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Lunar & Mars Mission Architecture Utilizing Tether-Launched LLOX

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ABSTRACT

A tether launch system (TLS) on the lunar surface can launch 10 tonne payloads of lunar produced oxygen (LLOX) into low lunar orbit or lunar escape using existing materials and technologies. The TLS has several advantages over the quenchgun or ram accelerator. It is much lighter with a weight of only ten times the payload. It has no power storage needs. It has a small surface footprint and the ability to launch into any inclination. And, finally, it can be used as an auxiliary power storage device during long lunar nights. Using LLOX in conjunction with the tether launcher reduces Earth-launched propellant needs by seven times for piloted lunar missions and nearly six times for piloted Mars missions. Design parametrics and four point designs are presented spanning different release speeds, payload weights, and cord strengths.

TYPICAL LAUNCH SCENARIO

The tether launcher consists of a single tower that holds two tethers reeled up on two large spools. One tether swings the payload and the other swings lunar dirt as a counter-balance. The rotor hub is driven (and braked) with an electric motor/generator. A 10 tonne tank of LLOX is brought to the tower on a lunar utility rover and the tether end is attached. The tether end consists of a laser reflector and laser initiated release mechanism. At lunar dawn, a 100 kW solar collector array begins to generate power that starts to flow to the rotor hub motor. The LLOX and dirt counter balance begin to spin around and swing out from centrifugal acceleration. As power continues to flow into the rotor motor and the payloads rise, the tethers are fed out. Significant energy is created when the tether storage reels unwind under tension. This energy is not wasted

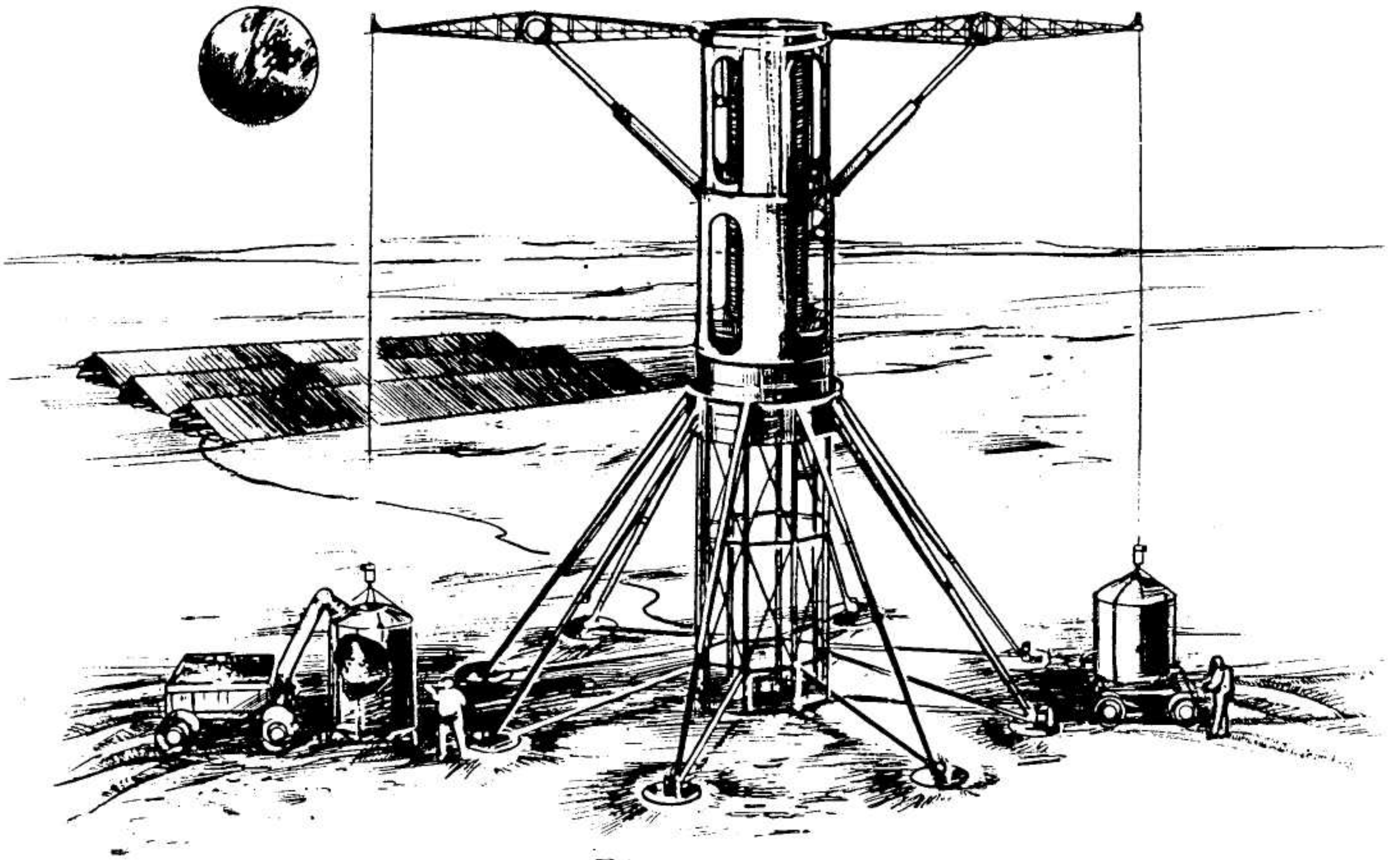

Figure 1 Tether Launch System Being Prepared for Launch at Lunar Dawn

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but is fed to the rotor motor. (The reverse process will be employed when the tether is reeled back in.) The counter balance tether length is servo-driven to maintain a force balance in the central rotor hub's bearing. After twelve Earth-days the tether is going fast enough that the LLOX payload will go into a 0 by 100 km orbit when released. The laser tracker/command link sends the release command to both the dirt and LLOX release mechanisms to maintain balance. (The inclination of the orbit is determined by the timing of the release.) Because the dirt counterbalance is heavier it is not going fast enough to orbit and impacts shortly after release. The LLOX tank streaks along the ground, then begins to gain altitude. After 56 minutes it reaches apolune at 100 km and a timer initiates a 500 Newton (112 lb) thruster firing for 460 seconds placing the LLOX tank into a 100 by 100 km orbit. Back at the launch site, the tethers begin to brake and reel-in maintaining ground clearance as they go. Finally the tethers are retrieved and a new 10 tonne tank and dirt counterbalance are loaded. Future versions will use two launchers so the braking energy of one is fed to the spin-up motors of the other.

Tether applications have traditionally fallen into three categories[1]: spacecraft separation, momentum exchange and electro-orbital energy exchange. The tether launch system (TLS) does not fit into any one of these classes. The tether launch system is more akin to an electric propulsion system. It uses electric motors to horizontally spin up a surface mounted tether to accelerate a payload to orbital speed. Figure 1 shows a smaller, 2.65 tonne capability TLS on the lunar surface being prepared for a LLOX test launch. This subscale launcher was delivered on a single LTV/LEV[2] cargo flight and has a mass of 27 tonnes. On the left an astronaut oversees the loading of lunar regolith into the counter-balance hopper. On the right is a LLOX delivery tank. The solar panels in the background will feed power to the rotor motor when the loading is complete. As will be shown, this tether application is well within the capabilities of existing materials and can greatly enhance the cost effectiveness of LLOX for space transportation over rocket propelled tanker vehicles operating between the surface and LLO. For a rocket tanker, each 100 kg of LLOX payload delivered to LLO consumes a propellant load of 82 kg LLOX plus 14 kg of Earth-supplied hydrogen. Hydrogen is bound to be a scarce and valuable resource on the moon. The tether launcher uses no consumables. It runs only on solar electric power or shares the power source being used for mining and/or base operations.

PARAMETRIC DESIGN APPROACH

Several parameters need to be considered in designing a tether launcher. How long should the tether be? How high should the rotor tower be? How heavy should the payloads be? What should the payload release speed be? Should the tether be tapered, and, if so, what should the taper profile look like?

For starters we pick 10 tonnes for the payload mass based on qualitative arguments. One, 10 tonnes, is an order of magnitude larger than most proposed quenchgun payloads and therefore provides a clear discriminator. Two, 10 tonne payloads do not require a catcher vehicle in LLO because only a few need to be gathered per mission from Earth. A transfer vehicle can simply rendezvous with two or three tanks in LLO before beginning the descent. (A lander vehicle can feed its engines directly from the LLOX tank and in the process deliver it back to the lunar surface for reuse.) Larger payloads are ruled out because minimal missions may not require more than 10 tonnes and because a larger payload means a larger tether system on the lunar surface.

The second design choice, release speed, is also answered qualitatively. Five ranges of speed exist: suborbital, minimum orbital, high energy orbital, minimal escape, or high energy escape. The first option, suborbital, is eliminated because the payloads are released tangential to the lunar surface with very little time before they will impact. A supplementary rocket boost system would need a high thrust guidance and propulsion system. Furthermore the advantage of the tether over simple rocket tankers is reduced. The last option, high energy escape, is eliminated because the propellant needs to be sent to some location where it can be picked up by vehicles, such as lunar orbit, or a libration point. Firing directly to low Earth orbit (LEO) constitutes a high energy escape but is ruled out because an aerobrake is needed for circularization at LEO. It is more efficient to mate the aerobrakes to the LLOX payloads in space, either LLO or perhaps L2. This leaves the choices for release speed between minimal orbital and escape. Figure 2 shows the relationship between release speed and apolune altitude for captured orbits. Sending LLOX to elliptic orbits is ruled out because these orbits will precess due to gravitational perturbations. Launching at several day intervals would leave the LLOX tanks in different orbits requiring large delta-V's to transfer between them. This leaves only two options: Minimal orbital and minimal escape.

The launch speed needed for a 0 km by 100 km minimal orbit is 1702.7 m/s and for minimal escape it is 2375 m/s. Interestingly, the tether's mass and the time required to launch a payload is independent of the tether's length. For minimal orbital speed one of the two tether cords alone will have a mass of 98,122 kg and require 12.6 days for a launch. For escape these values shoot up to 436,508 kg and 65 days to launch. These values assume a safety factor of two and a cord mass/strength ratio of 0.764 g/N/km. This cord strength is based on Cortland data for their 3500 lb, 8lb/1000ft Kevlar braid. Also assumed is a power source of 100 kWe with 90% end-to-end efficiency. No power storage systems are assumed, i.e. after each launch the tether is braked to a stop for reloading.

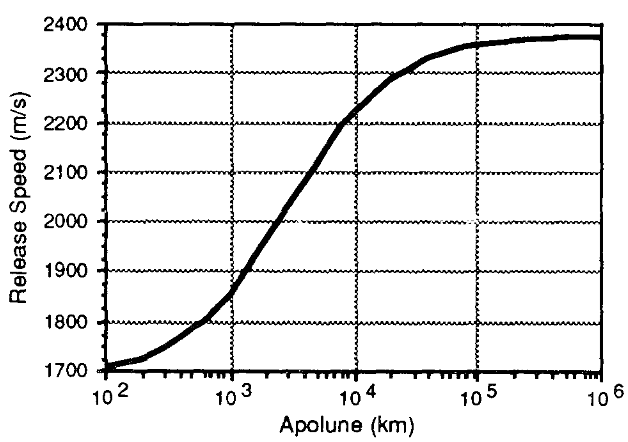

Figure 2 Apolune Altitude vs Release Speed for Captured Lunar Orbits

If a 50% overhead mass is assumed for the launch tower structure then the total system mass for minimal orbital launches is 294,366 kg and for minimal escape is 1,309,524 kg. Although large, these numbers are conservative because of the existing tether strength assumptions and the safety factor of two in tether strength. If more aggressive values are assumed (Safety factor=1.4 and mass/strength=0.5 g/N/km) then the values drop dramatically. For minimal orbital the total system mass becomes 101,385 kg and for minimal escape it becomes 331,050 kg.

For orbital and escape speeds there remains a trade-off between tether length, G-force felt by the payload, and tether droop due to the moon's gravity. Droop drives how tall the central rotation tower must be to prevent scraping the payload along the ground.

From Figure 3 we see a trade-off between required tower height and G-force imparted on the payload. For the orbital case a 7,000 m tether has a droop of 58.5 meters and the payload experiences 42 g. This seems like a good compromise since longer tethers only slightly reduce the G-force but greatly increase droop. (At 10 km the G-force is only down to 30 g's but the droop has increased to 120 meters.) Conversely a shorter tether rapidly increases G-force without much savings in droop distance. In reality only one tether system will be installed so the design must be capable of either orbital or escape missions.

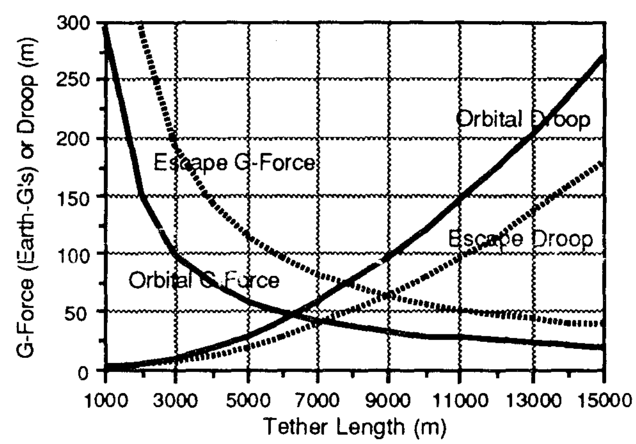

Figure 3 Tether Droop and Payload G-force vs Tether Length

If this is done, a tether designed for 10,000 kg payloads to orbit will also be able to launch 2250 kg payload to escape. For either mission the tether must be tapered or it cannot support its own mass when spinning with orbital tip speeds, or greater. If the taper is made proportional to the tension in the tether the minimum tether mass will result.

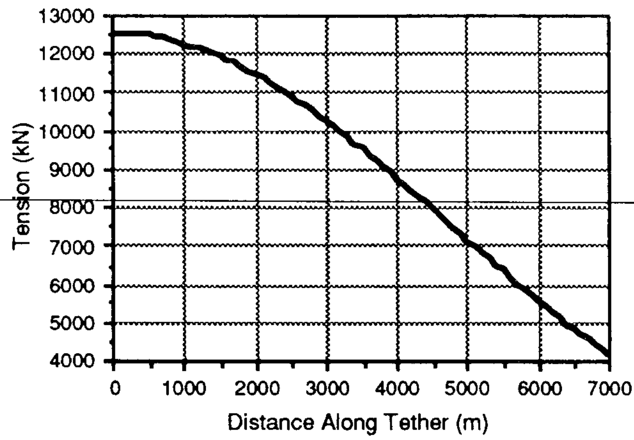

Figure 4 Tether Tension vs Length

Figure 4 shows the tension as a function of length for the 7 km minimum orbital tether and figure 5 shows the tether's diameter as a function of length. We used a numerical integration, in 100 m constant diameter segments, to develop the taper profile. In reality the tether may be assembled in a similar fashion with segments of constant diameter cord linked together with end fittings. This would allow the light weight tower to be initially emplaced devoid of tether cord. Subsequent missions would add tether sections until both tethers were complete. Tests could be carried out to refine the control laws as the system awaited completion.

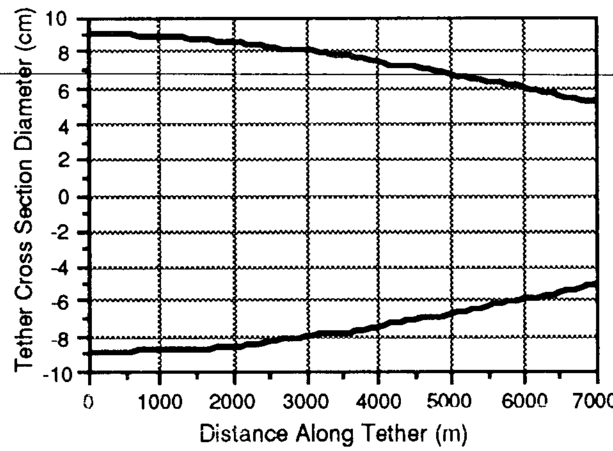

Figure 5 Tether Diameter vs Length

Table 1 presents four point designs for tether launchers. The left column launches 10 tonnes to LLO and has conservative values for safety factor and tether cord strength. The next column uses more aggressive values for safety factor and

Table 1 Four Tether Launch System Point Designs

	10 t to LLO SF:2, crd:0.76	10 t to LLO SF:1.4,crd:0.5	10 t to Esc SF:1.4,crd:0.5	2.65 t to LLO SF:1.4,crd:0.5
Payload Mass (tonne,t)	10	10	10	2.65
Total System Mass (t)	294.3	101.4	331.1	26.9
Single Tether Mass (t)	98.1	33.8	110.3	8.96
Tether Length (m)	7000	7000	7000	7000
Payload Acceleration (g)	42.2	42.2	82.1	42.2
Spin Rate (rpm)	2.32	2.32	3.24	2.32
Maximum Droop (m)	58.5	40.0	25.0	40.0
Safety Factor	2.0	1.4	1.4	1.4
Input Power (kWe)	100	100	200	10
Time to First Launch (day)	12.6	7.2	12.5	18.8
Time to Re-launch (day) *	3.8	3.8	3.6	9.8
Cord Strength (g/N/km)	0.764	0.500	0.500	0.500
Cord Max Diameter (cm)	17.9	12.4	24.3	6.4
Cord Min Diameter (cm)	10.3	8.6	12.0	4.4
Spool Length (m)	4.0	4.0	4.0	4.0
Spool ID (m)	8.9	6.2	12.1	3.2
Spool OD (m)	17.3	8.2	15.5	4.2

* Assumes Energy of Tether Captured During Wind-Down

strength. Note how sensitive total system mass is to cord strength assumptions. Using these same aggressive assumptions, column 3 is a design for launch to lunar escape. The last column is a scaled down version that uses aggressive strength values and launches to LLO. It is designed to have a total mass of 27 tonnes so that a reference LTV/LEV[2] could deliver it in one flight. This system can launch 2.65 tonnes per cycle.

Tether Launch Trade Study

In order to assess the value of the tether launch system to a lunar transportation architecture, a trade study was conducted. The impact of the lunar tether launch system on launch requirements was evaluated. We used the baseline scenario from NASA's 90 day study[2] which has four person piloted flights, carrying 16 tonnes of cargo and 27 tonne cargo only flights. All vehicles are reusable and the propellant numbers include returning vehicles to their starting points--LEO for the lunar Transfer Vehicle (LTV) and LLO for the lunar Excursion Vehicle (LEV). Hydrogen/Oxygen propellants are assumed for both vehicles with specific impulses of 481 seconds for the LTV and 465 seconds for the LEV. Note that ETO mass also includes the 16 tonne payload.

As shown in table 2, the standard NASA lunar initiative manned mission (scenario A) requires 135 tonnes to be lifted from Earth to LEO (ETO mass) when no LLOX is used. When LLOX is used at the surface of the moon only (scenario B), the ETO mass is reduced to 86 tonnes with 25 tonnes of LLOX needed from the Moon . If rocket tankers are used to ferry LLOX to LLO and LEO (scenario C), the ETO mass can be reduced further to 53 tonnes, but now 202 tonnes of LLOX must be produced, a consideration which probably outweighs the 33 tonne ETO saving compared to scenario B.

Scenarios D and E, however, now show how the lunar tether changes this result. In scenario D, the tether is used to launch LLOX to LLO, where it becomes available for both LEV and LTV return refueling. It can be seen that the ETO mass is reduced to 73 tonnes, and the LLOX requirement is only 22 tonnes. If rocket tankers are used to ferry LLOX to LEO (scenario E), the ETO mass is reduced to 33 tonnes (a reduction by a factor of 4 compared to the scenario A baseline), while 104 tonnes of LLOX are now required per mission.

Table 2 Impact of LLOX and Lunar Tether on STV Launch Requirements

Piloted Mission	A	B	C	D	E
LLOX	0	25	202	22	104
Ox to Orbit	102	56	0	46	0
LH2 to Orbit	17	14	37	11	17
Cargo	16	16	16	16	16
ETO Mass	135	86	53	73	33
Cargo Mission					
LLOX	0	31	245	22	119
Ox to Orbit	111	60	0	53	0
LH2 to Orbit	19	15	41	13	20
Cargo	27	27	27	27	27
ETO Mass	157	102	68	93	47

Scenarios:

A: All propellant comes from Earth.
B: LLOX is available at surface of the Moon and is used by LEV for round trip to LLO.
C: LLOX is available at surface of the Moon and is ferried by rocket to LLO and LEO.
D: LLOX is available at the surface of the Moon and is supplied by tether to LLO.
E: LLOX is available at the surface of the Moon and is supplied by tether to LLO. LLOX is ferried from LLO to LEO by rocket.

Now we compare rocket transfer and tether transfer scenarios for transporting and using LLOX. Scenarios C and E both use LLOX at LLO and LEO. They also both use rocket transfer of LLOX from LLO to LEO. The only difference is that scenario E uses a tether to launch LLOX to LLO and scenario C uses rocket tankers. Scenario C saves 33 tonnes of Earth propellant but requires 177 tonnes of LLOX. This gives a ratio of 0.185, defined as Earth propellant saved divided by LLOX needed. Similarly, scenario E saves 53 tonnes at Earth and requires 79 tonnes of LLOX, resulting in a more favorable ratio of 0.667. This ratio can be thought of as a cost break-even threshold. For scenario C, LLOX usage only makes economic sense of its cost of manufacture on the moon is less than 18.5% of the cost of delivering LOX from Earth to LEO. But for scenario E LLOX can be more expensive and still be economic to use. With scenario E LLOX production costs can be 67% of the cost to deliver LOX from Earth to LEO and still make economic sense. Similar conclusions are derived by examining the results of the 27 tonne cargo missions.

Assuming the more aggressive tether system mass numbers from above, the tether installation will require 4 cargo missions for delivery to the Moon. Since these will be flown under scenario B conditions, this amounts to an initial ETO overhead of 408 tonnes to establish the installation. Once the tether is in place, scenario E is in effect, resulting in an ETO saving of 55 tonnes for each subsequent cargo and 53 tonnes for each subsequent piloted mission. The ETO requirements, thus, break even after 8 additional (crew or cargo) missions are flown. Since the lunar base is intended to be used indefinitely, this would appear to be a highly favorable trade.

Mars Missions Using Tether Launch System

An attractive approach for repeated Mars missions is to assemble the Mars Transfer Vehicle (MTV) in a high energy orbit about Earth, mate the Mars Excursion Vehicle (MEV) to it, send it to Mars where it captures into another high energy orbit and then bring it back to the same park orbit back at Earth. This has the advantages that no aerobraking is needed at either planet and the delta-V's to go from one planet to the other are greatly reduced. Given such a scenario the following trade study shows how much Earth-launched propellant can be saved per Mars mission.

The reference for comparison will assume a 100 tonne MTV and a 44 tonne MEV. The MTV mass does not include any propulsion systems. The MEV does include 24.5 tonnes of propellants. For simplicity all propellants are assumed to be hydrogen/oxygen with an Isp of 481 seconds. A propulsion system must be mated to the combined MTV/MEV in the 4-day Earth orbit. This system has a mass of 195.2 tonnes and pushes both vehicles out of Earth orbit (845 m/s), captures them at Mars (985 m/s), leaves Mars orbit without the MEV (985 m/s), and captures the MTV back at Earth (845 m/s). On the interplanetary legs 50 m/s is assumed each way, and at Mars a 100 m/s orbital change capability is included. So the total propellant needed per mission is the 24.5 tonnes for the MEV and 177.8 tonnes for the trans-planetary propulsion system.

Since the MTV is parked in a four day orbit at Earth a propulsion system is needed to deliver the mission propellant from LEO to the park orbit. 3001 m/s is required for this transfer which means the transfer stage has a gross mass of 257.5 tonnes to push 202.3 tonnes of propellant contained in a 30.3 tonne tank/transport container. So the total mass in LEO is 490.1 tonnes when no LLOX is used.

If LLOX is used with the TLS launching it to LLO then the total LEO mass drops to 86.3 t. Of this 86.3 tonnes, 45.5 tonnes is the transfer vehicle (using Earth H_2 and LOX) which takes a payload of 40.8 tonnes of hydrogen and tankage to the four day orbit. From here, 28.9 tonnes of H_2 is loaded into the MTV and MEV, 6.56 tonnes of H_2 is loaded into the LLO tanker/transfer vehicle and the remaining 5.34 tankage is discarded. We now introduce a new vehicle, called the LLO Tanker, which ferries LLOX from LLO to the 4-day MTV orbit. The LLO tanker, using hydrogen from Earth and LLOX from the previous mission, departs the 4-day orbit, goes to LLO and picks up 240 tonnes of LLOX and tankage at LLO. It then transfers back to the four day orbit, using 37 tonnes of LLOX in the process, and delivers 173.4 tonnes of oxygen to the MTV/MEV and keeps 2 tonnes for the next mission. The remaining 27.6 tonnes is tankage. This completes the loading sequence for the MTV and MEV.

For an all Earth-based propellant supply, each Mars mission requires 490.1 t. Using LLOX and the tether reduces the Earth dependency to 86.3 tonnes but now requires the production of 212.7 tonne of LLOX. We are saving 403.8 tonnes in LEO at the cost of 212.7 tonnes of LLOX production. Hence, the cost of LLOX mining, processing and tether launching can be 1.9 times the cost of propellant in LEO and still be cost effective.

Alternatives to the Lunar Tether Launch System

The idea of using a stationary launch system to fire unmanned payloads off the Moon is not new, and numerous ideas for such devices have been advanced in the past.[3] Two of the most promising of these are the electromagnetic quench gun[4] (or "coil gun" or "mass driver,") and the ram accelerator[5,6].

Quench guns generate thrust on a projectile through the interaction between the currents in the gun barrel and that in the projectile, with the accelerating thrust given by:

$$\text{Thrust} = I_{(barrel)} I_{(projectile)} dM/dz$$

where dM/dz is the mutual inductance gradient. Because such systems represent a direct transfer of inductive energy to projectile kinetic energy, they can in principle be very efficient if resistive losses are eliminated. This can be done through the use of superconducting coils. Furthermore, just as in the case of the tether launch system, no propellant is required to project a payload from the lunar surface into orbit.

The disadvantage of electromagnetic quench guns, however, is that they tend to be relatively massive compared to the size of the payload they can deliver. For example, in a recent study[7] of a lunar quenchgun done by Electromagnetic Launch Research, a quench gun with a total mass of 256 tonnes (about 225 tonnes of which was imported high technology) was required in order to launch 1 tonne payloads into low lunar orbit. The operational complications of having to chase down and gather large numbers of 1 tonne payloads in lunar orbit make such a system undesirable. On the other hand, scaling the system up by a factor of 10 so as to be able to launch convenient 10 tonne payloads would result in a system mass requirement of over 2500 tonnes, which is clearly excessive.

The other promising lunar launch system is the ram accelerator. This system is composed of a long tube which is filled with a mixture of combustible gases. A projectile is fired down the tube, igniting the gas behind it as it goes. The ultimate velocity of a ram accelerator is thus not limited by the sound speed of the gas, as conventional guns are, and projectile velocities have already been achieved in experiments at the University of Washington well in excess of lunar escape. Because the energy storage capability of chemical fuels is available (instead of capacitor banks or other electromagnetic devices), very large payloads can be launched (> 20 tonnes). If a high speed shutter is properly employed, the amount of gas exhausted from the tube with the projectile can be kept to a small percentage of the total, and after firing, the exhaust water vapor can be condensed and electrolysed for re-use. The primary disadvantage of the ram accelerator is that it is massive. It is estimated[8] that a ram accelerator capable of launching 20 tonne payloads into LLO would have a mass of over 3000 tonnes. This would clearly be prohibitive to transport from Earth. Most of the mass of the system is aluminum pipe, and could conceivably be manufactured on the Moon. A rather large base infrastructure would be required, however.

Both the ram accelerator and the quenchgun are linear devices whose size is minimized by firing their projectiles as very high accelerations, typically 400 to 1000 g's. This is more than an order of magnitude greater than that required by the tether launch system. An additional disadvantage of ram accelerators and quench guns is that they can fire in only one direction, whereas the tether can release in any. Hence, the tether is able to launch to any inclination that is greater than the latitude of the tether facility.

Any linear accelerating device requires a rapid release of energy to accelerate the payload in as short a distance as possible. For a quench gun this requires the storage of at least 690 kW-hrs which is simply the kinetic energy needed by the payload. Both the ram accelerator and the tether have the advantage that the power can be built up slowly. In the ram accelerator the power is stored as chemical reactants and in the tether as kinetic energy. A unique spin-off of the tether power system is its ability to double as a lunar base power management system--absorbing power when extra is available and releasing power when demand exceeds supply. This is made more significant when considering the long lunar nights.

Taken together, these four advantages of a large payload to system mass ratio, modest g-loads, variable launch azimuth, and auxiliary power storage, appear to indicate that the TLS may offer superior potential as a lunar launch system over any of the previously studied alternatives.

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