trajectories are used for cargo, resulting in a landed cargo mass of 16 t per passenger transported to Mars. We assume that the return capacity, which would probably be used for scientific samples initially, is repurposed for passenger transport over time.

3.8 Propellant spacecraft

We assume that robotic spacecraft (e.g., without need for life-support equipment) will transport propellant from Earth surface to LEO for refuelling by waiting spacecraft. Assuming ~18 propellant delivery trips per outbound human transport trip, the spacecraft mass is 70 t and propellant payload is 53 t, about the same as the Falcon Heavy. (Alternatively, ~6 human transport-sized spacecraft could be used). Each trip requires ~3,400 t of propellant to transport it into LEO; a small amount is held in reserve for the return to Earth's surface.

3.9 Scale-up assumptions

To model the build-up to a million-person Mars settlement, we had to make assumptions about how the number of people and thus spacecraft fleet would grow over time. Assuming settlement begins in the early 2040s (Musk has announced a planned human flight in 2024 [43], but we choose 2042 as our base year for settlement) with an initial fleet of three 100-person spacecraft, and transport capacity doubling every 6 years, we estimate it will take until 2100 for the Mars settlement population to reach 1 million people. However, this assumption neglects the important effects of birth and death rates on Mars, people returning to Earth (attrition), constraints on maximum fleet size, and (for estimating total mass and energy) the finite lifetime of spacecraft.

The reason to limit the maximum fleet size is to maintain a sustainable level of infrastructure; without this constraint, the spacecraft fleet continues to grow exponentially and is many times the capacity needed to maintain a 1 million-person population in 2100. With limited capacity, infrastructure is maximally utilized, and can support growth grow beyond 1 million people with modest increases in fleet size.

A more realistic scenario, based on assumptions developed in [12], is shown in Table 3. This scenario reaches a million-person settlement population in 2131 rather than 2100; the delay is due to a combination of attrition (people returning to Earth) and the capacity limitation. Sensitivities around these parameter values were explored in [12].

Table 3. Scale-up parameter assumptions

Parameter	Value	Units
Initial transport capacity	300	Passen-gers
Transport capacity doubling rate	6	Years
Settlement net growth rate (birth rate minus death rate)	1.3	%/yr[a]
Attrition rate	2.5	%/yr[a]
Maximum human fleet size[b]	534	Ships
Maximum total fleet size	5,871	Ships
Maximum human transport capacity	25,000[c]	Passen-gers/yr
Spacecraft lifetime	40	Years

[a]Percentage of settlement population. [b]Assumed ship size is 100 passengers outbound to Mars (159 t mass equivalent in cargo). [c]The capacity per synodic period is 53,400 passengers.

3.10 Other parameters

A list of other parameter assumptions can be found in [12].

4 Results and Discussion

4.1 Base Case (BC) results

Table 4 shows results for the BC. We find that ~5,900 spacecraft have a cumulative mass of 3.10 Mt and will consume ~1,060 Mt of propellant in transporting 22 Mt of cargo and growing the settlement population to 1 million people over ~90 years. In addition, 17.5 Mt of propellant spacecraft mass and ~4,500 Mt of propellant is needed to supply ~140 Mt of propellant to LEO. A similar amount of propellant mass is produced on the Mars surface to return spacecraft to Earth.

An enormous quantity (~80%) of propellant is required simply to move propellant into LEO for refuelling. Propellant from a source in a lower gravity well (lower delta-v), such as the Moon or asteroids, would represent a significant savings, regardless of other energy- or mass-saving design opportunities that may exist.

The energy required to produce this propellant is 143 EJ, or 1.4 years of current U.S. primary energy consumption. Compared with propellant production, the energy required to produce spacecraft is relatively modest at 4.4 EJ, about 4% of current U.S. annual primary energy consumption. The mass of material required is equivalent to 12 years of current U.S. aluminium production (though not all spacecraft material is assumed to be aluminium).

Table 4. Base Case result parameters

Parameter	Value	Units
Human/cargo transport spacecraft		
Empty ship mass	150	t
Human, consumable and cargo mass	91	t
Propellant mass		
Earth surface to LEO	5,153	t
LEO to Mars surface	946	t
Mars to Earth surface	1,079	t
Total round-trip	7,178	t
Year maximum capacity reached	2089	
Number of ships at maximum capacity	5,871	
Year settlement population reaches 1 million	2131	
Cumulative ship mass at 1 million people	3.096	Mt
Cumulative propellant mass at 1M people	1,057	Mt
Cumulative settlement cargo transported at 1 million people	21.57	Mt
Cumulative number of trips (including cargo trips)	149	thousand
Propellant transport spacecraft		
Number of trips per human spacecraft	18	
Ship mass	70	t
Payload mass	53	t
Propellant mass	3,384	t
Cumulative ship mass at 1 million people	17.53	Mt
Cumulative propellant mass at 1M people	4,539	Mt
Cumulative propellant mass		
Produced on Earth		
For Earth surface to LEO	5,307	Mt
For LEO to Mars surface	141	Mt
Produced on Mars	148	Mt
Total	5,596	Mt
Cumulative energy requirements		
Spacecraft production	4.38	EJ
Propellant production	143	EJ
Total per passenger	109	TJ

Perhaps most surprising is the enormous per capita energy requirement (109 TJ) to move a person to Mars. As the average U.S. person annually consumes ~320 GJ of primary energy and of that, 44 GJ of electrical energy [44], Mars transport requires ~340 times more primary energy (and ~2,500 times more electrical energy) than the U.S. average. Thus, each person emigrating to Mars incurs an enormous "energy debt" requiring many centuries to fully "pay back."

Because >97% of propellant is combusted in Earth's atmosphere or in LEO (where it likely returns to the atmosphere), CO_2 emissions are also important to consider. We estimate ~460 t/passenger (~27× the annual U.S. average) and ~3,700 Mt cumulatively (~8 months of total U.S. emissions) of CO_2 [44].

4.2 Larger spacecraft volume and/or inclusion of contingency consumables

Increasing the amount of habitable volume from 5 m^3 to a more comfortable 20 m^3 increases habitation-related mass 2.4×. Total spacecraft mass is likewise increased, to 5.88 t/passenger.

As mentioned earlier, including a contingency supply of consumables nearly doubles total spacecraft mass to 4.52 t/passenger.

Combining both variants increases total mass 3.3× to 7.99 t/passenger. These changes result in linear increases in propellant, energy and other metrics.

However, if cumulative settlement cargo mass were fixed (e.g., at 22 Mt in BC), it would result in significant reductions in needed cargo spacecraft and overall increases in propellant would be less. For instance, in the combined scenario above, the number of cargo spacecraft per human transport spacecraft can be reduced from 10 to ~3, and cumulative propellant requirements are nearly the same as the BC.

4.3 Use of H_2/O_2 in lieu of CH_4/O_2

We find that for H_2/O_2, assuming a vacuum I_{sp} of 456 s [45] and propellant storage mass ratio of 6.2% [40], human transport spacecraft propellant demand would be reduced 34% to ~4,700 t per round-trip, and total propellant mass for 1 million people would be reduced 29% to ~4,000 Mt. However, because of the greater specific energy required to make H_2/O_2, there is a smaller net savings in propellant energy (3.3%) and total energy (2.1%) over CH_4/O_2. Note that our estimates include the required energy to cool propellants to just above their freezing points, but do not take into account the possible additional energy (and mass) that may be required to maintain these temperatures, which could reduce overall savings, though our propellant storage mass ratio estimate is an average value for large (>1 kt) propellant spacecraft and significantly larger than the Space Shuttle external tank (3.7%) [40], so might allow for additional cryogenic equipment mass.

Elon Musk has stated that the performances of H_2/O_2 and CH_4/O_2 are roughly similar (owing to the trade-off between I_{sp} and propellant storage mass ratio), but the higher freezing point and easier handling of CH_4 makes it preferable overall to H_2 [15]. Given the small energy advantage we find, these conclusions appear defensible. However, depending on where propellant is manufactured, there could be advantages to H_2/O_2; see section 4.4.

4.4 Making propellant on the Moon

Making propellant on the Moon and shipping it to LEO, rather than making and launching it from Earth, carries the potential for large savings in propellant due to the Moon's significantly lower gravity. (The Moon does not even represent the lowest energy source of propellant, as many C-type asteroids potentially rich in volatiles are accessible from LEO at lower delta-v's than the Moon [46].)

For the Moon, we estimate a round-trip savings of 4.8 km/s (including contingency), resulting in a 96% reduction in propellant transport mass to 152 t per refuelling, and a 77% reduction in total propellant mass to ~1,300 Mt needed to reach a million-person settlement population, with proportional reductions in propellant energy.

Combining this change with the use of H_2/O_2 in lieu of CH_4/O_2 would result in an 8% further reduction in total propellant mass to ~830 Mt.

To make CH_4/O_2 on the Moon requires sources of hydrogen, oxygen and carbon. While there is likely abundant water in permanently shadowed lunar craters [47], evidence for carbon (as either CO or CO_2) is less compelling, and lunar rocks do not contain appreciable quantities of carbonate minerals [48]. Therefore, if there were insufficient carbon on the Moon, it would need to be supplied from asteroids or transported from Earth (probably as CO, since the optimal oxygen/fuel ratio for CH_4/O_2 is three [45], requiring one CO for every two H_2O molecules). We estimate in this case a need for 151 Mt of CO, which is about the same as the mass of CH_4/O_2 propellant transported from the Moon to LEO, which would increase total transport mass and energy, and could confer an advantage to using H_2/O_2 propellant.

However, the amount of lunar water required to supply propellant (either as CH_4/O_2 or H_2/O_2) is ~190 Mt, or ~12% of the total estimated resource at the lunar poles (~1,600 Mt) [49], and thus may represent a significant depletion of this limited resource. If spacecraft mass is increased (e.g., by increasing habitable volume as discussed in section 4.2), the depletion approach ~30%.

It is practical to use Earth-supplied propellant for initial human transport missions to Mars, but it will be advantageous to shift to lower-gravity sources eventually. The Moon represents one such option, but with significant infrastructure requirements prior to utilization, and possible long-term resource constraints. Near-Earth asteroids represent another significant (and perhaps more mass efficient) set of propellant sources, with similar infrastructure requirements as the Moon, and no foreseeable resource constraints, but significant limitations in terms of timing (launch opportunities may only occur every few years). Sources such as these will be required, however, to meet long-term viability and cost reduction goals.

4.5 Total mass of shipped cargo

The total mass of shipped cargo over the course of a million-person settlement build-up is not well constrained, other than Musk's statements that there will be 10 cargo trips per human trip initially, and a total of 100,000 trips over the course of establishing a Mars settlement [9] (we estimate ~136,000 cargo trips in our BC). If the total cargo mass in our BC (22 Mt) is modified, it has an almost linear effect on the total spacecraft mass, propellant mass and energy required; halving it to 11 Mt, for instance, reduces cumulative propellant mass to ~3,100 Mt and total energy per passenger to 59 TJ, a 45% reduction. Thus the total mass of necessary cargo to establish a self-sufficient settlement forms a critical input assumption.

4.6 No aerocapture/aerobraking at Mars

If Mars EDL is accomplished propulsively, e.g., without aerocapture or aerobraking to reduce the total required propellant, an additional delta-v of 5.4 km/s is needed (nearly double the BC value), which would completely change the design requirements of the SpaceX system. One possible remedy would be to refuel again in Mars orbit, after using a minimal amount of propellant (<1.1 km/s) to capture into a high elliptical Mars orbit. However, this would greatly increase energy and mass requirements by requiring additional propellant and propellant resupply spacecraft. While trickier to implement than at Earth, Mars aerocapture and aerobraking should be an effective means of propellant savings.

4.7 Induced torpor to reduce spacecraft mass

Suspended animation or "induced torpor," currently used as a therapeutic medical treatment for traumatic injuries, could also provide major mass savings for space travel [26]. By lowering the body temperature of passengers 2.8 to 5.6°C, inducing a reversible, coma-like state, the habitable volume, consumables and crew size could all be significantly reduced. We assume reductions of 50% in habitable volume and 88% in consumables, based on [26], and a crew size reduction to 5 per 100 passengers [12].

We find a reduction in total spacecraft mass (not including propellant) from 2.41 to 0.94 t/passenger. Round-trip human spacecraft propellant mass is reduced to ~2,800 t, a 61% reduction from the BC. Cumulative total propellant is likewise reduced to ~2,200 Mt, and cumulative energy per passenger is reduced to 43 TJ.

With passengers mostly unconscious, the necessity to minimize transit times is removed, and additional propellant mass savings may be possible by extending outbound transit times, reducing delta-v (e.g., Scenario 2 in Table 1).

4.8 Space elevators

The development of space elevators on the Moon, Mars or Earth would have profound impacts on total mass and energy of the SpaceX system. According to Pearson [50], a lunar space elevator is feasible with current materials, and we estimate it would result in further savings of ~80% in propellant mass and energy [12], though given the 77% savings already conferred in moving from Earth- to Moon-based refuelling (see section 4.4), this may be less important. Similarly, a Mars space elevator could provide a similar level of energy savings over Mars-derived propellants. The most challenging location to build a space elevator is on Earth, and absent a breakthrough in materials properties, is unlikely to be realized in the near future.

5 Conclusions

We have estimated the mass and energy requirements of an Earth-Mars human transport system that resembles SpaceX's Mars Colonial Transporter (MCT) concept as closely as possible, based on publicly available information. In addition to estimating parameters for an individual spacecraft capable of transporting 100 passengers (or 16 t of cargo) between Earth and Mars, we have developed a scale-up scenario to estimate the cumulative mass and energy requirements to grow a Mars settlement to 1 million people.

For our Base Case (BC), which assumes a ~3.5 month transit between Earth and Mars, 5 m^3/person habitable volume, and transport capacity for 100 passengers plus 10 crew, the spacecraft dry mass is 241 t plus 946 t of CH_4/O_2 propellant, and delivers a 175 t payload to the Mars surface, including 95 t of passenger payload, 10 t of crew payload, and 70 t of waste consumables. The first-stage rocket (consuming ~4,200 t of propellant) is assumed to return to Earth's surface, while the second stage rocket (initially consuming ~900 t of propellant on its way to orbit) is refuelled in LEO before leaving for Mars. The payload mass is ~3× that of a Falcon Heavy payload.

To grow the settlement to 1 million people requires ~90 years and a total of 5,871 spacecraft (each with an assumed 40-year life). More than 90% are used for transporting cargo from Earth to Mars (22 Mt in total). Total propellant mass (including propellant needed to transport refuelling propellant from Earth to LEO) is 5,596 Mt. Spacecraft mass is comparatively small at 20.6 Mt. Total energy requirements are 148 EJ, dominated by propellant production (97%). This is equal to ~1.5 years of U.S. primary energy consumption; however, the energy consumption per passenger is far greater at 109 TJ (~340 years' worth).

We find that increasing the habitable volume from a cramped 5 m^3 to a more spacious 20 m^3 inflates total spacecraft mass, propellant and energy demands 2.4×. On the other hand, switching from Earth- to Moon-based propellant refuelling in LEO could reduce total propellant and energy demand by 77%, more than offsetting this. However, a source of carbon is needed to make CH_4/O_2 on the Moon. Alternatively, switching to H_2/O_2 would obviate this problem, and could confer a small energy-saving benefit, albeit with the greater handling challenges of H_2. Depletion of limited water supplies on the Moon poses another long-term concern, however, and asteroid sources of water and carbon may be a more sustainable solution.

Other ways of saving mass and energy include reducing the total mass of shipped cargo, inducing torpor in passengers to save on spacecraft mass and consumables, and the eventual construction of space elevators, particularly on the Moon where it is technically feasible today.

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