COMPARATIVE ASSESSMENT OF HUMAN-MARS-MISSION TECHNOLOGIES AND ARCHITECTURES

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Abstract—We compare a variety of Mars mission scenarios to assess the strengths and weaknesses of different options for interplanetary exploration. We model the mission design space along two dimensions: propulsion system technologies and trajectory architectures. The various combinations of technologies and architectures thus span the scenarios for Mars exploration and colonization. We examine direct, semi-direct, stop-over, semi-cycler, and cycler architectures, and we include electric propulsion, nuclear thermal rockets, methane and oxygen production on Mars, Mars water excavation, aerocapture, and reusable propulsion systems in our technology assessment. The mission sensitivity to crew size, vehicle masses, and crew travel time is also examined. Our primary figure of merit for a mission scenario is the injected mass to low-Earth orbit (IMLEO), though we also consider technology readiness levels (TRL) in our assessment. We find that Earth-Mars semi-cyclers and cyclers require the least IMLEO of any architecture and that the discovery of accessible water on Mars has the most dramatic effect on the evolution of Mars exploration.

1. INTRODUCTION

For millennia, Mars has held the imagination of humanity, yet only in the past century has it become feasible to send explorers to Mars and extend our presence to a new world. To this end, mission designers have proposed a variety of scenarios for how humans could travel to Mars and return home safely [1]–[21]. However, there is still no definitive answer to how we shall explore Mars, despite decades of comparative analyses [22]–[34]. Even in recent years, new trajectory architectures (e.g. Aldrin's cycler [35]) and advancements in propulsion technology (e.g. Deep Space 1 [36]) have added to the already myriad options for human exploration of Mars. To explore and characterize these options, we examine promising technologies and architectures and apply various combinations to achieve the same mission goals (i.e. crew size, payload, vehicles, Mars stay time, and interplanetary transfer times). In this way, we develop a better understanding of the strengths and weaknesses of the available mission options to establish and sustain human exploration of Mars.

When a new technology or architecture is applied to a given mission, the fundamental benefit is a reduction in mass. (Provided the crew, payload, vehicles, and mission timeline are held constant.) Thus, we calculate the injected mass to low-Earth orbit (IMLEO) to compare the strengths of the design options. This reduction in mass is achieved through the development of a technology or sub-system to reliably (i.e. with low risk) perform at a required level. We examine the technology readiness level (TRL) of a technology or architecture to estimate the additional investment required to accomplish the mission [37]. We note that both the IMLEO and TRL values play a significant role in estimating the dollar cost of a given mission; however, the exact role of each (combined with other cost drivers) is somewhat of an art and is not examined here [38]–[39]. Instead, we calculate the IMLEO so the benefit from developing a potential technology is known a priori to help direct the path of Mars exploration.

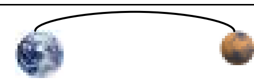
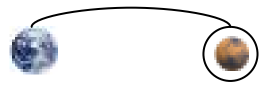
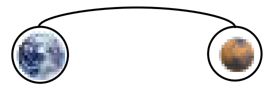
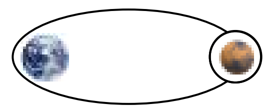
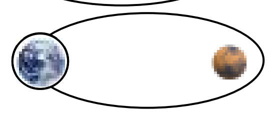
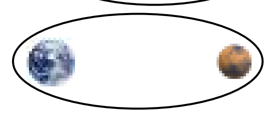
2. MISSION ARCHITECTURES

As shown in Table 1, we characterize Mars-mission architectures by the placement of the interplanetary transfer vehicle at Earth and Mars (e.g. the direct surface to surface or cycler flyby to flyby). The transfer vehicle is the interplanetary habitat for the crew and provides life support, radiation shielding, artificial gravity (possibly), furniture, support structure, etc. Because much of this mass is not required on the surface of Earth or Mars (assuming a separate surface habitat), considerable mass savings arise if the transfer vehicle captures into a parking orbit or performs a flyby at Earth or Mars instead of launching from the surface. For example, in a direct mission the transfer vehicle launches from Earth with the crew, lands on Mars, then departs Mars (from the surface) to transport the crew back to Earth [15], [19]. However, in a semi-direct architecture (as in NASA's DRM [20], [21]) the transfer vehicle is placed into a parking orbit at Mars where it remains until the crew is ready to return to Earth. The crew performs the same mission in both scenarios, but the transfer vehicle remains at a different location during the Mars stay time.

The crew travels from the transfer vehicle to the surface (and vice-versa) via a "taxi" vehicle. The taxi is less massive than the transfer vehicle because it only supports the crew between the transfer vehicle and the surface and does not require as much life support, radiation shielding, or structure. (In NASA's DRM the taxi is called the Mars Ascent Capsule.) A reduction in IMLEO occurs because the smaller taxi performs the ΔV from the surface to the parking orbit (instead of the relatively massive transfer vehicle performing the same maneuver). We also examine stop-over architectures [40], [41], where the transfer vehicle enters and departs parking orbits at both Earth and Mars; Mars-Earth semi-cyclers [42], with Earth flybys and a Mars parking orbit; and Earth-Mars semi-cyclers [43], with a parking orbit at Earth and flybys at Mars. The idea of limiting the maneuvers performed by a transfer vehicle is taken to the extreme with the cycler architecture where the transfer vehicle remains in heliocentric space and receives periodic gravity assists from Earth and Mars, but never stops at either planet [35], [44], [45]. Again, a taxi ferries the crew between the planet's surface and transfer vehicle during the planetary flybys.

The IMLEO for missions with libration-point stations (Sun-Earth or Earth-Moon) is comparable to stop-over missions, because the energy requirements for the transfer vehicle are similar [12], [46]. Thus, we do not include libration-point "gateway" stations as a separate architecture in our analysis.

Table 1
Placement of interplanetary transfer vehicle for different architectures

Architecture	Earth Encounter	Mars Encounter	Schemata
Direct	Surface	Surface	
Semi-Direct	Surface	Parking Orbit	
Stop-Over	Parking Orbit	Parking Orbit	
M-E Semi-Cycler	Flyby	Parking Orbit	
E-M Semi-Cycler	Parking Orbit	Flyby	
Cycler	Flyby	Flyby	

3. TECHNOLOGY OPTIONS

Another dimension to the Mars-mission design space is the application of upcoming technologies. We have gathered several promising technologies in Table 2, and rank their current development (for a mission to Mars) with an approximate technology readiness level. For example, chemical propulsion (with a TRL of 9) has been the workhorse for human space exploration, but the higher specific impulse of nuclear thermal rockets or electric propulsion can significantly reduce the required propellant mass. (We place transfer-vehicle electric propulsion at a lower TRL than cargo-vehicle propulsion because of the considerably higher thrust required to achieve short interplanetary crew transfers.) Further mass savings are possible if the propulsion system can be reused, which reduces the hardware mass launched from Earth. The atmosphere of Mars has been used to decelerate spacecraft for surface landing and to lower the energy of a parking orbit, but aerocapture, where the spacecraft is decelerated from the interplanetary transfer into a parking orbit, has yet to be attempted. Mission architectures that rely on a parking orbit at Earth or Mars can benefit from aerocapture (which is currently at a mid-TRL) because a heat shield replaces the relatively massive propulsion system for orbit capture.

We also examine the benefits of using the natural resources of Mars. For example, a feedstock of hydrogen from Earth can be combined with the carbon dioxide in the atmosphere of Mars to produce methane and oxygen (in-situ propellant production), eliminating the need to launch the return propellant from Earth. Moreover, the development of a reliable method to extract water from the Martian regolith would provide hydrogen and oxygen on Mars without the need of terrestrial feedstock.

Other technologies that we consider in Mars-mission design are parking-orbit rendezvous and hyperbolic rendezvous at Earth and Mars. Parking-orbit rendezvous is required to dock the taxi (carrying the crew) with the transfer vehicle in a parking orbit. Similarly, hyperbolic rendezvous transfers the crew to the transfer vehicle during planetary flyby (when the transfer vehicle is on a hyperbolic arc with respect to the planet). The elements of hyperbolic and parking-orbit rendezvous are the same; however, hyperbolic rendezvous is critical to crew survival because there is only one opportunity for rendezvous as the taxi has already committed towards the next planet. During parking-orbit rendezvous the crew could abort to the surface because the taxi is still captured about the planet. As a result, additional development is necessary to reduce the risk of hyperbolic rendezvous when compared with parking-orbit rendezvous. Finally, we examine the benefit of launching propellant (via a tanker) for Mars upper-stages to a parking orbit instead of the surface. This option requires docking of the tanker with the upper-stage before refueling. There may also be some benefit from launching propellants produced at Mars (e.g. via regolith excavation) to Earth orbit for use by Earth upper-stages. Here, we note that targeting Earth from the surface of Mars requires less ΔV than reaching LEO from the surface of Earth.

Table 2
Current and near-term technologies

Technology	Approximate Readiness Level	Definition[a]
Chemical Propulsion	9	System flight proven
Parking Orbit Rendezvous (Earth)	9	
Parking Orbit Rendezvous (Mars)	8	System flight qualified
Refuel in Orbit (Earth)	8	
Cargo Electric Propulsion (EP)[b]	7	Prototype in space
Refuel in Orbit (Mars)	7	
Hyperbolic Rendezvous (Earth)	7	
Hyperbolic Rendezvous (Mars)	6	Prototype demonstration
Nuclear Thermal Rocket (NTR)	6	
Reusable Mars Launch Vehicles	5	Component demonstration
Aerocapture	5	
Transfer Vehicle Electric Propulsion[b]	5	
In-Situ Propellant Production	5	
Mars Launch Vehicle NTR	4	Component in laboratory
Mars Water Excavation	3	Proof of concept

[a]For a more detailed definition of technology readiness levels see [37].
[b]The TRL values correspond to nuclear electric propulsion, but the IMLEO values are applicable to both solar and nuclear electric systems.

There is an important distinction between technology readiness and development cost. The technology readiness level indicates the current state of a system, i.e. the investment already put into the system. Of greater consequence (but harder to estimate) to the economy of a mission is the additional cost required to reliably apply that technology to the mission. For example, NTR technology is at a higher TRL than in-situ propellant production. However, it may be cheaper (and easier) to create methane on Mars than to develop human-rated nuclear thermal rockets. In this case, the TRL does not explicitly rank the relative development costs. While we rely on the TRL values to provide a basis for technology and system comparisons, the TRL itself does not determine the future investments required to explore Mars with a given system.

4. MARS MISSION SPECIFICATIONS

We characterize a mission to Mars with five parameters: 1) the crew size, 2) the taxi capsule mass, 3) the transfer vehicle cabin mass, 4) the cargo mass, and 5) the maximum allowable time of flight (TOF) between Earth and Mars. The crew size provides a good indication of how much work and exploration can be achieved on the surface (at the cost of higher IMLEO for larger crews). The taxi mass, transfer vehicle mass, and interplanetary TOF are driven by risk mitigation. The taxi and transfer vehicles must have sufficient mass to ensure the safety and comfort of the crew, yet smaller vehicles generally reduce IMLEO. For example, a large transfer vehicle may provide spacious living quarters, plentiful radiation shielding, and artificial gravity, requiring a larger IMLEO to ferry the additional mass between the planets. The allowable TOF is determined by the permitted exposure to radiation and zero-gravity (if the transfer vehicle provides no artificial gravity). Lowering the TOF reduces these deleterious effects at the cost of higher ΔV and IMLEO. We also note that low TOF trajectories usually allow longer Mars stay times. The cargo mass indicates the amount of resources available to the crew on Mars. Cargo includes the surface habitat, power plant, scientific equipment, and any infrastructure for in-situ resource utilization. Again, more resources generally lead to higher IMLEO.

Once the crew, resources, vehicles, and timeline for a mission are established any combination of technologies and architectures may be applied to complete the mission. For example, a crew of six on Mars for 550 days with 40 mt of resources provide the same scientific return whether they arrived using chemical or NTR propulsion or traveled along a stop-over or cycler trajectory. The available technologies and architectures are a means by which a given mission is accomplished. Further, we do not directly compare missions with different vehicle masses or TOF (e.g. a 20 mt stop-over transfer vehicle versus a 30 mt cycler transfer vehicle) because the difference in vehicle masses (and crew safety and comfort levels) would alter the IMLEO, obscuring any potential benefit from using one technology or architecture over another. Thus, for our analysis we specify a given mission and compare how well the various sets of technologies and architectures complete the mission. Should one set significantly reduce the IMLEO then it should be considered for sustained Mars exploration; conversely, if the development of new technology or architecture increases IMLEO, then it may be discarded as it provides no intrinsic benefit to establishing our presence on Mars.

5. MISSION ASSUMPTIONS

The following assumptions specify the IMLEO to sustain recurring missions to Mars.

1.) A mission occurs during each synodic opportunity (i.e. every 2.14 years). We do not include one-time costs (e.g. reusable transfer vehicle launches, Mars infrastructure, or technology development) in our IMLEO assessment; we instead focus on the mass required to sustain a human presence on Mars. We judge the prudence of these one-time investments by analyzing the resulting reduction in IMLEO.

2.) There are four crew members. (However, we note that the IMLEO is approximately proportional to the crew size.) Moreover, we specify vehicle, consumable, and cargo masses in terms of mt/person so the IMLEO may be scaled for an arbitrary crew size.

3.) The nominal taxi capsule mass is 1.5 mt/person (without the heatshield). (The Earth Entry/Mars Ascent Capsule in NASA's Design Reference Mission [21] is 4.8 mt for six people, and the Apollo Command Module was 5.5 mt [47] and returned three people to Earth.) We also calculate the sensitivity of IMLEO to the taxi mass.

4.) The transfer vehicle cabin mass is 6 mt/person. (The Earth Return Vehicle in NASA's Design Reference Mission [21] has a Habitat Element mass of 26.6 mt for six people and Zubrin's Mars Direct [19] has an Earth Return Cabin of 11.5 mt for four people. Our estimate is higher than these proposals because neither included substantial radiation shielding.) The cabin mass includes living quarters, life support, structure, power, radiation shielding, etc, but not consumables or the propulsion system. The transfer vehicle mass is also varied from 1.5–15 mt/person to examine the cost of additional safety and comfort for the crew.

5.) Cargo is varied from 0–10 mt/person. Cargo includes the surface habitat, laboratory, power system, etc., but not consumables (food, air, water). A mission with no cargo implies that there are sufficient resources on the surface of Mars from previous missions.

6.) The crew requires 5 kg/day/person of consumables. If in-situ resource utilization is assumed at Mars, then only 2 kg/day/person are required from Earth. The remaining 3 kg/day/person is water and oxygen produced at Mars (e.g. from a hydrogen feedstock or water excavation).

7.) Stop-over, semi-cycler, and cycler architectures require reusable transfer vehicles. We do not include the one-time cost of launching these transfer vehicles from Earth; the initial launch is assumed to have occurred during a previous mission. However, we include mass to completely refurbish each transfer vehicle every 15 missions (or 6.67% of the transfer vehicle mass is launched each mission for refurbishments).

8.) Direct and semi-direct scenarios require a new transfer vehicle for each mission. Stop-over and Mars-Earth semi-cyclers require two reusable transfer vehicles. Earth-Mars semi-cyclers and cyclers require four reusable transfer vehicles to complete a crew transfer every synodic period. We note that there are scenarios that require fewer transfer vehicles, but the TOF or V_∞ are usually undesirable and typically cause an increase in IMLEO. We thus choose more vehicles with small propulsion systems over fewer vehicles that require relatively massive propulsion systems.

9.) A new propulsion system is launched and attached to a reusable transfer vehicle each mission (i.e. the propulsion systems are modular). If the propulsion system is reusable, then only propellant and tanks are launched.

10.) Reusable upper stages return to low-circular orbit via aerobraking. (Another option, which we do not examine here, is to return the upper stage to low-circular orbit via propulsive maneuvers.)

11.) We assume that propellant tanks come with a cyrocooler [48], [49], so we do not explicitly account for propellant boiloff losses. The cryocooler mass is included in the tank mass fraction $m_{\text{tank}}/m_{\text{propellant}}$.

12.) If in-situ propellant production is assumed, then 18 mt of liquid methane and liquid oxygen are produced for every 1 mt of hydrogen feedstock sent to Mars [19].

13.) The mass fraction for the heatshield is given by

$$m_{\text{heatshield}}/m_{\text{landed}} = \begin{cases} 15\% & \text{if } V_\infty \leq 5 \text{ km/s} \\ 15\% + (V_\infty - 5 \text{ km/s})\, 2\,\%/\text{km/s} & \text{if } V_\infty > 5 \text{ km/s} \end{cases}$$

This heuristic equation accounts for additional thermal protection at higher entry speeds. (In other studies a constant $m_{\text{heatshield}}/m_{\text{landed}} = 15\%$ is assumed [18], [21], [29].)

14.) Heatshields are not reused.

15.) A ΔV of 500 m/s is budgeted for a soft landing on Mars.

16.) The crew, taxi, and transfer vehicle travel between Earth and Mars on constrained TOF trajectories. The TOF is varied between 120 and 270 days, with a nominal mission TOF of 210 days.

17.) The average V_∞ as a function of TOF for each architecture is provided in [50].

18.) Cargo and surface consumables are sent to Mars on a minimum energy (Hohmann-like) transfer.

19.) The average surface stay for all architectures is assumed to be

$$\text{Staytime} = 740 \text{ days} - \text{TOF}$$

The total mission duration (from Earth launch to Earth arrival) is thus

$$\text{Mission duration} = 740 \text{ days} + \text{TOF}$$

We note that these staytime and mission duration values are approximate, but serve to keep the mission consistent among the different architectures. (That is, we do not want to compare missions with different staytimes or durations.)

20.) All parking orbits have a periapsis altitude of 300 km and a period of four days. The allotted ΔV to reorient a parking orbit for proper departure V_∞ alignment is 350 m/s at Earth and 180 m/s at Mars [51].

21.) The ΔV to dock the taxi with the transfer vehicle during hyperbolic rendezvous is 150 m/s at Earth and Mars [52], [53]. To reduce the chance of failure during hyperbolic rendezvous we do not place the taxi into an intermediate parking orbit or use low-thrust propulsion after departure from low-circular orbit. Both of these options introduce additional timing and phasing concerns during rendezvous.

22.) We determine the number of stages for a maneuver from the mass ratio m_0/m_{pay} of a single stage. If $m_0/m_{\text{pay}} < 4$ then only one stage is used, and if $m_0/m_{\text{pay}} \geq 4$ then two stages complete the maneuver.

23.) The altitude for low-circular orbits at Earth and Mars is 300 km. Crew, vehicles, and cargo returning to Earth from Mars are first launched into a low-Mars orbit.

24.) Only high thrust (impulsive ΔV) propulsion is used to transfer the crew from a low-circular orbit to a high-energy (parking or hyperbolic) orbit (because low-thrust transfers would take several months and would increase radiation exposure through the Van Allen belts).

25.) All hardware comes from Earth.

The key propulsion system characteristics are provided in Table 3. The parameters in Table 3 correspond to the technology readiness levels in Table 2 so that the various systems are compared on a known basis. The inert mass m_{inert} for chemical systems includes the engine, tank, cyrocooler, and supporting structure, whereas the inert mass for NTR also includes a reactor and shielding. The tank mass m_{tank} includes both the tank and a cyrocooler to store propellant. The inert mass for electric propulsion (EP) is determined from $\alpha/\eta = m_{\text{hardware}}/P_{\text{jet}}$, where m_{hardware} includes the reactor and shielding (or solar arrays and supporting structure for solar electric propulsion), power conversion, thrusters, etc, but excludes the tank mass. The jet power P_{jet} is determined from the thrust T and specific impulse I_{sp} via

$$P_{\text{jet}} = TgI_{sp}/2 \tag{1}$$

A relatively low value for α/η is required for transfer-vehicle EP to allow short (120 day) TOF transfers, placing this technology at a lower TRL than cargo EP which may require up to two synodic periods (1,560 days) from LEO to Mars arrival. The transfer-vehicle-EP I_{sp} varies linearly from 3,000 s at 120 days TOF to 5,000 s at 270 days TOF. These values are determined from the heuristic optimization method presented by Zola [54], and agree to within a few percent with higher fidelity numerical optimization methods. Lower I_{sp} ($\leq$ 5,000 s) allows the use of lithium propellant, which is more storable than hydrogen. We assume magnetoplasmadynamic thrusters for the EP systems because of their high thrust densities.

Table 3
Propulsion system parameters

Propulsion System	I_{sp} (sec.)	$\dfrac{m_{\text{inert}}}{m_{\text{propellant}}}$ or $\dfrac{\alpha}{\eta}$	$\dfrac{m_{\text{tank}}}{m_{\text{propellant}}}$
Chemical (H_2/O_2)	450	0.16	0.12
Chemical (CH_4/O_2)	380	0.12	0.08
Nuclear Thermal (H_2)	900	0.60	0.16
Cargo EP (Li)	5,000	10–50 kg/kW[a]	0.04
Transfer Vehicle EP (Li)	3,000–5,000[b]	10 kg/kW	0.04

[a]An α/η of 50 kg/kW has an approximate TRL of 7, while $\alpha/\eta = 10$ kg/kW is at TRL 5.
[b]The transfer vehicle EP I_{sp} varies linearly from 120–270 days TOF.

The first stage of the Mars taxi achieves a low-circular orbit (LCO) about Mars from the surface. We do not explicitly include drag, steering, or gravity losses nor the velocity due to planetary rotation in the launch ΔV; instead we add a 5% ΔV cost.

$$\Delta V_{launch} = 1.05\sqrt{GM\left(\frac{2}{r_{surf}} - \frac{1}{r_{LCO}}\right)} \quad (2)$$

The ΔV required to reach the HPO from the LCO by an upper stage is

$$\Delta V_{US} = \sqrt{GM\left(\frac{2}{r_{LCO}} - \frac{1}{a_{HPO}}\right)} - \sqrt{\frac{GM}{r_{LCO}}} \quad (3)$$

or, for a low-thrust transfer

$$\Delta V_{US} = \sqrt{\frac{GM}{a_{HPO}}} - \sqrt{\frac{GM}{r_{LCO}}} \quad (4)$$

Finally, the ΔV to achieve a given V_∞ from the HPO is

$$\Delta V_{escape} = \sqrt{\frac{2GM}{r_{LCO}} + V_\infty^2} - \sqrt{GM\left(\frac{2}{r_{LCO}} - \frac{1}{a_{HPO}}\right)} \quad (5)$$

The ΔV to escape or capture into a parking orbit via low-thrust is (from [54])

$$\Delta V_{escape} = 1.5\left(V_\infty + \sqrt{\frac{GM}{a_{HPO}}}\right) \quad (6)$$

The initial acceleration a_0 for low-thrust cargo and low-thrust LCO-HPO transfers is 10^{-7} km/s^2, which is approximately the lowest acceleration that allows cargo transfers with flight times less than two synodic periods. The initial acceleration for low-thrust transfer vehicle trajectories is determined from the method of [54]. For trajectories that depart an Earth HPO and arrive into a Mars HPO (or vice-versa) with a powered arrival, the initial acceleration is

$$\begin{aligned} \Delta V &= \Delta V_{escape} + \Delta V_{capture} \\ a_0 &= 3\frac{gI_{sp}}{\text{TOF}}\left[1 - e^{-\Delta V / gI_{sp}} - 2\frac{gI_{sp}}{\Delta V}\left(1 - e^{-\Delta V / 2gI_{sp}}\right)^2\right] \end{aligned} \quad (7)$$

The a_0 for trajectories that employ atmospheric braking (direct entry or aerocapture) at arrival is

$$\begin{aligned} \Delta V &= \Delta V_{escape} \\ a_0 &= 4.5\frac{gI_{sp}}{\text{TOF}}\left[1 - e^{-\Delta V / gI_{sp}} - 2\frac{gI_{sp}}{\Delta V}\left(1 - e^{-\Delta V / 2gI_{sp}}\right)^2\right] \end{aligned} \quad (8)$$

This larger acceleration (than that determined by Zola's method) allows us to limit the arrival V_∞ for aerocapture trajectories.

The rocket equation [55] is used to determine mass fractions for a single stage

$$\mu_{stage} = \frac{m_0}{m_f} = \exp\left(\frac{\Delta V}{\text{n}gI_{sp}}\right) \quad (9)$$

where n is the number of stages to complete the ΔV. The ratio of initial mass to the payload mass for an impulsive ΔV is thus

$$\frac{m_0}{m_{\text{pay}}} = \left[\frac{\mu_{\text{stage}}}{1 - \frac{m_{\text{inert}}}{m_{\text{propellant}}}\left(\mu_{\text{stage}} - 1\right)} \right]^n \tag{10}$$

or with low-thrust

$$\frac{m_0}{m_{\text{pay}}} = \frac{\mu_{\text{stage}}}{1 - \mu_{\text{stage}} \frac{\alpha}{2\eta} a_0 g I_{sp} - \frac{m_{\text{tank}}}{m_{\text{propellant}}}\left(\mu_{\text{stage}} - 1\right)} \tag{11}$$

The mission payload, heatshields, and propulsion systems may be combined and stacked to produce the IMLEO.

6. IMLEO RESULTS

We provide the mass that must be injected into low-Earth orbit from the surface of Earth for a variety of technologies and architectures in Table 4 and Table 5. The tables are arranged so that technology readiness roughly increases from top to bottom and architecture complexity increases from left to right. The nominal mission assumptions (crew = 4, taxi capsule = 1.5 mt/person, transfer vehicle cabin = 6 mt/person, consumables = 5 kg/person/day, TOF = 210 days) are used to calculate the injected mass to low-Earth orbit (IMLEO) values in these tables. Table 4 contains values where a substantial amount of cargo (10 mt/person) is sent to Mars to develop a permanent base; Table 5 assumes no cargo transfer to Mars and represents the IMLEO required for crew transfer only. We note that the IMLEO values in Table 4 and Table 5 are for recurring Mars missions and are calculated assuming that the reusable transfer vehicles for stop-over, semi-cycler, and cycler architectures are already operating in space.

The four letters in the second column of Table 4 and Table 5 denote the propulsion system used by four Mars exploration vehicles. For example, in row *5* the Earth upper stage uses an electric propulsion system, while the Mars launch vehicle, Mars upper stage and transfer vehicles all have liquid oxygen and liquid hydrogen propulsion systems. When an EP upper stage is used, the crew taxi propulsion system is the same as the Mars launch vehicle system. (Thus in row *5*, cargo, consumables, and propulsion systems depart LEO via electric propulsion, but the crew departs LEO via LOX/LH_2 chemical propulsion to avoid prolonged transfers through the Van Allen belts.) We note that the Direct column of row *8* corresponds to Zubrin's Mars Direct mission [19] where the Earth-return vehicle (transfer vehicle) lands directly on Mars and is fueled with methane produced at Mars. The scenario corresponding to NASA's Design Reference Mission [20] is found in the Semi-Direct column of row *29*. (The Design Reference Mission assumes a crew of six, while we assume a crew of four.) This mission includes Earth upper stages that employ nuclear thermal rockets, Mars launch vehicles and upper stages that utilize in-situ produced methane and oxygen, and a transfer vehicle that aerobrakes into a parking orbit about Mars. Because we assume that the IMLEO is approximately proportional to crew size, our estimate of the IMLEO for a six-person crew would be about 1.5 times that of the values presented in Table 4 and Table 5.

Table 4
Recurring IMLEO to transfer a crew of four with 40 mt of cargo every synodic opportunity (TOF = 210 days, taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day)

	Propulsion System[a]		Trajectory Architecture					
	$U_E L_M U_M T$[b]		Direct	Semi-Direct	Stop-Over	M-E S-C	E-M S-C	Cycler
1	MMMM		1350	611	705	758	622	631
2	HHHH		953	489	540	564	473	505
3	MMMM	T_M	1090	570	665	698	503	510
4	HHHH	T_M	807	465	516	530	404	429
5	E_{50}HHH		548	274	304	414	265	332
6	NMMN		779	370	368	431	385	411
7	HHHH	A	953	455	442	486	444	505
8	MMMM	I	499	463	498	476	379	372
9	E_{10}HHE_{10}		566	320	442	396	297	280
10	MMMM	AT_M	1060	519	512	577	464	498
11	HHHH	W	386	375	367	352	308	314
12	NNNN		495	319	318	353	285	300
13	E_{50}HHN		478	247	246	323	242	292
14	E_{50}MMM	I	278	231	240	288	199	243
15	E_{50}HHH	A	548	254	247	355	248	332
16	E_{50}HHH	R	542	259	286	414	254	326
17	NMMN	I	330	275	273	295	229	237
18	NHHN	A	662	334	314	356	327	363
19	NHHN	R	592	305	289	318	305	315
20	E_{50}HHH	W	253	220	215	235	185	221
21	MMMM	IR	417	424	412	397	347	338
22	E_{10}HEE_{10}	R	525	275	298	327	273	282
23	NHNN	W	290	270	257	265	227	227
24	HHHH	WR	317	338	296	283	257	264
25	E_{50}HHH	WT_E	246	218	213	219	178	209
26	NHHN	WT_E	294	278	265	262	231	227
27	HHHH	WT_ER	117	111	91.9	96.9	92.8	93.3
28	E_{50}NNN	R	311	203	191	230	182	207
29	NMMM	IA	340	289	274	279	244	247
30	NMMM	IR	259	263	253	227	213	196
31	NMMN	IR	251	226	211	219	186	190
32	E_{10}HEE_{10}	AR	514	267	251	304	251	281
33	NHNN	WT_ER	121	114	91.6	97.8	95.1	97.5
34	MMMM	IAT_ER	403	371	340	364	314	338
35	E_{50}MMM	IAT_ER	222	179	166	179	154	168
36	NMMN	IAR	204	169	153	189	143	168

[a]A = Aerocapture, E_{10} = EP with α/η = 10 kg/kW, E_{50} = EP with α/η = 50 kg/kW, H = LOX/LH_2, I = ISPP, M = LOX/CH_4, N = NTR, R = Reusable propulsion systems, T_M = Tanker to Mars, T_E = Tanker to Earth, W = Mars Water
[b]U_E = Earth upper stage, L_M = Mars launch vehicle, U_M = Mars upper stage, T = transfer vehicle

Table 5
Recurring IMLEO to transfer a crew of four with no cargo every synodic opportunity (TOF = 210 days, taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day)

Propulsion System[a]			Trajectory architecture					
	$U_E L_M U_M T$[b]		Direct	Semi-Direct	Stop-Over	M-E S-C	E-M S-C	Cycler
1	MMMM		1170	435	530	582	447	456
2	HHHH		801	337	388	413	321	353
3	MMMM	T_M	918	395	490	523	328	334
4	HHHH	T_M	655	314	365	379	253	277
5	E_{50}HHH		469	196	226	336	186	253
6	NMMN		664	255	253	316	270	296
7	HHHH	A	801	303	290	335	292	353
8	MMMM	I	324	287	323	300	203	197
9	E_{10}HHE_{10}		497	252	373	328	228	212
10	MMMM	AT_M	888	344	336	402	288	323
11	HHHH	W	235	223	216	200	157	162
12	NNNN		380	204	203	238	171	185
13	E_{50}HHN		400	169	168	245	163	213
14	E_{50}MMM	I	200	153	162	209	121	165
15	E_{50}HHH	A	469	176	169	277	170	253
16	E_{50}HHH	R	462	178	205	332	174	244
17	NMMN	I	215	160	159	180	114	122
18	NHHN	A	547	219	199	241	212	248
19	NHHN	R	490	203	187	216	203	213
20	E_{50}HHH	W	175	142	136	157	107	143
21	MMMM	IR	246	253	242	227	177	168
22	E_{10}HEE_{10}	R	457	206	230	257	204	212
23	NHNN	W	175	155	142	150	112	112
24	HHHH	WR	168	189	147	135	108	116
25	E_{50}HHH	WT_E	167	140	135	157	99.3	140
26	NHHN	WT_E	179	163	150	147	116	112
27	HHHH	WT_ER	61.7	55	36.2	41.2	37.1	37.6
28	E_{50}NNN	R	231	122	111	159	102	137
29	NMMM	IA	225	174	159	164	129	132
30	NMMM	IR	157	162	151	125	111	94.1
31	NMMN	IR	149	124	109	117	84.5	87.7
32	E_{10}HEE_{10}	AR	446	198	182	234	181	212
33	NHNN	WT_ER	62.9	56.2	33.6	39.8	37.1	39.5
34	MMMM	IAT_ER	232	201	169	194	144	168
35	E_{50}MMM	IAT_ER	142	98.8	85.4	116	73.4	106
36	E_{50}MMN	IAR	123	88.5	72.7	106	62.7	85.7

[a]A = Aerocapture, E_{10} = EP with α/η = 10 kg/kW, E_{50} = EP with α/η = 50 kg/kW, H = LOX/LH_2, I = ISPP, M = LOX/CH_4, N = NTR, R = Reusable propulsion systems, T_M = Tanker to Mars, T_E = Tanker to Earth, W = Mars Water
[b]U_E = Earth upper stage, L_M = Mars launch vehicle, U_M = Mars upper stage, T = transfer vehicle

Each IMLEO value in Table 4 and Table 5 represents a single design point for Mars missions; however, further insight is gained by examining how the IMLEO varies throughout the design space as illustrated in Fig. 1–Fig. 12 and in Table 6–Table 11. The odd-numbered figures (of Fig. 1–Fig. 12) demonstrate how the optimal architecture changes for different transfer-vehicle masses and TOF. The solid black lines demarcate regions where one architecture requires less IMLEO than all the others. For example, in Fig. 1 cyclers require the least IMLEO for large transfer vehicles and short TOF; Earth-Mars semi-cyclers are optimal for large transfer vehicles and long TOF; and the semi-direct architecture requires the least IMLEO with small transfer vehicles.

The dashed lines in these figures are contours of constant IMLEO and demonstrate how the optimal IMLEO varies with cabin mass and TOF. For example, in Fig. 1, a 38 mt transfer vehicle traveling along a 240-day TOF Earth-Mars semi-cycler trajectory requires the same IMLEO (of 330 mt) as a 15 mt transfer vehicle traveling along a 180-day TOF semi-direct trajectory. The point with 210-day TOF and 24-mt transfer vehicle corresponds to the lowest IMLEO found in row *2* of Table 5 (321 mt). Because cargo transfers are independent of the trajectory architecture (cargo follows the same minimum-energy transfer regardless of the transfer vehicle trajectory) the IMLEO due to cargo is constant throughout the transfer-vehicle, TOF design space. (In the case of Fig. 1 the cargo adds a factor of 3.80 times the cargo mass to the IMLEO, thus 40 mt of cargo adds 152 mt resulting in the (321 + 152 =) 473 mt found in row *2* of Table 4. We note that the discontinuity in the 420 mt contour line at 180-day TOF is due to the cycler taxi switching from two stages to one as the ΔV requirements decrease with increasing TOF (as determined by Assumption 22.).

The even-numbered figures (of Fig. 1–Fig. 12) show how the IMLEO varies with TOF when the transfer vehicle cabin mass is held at 24 mt. These figures represent a cut along the 24 mt line of the optimal transportation figures. For example, in Fig. 2 the lowest-IMLEO architecture is a cycler for TOF < 180 days and is an Earth-Mars semi-cycler for TOF > 180 days, as found along the 24 mt transfer vehicle line in Fig. 1. On the other hand, if the TOF is held constant, then the IMLEO is only affected by mass values. Moreover, as demonstrated by Eqs. (10) and (11) the IMLEO is directly proportional to these mass values (the payloads). The mass coefficients to calculate IMLEO for any vehicle size, consumable rate, and cargo amount for 210-day transfers are provided in Table 6–Table 11. The values in these tables illustrate the sensitivity of IMLEO to the mission components. For example, in Table 6 a 1-mt increase in transfer-vehicle cabin mass causes a 27-mt increase in IMLEO for direct architectures. The IMLEO values in Table 4 and Table 5 may be reproduced by summing the product of the nominal mass values with the coefficients presented in Table 6–Table 11.

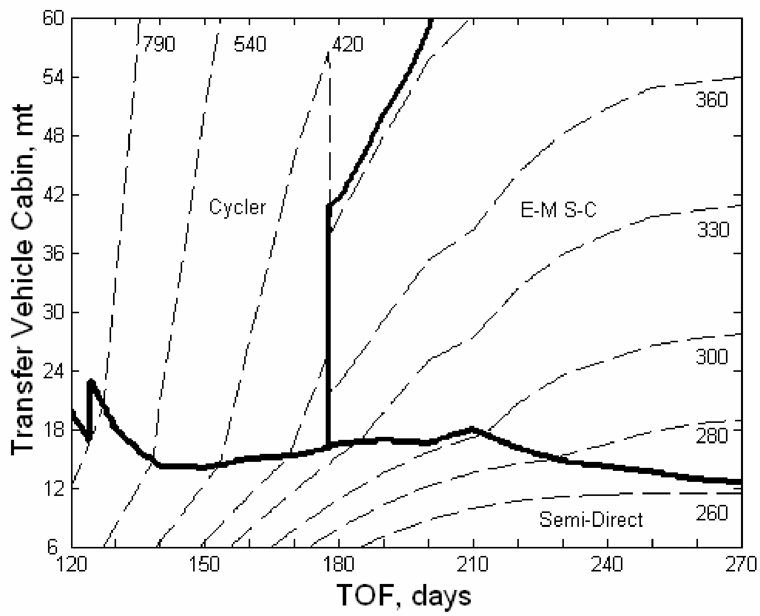


Fig. 1 Optimal transportation architectures corresponding to row *2* of Table 5. Contour lines are IMLEO in mt. Cargo transfer adds 3.80 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, consumables = 20 kg/day.)

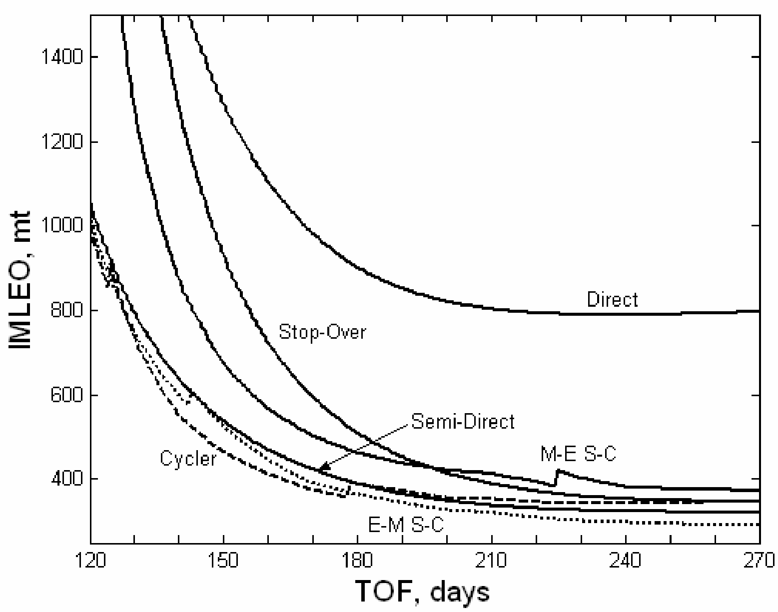


Fig. 2 IMLEO a function of TOF for the six architectures in row *2* of Table 5. Cargo transfer adds 3.80 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day.)

Table 6
Sensitivity of IMLEO to mission masses for row *2* of Table 4 and Table 5 with 210-day TOF where $\text{IMLEO} = a \bullet (\text{TV cabin}) + b \bullet (\text{taxi capsule}) + c \bullet (\text{consumables}) + d \bullet (\text{cargo})$

Architecture	*a*, mt/mt	*b*, mt/mt	*c*, mt/(kg/day)	*d*, mt/mt
Direct	27.0	0	7.78	3.80
Semi-Direct	5.48	21.7	3.84	3.80
Stop-Over	7.15	22.7	4.08	3.80
M-E S-C	5.25	32.3	4.65	3.80
E-M S-C	2.73	31.5	3.31	3.80
Cycler	2.09	37.5	3.85	3.80

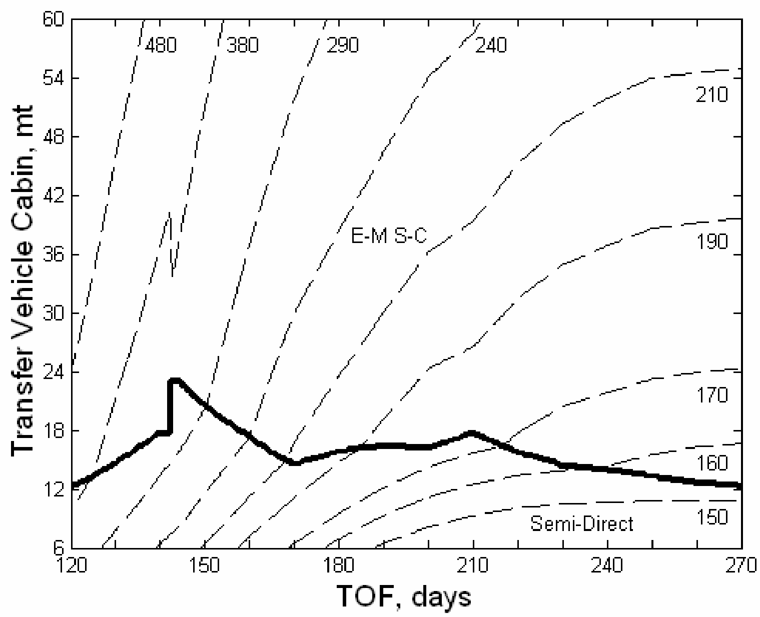


Fig. 3 Optimal transportation architectures corresponding to row *5* of Table 5. Contour lines are IMLEO in mt. Cargo transfer adds 1.96 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, consumables = 20 kg/day.)

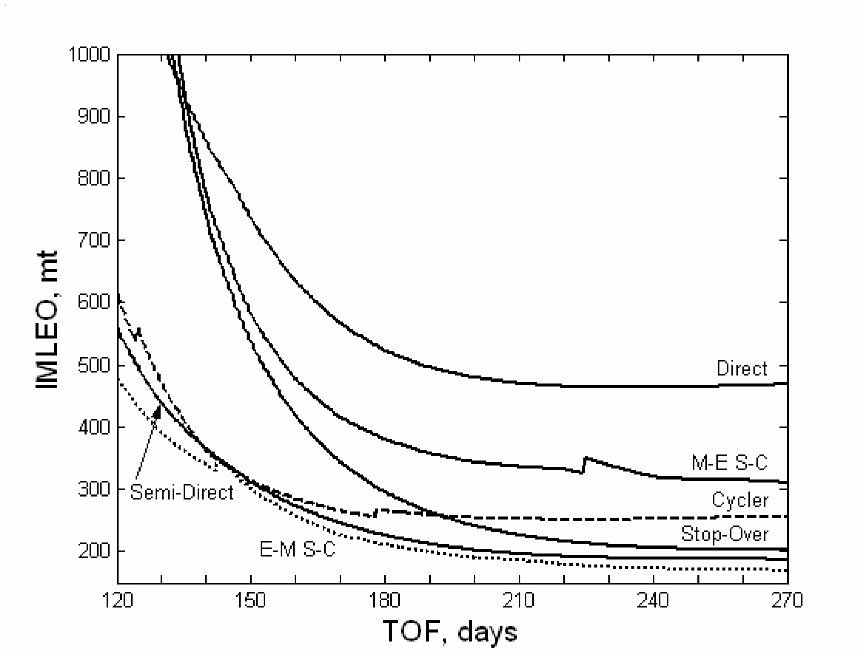


Fig. 4 IMLEO a function of TOF for the six architectures in row *5* of Table 5. Cargo transfer adds 1.96 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day.)

Table 7
Sensitivity of IMLEO to mission masses for row *5* of Table 4 and Table 5 with 210-day TOF where $\text{IMLEO} = a \bullet (\text{TV cabin}) + b \bullet (\text{taxi capsule}) + c \bullet (\text{consumables}) + d \bullet (\text{cargo})$

Architecture	*a*, mt/mt	*b*, mt/mt	*c*, mt/(kg/day)	*d*, mt/mt
Direct	15.9	0	4.45	1.96
Semi-Direct	3.10	13.4	2.08	1.96
Stop-Over	4.10	14.0	2.22	1.96
M-E S-C	5.24	22.8	3.69	1.96
E-M S-C	1.56	18.9	1.77	1.96
Cycler	2.08	24.3	2.88	1.96

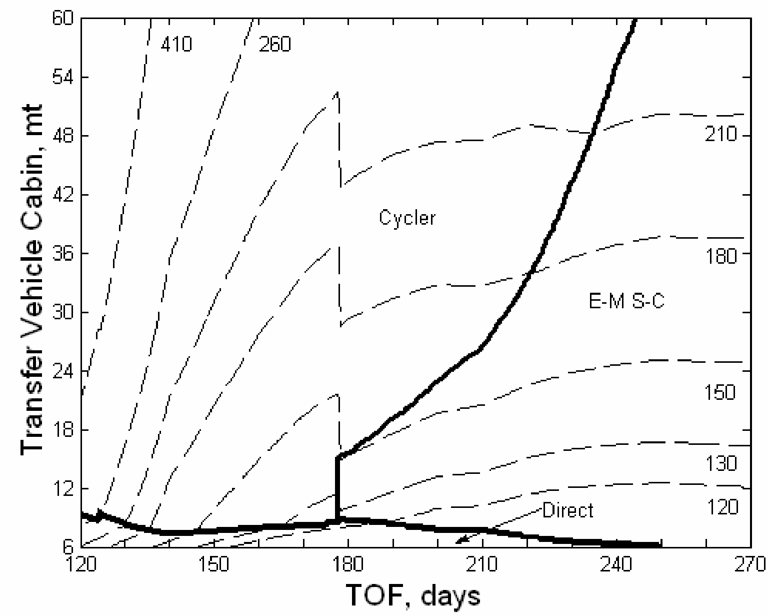


Fig. 5 Optimal transportation architectures corresponding to row *11* of Table 5. Contour lines are IMLEO in mt. Cargo transfer adds 3.80 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, consumables = 20 kg/day.)

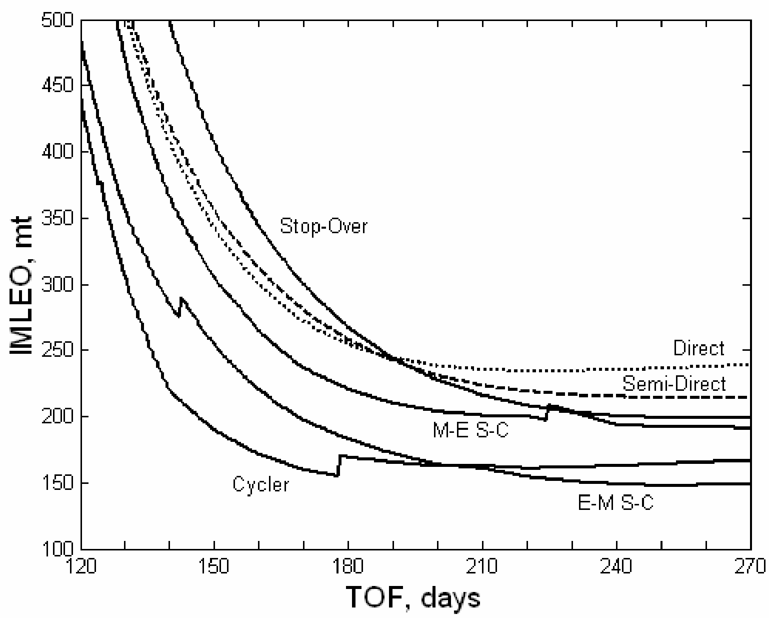


Fig. 6 IMLEO a function of TOF for the six architectures in row *11* of Table 5. Cargo transfer adds 3.80 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day.)

Table 8
Sensitivity of IMLEO to mission masses for row *11* of Table 4 and Table 5 with 210-day TOF where $\text{IMLEO} = a\bullet(\text{TV cabin}) + b\bullet(\text{taxi capsule}) + c\bullet(\text{consumables}) + d\bullet(\text{cargo})$

Architecture	*a*, mt/mt	*b*, mt/mt	*c*, mt/(kg/day)	*d*, mt/mt
Direct	7.60	0	2.57	3.80
Semi-Direct	5.35	7.78	2.40	3.80
Stop-Over	4.95	7.95	2.45	3.80
M-E S-C	3.18	11.0	2.91	3.80
E-M S-C	2.98	8.18	1.99	3.80
Cycler	2.07	12.5	2.56	3.80

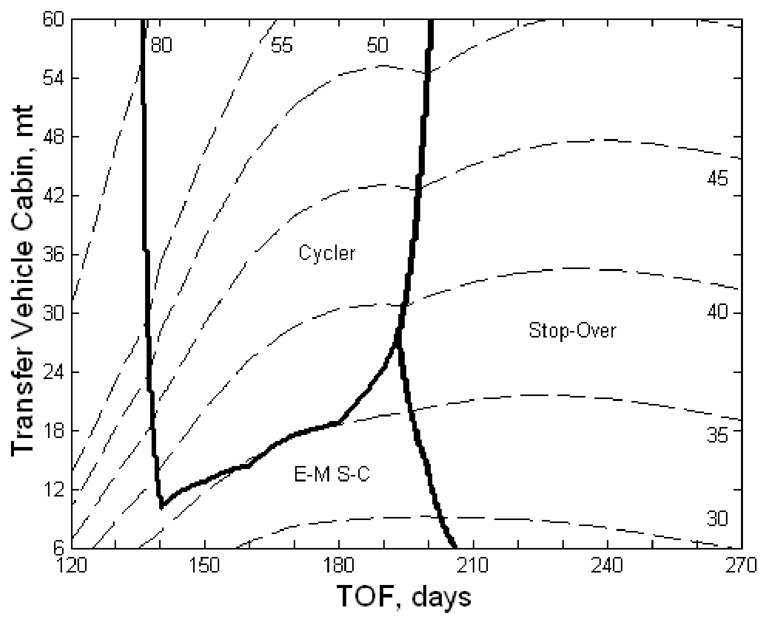


Fig. 7 Optimal transportation architectures corresponding to row 27 of Table 5. Contour lines are IMLEO in mt. Cargo transfer adds 1.39 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, consumables = 20 kg/day.)

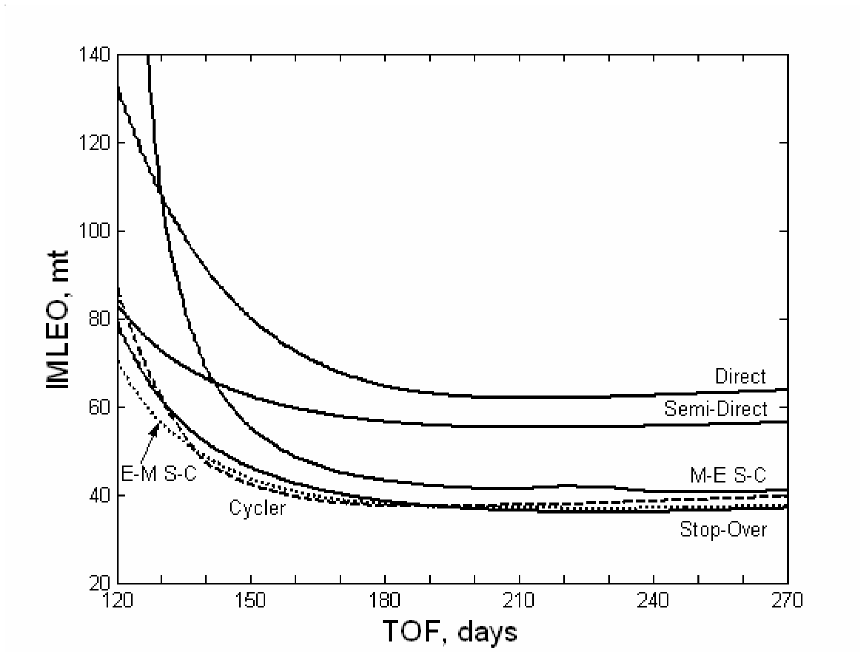


Fig. 8 IMLEO a function of TOF for the six architectures in row *27* of Table 5. Cargo transfer adds 1.39 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day.)

Table 9
Sensitivity of IMLEO to mission masses for row *27* of Table 4 and Table 5 with 210-day TOF where $\text{IMLEO} = a \cdot (\text{TV cabin}) + b \cdot (\text{taxi capsule}) + c \cdot (\text{consumables}) + d \cdot (\text{cargo})$

Architecture	*a*, mt/mt	*b*, mt/mt	*c*, mt/(kg/day)	*d*, mt/mt
Direct	1.89	0	0.806	1.39
Semi-Direct	1.21	1.87	0.737	1.39
Stop-Over	0.425	1.84	0.748	1.39
M-E S-C	0.478	2.19	0.827	1.39
E-M S-C	0.470	1.90	0.722	1.39
Cycler	0.420	2.01	0.773	1.39

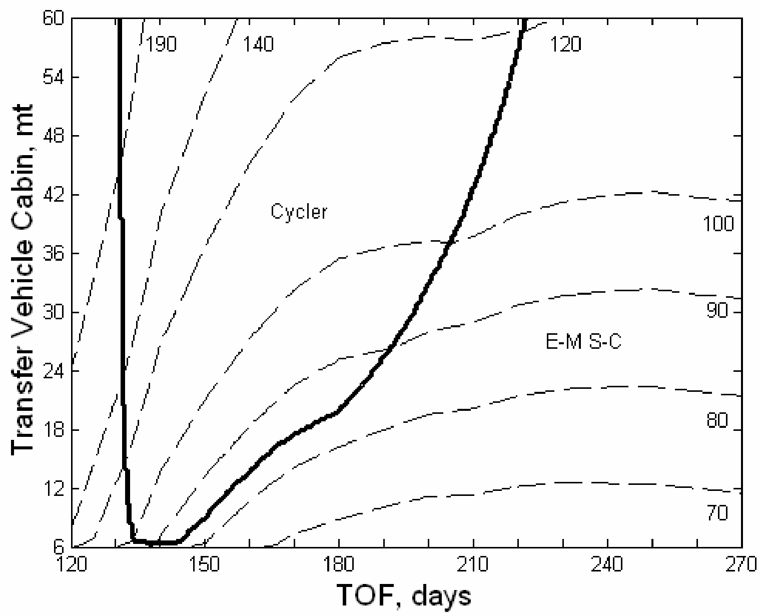


Fig. 9 Optimal transportation architectures corresponding to row *31* of Table 5. Contour lines are IMLEO in mt. Cargo transfer adds 2.55 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, consumables = 20 kg/day.)

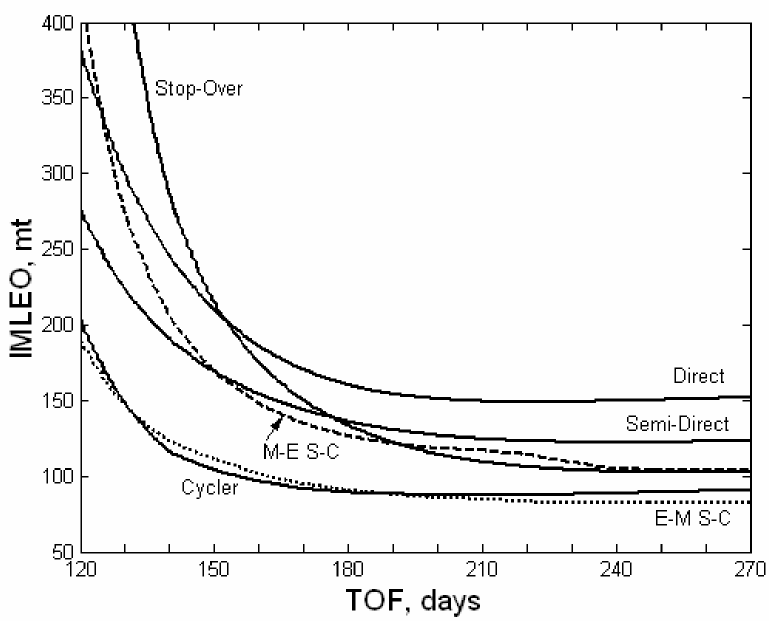


Fig. 10 IMLEO a function of TOF for the six architectures in row *31* of Table 5. Cargo transfer adds 2.55 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day.)

Table 10
Sensitivity of IMLEO to mission masses for row *31* of Table 4 and Table 5 with 210-day TOF where $\text{IMLEO} = a \bullet (\text{TV cabin}) + b \bullet (\text{taxi capsule}) + c \bullet (\text{consumables}) + d \bullet (\text{cargo})$

Architecture	*a*, mt/mt	*b*, mt/mt	*c*, mt/(kg/day)	*d*, mt/mt
Direct	4.80	0	1.69	2.55
Semi-Direct	2.80	4.53	1.48	2.55
Stop-Over	2.09	4.70	1.54	2.55
M-E S-C	1.70	6.52	1.83	2.55
E-M S-C	1.16	4.93	1.35	2.55
Cycler	0.978	5.55	1.54	2.55

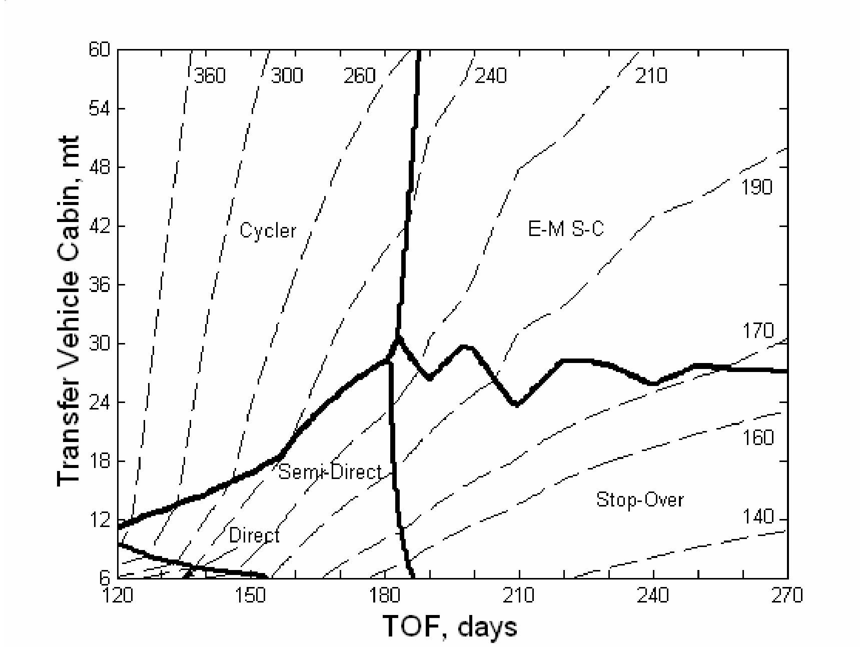


Fig. 11 Optimal transportation architectures corresponding to row *32* of Table 5. Contour lines are IMLEO in mt. Cargo transfer adds 1.73 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, consumables = 20 kg/day.)

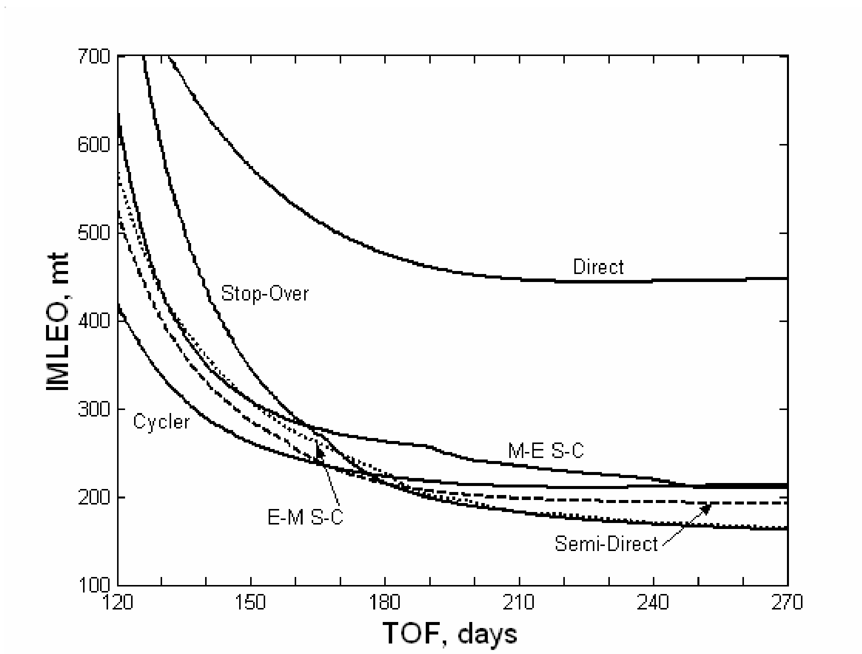


Fig. 12 IMLEO a function of TOF for the six architectures in row *32* of Table 5. Cargo transfer adds 1.73 times the cargo mass to the IMLEO values. (Taxi capsule = 6 mt, TV cabin = 24 mt, consumables = 20 kg/day.)

Table 11
Sensitivity of IMLEO to mission masses for row *32* of Table 4 and Table 5 with 210-day TOF where $\text{IMLEO} = a \bullet (\text{TV cabin}) + b \bullet (\text{taxi capsule}) + c \bullet (\text{consumables}) + d \bullet (\text{cargo})$

Architecture	*a*, mt/mt	*b*, mt/mt	*c*, mt/(kg/day)	*d*, mt/mt
Direct	15.0	0	4.23	1.73
Semi-Direct	2.69	15.7	1.97	1.73
Stop-Over	2.05	15.8	1.91	1.73
M-E S-C	2.53	19.1	2.96	1.73
E-M S-C	1.21	19.9	1.67	1.73
Cycler	1.09	22.8	2.46	1.73

7. IMLEO COMPARISON

The first twelve rows of Table 4 and Table 5 provide the IMLEO savings of developing a single technology (excluding row *10*, which considers two technologies). Electric propulsion (row *5*, Fig. 3, Fig. 4, and Table 8) is effective when a substantial amount of cargo is transferred to Mars (as in Table 4), especially for semi-direct, stop-over, and Earth-Mars semi-cycler architectures. The combination of NTR launch vehicles and upper stages (row *12*) also produces low IMLEO values. This combination is effective because the NTR Mars launch vehicles reduce the taxi mass while the NTR Earth upper-stages reduce cargo vehicle mass. Mars water excavation (row *11*, Fig. 5, Fig. 6, and Table 9) provides substantial IMLEO savings when the crew travels to Mars without cargo (as in Table 5). Technologies that reduce Mars taxi mass, such as Mars water excavation, in-situ propellant production, and NTR launch vehicles are most beneficial to direct, Earth-Mars semi-cycler, and cycler missions as the Mars launch-vehicle requirements are greatest with these architectures. In a direct mission the launch vehicle must inject the relatively massive transfer vehicle into orbit, while in Earth-Mars semi-cycler and cycler missions the Mars taxi must achieve a substantial V_∞ to rendezvous with the transfer vehicle. Another way to reduce the Mars launch-vehicle mass is to capture the upper stage into a parking orbit at Mars arrival (as in rows *3* and *4*) instead of landing it on the surface and then launching it into a parking orbit. Technologies that reduce transfer vehicle requirements, such as aerocapture, nuclear thermal rockets, and EP upper-stages are most effective on semi-direct, stop-over, and (to a lesser extent) Mars-Earth semi-cycler missions as the transfer vehicle requires more ΔV capability with these architectures. Electric propulsion for transfer vehicles (row *9*) is effective for Earth-Mars semi-cyclers and cyclers because the ΔV and acceleration requirements for these trajectories are relatively small. On the other hand, stop-over trajectories require substantial ΔV and acceleration to travel between the planets with a limited TOF. This additional acceleration requires more thrust, power, and system mass, which increases the IMLEO. Finally, the development of reusable propulsion systems alone does not significantly alter the IMLEO from the expendable propulsion system scenario (rows *1* and *2*). This case is therefore omitted from Table 4 and Table 5. Based on the IMLEO values in these tables, the approximate rank order (from lowest to highest IMLEO) by developing a single technology is given in Table 12. We note that Table 12 considers the IMLEO benefits of employing only one new technology in a given mission, and that substantial mass reductions are possible by combining technologies for Mars exploration.

Table 12
Lowest IMLEO by developing a single technology
(averaged across the values in Table 4 and Table 5)

Rank	Technology	TRL[a]
1	NTR Mars launch vehicles	4
2	Mars water excavation	3
3	Cargo electric propulsion	7
4[b]	NTR upper stages	6
4[c]	In-situ propellant production	5
4[d]	Transfer vehicle electric propulsion	5
7[b]	Aerocapture	5
7[c]	Tankers to Mars	7
9	Reusable Mars launch vehicles	5

[a]Table 2 contains descriptions of technology readiness levels.
[b]For semi-direct, stop-over, and Mars-Earth semi-cycler architectures.
[c]For direct, Earth-Mars semi-cycler, and cycler architectures.
[d]For missions with large cargo transfers.

Though less storable, hydrogen-based propulsion systems (row *2*, Fig. 1, Fig. 2, and Table 7) require at least 100 mt (and up to 400 mt with direct missions) less IMLEO than methane-based systems (row *1*). Alternatively, methane propulsion systems must be supplemented by Mars tankers and aerocapture technology (row *10*) to provide similar IMLEO values as LOX/LH_2 systems with no other technology development. Moreover, the lowest IMLEO scenarios (row *27*, Fig. 10, Fig. 11, and Table 10) incorporate hydrogen-based propulsion systems. If a reliable process is developed to create LOX/LH_2 from water found on Mars, then no propellant is required from Earth to depart Mars. Moreover, if the propulsion systems (and propellant tanks) are reusable, then very little hardware must come from Earth for Mars departure. Finally, if reusable tankers transport LOX/LH_2 from Mars to LEO, then no propellant must be launched from Earth into LEO for Earth departure. In this case, only the crew, taxi, transfer vehicle (or refurbishments), cargo, consumables, and heatshields are injected into LEO by Earth launch vehicles, hence the low IMLEO values in row *27*. The use of nuclear thermal rockets (as in row *33*) reduces the amount of water that must be excavated at Mars, but typically increases IMLEO because more massive heatshields are necessary to reclaim the spent NTR stages (which have more inert mass than chemical systems) at Mars. The use of hydrogen propellant in EP upper stages has a similar effect.

If water on Mars is not readily available, then the minimum IMLEO with methane-based propulsion systems is found in rows *35* and *36*. In row *35*, LOX/CH_4 is sent to Earth orbit for use by the transfer vehicles and taxis, but not Earth-Mars cargo vehicles. Mars-produced methane is not used by cargo vehicles because the additional hydrogen feedstock (to create methane on Mars) results in excessive IMLEO. (We note that no feedstock is necessary if water is available on Mars.) In row *36*, no methane is returned to Earth and nuclear thermal rockets carry the crew out of LEO. The minimum methane-based IMLEO values vary from 1.5 times to over twice the minimum hydrogen-based values, as seen by comparing row *36* with row *27*.

The IMLEO for the combination of electric propulsion with in-situ propellant production, aerocapture, or reusable propulsion systems is found in rows *14–16*, and IMLEO for the combination of nuclear thermal rockets with each of these three technologies is provided in rows *17–19* of Table 4 and Table 5. The combination of electric propulsion and in-situ propellant production is particularly effective, and requires less IMLEO than the combination of electric propulsion and nuclear thermal rockets (row *13*). However, the combination of nuclear thermal rockets and in-situ propellant production is also attractive when no cargo transfer is required (row *17* of Table 5). Moreover, a significant design trade arises when comparing electric propulsion and nuclear thermal rockets for cargo transfers, as EP may take up to four years to reach Mars from Earth whereas NTR require less than a year to transfer cargo to Mars.

The IMLEO for Mars missions that incorporate NTR upper stages, in-situ propellant production, and aerocapture is provided in row *29*. However, if reusable propulsion systems (including Mars launch vehicles) require the same development cost as aerocapture technology (e.g. heat shields and guidance algorithms for the transfer vehicles), then lower IMLEO values are possible with the same technology investment (as seen by comparing row *30* with row *29*). Moreover, if the NTR technology employed by the upper stages is adapted for use on the transfer vehicles (as in row *31*, Fig. 9, Fig. 10, and Table 11), then even further reductions in IMLEO are possible. Again, there is a significant trade between the higher performance of hydrogen-based propulsion systems (row *31*) and the longer storability of methane-based systems (row *30*).

In the odd-numbered figures of Fig. 1–Fig. 12, the minimum IMLEO architectures are usually Earth-Mars semi-cyclers or cyclers for large transfer vehicles, and semi-direct or stop-overs for smaller transfer vehicles. (Fig. 7 is a notable exception, where stop-overs are optimal regardless of transfer vehicle mass for long TOF.) Further, cyclers are IMLEO-optimal for any combination of transfer vehicle mass and transfer TOF with in-situ propellant production (row *8*); Earth-Mars semi-cyclers are always optimal assuming the technology development of rows *14* or *36*; and the optimal-architecture plots corresponding to rows *12* and *17* have similar characteristics as the plot corresponding to row 31 (i.e. they resemble Fig. 9 with different contour values). Indeed, the lowest IMLEO values in Table 4 and Table 5 are predominantly Earth-Mars semi-cyclers and cyclers.

The coefficients presented in Table 6–Table 11 drive this trend. The sensitivity of IMLEO to the transfer vehicle mass (column *a* of Table 6–Table 11) for Earth-Mars semi-cyclers and cyclers is usually half the sensitivity for semi-direct and stop-over missions. Thus, as the transfer vehicle mass increases (to values that are increasingly safe and comfortable for the crew) the IMLEO increases at only half the rate for Earth-Mars semi-cyclers and cyclers when compared to the other architectures. However, if the taxi capsule mass is relatively large compared to the transfer vehicle cabin mass, then semi-cyclers and cyclers are at a disadvantage because the taxi must achieve a higher departure V_∞ to follow the semi-cycler or cycler trajectory. The corresponding ΔV is reflected in the higher coefficients for semi-cycler and cycler taxis in column *b* of Table 6–Table 11. Hence, for smaller transfer vehicles (or larger taxis), the semi-direct and stop-over scenarios require relatively less IMLEO. The direct transfer vehicle, semi-direct taxi, and stop-over taxi have similar coefficients in these tables because they all require about the same ΔV during a Mars mission. The approximate ranking of the architectures based on the overall IMLEO values is provided in Table 13.

Table 13
Rank order of architectures from lowest to highest IMLEO
(averaged across the values in Table 4 and Table 5)

Rank	Architecture
1	E-M semi-cycler
2	Cycler
3[a]	Semi-direct
3[b]	Stop-over
5	M-E semi-cycler
6	Direct

[a]For electric propulsion and Mars tanker technologies.
[b]For NTR, aerocapture, and reusable propulsion system technologies.

In the even-numbered figures of Fig. 1–Fig. 12, we see that the IMLEO becomes nearly constant for flight times longer than 170–220 days. The IMLEO values reach a minimum at a shorter TOF (of around 170 days) in Fig. 7, because the propellant and propulsion systems for the transfer vehicles, which are most sensitive to the TOF, are not launched into LEO in this scenario. (The propellant comes from Mars and the systems are reused.) On the other hand, in Fig. 12 the IMLEO do not reach minimum values until longer TOF (of approximately 220 days), because the ΔV for low-thrust transfers continue to decrease as the TOF is extended beyond 270 days. (The ΔV for impulsive transfers usually reaches a minimum value before 270-days TOF.) Cycler architectures achieve low IMLEO values at shorter TOF because the cycler trajectories naturally follow short TOF transfers [45]. The Mars-Earth semi-cyclers reach minimum IMLEO values at longer TOF because their ΔV do not significantly decrease until after approximately 240-days TOF [42]. The IMLEO usually increase at long TOF because more consumables are required for the corresponding longer mission durations, and the transfer vehicle ΔV is no longer decreasing at an appreciable rate. The minimum IMLEO is usually found at around 240 days of TOF. The effect on IMLEO due to TOF is also apparent in the odd-numbered figures of Fig. 1–Fig. 12. In these figures, nearly vertical contours indicate significant reductions in IMLEO for increasing TOF, while nearly horizontal contours indicate little sensitivity to TOF. Again, the transition from high to low sensitivity to TOF usually occurs between 170 and 220 days and the minimum IMLEO values occur around flight times of 240 days.

If water is unavailable on Mars, then Mars exploration will likely involve methane-based propulsion systems to make use of the indigenous resources (namely, carbon dioxide). However, we suggest that nuclear thermal rockets for Earth upper stages and transfer vehicles should be developed first. This technology is better suited to establish a foothold on Mars than in-situ propellant production because it can be used to transport cargo to Mars. Based on the architecture simplicity, the first few missions could be semi-direct with LOX/CH_4 chemical propulsion systems for the Mars taxis and NTR for cargo, Earth upper stages, and transfer vehicles. For a crew of four with 40 mt of cargo the initial IMLEO will be 370 mt (from row *6* of Table 4). During the first missions the transfer vehicle (and taxi) will most likely evolve over several design iterations, but at some point the design will be optimized and it will be appropriate to begin reusing the transfer vehicles. Once a base on Mars is established, the IMLEO to transport a crew of four without any cargo is 253 mt with the stop-over architecture (from row *6* of Table 5). Next, a system to produce methane and oxygen on Mars could be developed. (For example, resources that were used to design and test nuclear thermal rockets may be switched over to ISPP development.) With the construction of two more transfer vehicles (for a total of four), the Earth-Mars semi-cycler architecture provides an IMLEO of 114 mt (from row *17* of Table 5). Then, if reusable Mars launch vehicles and transfer vehicle propulsion systems are developed, the IMLEO is 84.5 mt (from row *31* of Table 5). At this point, we may wish to double the crew size (to eight) and expand our capability to explore Mars. To accomplish this, the four transfer vehicles may be combined into two larger transfer vehicles for use in a stop-over architecture. Assuming 60-mt transfer vehicles (the combination of two 24-mt vehicles plus an extra 12 mt for added safety and comfort) and a crew of eight, the IMLEO is 243 mt with the stop-over architecture (from Table 10). (Here, we also assume 12-mt taxi capsules and 40 kg/day of consumables.) The IMLEO may be reduced to 183 mt with the construction of two more 60-mt transfer vehicles for use in the Earth-Mars semi-cycler architecture. However, the IMLEO benefits must justify the cost of building two extra transfer vehicles. We also note that the development of additional technologies such as electric propulsion and aerocapture can further reduce the IMLEO (e.g. compare row *31* with row *36* in Table 4 and Table 5). Again, the cost to design and test these new technologies may outweigh the advantages of lower IMLEO.

Table 14
Possible scenario to establish and sustain Mars exploration without Mars water excavation

Phase	Technolgy Development	Architecture	IMLEO
Develop infrastructure	Nuclear thermal rockets	Semi-direct	370
Explore with crew of 4	Reusable transfer vehicles	Stop-over	253
Explore with crew of 4	Hyperbolic rendezvous and in-situ propellant production	E-M semi-cycler	114
Explore with crew of 4	Reusable propulsion systems	E-M semi-cycler	85
Explore with crew of 8	Advanced transfer vehicles (additional mass for safety and comfort)	Stop-over *or* E-M semi-cycler	243 183

If water is available on Mars, then we advocate the following scenario to establish and sustain human exploration of Mars based on the combination of IMLEO benefits and technology development. Before the first mission to Mars, electric propulsion systems with thrust levels of around ten Newtons (at a specific mass of 50 kg/kW) should be developed. These systems will be used to transport cargo to Mars (to build infrastructure for exploration) and boost transfer vehicles from LEO to a high-energy elliptical Earth orbit. The first few missions should be semi-direct with electric propulsion for cargo and LOX/LH_2 chemical propulsion systems for the taxis and transfer vehicles. With a crew of four, the initial IMLEO will be 274 mt (from row *5* of Table 4). Then, after the construction of four reusable transfer vehicles, the Earth-Mars semi-cycler architecture only requires 186 mt of IMLEO with no cargo transfer (from row *5* of Table 5). The next step is to develop a method to collect and electrolyze water on Mars and store the LOX and LH_2 propellants. With this technology, the IMLEO is reduced to 107 mt (from row *20* of Table 5). With the development of reusable Mars launch vehicles and transfer vehicle propulsion systems, the IMLEO becomes 108 mt (from row *24* of Table 5) and no more electric propulsion vehicles are required. Moreover, we can reduce the IMLEO significantly by sending Mars-produced propellants to Earth. Assuming 60-mt transfer vehicles to support a crew of eight, the IMLEO is only 77.5 mt using the stop-over architecture (from Table 9). With this architecture and technology base, Mars exploration can continue to grow in terms of crew number and vehicle size with the least impact on IMLEO as compared to other scenarios. Only two transfer vehicles are required and no exotic propulsion systems are used. Furthermore, only half as many launch vehicles are needed to transport twice the crew of the initial exploration missions. Such a scenario can be a safe, economic, and reliable means to sustain a human presence on Mars.

Table 15
Possible scenario to establish and sustain Mars exploration with Mars water excavation

Phase	Technolgy Development	Architecture	IMLEO
Develop infrastructure	Cargo electric propulsion	Semi-direct	274
Explore with crew of 4	Hyperbolic rendezvous and reusable transfer vehicles	E-M semi-cycler	186
Explore with crew of 4	Mars water excavation	E-M semi-cycler	107
Explore with crew of 4	Reusable propulsion systems and phase out EP systems	E-M semi-cycler	108
Explore with crew of 8	Transport propellant from Mars to Earth	Stop-over	78

8. CONCLUDING REMARKS

If only one technology is to be developed for Mars exploration, then NTR Mars launch vehicles and upper stages provide the lowest IMLEO. However, electric propulsion for cargo transfers has a low IMLEO and is currently at a higher technology readiness level than NTR launch vehicles. For a given technology base Earth-Mars semi-cyclers and cyclers usually require the least IMLEO of any architecture. Moreover, the the IMLEO is about half as sensitive to the transfer vehicle mass with these architectures when compared to the alternatives. If water is unavailable on Mars then the combination of NTR upper stages, in-situ propellant production, and reusable propulsion systems require little IMLEO and only three new technologies are required. However, if water may be excavated at Mars then the required IMLEO can be half of the mass required with methane-based propulsion. In this scenario, traditional LOX/LH_2 propulsion is used with the addition of Mars water, reusable propulsion systems, and propellant tankers that travel from Mars to Earth. The discovery of significant quantities of accessible water on Mars would have the most dramatic impact on how humans travel to and explore Mars. Thus the search for water on Mars via robotic missions is strongly indicated before humans embark on exploring and colonizing the planet.

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