PROPELLANT AND CAPITAL EFFICIENT TRANS-MARS INJECTIONS USING LUNAR PROPELLANT, TRANSFORMING THE SPACEX MARS PROJECT. Nicholas J. Bennett[1], Andrew G. Dempster[2], and Serkan Saydam[3], [1] PhD Candidate, *Australian Centre for Space Engineering Research (ACSER), School of Electrical Engineering and Telecommunications, University of New South Wales (UNSW), Sydney, NSW, 2052, Australia,* nicholas.j.bennett@student.unsw.edu.au, [2]Director, *Australian Centre for Space Engineering Research (ACSER). Professor, School of Electrical Engineering and Telecommunications, University of New South Wales (UNSW), Sydney, NSW, 2052, Australia.* [3]Deputy Director, *Australian Centre for Space Engineering Research (ACSER). Professor, School of Minerals and Energy Resources Engineering, University of New South Wales (UNSW), Sydney, NSW, 2052, Australia*.

Introduction: The authors draw on their published work to formulate and quantify Concepts of Operations (CONOPs) supporting trans-Mars injections using lunar oxidizer. [1]-[5] The authors achieve propellant and capital efficiency by leveraging the astrodynamics of the Earth-Moon system, the oxygen to hydrogen ratio of water versus hydrolox, likely Mars-bound vehicles, and the concentration of vehicle use in cislunar space. Using the SpaceX Mars Project as a baseline, these contributions together reduce trans-Mars Starships and at-Mars propellant production by a factor of 4, total Earth launches by a factor of 4, rendezvous by nearly a factor of 2, and propellant tanker launches by a factor of 12 (Fig. 1). The proportion of Earth launches carrying high intrinsic value cargo increases from 17% to 70%.

The lunar oxidizer delivery CONOPs are not detailed, however, 53% of the baseline tanker launch costs, nearly 2,700 eliminated propellant launches, could be captured by a lunar oxidizer supplier. The authors discuss value capture from other more difficult to quantify benefits, like reduction of rendezvous and increased programmatic resilience.

The reductions in costs and Earth launches could be flipped to maintaining baseline spending and Earth launch cadence while increasing the payload mass flow to Mars by a factor of 4. Reducing cost or increasing return will greatly increase the project's IRR relative to the baseline, IRR of a breakeven 30-year Mars Project increases to 13.5%. One could make similar arguments regarding the non-financial benefits.

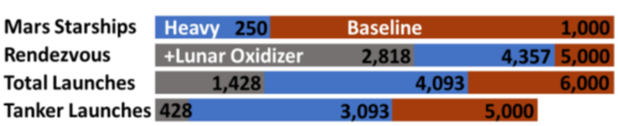

Figure 1: A selection of model metrics from the three scenarios. *Baseline*: SpaceX Mars Project (brown). *Heavy*: aggregated cargos marshalled in GTOs (blue). *Heavy Luna*: using lunar oxidizer (grey). The difference between *Heavy* and *Heavy Luna* is value that could be captured by a lunar oxidizer supplier.

The Moon as a Source of Oxidizer: Lunar sourced oxygen in GTOs has low transportation cost from the Moon and high value to a customer doing TMIs, the SpaceX Mars project will require the equivalent of ≈ 450,000 t/y of LOX in LEO. The authors examine the case of using lunar polar water to produce LH2LOX and excess oxygen byproduct. The hydrolox is then consumed to deliver the excess oxygen as oxidizer, increasing a given production facility's deliverable product by 50%. (Fig. 2)

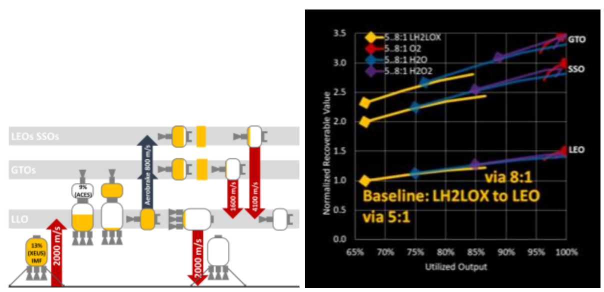

Figure 2: A transport model and the resulting lunar surface water propellant plant's production utilization vs capturable value, normalized to the case of delivering hydrolox in LEO with 5:1 LOX to LH2 propellant. Lines from the diamonds show the effect of varying transportation O:H ratio up to 8:1.

As the Moon passes through the Earth's equatorial plane, a trans-Earth injection performed from a lunar polar orbit can freely select an Earth orbit inclination to match a Mars marshalling orbit. The lunar vehicle can be inserted into Earth orbits between lunar distant and low Earth, with highly elliptical orbits (HEEOs) avoiding the higher propellant or aerobraking mass cost of lower apogee orbits and reducing the delta-v of the return to the Moon. Precession effects that drive sun-synchronous orbits can be harnessed by tuning the apogee to trade propellant against time to align lunar vehicle orbits for a rendezvous with elements marshalling for Mars.

A near GTO apogee is a compromise between low propellant cost from the Moon and a short orbital period for convenience of rendezvous. However, one might go as high as the lunar distant high Earth orbits used in some recent NASA NTR Mars proposals (with different motivations). [6, 7]

Heavy **Scenario; Transforming the Baseline SpaceX Mars Project into a More Valuable Customer for a Lunar Oxidizer Supplier:** The authors consider only the case of cargo transfers; the same dynamics apply to passenger transfers, but it is simpler to forgo considering human factors.

A lunar oxidizer supplier increases deliverable mass as it increases the apogee of a HEEO delivery orbit. A Starship in a GTO filled with propellant can inject four times its nominal cargo mass into a Hohmann transfer to Mars. [8]

This means one would aggregate both cargo and propellant in LEO, for trans-Mars cargo Starships and propellant tankers destined for GTO. For on orbit cargo transfers one could imagine a "palletized" system like the "PEZ-dispenser" SpaceX envisages for Starlink; in LEO two cargo vehicles "mate" and one donates "pie slice" or hex pallets of cargo to the other. Starship has 1,100 m^3 of cargo volume, so there are likely many cargos that are not volume constrained.

All vehicles then boost to GTO, and the GTO tankers refill the trans-Mars Starships with propellant. From GTO the tankers can drop their perigee into the atmosphere with only a few tens of m/s delta-v. The approximately 11-hour period of a GTO means the GTO tankers could be reused very frequently, perhaps daily but certainly every few days. Most of the trans-Mars injection impulse could be amortized over the entire synodic period, allowing the task to be completed with relatively few tankers and cargo lifters.

With more cargo mass on board, the Mars capture and EDL would be more challenging, however, the increased thermal demands at Mars are likely lower than SpaceX's posited Earth point-to-point cargo reentries. If one did a minimal propulsive capture at Mars, followed by multiple aerobraking passes to LMO (to control peak and total heat of a pass), and eschewed EDL in favor of Mars based cargo ferries, one could aggregate even more cargo in LEO, further reducing capital expenditure and propellant costs. There may well be advantages to leaving cargo in LMO until it is required on the surface. Cargo is already packaged for years in vacuum and one can maintain a near constant rate of cargo landing flights, rather than bursts of activity around the Mars arrival windows. Spares for stochastic failures need not be landed until surface resident supply levels drop below replacement thresholds.

At the extreme this architecture looks like small pools of vehicles at Earth and Mars servicing interplanetary transporters and one might think vehicle specialization would deliver advantages. However, for the interplanetary vehicles, the TPS and engine masses are a tiny fraction of non-propellant mass, so at least for chemical vehicles, the relative disadvantage of the generalist vehicle is small. The absolute advantage is that one can land them at any time for detailed inspection and servicing, avoiding the need for orbital maintenance facilities on the critical path to high mass flows to Mars.

***Heavy Luna*; Adding lunar Oxidizer:** To reduce the mass of oxidizer that must be more expensively delivered deep in Earth's gravity well, the authors modelled providing oxidizer in 500 m/s increments from LEO through to GTO; vehicles contain at most 500 m/s of LOX, all sourced from the Moon. At GTO the trans-Mars vehicles are filled with CH_4 by the GTO tankers and LOX by the lunar oxidizer supplier. With this strategy the CH_4 and LOX that must be burnt is reduced because less total propellant is lifted from LEO to GTO than is the case for a single monolithic burn. CH4LOX is about 22% CH_4 by mass, but the incremental boost strategy only requires lifting about 60% the amount of a monolithic burn. Also, apparently paradoxically, although each Earth vehicle has 5 additional rendezvous, there are far fewer vehicles, so total rendezvous are reduced by about 40%. Adding local rendezvous reduces global rendezvous, reducing operations costs. No attempt was made to optimize the CONOPs, one may be able to do better.

Conclusion: Relative to the baseline SpaceX Mars Project and the canonical "deliver lunar propellant in LEO" scenario, the proposed CONOPs greatly reduce Mars vehicle capital and cislunar operations costs and increase lunar propellant's recoverable value per lunar surface ton of water processed. One can apply these CONOPs to other interplanetary transfers. [9]

The scale of the SpaceX Mars project would make it the holy grail of Space Resources, a large long term anchor customer. Supplying lunar propellant at this industrial scale would make it available to other exploration missions as a plug in, on demand, capability that would allow us to reimagine solar system exploration.

References:

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