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USE OF LUNAR PRODUCED PROPELLANTS FOR MANNED MARS MISSIONS

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ABSTRACT

Manned Mars Mission departures from low lunar orbit (LLO), L2, and low Earth orbit (LEO), using oxygen or oxygen and hydrogen produced on the Lunar surface; or Phobos produced propellants; are compared to departures from LEO using Earth produced propellants. The economy of a given scheme is a function of the ratio of Earth launch to lunar launch costs per unit mass. To achieve savings on the order of 40% of total Earth launch costs for steady state operations requires the availability of both oxygen and hydrogen on the Moon and launch per unit mass costs of lunar surface to LLO in the range of 25% of Earth to LEO costs.

INTRODUCTION

A manned lunar base capable of producing propellants on the lunar surface has been the subject of a number of recent studies (References 1, 2, & 3). Lunar oxygen propellant production for lunar landers appears to be economical if a large base is operated. Similar propellant production capability can be postulated for the Martian moons, Phobos and Deimos. This paper discusses the conditions under which propellant for manned mars missions could be economically produced off-Earth. Regular departure of manned missions to Mars will require roughly 1,000 metric tons of propellant, mostly oxygen, every two years.

COMPARATIVE SCENARIOS

Propellants produced on Earth, Phobos or Deimos, or the Lunar surface can be ferried to a Mars spacecraft and loaded in a number of different orbits. Three propellant loading points for the trans-Mars injection (TMI) burn were considered: LEO (500 km circular); LLO (500 km circular); and L2 (the Lagrangian point behind the Moon). Reference 4 discusses L2 in more detail. Spacecraft departing from the Earth-Moon system can also be loaded with propellants at a Martian moon for the return trip. There are many options and combinations of options. Table 1 shows the combinations that are considered in this paper, which does not include all combinations or options. Departure from geo-synchronous

TABLE 1

CASES PLOTTED

Case #	Departure Point			Propellant from Dep. Point on Produced at							
	LEO	LLO	L2	Earth		Luna		Mars		Phobos	
				O2	H2	O2	H2	O2	H2	O2	H2
1	X			X	X						
2		X			X	X					
3		X				X	X				
4			X		X	X					
5			X			X	X			X	
6	X			X	X					X	
7	X			X	X					X	X
8		X			X	X				X	
9		X				X	X			X	X
10	X				X	X					
11	X				X	X	X*				
12	X					X	X				

*Lunar produced with hydrogen used in LLO-LEO OTVs only. Not in Mars stack.

orbit is not addressed and the possibility of returning Martian moon produced propellants to LEO is not considered.

Table 2 shows the delta V, propulsion, and spacecraft mass assumptions for the cases considered. The baseline case (#1) departs from 500 km circular LEO with Earth produced propellants on a generic conjunction class trajectory to Mars. This trajectory favors optimum performance over speed. Twenty-four hour period, 500 km periapsis, Earth (on return to Earth) and Mars parking orbits are assumed. The baseline trajectory includes 5% delta V reserves, 10% added to C3's for windows, and 100 m/sec midcourse corrections.

The baseline spacecraft, derived from the configuration described in reference 6, uses three stages for LEO departure; the first two (TMI and MOI) use O_2/H_2 propellant. The last stage makes two burns (TEI and EOI), uses drop tanks, and O_2/propane propellant. The baseline propulsion is sized to deliver a large load to Mars (3 landers and a Mars orbital transfer vehicle), and is the type of design that might be appropriate for a 10 mission, 20 year base-building scenario.

All the other options also use this baseline spacecraft with some modifications. For the LLO departure scenarios, trans-lunar injection (TLI), lunar orbit insertion (LOI), and trans-Mars injection (TMI) are all done with the first stage. The spacecraft departs LEO, is loaded with propellants again in LLO, and then goes to Mars. The TLI and LOI burns size the first stage. The oxygen tank must be large enough to supply TLI and LOI burns and then be filled for TMI. The hydrogen tank must supply all three burns, if no lunar hydrogen is available. L2 departure works the same way, with all the burns up to and including TMI done with the first stage.

<u>BASELINE (CASE NO. 1)</u>

Case No. 1, the baseline, masses 1,300 metric tons in LEO and is described in detail in reference 5 and the tables. It is a three stage, conjunction clase, base-building design, which is all expended except the 53 metric ton mission module which is returned to Earth. It and all the other cases carry three landers and a small Mars orbital transfer vehicle (MOTV).

TABLE 2

MASS, PROPULSION, AND ORBITAL MECHANICS ASSUMPTIONS

BURN	DELTA V (KM/SEC)	ISP (SEC)	PROPELLANT	MASS FRACTION
Baseline LEO Departure:				
TMI	3.808	468	L02/H2	.925
MOI	1.666	480	New L02/H2	.850
TEI	1.490	370	L02/Methane (Mixture = 3.5:1)	.940
EOI	0.967	370	L02/Methane	.890
Low Lunar Orbit Departure:				
TLI	3.1555	468	L02/H2	.925
LOI	0.975	468	L02/H2	.925
TMI (2 burns - TEI & burn at earth flyby)	1.628	468	L02/H2	.925
L2 Departure:				
TL1I	3.150	468	L02/H2	.925
L2OI (2 burns - lunar flyby & at L2)	0.350	468	L02/H2	.925
TMI (2 burns - L2 departure & earth flyby	1.008	468	L02/H2	.925
LLO to L2 (2 burns - LLO departure & L2 arrival	0.800	480	L02/H2	.850

Payload Mass (delivered by each mission):

Item	--	mass, metric tons
Mission Module (all returned to earth)	--	53
Mars Landers (3)	--	62 each (186 total)
Mars Orbit Transfer Vehicles	--	31

LLO DEPARTURE WITH LUNAR O2 (CASE NO. 2)

Case No. 2 assumes a modified baseline stack is launched from LEO to LLO carrying all its own hydrogen and methane, but with only enough oxygen for TLI and LOI. The Mars spacecraft is then filled with lunar produced oxygen in LLO. Figure 5 shows the Mars spacecraft and a lunar orbit propellant depot. An Earth flyby is used during TMI. Two burns, one in LLO, and one at Earth flyby are required.

Figure 1 shows that case No. 2 reduced Earth launch mass around 23% compared to the baseline (case No. 1) Lunar launch requirements are not insignificant however. Figure 3 indicates total cost savings of 10% if launch costs of Earth to LEO are 25% of launch costs from the lunar surface to LLO. The payoff would be greater if more of the post-LOI mass was oxygen or some lunar produced propellant or material because TMI from LEO (3.8 km/sec) is less than TLI and LOI (3.155 + .975 km/sec). The payoff might be greater if the outbound C3 was much higher [80 to 100 $(km/sec)^2$].

LLO DEPARTURE WITH LUNAR O2 AND H2 (CASE NO. 7)

Case No. 7 is the same as case No. 2, except lunar oxygen and hydrogen are provided to the Mars spacecraft in LLO. The TMI and MOI stages are filled with lunar derived hydrogen and oxygen. The TEI/EOI stage carries its own pwopane, but uses lunar oxygen. Figure 2 shows a 46% reduction compared to baseline Earth launch mass. Figure 4 shows a 38% reduction in total launch costs is a ton can be launched from the lunar surface to LLO for 25% of the cost of launching it from the Earth's surface to LEO.

L2 DEPARTURE WITH LUNAR O2 (CASE NO. 3)

Case No. 3 is similar to case No. 2 except L2 is used as the propellant loading point instead of LLO. The Mars spacecraft carries all its own hydrogen and propane. A small OTV delivers oxygen from LLO to the Mars spacecraft at L2. Hydrogen for the lunar landers and small OTV, and propellant to get this hydrogen to LLO is also charged to the LEO mass of the Mars spacecraft. The oxygen for the small OTV is charged to the lunar surface to LLO launch mass.

Case No. 3 is slightly better in terms of LEO mass reduction and cost than case No. 2. This is because TL2I + L2OI + TMI = 4.508 km/sec (3.150 + .350 + 1.008), is less than TLI + LOI + TMI = 5.758 km/sec

Fig. 1 Launch Requirements Versus Scenario

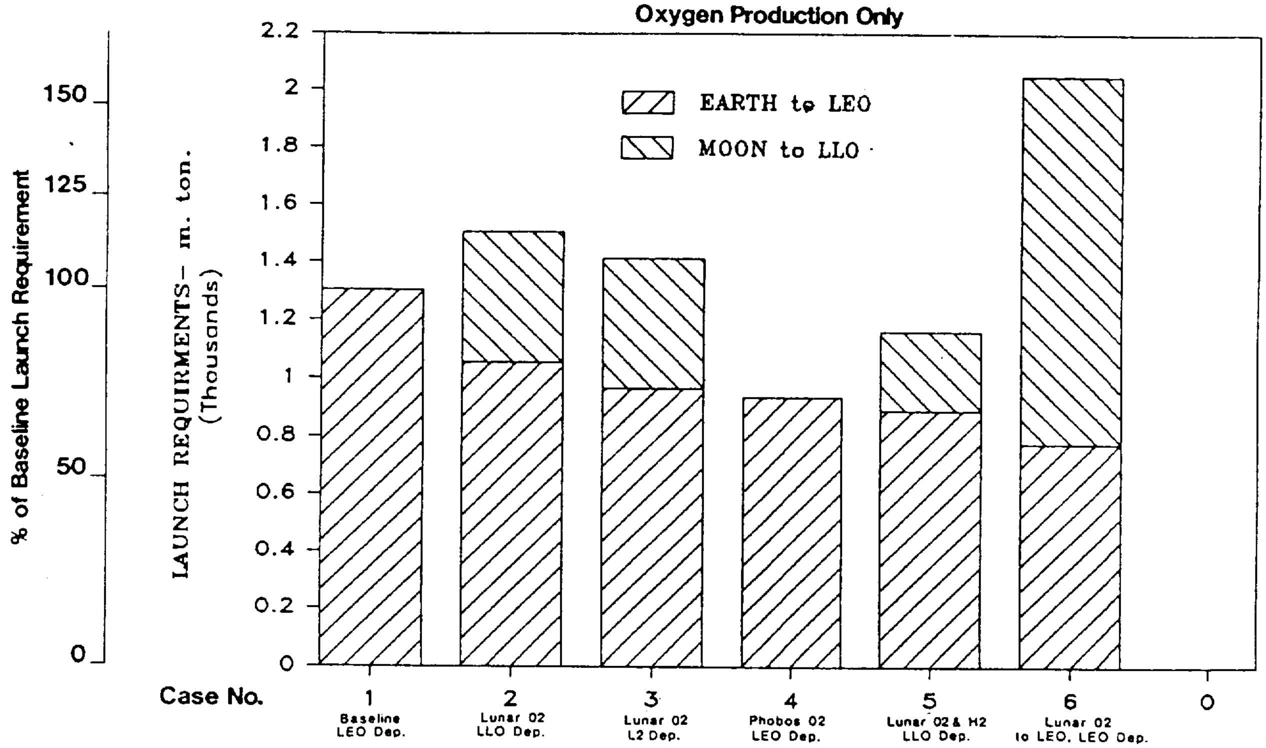


Fig. 2 Launch Requirements Versus Scenario

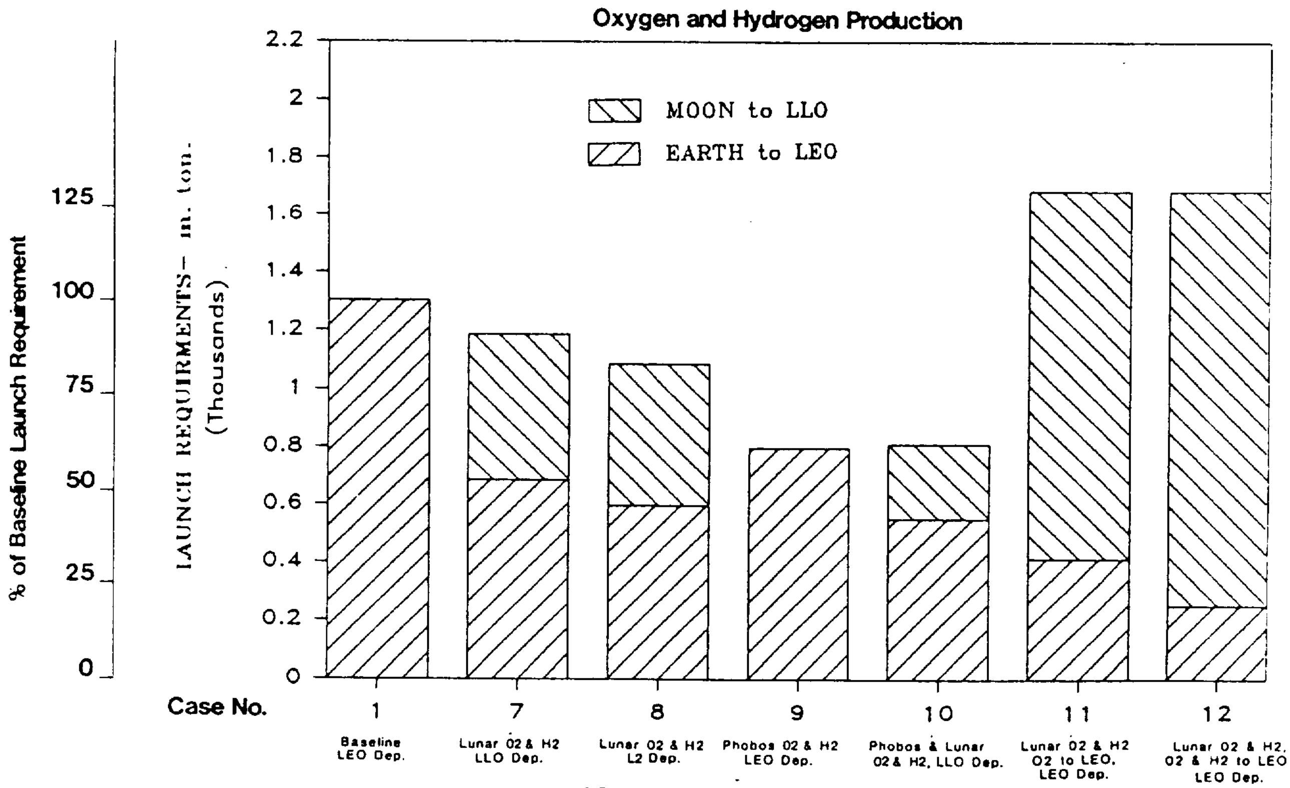


Fig. 3 Launch Cost Ratios

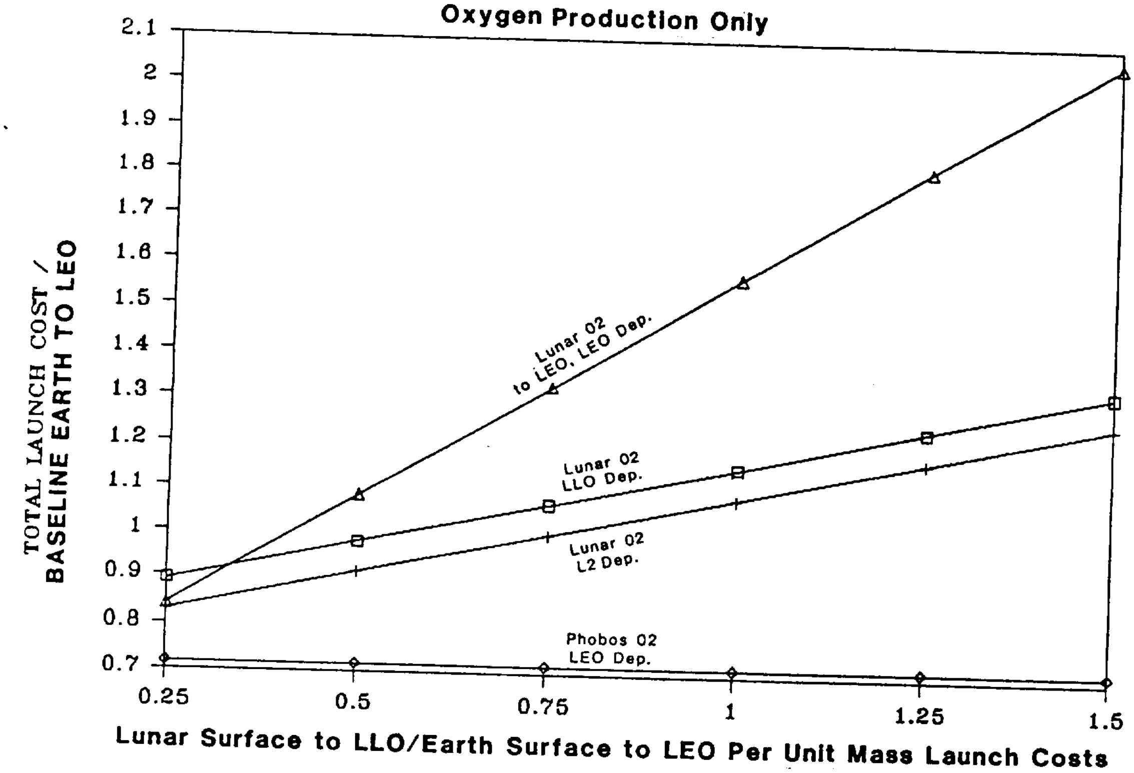


Fig. 4 Launch Cost Ratios

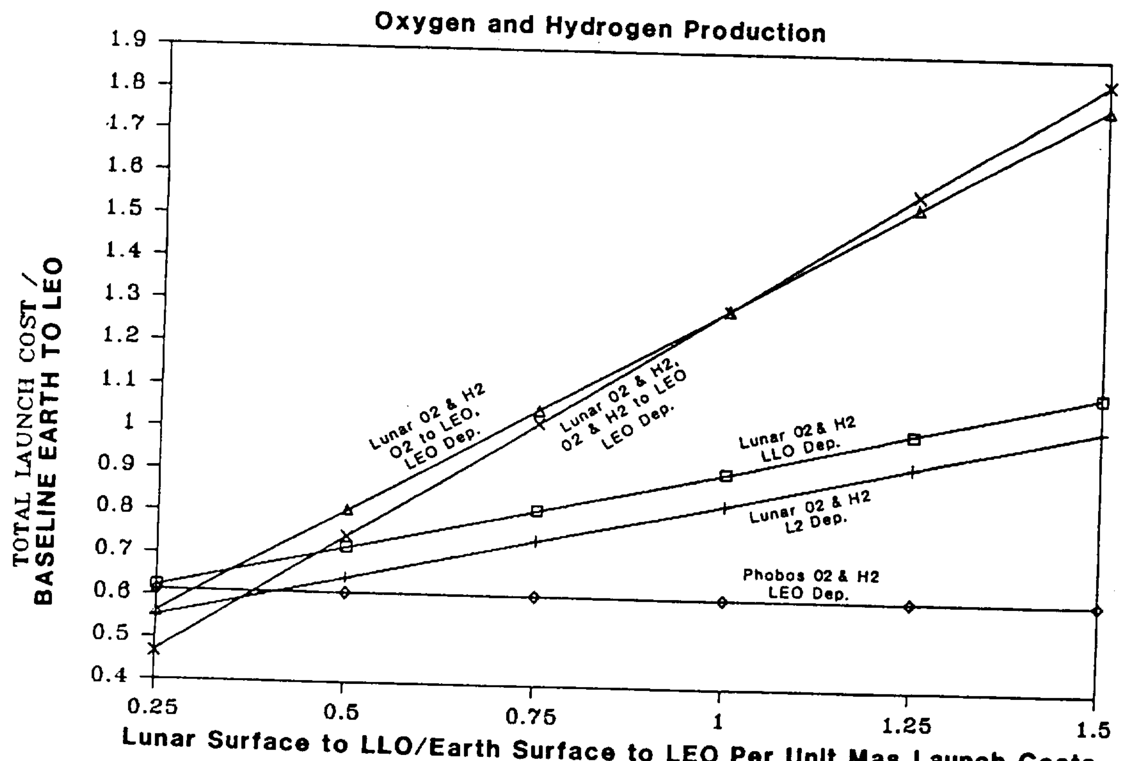
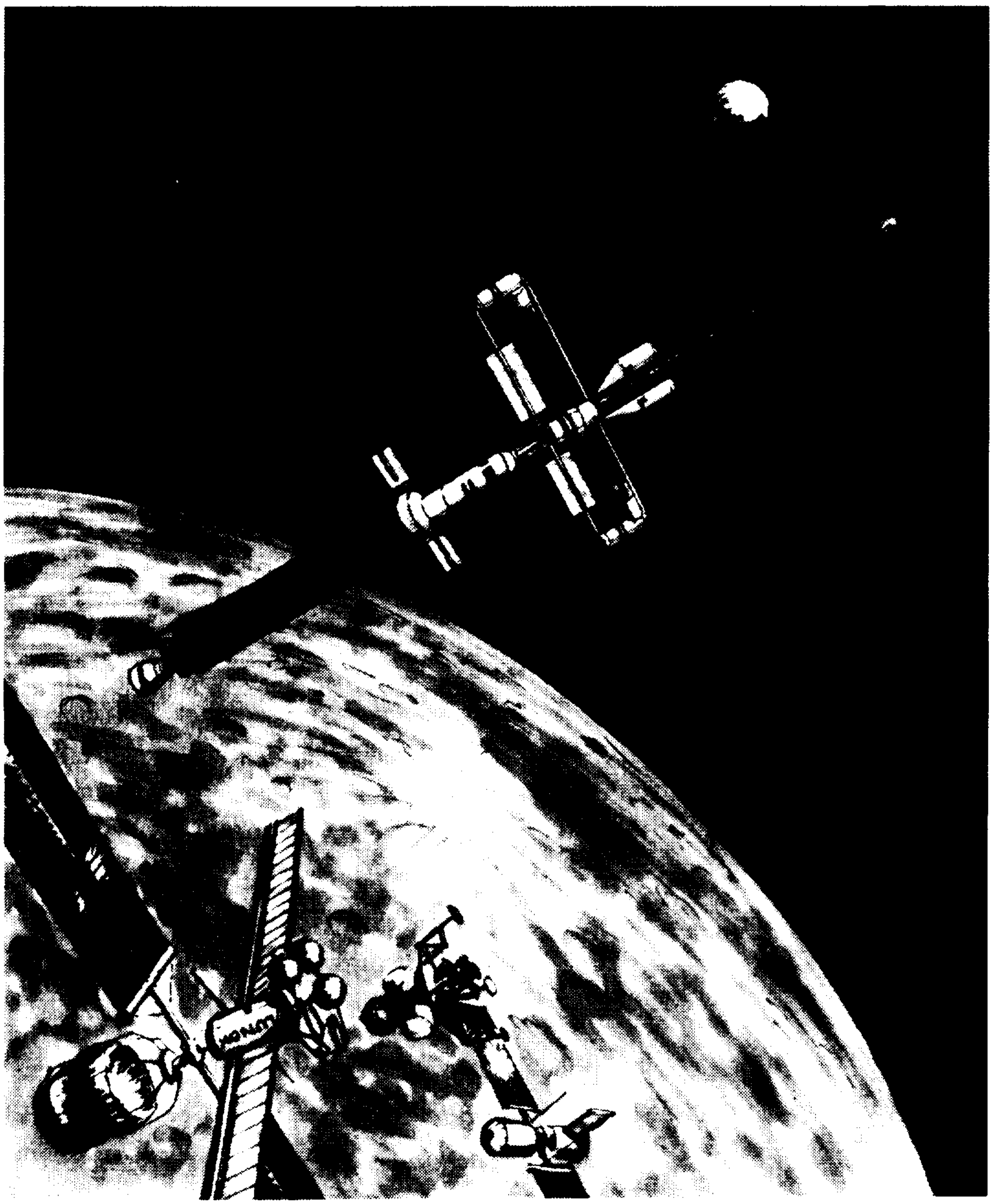


Fig. 5 Mars Spacecraft in Low Lunar Orbit



(3.155 ÷ .975 ÷ 1.628). This is due to not having to go into lunar orbit. Propellant does have to be carried up further out of lunar orbit, and the extra stage (the small OTV) needed to do this may negate the cost savings over LLO departure.

<u>L2 DEPARTURE WITH LUNAR O2 AND H2 (CASE NO. 8)</u>

Case No. 8 is the same as case No. 3 except lunar produced hydrogen as well as oxygen is provided. Propellant is delivered to L2 from LLO with a small OTV. The Mars spacecraft carries only its own propane for the TEI and EOI burns. As with cases 2 and 3, case 8 is slightly better than case 7 in terms of Earth launch mass and cost. However, both cases 7 and 8 (with hydrogen) are dramatically better than cases 2 and 3 (oxygen only). Hydrogen does not have to be brought from Earth for landers and OTVs for cases 7 and 8. OTV hydrogen and oxygen is charged to lunar launch mass however.

<u>LEO DEPARTURE WITH PHOBOS O2 (CASE NO. 4)</u>

This case is similar to the baseline (case No. 1), except Phobos produced oxygen is delivered with a small OTV to the TEI and EOI stages and Mars landers in 24 hour elliptical Mars orbit. This case is slightly better than LLO and L2 departures with lunar oxygen, but the Earth launch requirement is not as great. Figure 3 implies the cost curve is essentially independent of Earth launch costs. This is not precisely true. Transfer of propellants from Phobos orbit (6,068 km circular) to the Mars spacecraft parking orbit (500 x 32,963 km, 24 hour period) is not free (800 to 900 m/sec one way), but may be less difficult and expensive than lunar ascent/descent (roughly 2.0 km/sec each way).

High elliptical Mars parking orbits are best for scenarios without Mars propellant production. The parking orbit for the Mars spacecraft needs to be optimized for scenarios with Mars propellant production. The parking orbit for the Mars spacecraft needs to be optimized for scenarios with Mars propellant production. If oxidizer and propellant are both available, it may be optimum to park in Phobos orbit.

<u>LEO DEPARTURE WITH PHOBOS O2 AND H2 (CASE NO. 9)</u>

Case No. 9 is the same as case No. 4 (LEO departure with Phobos O_2) except hydrogen is also assumed to be available at Phobos. Phobos produced hydrogen and oxygen are used in the TEI and EOI stages and the landers. This results in a 38% reduction in LEO launch mass compared to the baseline. Oxygen alone at Phobos results in a 29% reduction in launch mass. Hydrogen at Phobos does not make as dramatic a difference as it does on the Moon.

<u>LLO DEPARTURE WITH PHOBOS AND LUNAR 02</u>

Case No. 5 is the same as case No. 2 (LLO departure with lunar O_2) except oxygen is now provided at Phobos. The TMI and MOI stages are filled with lunar produced oxygen in LLO and TEI and EOI stages and Mars landers are filled with Phobos produced oxygen in Mars orbit. The Mars spacecraft carries its own hydrogen and propane. The hydrogen required for the lunar landers and propellant to get the hydrogen to lunar orbit is charged to the LEO mass.

This produces almost no improvement over Phobos O_2 or lunar O_2 alone. Since the delta V to get from LEO to LLO is more than LEO TMI, unless considerable propellant for later burns or payload is loaded in LLO, the scenario will not pay.

<u>LLO DEPARTURE WITH PHOBOS AND LUNAR 02 DELIVERED TO LEO (CASE NO. 6)</u>

Case No. 6 assumes lunar produced oxygen is delivered by aerobraked OTV to LEO at a mass payback ratio of 2.45 (Ref. 1). The mass payback ratio is the oxygen returned to LEO over hydrogen sent out from LEO for a given lunar oxygen production scheme. Ref. 1 explains such a scheme in detail. The oxygen is used to fill all stages of the Mars spacecraft. Hydrogen delivered to LLO for the OTVs and landers, and the hydrogen used in the OTVs to get it there is charged to the LEO launch mass.

This effectively reduced the LEO launch originally dedicated to launching oxygen in the baseline by 2.45. The mass payback ratio is highly sensitive to aerobrake and boiloff parameters, so this scenario could easily change. As it is, a 40% reduction in LEO launch mass is predicted, but the lunar launch requirements are now more than Earth launch requirements and, not surprisingly, Figure 3 shows this scenario highly sensitive to lunar/Earth launch cost ratio.

<u>LEO DEP. WITH LUNAR 02 DEL. TO LEO, LUNAR H2 AVAIL. (CASE NO. 11)</u>

Case No. 11 is the baseline case with lunar produced oxygen delivered by aerobraked OTV to LEO at a mass payback ratio of infinity, that is, nothing must be sent out to get oxygen back. All the Mars spacecraft stages are filled with lunar produced oxygen. Earth launched hydrogen and propane are used in the Mars spacecraft however. Lunar produced oxygen and hydrogen are used in the LEO to LLO OTVs and in the lunar landers. The Earth launch requirement is now 70% less than the baseline but the lunar launch requirements are not as much as the entire baseline LEO mass. Figure 4 predicts a 45 % reduction in launch costs if lunar launch per unit mass costs are 25% Earth to LEO costs.

LEO DEPARTURE WITH LUNAR O2 AND H2 DELIVERED TO LEO (CASE NO. 12)

Case No. 12 is the "best" case for lunar produced propellants with all the Mars spacecraft oxygen and hydrogen delivered in LEO at a mass payback ratio of infinity. Except for the propane, all propellants for all vehicles are lunar produced. This results in an 80% reduction in Earth launch requirements, a large lunar launch requirement, and a possible over 50% reduction in costs if the lunar to Earth launch cost ratio is 25%.

RESULTS AND CONCLUSION

Figures 1 and 2 show the launch requirements from Earth and the Moon for the twelve cases examined. Figure 2 cases, which assume lunar or Phobos hydrogen as well as oxygen production, show a substantial reduction in Earth launch mass. The launch requirements from the lunar surface are not trivial however, and it is clear that the lowest cost solution will depend on the ratio of Earth launch to lunar launch costs.

Figures 3 and 4, for lunar oxygen, and oxygen and hydrogen production respectively, show total launch cost (normalized to baseline Earth to LEO launch costs) as a function of the relative launch costs per unit mass from the lunar surface to lunar orbit to be cost effective. This lunar to Earth launch ratio must be low enough to drive the total cost below the baseline, to be cost effective.

For a continuing Mars program, O_2 production at Phobos shows the most cost gain for the least investment and with virtually no infrastructure required. The only real problem is whether O_2 in significant amounts is easily available at either martian moon. (The result would be essentially the same if Deimos were the O_2 source.)

Lunar production of H_2 (or any other fuel) as well as O_2 appears to be necessary for profitable lunar support of Mars missions. Without lunar produced fuel, much of the potential weight savings in LEO is used in transporting H_2 to the lunar surface to launch the O_2.

A prediction of the actual lunar surface to LLO/Earth surface to LEO per unit mass launch cost ratio is needed. Briefly comparing the delta Vs and mass ratios provides some insight: (1) Earth surface to LEO delta V = 8 km/sec, mass ratio = 5.9; and (2) Lunar surface to LLO, one way delta V= 2 km/sec, mass ratio = 1.6. An extremely crude estimation of the cost ratio is therefore 1.6/5.9 = .26. The mass ratios assume 460 second Isp, single stage propulsion. The lunar lander requires another 2 km/sec to descend, probably with a much smaller load however, and refurbishment in the lunar vicinity must be accounted for.

Looking at Figures 3 and 4, it can generally be concluded, that to effect a 20% - 40% reduction in total costs, lunar launch costs must be 25% or less of Earth launch costs if only oxygen is available and 50% or less if oxygen and hydrogen are available. Assuming launch costs of 1 million/metric ton, from the Earth's surface to LEO 1,300 metric ton mission would cost 1.3 billion to place in LEO. For a 10 mission program, 20% cost savings amounts to approximately 2.6 billion dollars; 40% amounts to 5.6 billion dollars. These must be large enough to pay for the extra infrastructure needed to operate the propellant production system. If no infrastructure had been emplaced for other purposes, even saving the total launch cost of a 20 year Mars program (13 billion) probably would not be enough to finance a Phobos or lunar base/propellant plant/OTV/lander infrastructure. However, if a lunar base has been established for other purposes and it is possible to produce hydrogen as well as oxygen, the non-terrestrial propellant production scenarios may be cost-effective.

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