ADVANCED PROPULSION FOR LEO-MOON TRANSPORT: II. TETHER CONFIGURATIONS IN THE LEO-MOON SYSTEM

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INTRODUCTION

This brief work discusses a possible application of a tether as a dynamical element in a low Earth orbit (LEO)-Moon transport system, and is a part of the Cal Space study of that transport system (*Stern,* 1989). To be specific, that study concentrated on the downward transport of O_2 from the Moon to LEO, where it is stored for use as a rocket propellant, thus reducing Earth liftoff mass requirements by a factor of about 8. Moreover, in order to display clearly the role of advanced technology, only one novel technology was introduced at a single node in the transport system, the rest being "conventional" rocket transport. For general background in tether applications in space, see *Penzo and Ammann* (1989), *Carroll* (1989), and *Bekey and Penzo* (1986).

Tethers were found useful in several different roles: hanging from platforms in lunar orbits, as supports for elevators, spinning in LEO, or spinning in a tether transport orbit, an elliptical orbit with perigee at ~600 km. Here we will consider only this last use. We will first display the usefulness of the tether, then discuss the nature of the tether system, the apparatus needed to support, deploy, and control it, and end with a discussion of needed developments. Although the authors assume responsibility, this is effectively the outcome of a joint study by the tether team, the enthusiasts—J. Carroll, H. Mayer, and P. Penzo—and the critics, especially B. Waldron, G. Babb, and H. Davis, who have played a major role in clarifying our ideas.

TETHER CHARACTERISTICS

We will characterize tether materials by a simple parameter, the specific tensile strength, i.e., the ratio of tensile strength to density. This may be represented as a characteristic length, the length of itself that a cable could support against the Earth's surface gravity. For steel, for example, this characteristic length is 46 km. Alternatively, the ratio can be expressed as the square of a characteristic velocity, and for steel this characteristic velocity is 0.6 km/sec. If, however, a material with the tensile strength of steel had a density of 1 gm/cm^3 (instead of 7), the corresponding characteristic velocity would be ~1.7 km/sec. There are materials available today (trade names kevlar, spectra) that have characteristic velocities greater than 1 km/sec (Table 1) and our illustrations will be based on this number. Of course, a tether material would have to satisfy many more conditions such as flexibility, resistance to abrasion, and resistance to the hostile space environment; in this study we will ignore such questions (*Jastrzebski,* 1989).

TABLE 1. Material properties.

Fiber	Density g/cm^3	Tensile Strength σ psi ($\times 10^5$)	Char. Length, L km	Critical Velocity, V_c km/sec
Si-Glass	2.54	5.07	190	1.36
Graphite	1.9	3.6	134	1.14
Silica	2.19	8.4	270	1.62
Aramid Polymer (Kevlar)	1.44	4.0	190	1.36
Polythene (Spectra)	0.97	4.3	310	1.75

THE MISSION

We suppose that an oxygen production facility has been established on the lunar surface, and that O_2 must be transported to LEO using lunar oxygen and hydrogen from the Earth's surface as propellant. The success of the scheme is measured by the mass payback ratio, the ratio of the net mass of O_2 delivered to LEO to the mass of H_2 that must be delivered from the Earth's surface to transport the O_2.

The system includes a lunar lander (LL) that transports O_2 from the lunar surface to an orbital transfer vehicle (OTV), which receives the O_2 and delivers the H_2 for the LL (Table 2). The OTV then flies back to LEO, dissipating energy by aerobraking, retaining enough O_2 for a return trip to LEO, delivering excess O_2 and picking up H_2 for the LL and the next return trip.

We will add to this reference system a tether platform (TP) in an elliptic orbit, which uses a spinning tether to add ΔV to the OTV, by recovering some of the orbital momentum of descending OTVs, on the "space elevator" principle (*Isaacs,* 1966).

TABLE 2. Vehicles for tether-assisted transport.

Vehicle	Mission	Gross (tonnes)	Dry	Fuel O:H	I_{sp} sec
Orbital Transfer Vehicle (OTV)	LEO<->LLO	60	14	6:1	470
Lunar Lander (LL)	LLO<->Moon	35	5	11:1	430
Tether Platform (TP)	TTO	400	---	6:1	470

THE LUNAR LANDER

The lunar lander has a dry weight of 5 tonnes and delivers a payload of 11 tonnes to the OTV. The LL uses an oxygen-rich fuel (1:2) with an I_{sp} of 430 sec. With a required ΔV of 2 km/sec, this uses a total of 16.2 tonnes of propellant/roundtrip, made up of 4 tonnes for the downward trip, carrying a payload of 1.5 tonnes of H_2, and 12.2 tonnes for the upward trip, which carries a payload of 15 tonnes of O_2 and uses 5.6 tonnes of H_2. We will use these numbers for the rest of the mission (see Table 3).

TABLE 3. The lunar lander.

Mission	ΔV km/sec	Payload (tonnes)	Total	Propellant O	H	Net O
LLO-Moon	2	1.5	4	3.66	0.33	
Moon-LLO	2	15	12.2	11.15	1.05	11
4 trips				Total H_2	5.5	44

REFERENCE CASE: OTV ALONE

In this case, the OTV leaves LLO, falls back to Earth, loses energy by aerobraking, and is placed in LEO needing a ΔV of ~1 km/sec. The vehicle has a dry weight of 14 tonnes, and uses a hydrogen-rich fuel (O:H = 6:1) with $I_{sp} = 470$ sec. With a payload of 34 tonnes, this requires 12 tonnes of propellant, 10.3 tonnes of O_2 and 1.7 tonnes of H_2; thus, 33.7 tonnes of O_2 reach LLO.

On the return (ascending) flight the payload is 6 tonnes of H_2, and a ΔV of 4 km/sec is required. This uses 28 tonnes of propellant, 24 tonnes of O_2 and 4 tonnes of H_2; thus, the net O_2 delivered to LLO is 9.7 tonnes and the total H_2 consumed is 11.3 tonnes. The payback ratio is then only 0.85 and there is a net loss (see Table 4).

TABLE 4. Reference case: OTV alone.

Mission	ΔV km/sec	Payload (Tonnes)	Total	Propellant O	H	Net O
LLO-LEO	1	34	12	10.3	1.7	33.7
LEO-LLO	4	6	28	24	4	9.7

Total H_2 5.7 + 5.6 = 11.3 tonnes

Payback Ratio = 0.85

THE SPINNING TETHER

Suppose now that the OTV is picked up by a tether of length 100 km, which is rotating prograde with a tip speed of 1 km/sec about a platform in an elliptic orbit with perigee at 600 km (100 km above the LEO circular orbit), and a perigee velocity of 8.3 km/sec (1 km/sec above the LEO velocity), so that the tether tip and the OTV have momentarily the same speed. The OTV is now swung around the platform, and at its maximum has speed of 9.3 km/sec (1 km/sec faster than the platform). Now it needs only 2 km/sec to reach LLO, and for a total load of 20 tonnes (14-tonne vehicle and 6-tonne payload) needs only 10.8 tonnes of fuel, including 9.3 tonnes of O_2, instead of the 24 needed in the reference case. Thus, the O_2 returned as payload to LEO is 24 tonnes, the H_2 used has been reduced to ~8.6 tonnes, and the payback ratio is increased from 0.85 to 2.8.

This must be reduced, however, since in the process of accelerating the loaded OTV, the tether platform has lost momentum 30.8 × 2 = 61.6 ton km/sec. This could be made up with a low-thrust, high specific impulse drive, such as an electric propulsion system, but if made up by the fuel that powers the OTV, needs 13.4 tonnes of fuel, including 11.4 tonnes of O_2 and 2 tonnes of H_2, and the payback ratio is reduced to 1.2.

If the descending OTV of mass 46.7 tonnes is not brought into LEO by aerobraking, but is instead put into an elliptic orbit with perigee at 700 km/sec and a velocity of ~9 km/sec, it can be caught by the tether, brought into LEO and released, giving a change in momentum of the opposite sign to that produced in upward-throw, with a magnitude of 93.4 ton km/sec. To remove the net Δp of 31.8 tonnes km/sec needs only 7 tonnes of fuel, including 6 tonnes of O_2 and 1 tonne of H_2. Then 18.3 tonnes of O_2 are available as payload, and the H_2 needed is 9 tonnes with a payback ratio of 2.1.

There is yet another possibility. Note that the Δp on throwing is about half of that on catching, and opposite in sign, thus if every second descending load is caught by the tether, the orbit of the TP will return almost to its initial value after every second throw, the net Δp being reduced to 1.8 tonnes/km/sec. Moreover, the ΔV experienced by the platform on a simple throw is $\Delta V(TP) = \Delta V(OTV) \times (M(OTV)/M(TP)) \propto 0.1$ km/sec for the masses we have chosen. If the throw and catch occur at perigee, this height is unaltered, and if the tether tip speed can be increased by 0.1 km/sec between throws, the OTV orbits are unchanged. An even better match is effected if two catches are made for every three throws. As displayed in Table 5, this increases the payback ratio to 2.7.

TABLE 5. Tether-assisted transport (optimal case).

Tether Assisted
(1) Tip Rendezvous: Throw + Optimal Catch + Aerobraking (3 Throw, 2 Catch)

Mission	Vehicle	ΔV Tonne km/sec	ΔV	Payload	Total	O	H	Net O_2
LEO-LLO	OTV		2	6	11	9.5	1.5	
LLO-LEO	OTV		1	34	12	10.3	1.8	
ΔV	TP/throw	1	—	—	0.25	0.2	0.05	
Net O_2								23.4
Total H						8.7		
Payback Ratio				2.7				

RENDEZVOUS AT PLATFORM

Babb (personal communication, 1988) observed that the tether tip rendezvous could be particularly difficult and suggested that instead rendezvous should be at the center of mass. This leaves the TTO-LLO section of the orbit unchanged, but requires that the ascending OTV make the transfer from LEO to the elliptical platform orbit, with a ΔV of 1 km/sec. This requires an added fuel consumption of 6.9 tonnes, including 6 tonnes of O_2. If the momentum loss of the tether platform is made up by a high specific impulse drive, the payback ratio is ~2.2. If, on the other hand, momentum loss is made by conventional rocketry, and the downcoming fuel is brought into LEO by aerobraking, the fuel required to make up 29 tonne/km/sec is 6 tonnes including 5.1 tonnes of O_2. The same amount is required to spin the load up to speed after capture; hence, allowing for these requirements, the net O_2 available as payload is 10 tonnes and the payback ratio is reduced to 1. It may be possible to reduce the fuel needed to spin up the load by using onboard manipulation of the tether tension, but the energy requirements for this might be prohibitive.

THE ROLE OF "UNOBTAINIUM"

In our analysis so far we have made the conservative assumption that tether materials are restricted to the specific tensile strengths available today. However, a LEO lunar transport system is probably at least a decade in the future, and materials science is developing at a rapid pace. As a speculation, let us consider the use of a tether for which v_c is 2 km/sec. The tether could then provide a ΔV of 4 km/sec and the OTV would then need only maneuvering capability of, perhaps, 0.8 km/sec and 3.7 tonnes of fuel, including 3.2 tonnes of O_2. If, moreover, the momentum loss of the tether platform is made up by a high specific impulse drive, the net O_2 payload becomes $33.7 - 3.2 = 30.5$ tonnes of O_2. The H_2 requirement is 8.5 tonnes and the payback ratio is 3.47. If the momentum transfer must be made up by rockets, this calls for 20 tonnes of fuel including 17.2 tonnes of O_2, and the payback ratio is reduced to 1.2; however, if the loaded OTV is caught on every fourth return, the net Δp of the TP is 12 tonnes km/sec, or 3 tonnes km/sec per throw. To replace this it needs only 0.65 tonnes of propellant including 0.56 tonnes of O. The net O_2 obtained is 30 tonnes, the total H_2 used, 8.4 tonnes, and the payback ratio is 3.4.

THE TETHER SYSTEM

The tether itself may be a rather simple structure, but the system as a whole, consisting of a ballast platform, the orbital makeup drive, the winches for controlling the tether, the onboard power system, the guidance and control needed to locate the center of mass and keep it in orbit, and the system needed to effect rendezvous, is complex, and in this brief description we will only sketch out the requirements.

The Tether

Tether mass (1.4 M_L). This is determined by the tip speed, which depends on v_c for the tether material. The mass is minimized if the area at any distance from the center of mass is selected so that the tension in that section is a fixed fraction of the breaking stress. It is readily shown that the cross section should have the form

$$a(x) = a_o \exp\left(-\frac{1}{2}\left(\frac{v_t x}{v_c l}\right)^2\right)$$

where l is the tether length and v_t the tip speed. The ratio between the load mass and the tether mass for $v_t = v_c$ is then 1.41. For our conditions in the throw only mode, this calls for a tether mass of 41 tonnes. In the throw and catch mode, the larger mass of the downcoming load (48 tonnes) increases this to 67 tonnes.

Tether length (100 km). This is determined by a compromise between the acceleration to which the load is subject (which decreases with tether length), the time for rendezvous (which increases with tether length), and the probability of damage or destruction by collision with space debris. At 100 km, the expected mean life is ~10 years, and the probability of destruction during the first year is ~10%.

The Tether Platform

Platform mass (~10M_L). On capturing and releasing a load, the platform experiences a change in velocity

$$\Delta V = \frac{\Delta p}{M_T}$$

where M_T is the final mass of the total system: tether, platform, and load on capture, tether and platform on release. The resulting change in the TTO leaves the perigee fixed (if throw and catch both occur at that point), but changes both the semimajor and semiminor axis. If the ballast mass is 10 times the load mass, the change in velocity on catch and throw is 0.2 km/sec, 2.5% of the orbital speed, which is acceptable for catch and throw at perigee, but would otherwise be marginal. For our case this ballast mass is 310 tonnes on throw and 480 tonnes on catch. Note, however, that most of this is ballast, and could be made of spent space units, such as external tanks.

Drive. To make up for momentum loss, a drive of some kind is needed, and since the changes in velocity required are ~0.2 km/sec, the propellant mass needed is

$$\frac{\Delta p}{g I_{sp}}$$

which we have included in our transport models, if conventional rocketry is used. We have observed that a very high I_{sp} drive, electrostatic with $I_{sp} \sim 10^4$, would greatly reduce the propellant mass (to 2% of the load mass) to ~0.6 tonnes for the upgoing load—although increasing the onboard power required.

Winch. The winch is needed to deploy and spin up the tether, and to alter tether length when catching a load. When fully deployed and spinning at angular velocity Ω or velocity V, the tether for a 1-T load has an energy E of $0.2 \times 1/2 M_T V^2 = 1.32 \times 10^8$ J/T and an angular momentum of $2E/\Omega = 2Er/V = 2.6 \times 10^{10}$ J sec/T. Note that revving up is a one-time operation, which might be provided by an OTV that draws out the tether and gives it the required angular momentum, or it may be carried out as part of the operation of placing the platform in orbit, if it is feasible to deploy the tether early. Since the orbital makeup thruster is not at the center of mass, it will alternately add to and take away angular momentum from a rotating tether. If the thrust is modulated with respect to the tether phase, the thruster can be used to modify the rotational angular momentum.

In low Earth orbit, angular momentum can be provided by the gravitational gradient. The available energy then is ~0.2 $M_T V_{esc}^2$ $(1/r)^2$, which for the lowest orbit (~200 km) is ~5% of the final required energy. To add angular momentum, the tether must be extended on the downswing and reeled in on the upswing. Initially, there are ~23 minutes to do this, and the initial power needed to reel the tether in is 4.8 kW/T.

If the winch can reel at a speed of 2.5 km/min at low load (800 rpm for a 1-m-diameter reel), then the energy increment is of order 2.5% of the final requirement/cycle, the power needed reaches 160 kW/T near the end of the build-up, and the full angular momentum can be supplied in about 10 days from the gravitational gradient. About 100 kW/T of winch power is needed during capturing maneuvers in which it will be important to change the tether length by amounts of order 1 km in times of order 1 min. The winch will also be involved in platform orbital correction operations. Since the drive site at the platform is 21.6 km from the center of mass, angular momentum is alternately added and taken away from the system while under drive. Modulating the tether length gives control of the net angular momentum addition.

Finally, the winch is needed to damp out unwanted vibrations of the tether, and to compensate for hysteretic losses in the gravitational gradient. This last operation will require continuous power of order 1.5 kW/T. The winch would have to be rather impressive since it must reel in at a few kilometers/minute under a tension of ~2.4T/T load.

Power Requirements

In addition to the drive, onboard power is needed to drive the winch, at a peak of 160 kW/T load. For our case, with only the upward load using the tether, this requires ~4.8 MW. If the downward load is also handled this becomes 9 MW. This power is needed only in pulses of a few minutes, and is most important during the final stage of spin up or during load capture.

Energy Storage

It would be useful to have some means of storing the energy and angular momentum of the tether, when modest changes in length are made. Since angular momentum is conserved, energy will be stored in the rotation of the platform about the center of mass, and in the speedup of the tether tip. If substantial reel-in is required, for example to avoid a collision, a modulated burn of the platform propellant could get rid of or replace angular momentum to keep the spin at a tolerable value.

Rendezvous Requirements: Tether Tip Vehicle (TTV)

There may be a need for a vehicle at the tether tip to make rendezvous with the incoming loads. We assume that the incoming vehicle can get within 1 km of the rendezvous. The TTV then has about 1 min to detect the incoming load at 100 km and effect a rendezvous. This can be done with an acceleration of 1 m/sec^2 and a maximum speed ~200 m/sec. The vehicle can carry a light line of length ~2 km and of mass ~1 kg, which can be used to draw the tether tip to the incoming load.

The TTV needs detectors and control for target acquisition and guidance, a drive giving ΔV ~200 m/sec and an acceleration of 10 m/sec^2 to make rendezvous with the incoming load, a releasable clamp to attach to the target, a reel that can pull the tether tip ~1 km in about 100 sec, and some scheme for clamping it to the load. In addition to a modest drive ($\Delta P = M_v \times 100$ m/sec) requiring ~3% of the vehicle mass (M_v) in propellant, the TTV needs an onboard power source and a motor yielding ~0.5 kW, enough to reel in the tether mass ~1 kg) in about 1 min. A reel of radius 16 cm, spinning at 1000 rpm under a load of 2 kg, would be adequate. A total TTV mass of 100 kg is probably generous. It might be preferable to mount the reel and the windup motor on the tether tip, thus reducing the TTV mass, but increasing the mass that must be reeled in. Note that the figures given here are per ton of load captured. For our case, the onboard power, the mass of the retrieval line, and the TTV mass must be increased by factors of 30 or 56 in the two cases.

An alternative might be to have the incoming vehicle throw out a line at right angles to the tether so that the lines cross and grapple. Then the TTV vehicle becomes superfluous, although a tether and reel will still be needed. The use of a tether in this mode calls for a "smart" orbiting vehicle, capable of making a rendezvous within less than a minute, within 1 m.

Repair and Maintenance

A serious problem faced by the tether is damage by collisions with debris in space. *Carroll* (1989) has analyzed this using data from *Keller* (1984) and finds that a major role is played by objects a few centimeters in length. If the tether were a single strand, or a single woven cable, then it would have approximately a 10% probability of having a collision and being destroyed each year. One way of compensating for this is to increase the tether mass and build in some redundancy. Moreover, instead of using a single strand, the tether could be composed of a number of strands separated by a few tens of centimeters. Then, although the probability of any given strand being broken is unaltered (and the probability of some collision is increased) a single collision is not fatal. This, by itself, gives no advantage, but if we add some method of repairing damage, either by reeling in the tether for repair, or by sending out some kind of machine that will repair the damaged section without reeling in, then the tether lifetime could be increased by a very large factor. Of course, if the amount of space debris increases in the future due to human activity, the hazards and the need for repair also increase.

CONCLUDING REMARKS

This study strongly suggests that even under very restrictive conditions tethers could play a major role in an Earth-Moon transport system. If a wider view is taken, and extra new technologies or multiple tethers are permitted, their role becomes even more significant. In a mature transport system, in which mass transfer up to the Moon and transfer down to LEO are more nearly equal, the momentum make-up problem could be greatly reduced, and the advantages of tethers become greater.

It must also be clear that the use of tethers depends on the solution of many novel and formidable problems. Can tether materials be developed that will provide not only the required specific tensile strength, but also the flexibility and resistance to abrasion, solar and particle radiation, and to heating in the upper atmosphere? Can reliable technologies for deploying and manipulating tethers, especially multistranded systems, be developed in view of the rates of reeling and the degree of control required? Can the winches, controls, and power sources be produced capable of these complex manipulations that must be carried out without manual intervention? Can the rendezvous problems at the tether tip be mastered? On a more basic level, what are the best orbits for tether missions? We have considered one, but are others more desirable? (Almost certainly, yes!) What are the orbital limitations to tether applications? (In equatorial orbits, a few days/month; in 20° orbits, a few days in every 80 for the orbits we have considered.) What are appropriate manipulation strategies? How should the equipment be designed?

The challenges here to invention, to control engineering, to robotics, and to understanding fundamental mechanical problems, are great enough to call the use of tethers in space an entirely new branch of engineering, and possibly one of greatest importance. Design and laboratory studies, supplemented by space testing, need dedicated resources and an early start; but tethers may eventually justify their most enthusiastic supporters.

REFERENCES

Bekey I. and Penzo P. (1986) Tether propulsion. *Aerosp. Am., 24,* 40-43.

Carroll J. (1989) Guidebook for analysis of tether applications. In *Tethers in Space Handbook,* 2nd edition (P. Penzo and P. Ammann, eds.). NASA Publication NSW-4341.

Isaacs J. D., Vine A. C., Bradner H., and Backus G. E. (1966) Satellite elongated into a true skyhook. *Science, 151,* 682.

Jastrzebski Z. D. (1989) *The Nature and Properties of Engineering Material.* Wiley, New York. 553 pp.

Keller D. J. (1984) *Orbital Debris Environment for Space Station.* JSC Publ. No. 20001, Houston.

Penzo P. and Ammann P., eds. (1989) *Tethers in Space Handbook,* 2nd edition. NASA Publication NSW-4341.

Stern M., ed. (1989) *Advanced Propulsion for LEO-Moon Transportation, Final Progress Report.* NAG9-186, California Space Institute, Univ. of California, San Diego.