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Terminology: CL-payload includes the payload landed on Mars, plus the entry systems for MOI and EDL (less propulsion for MOI and EDL).

EDL: Entry, Descent and Landing; ELA: Evolvable Lunar Architecture; ELC: Evolvable Lunar Campaign; IMLEO: Initial Mass in Low Earth Orbit; ISPP: In Situ Propellant Production; ISRU: In-situ Resource Utilization; LEO: Low Earth Orbit; MCTV: Mars Cargo Transfer Vehicle; MOI: Mars Orbit Insertion; TMI: Trans-Mars Injection; TMI-payload includes the payload landed on Mars, plus the entry systems for MOI and EDL.

Research Article

Lunar-Derived Propellants for Fueling Mars-Bound Spacecraft in Cis-Lunar Space

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Abstract

The conventional method to send payloads to Mars is by direct trans-Mars injection (TMI) from LEO. NASA is considering an alternative of fueling large Mars-bound cargo transfer vehicles in cis-lunar space with propellants derived from the Moon by in situ propellant production (ISPP) prior to trans-Mars injection from cis-lunar space.

A large team of investigators developed an Evolvable Lunar Campaign (ELC) that defined its strategic objective as follows:

"The ELC strategic objective is commercial mining of propellant from lunar poles where it will be transported to lunar orbit to be used by NASA to send humans to Mars."

Unfortunately, sending Mars-bound vehicles to cis-lunar space prior to trans-Mars injection saves little mass in LEO, unnecessarily includes lunar ISPP, which is costly, complex, and risky, and at the bottom line, has no benefits.

The problem is that the amount of propellant needed to go from LEO to cis-lunar space is roughly comparable to the amount of propellant used for direct TMI from LEO, so the lunar-derived propellants only offset a small amount of propellant used to augment Mars Orbit Insertion and Entry, Descent, and Landing, and the amount of propellant required in LEO is almost the same in both cases. The initial mass in low Earth orbit (IMLEO) is not reduced much by utilizing lunar ISPP.

At the bottom line, sending Mars-bound MCTV to cis-lunar space adds complexity, cost, and risk and provides essentially no benefits.

Introduction

A human mission to Mars will inevitably require sending large payloads to Mars. Rapp summarized various concepts for such a mission [1]. At this early stage, there are no firm requirements or plans or such a mission.

It is not yet clear how many tons of payload can be launched from Earth to low Earth orbit (LEO) in the years ahead, depending on future progress made by Space X. Nor is it clear how massive a load can ultimately be landed on Mars. There is likely to be a need for aggregation and/or assembly in space, and it is not certain where in space that would best be done. While some argue for cis-lunar space, it would be far more convenient to do this in LEO. Despite all this uncertainty about a potential future human mission to Mars, two important mission aspects can be relied upon as certain:

1. A significant amount of propellant will be needed to depart from LEO, either in trans-Mars injection or to approach cis-lunar space.

2. A lesser amount of propellant will be needed in conjunction with aero-assisted Mars orbit insertion (MOI) and entry, descent, and landing on Mars (EDL).

The conventional approach for sending large MCTVs from LEO to Mars is to send them directly out of Earth orbit via trans-Mars injection. The MCTV leaving LEO will carry the ultimate payload landed on Mars, plus the systems for MOI and EDL, which utilize aero-assist with a moderate amount of ancillary propulsion.

In recent years, several proposals were made to use cis-lunar space as a launching point for Mars-bound vehicles [2,3].

Jones, et al. (2020) and Charles, et al. (2015) suggested using a location in cis-lunar space for staging large loads and fueling them with propellants derived from the Moon by ISPP, prior to trans-Mars injection from that location [2,3]. The propellant ordinarily used in the conventional mission for trans-Mars injection from LEO would be replaced by the propellant required for sending the MCTV from LEO to cis-lunar space, plus the propellant for trans-Mars injection from cis-lunar space. Depending on specific launch dates, the propellant requirement for transfer from LEO to cis-lunar space is likely to be comparable (or slightly less) to that for trans-Mars injection from LEO. The net benefit of the lunar ISPP concept is not replacing the propellant used to depart LEO in the conventional mission, but rather, replacing the propellant used to support MOI and EDL at Mars. This important point needs to be understood before proceeding. It was not made clear by Jones, et al. (2020) and Charles et al. (2015).

This report presents an analysis of concepts by Jones, et al. (2020) and Charles, et al. (2015) for utilizing propellants produced on the Moon for fueling massive Mars-bound MCTV in cis-lunar space [2,3].

The concept of using a location in cis-lunar space for staging large loads and fueling them with propellants derived from the Moon by ISPP prior to trans-Mars injection was analyzed by Jones, et al. [2]. This paper began with the statement:

"Human exploration missions to Mars require large quantities of propellant in space to enable the transportation of required elements from Earth to Mars. Current and proposed launch vehicles are incapable of launching all of the requisite mass on a single vehicle; hence, multiple launches and in-space aggregation are required to perform a Mars mission [2]."

It appears almost certain that multiple launches will be required for a human mission to Mars, and aggregation is likely to be needed, depending on launch mass to LEO and maximum landing mass. However, it is not clear that aggregation in cis-lunar space has any advantage over aggregation in LEO, which is far more accessible.

Jones, et al. (2020) went on to say:

"Lunar in-situ resource utilization (ISRU) could be used to produce and deliver liquid oxygen and liquid hydrogen from the lunar surface to a propellant aggregation location. Such an approach could lead to future Mars missions requiring only the launch of spares and new Mars payloads from Earth to cis-lunar space, with the propellant being supplied from the Moon."

This statement fails to recognize that a large amount of propellant is needed in LEO, and only smaller amounts are needed after leaving LEO. The mass of propellants that could be supplied by lunar ISRU would be small compared to the propellant from Earth supplied to LEO for transfer to cis-lunar space. In fact, not much, if anything, is saved by utilizing cis-lunar space for Mars missions.

Jones, et al. (2020) then defined the scope of their study as:

"This research examined the question: how does propellant delivered to cis-lunar space from Earth compare to propellant delivered from the Moon on the basis of cost?"

In this statement, the term "propellant" must refer to the propellant used to assist MOI and EDL because the propellant to transfer from LEO to cis-lunar space seems to have been neglected.

Answers to questions only matter if you ask the right questions. This question is improperly formulated because it makes it appear as if one must proceed through a junction in cis-lunar space to proceed toward Mars. It assumes that there are two possibilities, both passing through a cis-lunar launch point toward Mars. In one case propellant to assist MOI and EDL is supplied to cis-lunar space from lunar ISPP, and in the other case, propellant to assist MOI and EDL is delivered from LEO to cis-lunar space from LEO. It ignores the fact that one can go directly from LEO to TMI without passing through cis-lunar space, which is the conventional approach (and the best approach by far).

So, the issue here is defined differently from Reference #2. Two competing concepts are defined:

(A) Send the Mars Cargo Transfer Vehicle (MCTV) directly from LEO into TMI. The MCTV leaving LEO includes the landed payload (mass=MPL), propellant for TMI from LEO (mass=MP_1), propellant to assist MOI (mass=MP_2), and propellant to assist EDL (mass=MP_3). The relevant initial mass in LEO (IMLEO) (neglecting the propulsion system mass) is:

$$\text{IMLEO-A} = MPL + MP_1 + MP_2 + MP_3$$

(B) Send the MCTV from LEO into cis-lunar space. The (MCTV) leaving LEO includes the landed payload (mass=MPL), propellant for transfer from LEO to cis-lunar space (MP_4), but not propellant for departure from cis-lunar space (mass=MCL), and not propellant to assist MOI and EDL (mass=MP_2 and MP_3) which is supplied by lunar ISPP. The relevant initial mass in LEO (IMLEO) – neglecting MCTV and propulsion system mass) is:

$$IMLEO\text{-}B= MPL + MP_4 + MCL + MP_2 + MP_3$$

Presuming that IMLEO-B is less than IMLEO-A, the net saving in mass in LEO by utilizing lunar ISPP is:

$$\Delta IMLEO=IMLEO\text{-}A – IMLEO\text{-}B$$

If the cost (dollars per ton) to send cargo to LEO is CLEO, then the cost saving by utilizing cis-lunar space is:

$$(SLEO)=(CLEO)(\Delta IMLEO)$$

It seems certain that the investment, infrastructure, implementation, logistics, and risk involved in prospecting, developing, validating, and implementing lunar ISPP (denoted as CISPP) far exceeds SLEO, especially as launch costs are dropping.

Charles, et al. (2015) also proposed the utilization of lunar ISPP to provide propellants to a "Mars Transfer Vehicle" in cis-lunar space. A quote from the Executive Summary is:

"The Evolvable Lunar Architecture (ELA) strategic objective is commercial mining of propellant from lunar poles where it will be transported to lunar orbit to be used by NASA to send humans to Mars [3]."

The propellant requirement to go from LEO to cis-lunar does not seem to have been included.

Delta-v, Gear Ratios and Propellant Requirements

Introduction

The present study is concerned with two concepts for supplying propellants to an MCTV for transport toward Mars, either in LEO or in cis-lunar space. In this section, the propellant requirements for each step of both mission concepts (direct and via cis-lunar space) will be estimated. For steps that are entirely carried out by impulsive propulsion, the method used is to employ the usual “rocket equation” that provides the propellant requirement to accelerate a payload mass through a given change in velocity (“delta-v”) for H_2–O_2 propellants. The delta-v is estimated first, and from that, an estimate of the ratio of propellant mass to mass transported is calculated. For MOI or EDL, entry is carried out mainly by an aero entry with an aero shield, and for landing, a parachute. A relatively smaller amount of propellant is required for these steps. The propellant requirement is based on complex entry models.

After propellant requirements for the mission steps are estimated, the various steps are organized into an end-to-end sequence in Section 3 to determine the propellant mass in LEO for both mission concepts.

The following transfers require propellants:

- TMI from LEO
- Transfer from LEO to cis-lunar space
- TMI from cis-lunar space
- Propulsion support for MOI using aero-assist
- Propulsion support for EDL using aero-assist

Trans-Mars injection from LEO

TMI from LEO was discussed at some length by Rapp [4]. At every launch opportunity, the "pork chop plot" typically shows two optimal regions for the departure date. The shortest (highest energy) trip is appropriate for crew delivery and the longest (lowest energy) trip is appropriate for cargo delivery. Over ten launch opportunities (separated by 26 months) the delta-v for cargo TMI from LEO varied from 3.6 km/s to 4.0 km/s [5]. On average, at 3.8 km/s, for each ton in LEO, there are about 0.35 tons of TMI payload, about 0.58 tons of propellant, and 0.07 tons of propulsion system. The TMI-propellant/payload ratio is about 1.66. (The "TMI-payload" includes the payload landed on Mars, plus the entry systems for MOI and EDL).

Transfer from LEO to cis-lunar space

The delta-v for transfer from LEO to cis-lunar space is widely circulated on the Internet to be roughly 3.7 km/s to 3.8 km/s which is in the same range as for TMI from LEO. Therefore, on average, for each ton in LEO, there are about 0.35 tons of "CL-payload", about 0.58 tons of propellant, and 0.07 tons of propulsion system. The propellant/payload ratio is about 1.66. The "CL-payload includes the payload landed on Mars, plus the entry systems for MOI and EDL (less propulsion for MOI and EDL)).

Trans-Mars injection from cis-lunar space

It is difficult to find formal estimates for delta-v for trans-Mars injection from cis-lunar space. Atomic Rockets suggested 0.74 km/s [6].

For each ton in cis-lunar space, there are 0.34 tons of propellants, 0.04 tons of propulsion system, and 0.62 tons of TMI-payload (less propellant for MOI and EDL).

Propulsion support for MOI and aero-assisted EDL

The analysis begins at the Mars surface. The landed mass is a 25-ton payload.

The next step is at the Mars orbit. Drake, B. G. (2009) provided an estimate that when the MCTV in Mars orbit is deorbited and carried through EDL, the mass of the landed payload is about 37% of the mass of the MCTV originally on orbit, and the propellant requirement for terminal descent is 10% of the mass of the MCTV on orbit [7]. However, studies of EDL by the Georgia Tech group, indicated that in aero-assisted EDL of large loads, the payload constituted 25.5% and propellant amounted to 28% of on-orbit mass prior to EDL [8]. All of these estimates are likely very approximate, but they are sufficient for our discussion. Here, we use the more optimistic estimate of Drake, B. G. (2009). The mass of the MCTV in Mars orbit is 25/0.37=68 tons. Of that, 6 tons is propellant, 25 tons is payload, and 37 tons is the EDL system.

Aerocapture was used for Mars Orbit Insertion (MOI) and some propellant is used in conjunction with the aerocapture process. Based on Georgia Tech studies, Rapp [9] estimated that about 60% of the mass of the MCTV approaching Mars can be put into Mars orbit using aerocapture. A rough guess is that propellant amounts to ~8% of the approach mass. The mass of the MCTV approaching Mars is 68/0.6=113 tons, of which 9 tons is propellant, 68 tons is the mass on orbit and 36 tons is the MOI system.

For purposes of discussion, use is made of these approximate estimates of mass percentages for delivery of a 25-ton payload to the Mars surface. The above estimates are very conservative. Hopefully, more efficient systems will be developed in the future to land higher percentages of payload on Mars. But regardless of the masses of entry systems for MOI and EDL, the main point of the present article is the near equality of propellant in LEO for TMI or transfer to cis-lunar space.

Results: End-to-end systems

Overview

In Section 2, the ratio of propellant mass to mass transported was estimated for each step of each mission concept. In this section, the absolute masses for each step are calculated. The process begins at Mars where a 25-ton payload is delivered to the surface. The process then involves working backward from the Mars surface, through the various steps, ending in LEO. The masses are calculated sequentially for each step from the Mars surface to LEO. The first steps evaluated are [Mars orbit ⇒ Mars surface], and [TMI ⇒ Mars orbit]. These are essentially the same for both mission concepts.

For the direct mission concept, the next step is [LEO ⇒ TMI]. For the mission concept utilizing cis-lunar space, the steps are [Cis-lunar ⇒ TMI] and [LEO ⇒ Cis-lunar].

The next section provides the details.

Direct transfer from LEO to Mars surface

In direct transfer from LEO to Mars, a first propulsion step sends the MCTV from LEO to TMI. On approaching Mars, an aerocapture system, aided by propulsion, inserts the MCTV into Mars orbit. EDL is implemented by a combination of aero-assist and propulsion. However, the calculational procedure works backward from landing a 25-ton payload on Mars, as explained previously. For example, it is estimated that it requires a 37-ton entry system plus about 6 tons of propellant to land the 25-ton payload from Mars orbit. Table 1 provides mass estimates for all steps of the mission.

The total amount of propellant through all stages is 204 tons. All of this propellant is supplied in LEO.

Transfer from LEO to Mars surface via Cis-Lunar space

In transfer from LEO to Mars via cis-lunar space, a first propulsion step sends the MCTV from LEO to cis-lunar space. In cis-lunar space, the MCTV is fueled with propellant to depart cis-lunar space, as well as for MOI and EDL. The MCTV that departs cis-lunar space approaches Mars and an aerocapture system, aided by propulsion, inserts the MCTV into Mars orbit. EDL is implemented with a combination of aero-assist and propulsion. Once in TMI, the steps are the same as for the direct mission concept. Table 2 provides mass estimates for all phases of the trip. In this table, the entries in red with an asterisk represent propellant requirements that are supplied by lunar ISPP. The masses in cis-lunar space and approaching Mars are distinguished by whether they include propellants produced by lunar ISPP, or whether they do not include those masses. In comparison to the direct mission concept, the masses excluding propellants produced by lunar ISPP should be used.

Table 1: Estimated masses at all stages of direct transfer from LEO to Mars surface.

Location	System	Mass (tons)
At Mars surface	Payload	25
On Mars orbit	Payload	25
	EDL propellant	6
	EDL system	37
	Total on-orbit mass	68
Approaching Mars	EDL system including payload	68
	MOI propellant	9
	MOI system	36
	Total mass approaching Mars	113
In LEO	System approaching Mars	113
	TMI propellant	189
	TMI propulsion	22
	Total mass in LEO	**324**

Table 2: Estimated masses at all stages of transfer from LEO to Mars surface via cis-lunar space.

Location	System	Mass (tons)
At Mars surface	Payload	25
On Mars orbit	Payload	25
	EDL propellant	6*
	EDL system	37
	Total on-orbit mass	68
	On-orbit mass from LEO	62
Approaching Mars	EDL system including payload	68
	MOI propellant	9*
	MOI system	36
	Total mass approaching Mars	113
	Total mass approaching Mars from LEO	104
In Cis-Lunar Space	System approaching Mars neglecting lunar-supplied propellant	104
	TMI propellant	35*
	TMI propulsion	4
	Total mass in Cis-Lunar space	143
	Total mass in cis-lunar space from LEO	108
In LEO	Mass sent to cis-lunar space	108
	Propellant in LEO	181
	Propulsion in LEO	21
	Total mass in LEO	**310**

The total amount of propellant through all stages is 231 tons. Of this, 50 tons of propellant is supplied by lunar ISPP and 181 tons of propellant is supplied in LEO.

The total mass in LEO for the mission utilizing cis-lunar space is 310 tons, compared to 324 tons for direct TMI from LEO. The mass saving in LEO from utilizing lunar ISPP is 14 tons.

Comparison of direct transfer to transfer via Cis-Lunar space

Veracity of the mass estimates: It was assumed that the Mars Cargo Transfer Vehicle is propelled into TMI by $H_2 - O_2$ propulsion with a specific impulse of 450 s. Upon approaching Mars, aerocapture is used for MOI, and aero-assist is used for EDL. The MOI and EDL steps require much smaller amounts of propellant than TMI.

The relative mass estimates for propulsion and propellants are reasonably accurate, but the absolute values are proportional to the estimated masses for the MOI system and the EDL entry systems, which are less certain. Conservative estimates were used for the masses of the MOI and EDL entry systems. It is possible that lesser values might be achievable, but that would not change any of the findings and conclusions in this paper.

Overall comparison of mission alternatives: A comparison of the masses in LEO in the two mission alternatives is shown in Figure 1.

A partial breakdown of the masses sent out of LEO is shown in Figure 2. In the direct mission, propellant is provided to support MOI and EDL. In the cis-lunar mission propellant to support MOI and EDL, and the propellant for TMI from cis-lunar space is shown as the white rectangle.

A full review of the masses involved in the steps of the two mission concepts is given in Figure 3.

Discussion

The concept of supplying large Mars-bound MCTV in cis-lunar space with propellant obtained by ISPP on the Moon has appeared in several NASA news releases and published papers.

Jones, et al. (2020) considered the use of lunar ISPP as a fuel supply in cis-lunar space a viable candidate, but estimated that the cost of ISPP might make it unattractive [2].

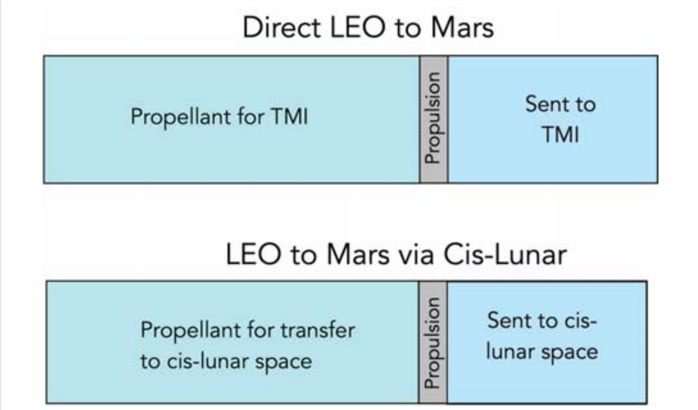

Figure 1: Comparison of the masses in LEO in the two mission alternatives. Propellant and propulsion account for about 2/3 of the initial mass in LEO.

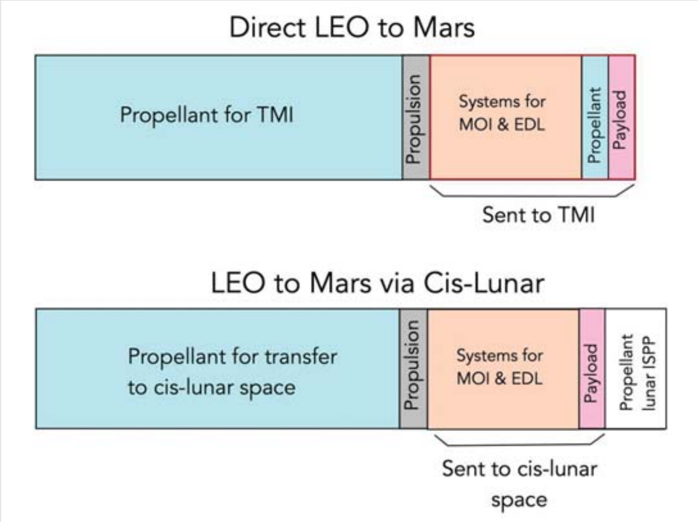

Figure 2: Partial breakdown of the masses sent out of LEO.

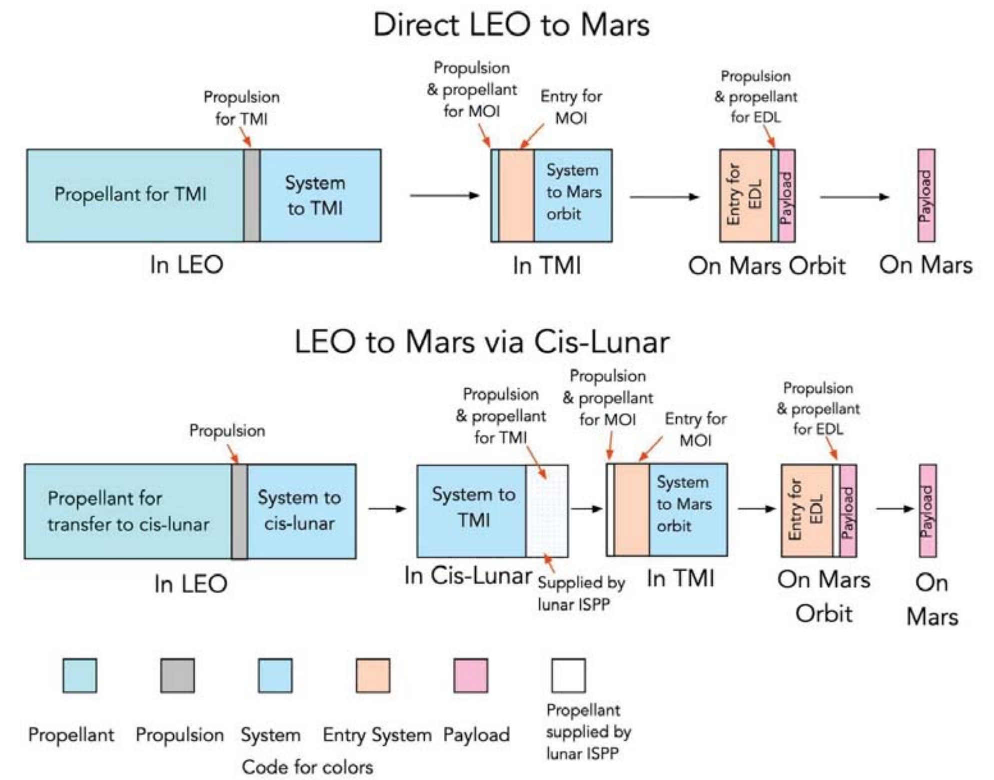

Figure 3: Masses involved in the two missions. Comparison of transfer steps in conventional and alternate concepts for delivery from LEO to the Mars surface.

Charles, et al. (2015) enthusiastically advocated the use of lunar ISPP for fueling large Mars-bound MCTV [3]. It is notable that this article was 103 pages, included six authors, and was reviewed by an "Independent Review Team" of 21 members. This large team of investigators analyzed an Evolvable Lunar Campaign (ELC) that defined its strategic objective as follows:

"The ELA strategic objective is commercial mining of propellant from lunar poles where it will be transported to lunar orbit to be used by NASA to send humans to Mars [3]."

Although they did not actually study the Mars architecture in detail, they argued that providing lunar-derived propellant to L2 in cis-lunar space for MCTV departure to Mars would be applicable to almost any evolving architecture. An extensive, costly enterprise to deliver propellants from the Moon to cis-lunar space was contemplated to provide the propellants.

What seems not to have been mentioned in these studies, is that it takes roughly the same amount of propellant to depart LEO for cis-lunar space as the amount of propellant required to go directly from LEO to TMI. If the goal is to reduce IMLEO, it simply doesn't work because no matter what steps follow, after the MCTV reaches cis-lunar space, the MCTV has already expended so much propellant transferring from LEO to cis-lunar space that IMLEO can't be reduced significantly by lunar ISPP.

While lunar ISPP can supply the propellant required for assisting MOI and EDL, these are relatively smaller amounts and do not justify the expense, complexity, logistics, and risk of lunar ISPP, which are discussed extensively by Rapp (2024) [10]. He reviewed the leading candidates for lunar ISPP including the carbothermal process to extract oxygen from lunar regolith, and the plan to extract putative ice embedded in permanently shadowed regions in lunar polar craters.

The carbothermal process entails 15 autonomous, sequential steps involving mining regolith, transporting it to a reactor in an autonomous vehicle, loading it into the reactor, reacting at 1,650 C (or higher), removing spent regolith, and delivering to a dump, returning the vehicle to the mining site, and processing the effluent from the reactor to produce liquid oxygen [11,12]. Four such deliveries would be made each day, and the system would operate continuously and autonomously for seven months.

The process to exploit putative ice in permanently shadowed regions of lunar polar craters requires an autonomous vehicle to remove frozen regolith, transport it to a heating chamber, dump it into the chamber, drive off the water vapor by heating, remove spent regolith, dump the spent regolith, and return to the mining site to repeat the process several thousand times [13-15]. Power would be supplied by beamed solar power from the rim of the crater [16]. The water so collected would have to be transported from the crater floor to the crater rim for electrolysis. Then H2 and O2 would have to be transported to the landing/ascent site.

Prior to the implementation described above, several missions to the Moon would be required for prospecting to locate veins of ice embedded in frozen regolith and validate the proposed process in situ [17].

In addition, an additional vehicle would be needed to ferry cryogenic propellants from the Moon to the MCTV in cis-lunar space.

The mass saving in LEO from the use of lunar ISPP has been shown to be minimal. The lunar ISPP enterprise is expensive and risky.

To put it simply:

The use of lunar ISPP to fuel Mars-bound MCTV in cis-lunar space makes no sense and ought to be discarded from consideration.

The issue involved in this paper is best illustrated by the diagram in Figure 4.

The usual (and sensible) approach for sending large MCTV to Mars is based on direct TMI from LEO as depicted by path "A". A large amount of propellant is required in LEO for path "A". Upon approaching Mars, the MCTV undergoes MOI and EDL to land on the surface. The MOI and EDL steps are mainly carried out by aero maneuvers, but small amounts of propellant are needed in these operations.

The alternative approach departs LEO bound for cis-lunar space via path "B". A large amount of propellant is needed in LEO (similar to that for path "A") for path "B". Lunar ISPP is used to produce propellants that are delivered to the MCTV in cis-lunar space using a propellant ferry via path "C". This propellant serves to enable path "D" from cis-lunar space toward Mars, as well as the small amounts of propellant used at Mars for MOI and EDL.

The problem is that since delta-v is essentially equal for both approaches, propellant requirements for paths "A" and "B" are almost equal, and the alternative approach does not save much mass in LEO [18]. Utilization of the alternate approach only serves to make the process more complicated, while adding the vast lunar ISPP enterprise, which is costly and risky. The best way to go to Mars from LEO is to go to Mars.

Conclusion

Based on the preceding results and discussion, the following conclusions are drawn.

1. A direct trans-Mars injection (TMI) from LEO to send an MCTV toward Mars is widely adopted in mission planning because it is simple and efficient.
2. The propellant requirement to depart LEO is large, and roughly comparable for either direct TMI or alternatively, for transfer from LEO to cis-lunar space.
3. The propellant requirement to support aero-assisted MOI and EDL at Mars is relatively small.

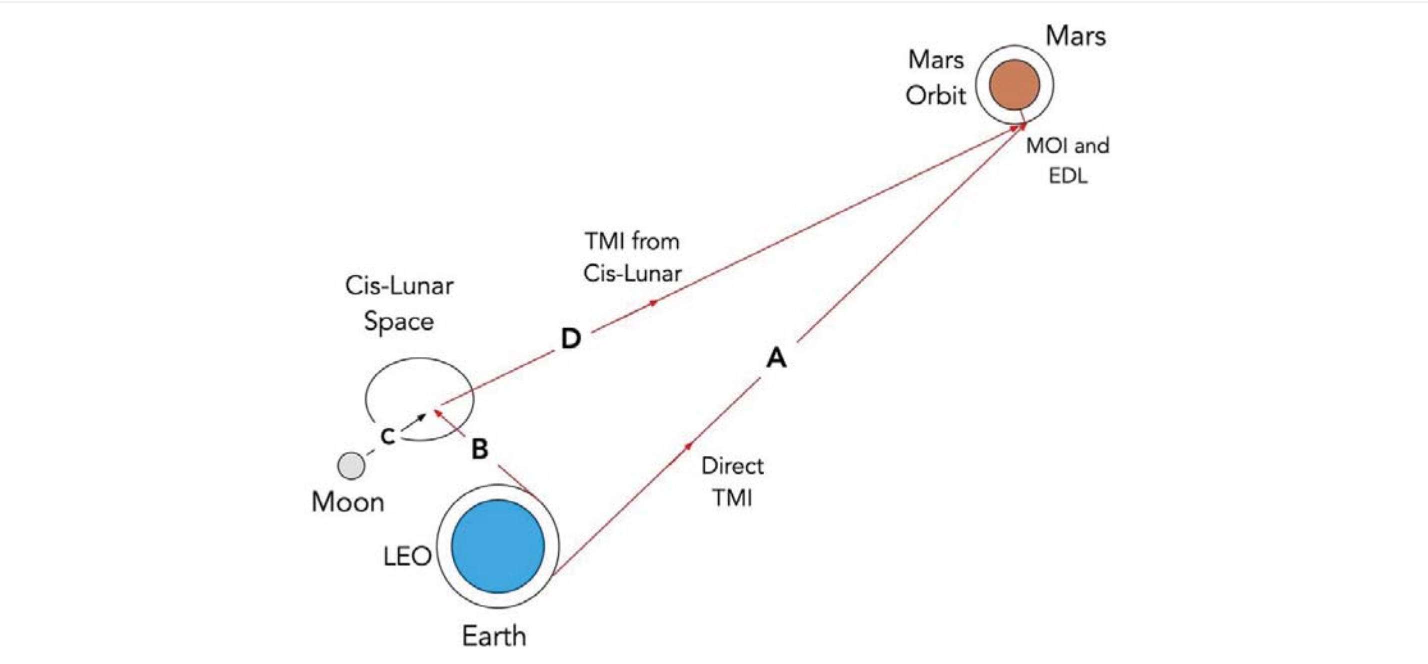

Figure 4: Alternate pathways for sending MCTV to Mars.

4. The proposal to utilize lunar ISPP to supply propellants to the MCTV in cis-lunar space only provides propellants for MOI and EDL, plus an extra step of TMI from cis-lunar space.
5. The initial mass in LEO (IMLEO) is only reduced a small amount by utilizing a pathway through cis-lunar space. The price paid for this small reduction is the cost and risk entailed by a large lunar ISPP enterprise plus a propellant ferry from the lunar surface to cis-lunar space.
6. The alternative approach to send the MCTV to cis-lunar space adds complexity, cost, and risk, and has essentially no benefit.

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