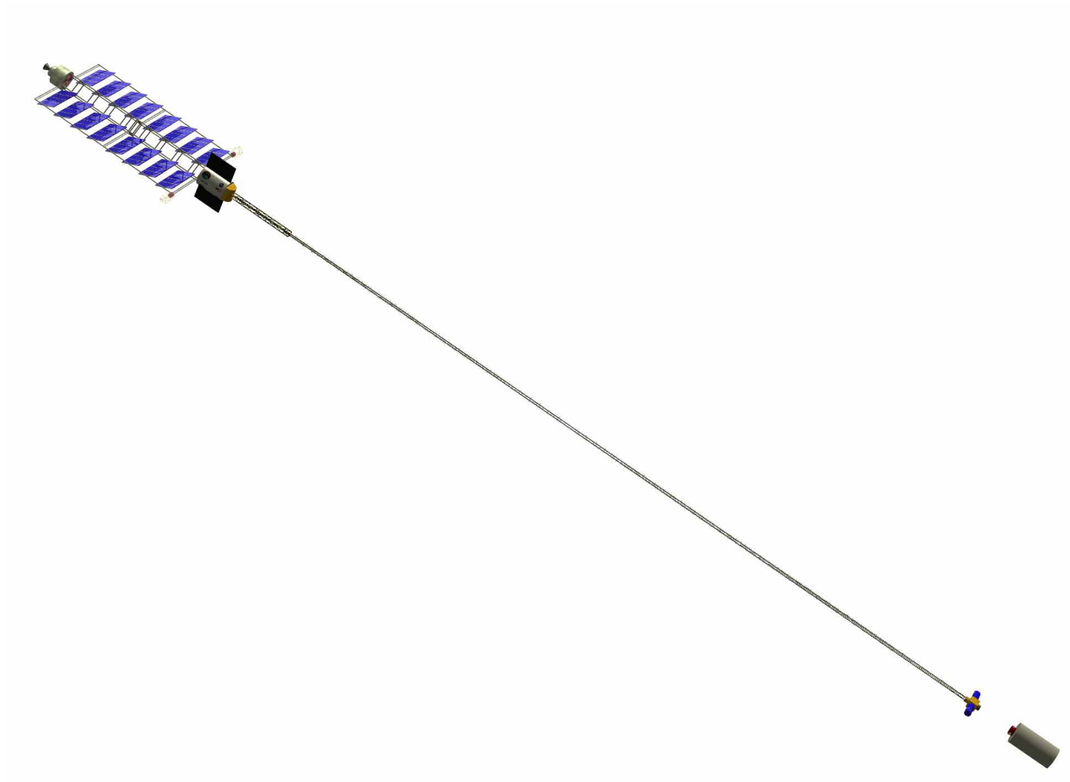
AIAA 2000-3866

# DESIGN AND SIMULATION OF A TETHER BOOST FACILITY FOR LEO⇒GTO TRANSPORT

R. Hoyt

*Tethers Unlimited, Inc., Seattle, WA*



**36th AIAA/ASME/SAE/ASEE**

**Joint Propulsion Conference & Exhibit**

17-19 July 2000

Huntsville, AL

# DESIGN AND SIMULATION OF A TETHER BOOST FACILITY FOR LEO ⇒ GTO TRANSPORT

Robert P. Hoyt
*Tethers Unlimited, Inc., Seattle, Washington*
*www.tethers.com*

**Abstract**

The LEO⇒GTO Tether Boost Facility will combine momentum-exchange tether techniques with electrodynamic tether propulsion to provide a reusable infrastructure capable of repeatedly boosting payloads from low Earth orbit to geostationary transfer orbit without requiring propellant expenditure. Designs for the orbital mechanics and system sizing of a tether facility capable of boosting 2,500 kg payloads from LEO to GTO once every 30 days are presented. The entire tether facility is sized to enable an operational capability to be deployed with a single Delta-IV-H launch. The system is designed in a modular fashion so that its capacity can be increased with additional launches. The tether facility can also boost 1000 kg payloads to lunar transfer orbits, and will serve as the first building block of an Earth-Moon-Mars Tether Transportation Architecture. The tether facility will utilize electrodynamic tether propulsion to restore its orbit after each payload boost operation. Using numerical modeling of tether dynamics, orbital mechanics, electrodynamics, and other relevant physics, we validate the orbital design of the system and investigate methods for performing electrodynamic reboost of the station.

## Introduction

Under funding from NASA's Institute for Advanced Concepts (NIAC), Tethers Unlimited, Inc. and the Boeing Company are developing a modular architecture for a tether transportation system. This system will utilize momentum-exchange techniques and electrodynamic tether propulsion to transport multiple payloads *with little or no propellant consumption*. The tether transportation system will be built incrementally. The first component of the system will be a Tether Boost Facility that will transfer satellites and other payloads from low Earth orbit (LEO) to geostationary transfer orbit (GTO). This same facility will also be capable of boosting payloads to lunar transfer orbit (LTO). Later components will increase the payload capacity of the Tether Boost Facility and enable frequent round-trip travel to the surface of the Moon[1,2] and to Mars.[3] In this paper we present results of the development of a conceptual design for the first component of the tether transportation architecture, the LEO⇒GTO Tether Boost Facility, and discuss simulations used to investigate the operation of the tether system.

## Background

### Momentum-Exchange Tethers

In a momentum-exchange tether system, a long, thin, high-strength cable is deployed in orbit and set into rotation around a massive central body. If the tether facility is placed in an elliptical orbit and its rotation is timed so that the tether will be oriented vertically below the central body and swinging backwards when the facility reaches perigee, then a grapple assembly located at the tether tip can rendezvous with and acquire a payload moving in a lower orbit, as illustrated in Figure 1. Half a rotation later, the tether can release the payload, tossing it into a higher energy orbit. This concept is termed a momentum-exchange tether because when the

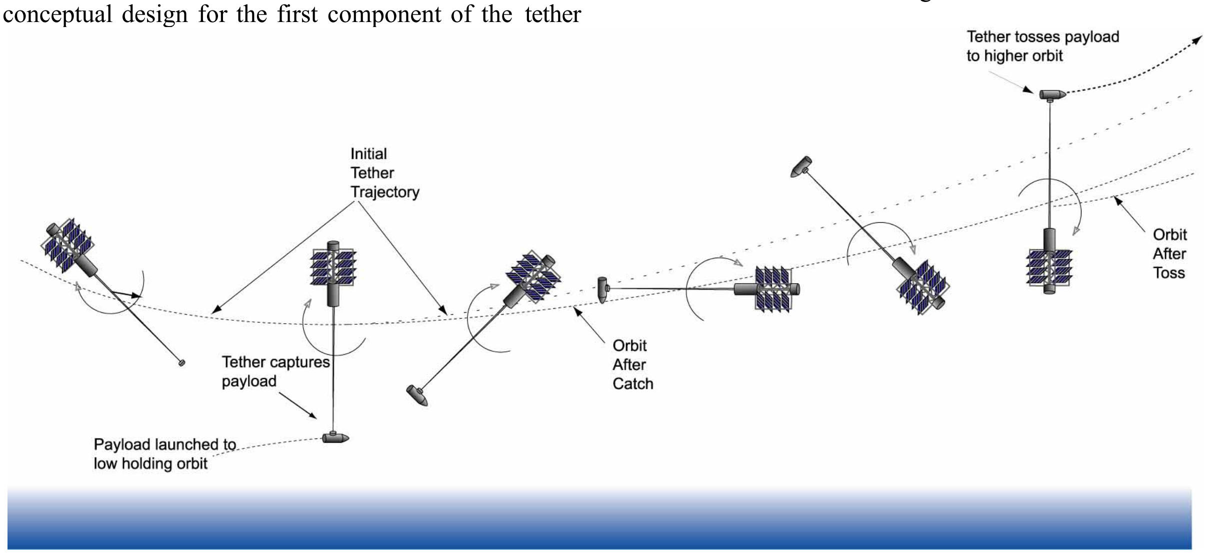



**Figure 1.** Momentum Exchange Tether catching and tossing payload.

tether picks up and tosses the payload, it transfers some of its orbital energy and momentum to the payload. The tether facility's orbit can be restored later by reboosting with propellantless electrodynamic tether propulsion or with high specific impulse electric propulsion; alternatively, the tether's orbit can be restored by using it to de-boost return traffic payloads.

**Prior Work**

Several prior research efforts have investigated conceptual designs for momentum-exchange tether systems. In 1991, Carroll proposed a tether transport facility that could pick payloads up from suborbital trajectories and provide them with a total ΔV of approximately 2.3 km/s.[4] Carroll's design, however, assumed that the tether would be placed in a circular LEO orbit. In order for this facility and tether to remain above the atmosphere after a payload boost operation, the central facility had to mass 50-100 times the payload mass. This large mass would require a very large launch cost to set up the tether facility, which would likely hinder the economic viability of the concept.

In 1997, Hoyt[5] investigated a concept proposed earlier by Forward[6] for a tether system for transporting payloads from LEO to the surface of the Moon. This design used two tethers in Earth orbits to minimize the total tether mass required for the system. Hoyt proposed placing the tethers in elliptical orbits and performing all catch and toss operations at or near perigee. Doing so minimized the drop in the tether's perigee, enabling a tether facility to boost a payload and still stay above the atmosphere with facility masses as low as 5-10 times the payload mass.

In 1998, Bangham, Lorenzini, and Vestal developed a conceptual design for a two-tether system for boosting payloads from LEO to GEO.[7] The tether transport system was proposed to stage the ΔV operations using two tether facilities in elliptical orbits so as to minimize the required tether mass. Their design proposed the use of high specific impulse electric thrusters to restore the orbit of the tether facilities after each payload boost operation. Even with the propellant mass requirements for reboost, they found that this system could be highly economically advantageous compared chemical rockets for GEO satellite deployment.

In a Phase I NIAC effort in 1999, Hoyt and Uphoff studied the orbital mechanics of multi-tether systems for transporting payloads between LEO and the surface of the Moon and found that orbital perturbations caused by Earth oblateness and other effects would make scheduling transfers in a staged system difficult or impossible.[1] Consequently, they concluded that tether systems for transporting payloads from LEO to GTO or LTO should use one tether facility in Earth orbit to provide all of the ΔV. Further study revealed that although a single-tether system requires a much larger total tether mass than a staged two-tether system, the total system mass for a one-tether system, including the mass required for the control station and grapple assemblies, is the same or less than a multi-tether system.[2]

## LEO⇒GTO Tether Boost Facility Design

**Design for Incremental Development**

The ultimate goal of this research effort is to develop a fully reusable in-space transportation infrastructure capable of providing frequent rapid round-trip transport between Earth, the Moon, and Mars. The technical development of such a transportation architecture must, however, follow a path that is commensurate with a viable business plan, in which early components can serve useful functions to generate revenue to fund the development of the rest of the system. Accordingly, as the first step in the deployment of this architecture, this effort has designed an initial tether transportation capability that will provide a cost-competitive transportation service for a significant and well-understood market, namely that of delivering payloads to GEO. The first component deployed will generate revenue by boosting commercial satellites and other payloads to GTO, as well as sending small payloads to the Moon. This revenue will be invested in the deployment of additional modules to increase the system capacity enable large payloads to be sent to either GEO or the Moon. Later, similar tether facilities will be deployed in orbit around the Moon and Mars, enabling round-trip transport between LEO, the lunar surface, and Mars orbit with zero transfer propellant requirements.

**System Requirements**

*Payload Mass:*

The mission of the LEO⇒GTO Tether Boost Facility will be to pick 2,500 kg payloads up from low-LEO orbits and inject them into transfer orbits to GEO altitudes. To do so, the Tether Boost Facility will provide the payload with a total ΔV of 2.4 km/s.

*Expandability:*

The 2,500 kg payload size was chosen primarily so that a fully operational tether facility can be launched on a single large launch vehicle. The likely "sweet spot" for the GTO market in 2010, however, is expected to be closer to 5,000 kg. Consequently, this effort has sought to design the Tether Boost Facility to be expandable so that a second launch of nearly identical equipment will enable it to handle larger payloads and larger ΔV's.

*Payload Design Impacts:*

The Tether Boost Station architecture must minimize the design impacts upon payloads. Consequently, the system is designed to expose the payload to dynamic loads that are no larger than those it would experience in a conventional launch vehicle such as an Ariane or Delta rocket. In order to enable the payload to be boosted by the tether facility, a payload accommodation adapter (PAA) will be fitted to the payload's standard mounting fixtures. The PAA will provide the rendezvous maneuvering and docking capabilities to the pay load, and may also provide the apogee kick $\Delta V$.

*Safety Factor:*
To provide ample margin for error and degradation of the tether over time, the tether structure is sized to pro vide a safety factor of 2 for the largest loads expected in the system. The largest loads will be due to transient oscillations immediately after the payload capture. These loads are predicted using numerical modeling with TetherSim™. Computed with respect to the nominal loads, the safety factor is roughly 3.5.

*Throughput:*
Because one of the primary advantages of momen tum-exchange tethers is their reusability, to maximize the cost-competitiveness of the system it will be de signed to boost payloads as frequently as once every 30 days.

**Momentum-Exchange/Electrodynamic-Reboost Facility Concept**
In order for the tether facility to boost one payload per month, the tether must restore its orbital energy after each payload boost operation. Previous efforts have proposed using ion thrusters or other electric pro pulsion to accomplish this reboost;[4,7] electric thrusters, however, require propellant expenditure and thus would incur launch mass costs and resupply operations costs which would limit the competitiveness of the tether system.

If the tether facility operates at least partly within LEO, it can instead utilize electrodynamic tether propulsion to perform reboost of its orbit. This concept, called the "High-strength Electrodynamic Force Tether" (HEFT) Facility (also referred to as a "Momentum-Exchange/Electrodynamic-Reboost (MXER) Tether Facility),[8] is illustrated in Figure 2. The Tether Boost Facility will include a control station housing a power supply, ballast mass, plasma contactor, and tether deployer, which would extend a long, tapered, high-strength tether. A small grapple vehicle would reside at the tip of the tether to facilitate rendezvous and capture of the payloads. The tether would include a conducting core, and a second plasma contactor would be placed near the tether tip. By using the power supply to drive current along the tether, the HEFT Facility could generate electrodynamic forces on the tether. By properly varying the direction of the current as the tether rotates and orbits the Earth, the facility can use these electrodynamic forces to generate either a net torque on the system to change its rotation rate, or a net thrust on the system to boost its orbit. The HEFT Facility thus could repeatedly boost payloads from LEO to GTO, and in between each payload boost operation it would

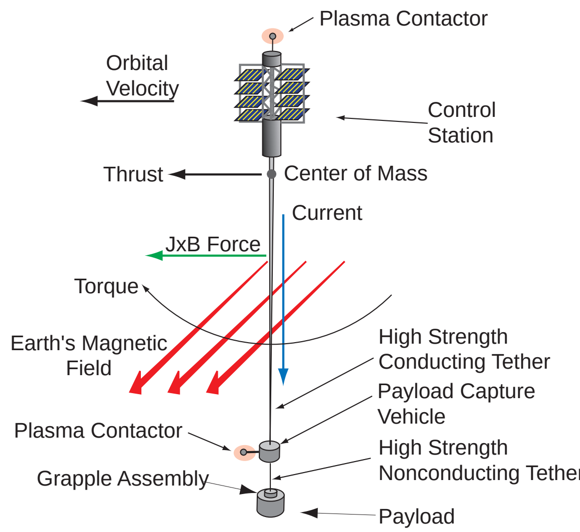



**Figure 2.** Schematic of the HEFT Facility concept.

use propellantless electrodynamic propulsion to restore its orbital energy.

**Orbital Design**
To boost a payload from LEO to GTO, the tether facility performs a catch and release maneuver to provide the payload with two $\Delta V$ impulses of approximately 1.2 km/s each. To enable the tether to perform two "separate" $\Delta V$ operations on the payload, the facility is placed into a highly elliptical orbit with its perigee in LEO. The tether facility's initial orbit is chosen so that when the tether is near perigee, its center of mass is moving approximately 1.2 km/s faster than the payload in circular LEO. It can then catch the payload, hold it for half a rotation, and then release it at the top of the tether's rotation. This injects the payload into the high-energy transfer trajectory.

Table 1 shows the orbital design for the LEO⇒GTO Tether Boost Facility. To minimize the mass of the tether, it is tapered along its length to maintain a constant load level; Figure 3 illustrates this tapering.

The orbital parameters and system masses shown in Table 1 are chosen so that the payload's orbit and the facility's initial orbit are harmonic. For this design the resonance is 41:20. This enables the tether facility to have multiple opportunities to capture the payload. If the payload and tether do not succeed in achieving docking during the first rendezvous attempt, they will wait for 2.6 days, adjusting the tether spin and correcting any trajectory errors, and then a second rendezvous will be possible without any significant maneuvering. The resonance design shown in Table 1 accounts for regressions of both orbits due to the Earth's non-ideal gravitational potential, up to the J4 term.

**Table 1. System Orbital Design for LEO⇒GTO Boost**

| **System Masses** | | |
|---|---|---|
| Tether mass | 8,274 | kg |
| CS Active Mass | 11,514 | kg |
| CS Ballast Mass | 3490 | kg |
| Grapple mass | 650 | kg |
| **Total Facility Mass** | **23,928** | kg |
| **Total Launch Mass** | **20,438** | kg |
| **Payload Mass** | **2,500** | kg |

| **Tether Characteristics** | | |
|---|---|---|
| Tether Length | 100,000 | m |
| Tether mass ratio | 3.31 | |
| Tether tip velocity at catch | 1,267 | m/s |
| Tether tip velocity at toss | 1,147 | m/s |
| Tether angular rate | 0.015514 | rad/s |
| Gravity at Control Station | 0.64 | g |
| Gravity at payload | 1.81 | g |
| Rendezvous acceleration | 2.00 | g |

| | | **Pre-Catch** | | **Joined System** | **Post-Toss** | |
|---|---|---|---|---|---|---|
| **Positions & Velocities** | | **Payload** | **Tether** | **Post-catch** | **Tether** | **Payload** |
| resonance ratio | | 41 | 20 | | 1 | 4.1 |
| perigee altitude | km | 325 | 407 | 399 | 391 | 473 |
| apogee altitude | km | 325 | 8445 | 7199 | 6105 | 35786 |
| perigee radius | km | 6703 | 6785 | 6777 | 6769 | 6851 |
| apogee radius | km | 6703 | 14823 | 13578 | 12483 | 42164 |
| perigee velocity | m/s | 7711 | 8978 | 8858 | 8738 | 10005 |
| apogee velocity | m/s | 7711 | 4109 | 4421 | 4739 | 1626 |
| CM dist. From Station | m | | 18356 | 26080 | 18356 | |
| CM dist. To Grapple | m | | 81644 | 73920 | 81644 | |
| ΔV to Reboost | m/s | | | | 240 | |
| ΔV to Correct Apogee | m/s | | | | | 0 |
| ΔV to Correct Precess. | m/s | | | | | 0 |
| ΔV To Circularize | m/s | | | | | 1449 |
| **Basic Orbital Parameters** | | | | | | |
| semi-major axis | km | 6703 | 10804 | 10177 | 9626 | 24508 |
| eccentricity | | 0.0 | 0.372 | 0.334 | 0.297 | 0.720 |
| inclination | rad | 0 | 0 | 0 | 0 | 0 |
| semi-latus rectum | km | 6703 | 9309 | 9041 | 8778 | 11787 |
| sp. mech. energy | m2/s2 | -2.97E+07 | -1.84E+07 | -1.96E+07 | -2.07E+07 | -8.13E+06 |
| vis-viva energy | m2/s2 | -5.95E+07 | -3.69E+07 | -3.92E+07 | -4.14E+07 | -1.63E+07 |
| period | sec | 5462 | 11176 | 10218 | 9399 | 38183 |
| period | min | 91.0 | 186.3 | 170.3 | 156.7 | 636.4 |
| station rotation period | sec | | 405.0 | 405.0 | 405.0 | |
| rotation ratio | | | 27.6 | 25.2 | 23.2 | |

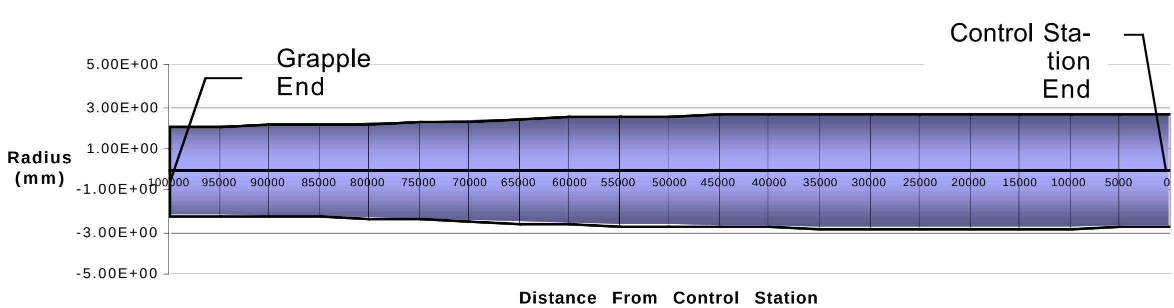



**Figure 3.** Taper of the tether cross-section (tether will actually be composed of multiple smaller lines).

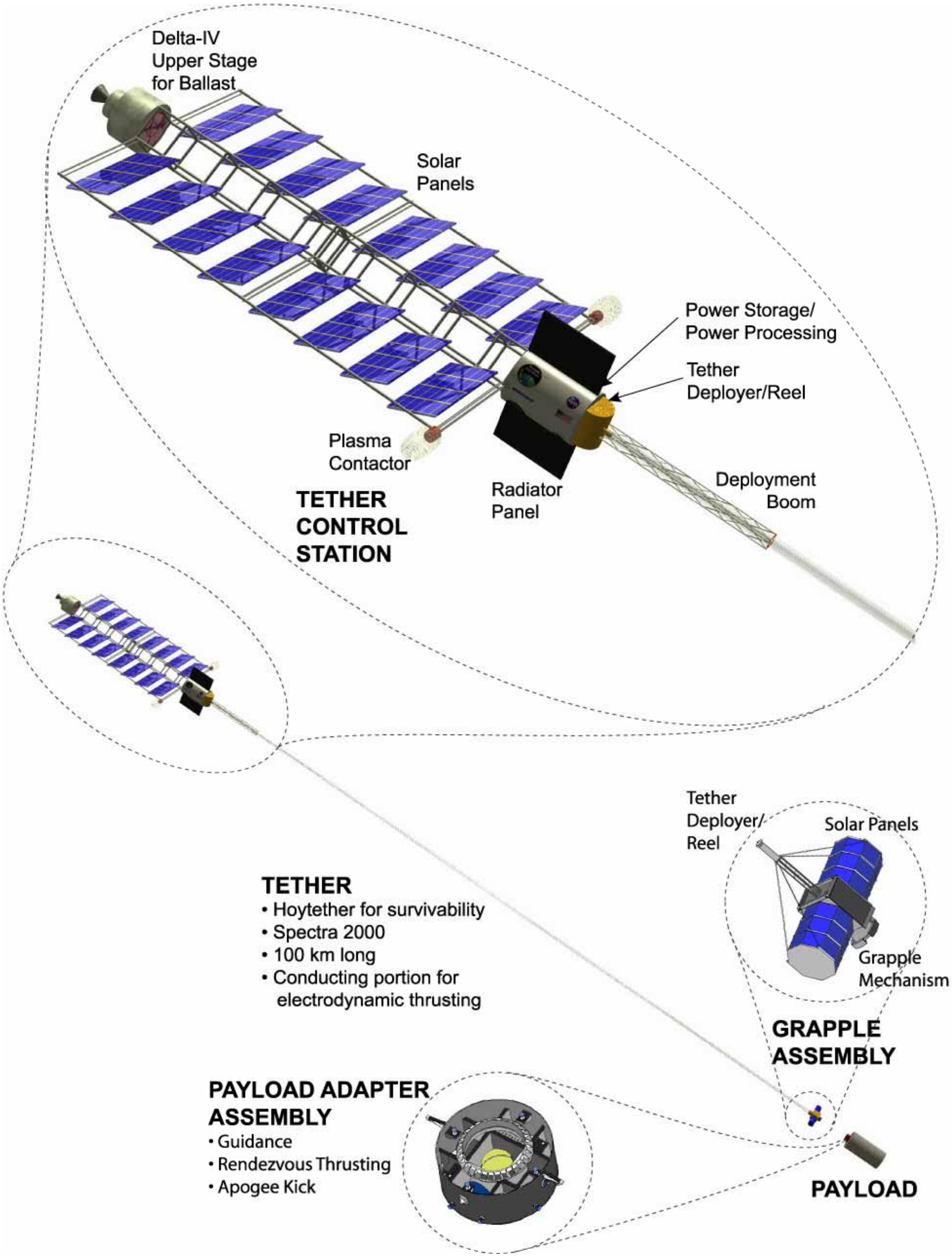



**Figure 4. System Design for a Tether Boost Facility.**

**Figure 5.** Tether Boost Facility with two modules, capable of tossing 5000 kg to GTO and 2000 kg to LTO. (Tether length not to scale)

**System Design**

Figure 4 illustrates the system concept design for the Tether Boost Facility. The Tether Boost Facility is composed of a Control Station, a tapered high-strength tether, and a Grapple Assembly. In addition, a Payload Accommodation Assembly (PAA) will be attached to the payload to provide maneuvering and guidance for rendezvous. For LEO⇒GTO traffic, this PAA will be an expendable unit incurring recurring costs.

To meet the requirement for operational capability with a single launch, the tether facility is sized to be deployed with a single launch of a Delta-IV-H or comparable vehicle. As Figure 4 shows, the 3490 kg Delta upper stage will be retained for use as ballast mass. The control station includes an array of solar panels which swivel to track the sun as the tether facility rotates. In this design, we have chosen to place the control station at the end of the tether, rather than at the center of mass of the facility. This choice was made for several reasons: because it minimizes the dynamical complexity, because it requires only one tether deployer, and because the center of mass of the system shifts when the payload is captured and released.

*Electrodynamic Tether:*

The tether in this system is composed of Spectra 2000® fibers braided into the Hoytether™ structure.[9] The nominal length of the tether is 100 km. Along the 80 km of the tether closest to the Control Station, a total of 500 kg of insulated aluminum wire is woven into the structure, providing a current path for electrodynamic thrusting.

*Power System Sizing:*

In order for the tether facility to reboost its orbit within 30 days, the facility will require a solar power generation capability of 100 kW. Because the facility will pass through the radiation belts frequently, its solar power system will utilize a concentrator-type solar panel design, such as the Scarlet design, with 150 mil Aluminum backside and 100 mil glass cover slides to shield the arrays from the belt particles. In order for the solar array to produce the desired power levels after 10 years of operation, they system will be deployed with 137 kW of initial power generation capability. Using Scarlet-type panel technology, this solar array would mass approximately 1,370 kg. The tether facility will collect this solar power during the roughly 80% of its orbit that it is in the sunlight, and store it in a battery system. Then, during perigee pass, it will drive the electrodynamic tether at an average power level of 300 kW (modulated as to be described later). In order to provide a maximum battery depth-of-discharge of 30%, the control station will have a battery system with 5,700 A•hr of capacity (120 V power system). Using advanced Li ion batteries, this will require approximately 4,600 kg of batteries. The control system will also require the capability to transform the 120 V battery voltage up to the 20+kV needed to drive tether currents on the order of 15 A.

*Payload Capacity vs. Tip Velocity*

The boost facility described herein is optimized for tossing 2.5 metric ton payloads to GTO. The same facility, however, can also service traffic to other orbits by changing its rotation rate and initial orbit. Because the stress in the tether increases exponentially with the rotation rate, the payload capacity drops as the tip velocity increases. Figure 6 shows the payload mass capacity versus the total ΔV that the tether facility could impart to the payload in a catch-toss operation. The boost facility could toss 1000 kg into a minimal-energy lunar transfer orbit, or toss 500 kg into an escape trajectory.

*System Modularity*

The Tether Boost Facility concept has been designed to enable it to be grown incrementally. After the initial facility, capable of tossing 2,500 kg to GTO and 1000 kg to LTO, has been deployed and tested, a second module of nearly identical hardware can be launched and combined in a parallel fashion with the first module, as illustrated in Figure 5. This will increase the system's capacity to 1,000 kg to LTO and 5,000 kg to GTO. The parallel construction will provide redundancy to the system, reducing the need for redundancy within each module. Cross-linking between the two parallel tethers could be added to increase their redundancy. Additional modules can be launched to increase the system capacity further.

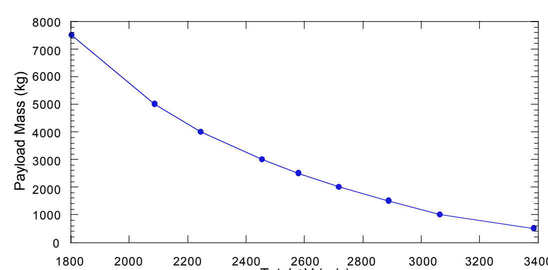



**Figure 6.** Payload capacity for the facility design given in Table 1 at different tip velocities.

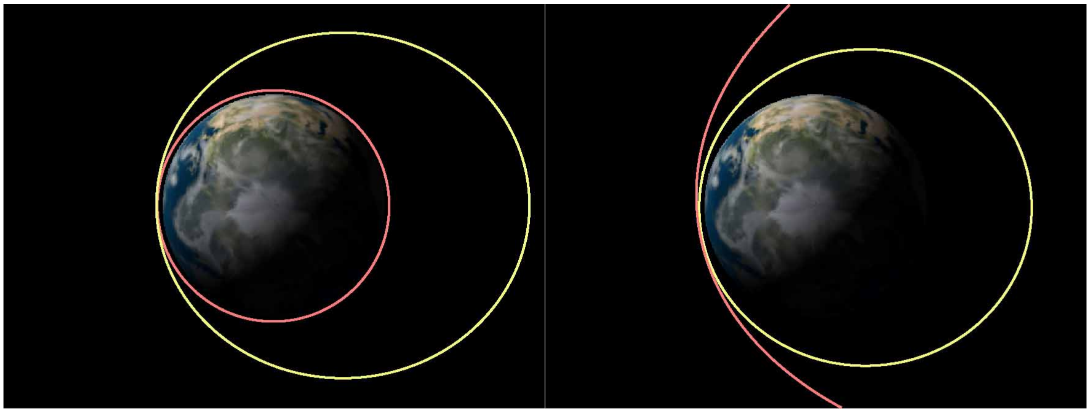


**Figure 7.** LEFT: Tether Boost Facility initial orbit (yellow ellipse) and payload initial orbit (red circle). RIGHT: Tether Facility orbit after payload boost (inner yellow ellipse) and Payload GTO (red outer ellipse).

## Simulation of Electrodynamic Reboost

As the Tether Boost Facility catches and tosses a payload into GTO, its orbit drops, as illustrated in Figure 7. The apogee drops 2340 km, and the perigee drops 16 km. To restore the orbit, the tether system must increase the facility's orbital energy by 54 GJ, and it will do so by performing electrodynamic thrusting while the tether is within the dense portion of the ionosphere near the perigee of its orbit. Because the tether is rotating, the direction of the current must be alternated as the tether rotates to produce a net thrust on the facility. Using the TetherSim™ program, we have modeled reboost of a rotating tether system to investigate the efficiency of the reboost, and to develop methods for controlling the electrodynamic thrust to achieve the desired final orbit.

**Method:**

To study the performance of electrodynamic reboost of the tether facility, TetherSim™ was used to simulate reboosting of the orbit of the Tether Boost Facility described in Table 1 over a period of two days. TetherSim™ is a numerical simulation tool that includes models for tether dynamics, orbital mechanics, electrodynamics, thermal behavior, geopotential, geomagnetic field, ionospheric density variations, neutral gas density variations, and other relevant physics.

In the simulations, thrusting was performed when the tether facility's altitude was under 2000 km. The electrodynamic tether system had hollow-cathode plasma contactors at both ends of the conducting tether, so that it could carry current in both directions. The thrusting was performed at a maximum power of 450 kW. The Control Station contained a 150 kW solar power supply, a 8500 A•hr (120 V) battery system. Peak tether current levels were limited to 20 A, with typical currents varying between 15 and 20 A. In addition, thrusting was performed only when the tether was within $\pi/4$ of vertical.

**Results**

*Reboost Simulations*

Figure 8 shows the orbit semimajor axis, and Figure 9 shows the orbit eccentricity during the two days of boosting simulated. The semimajor axis increases at 52 km/day. Note that if the electrodynamic boost system adds energy to the orbit at a constant rate, the rate of semimajor axis increase will accelerate due to the inverse relation between orbital energy and semimajor axis. The eccentricity increases at 0.0034/day. Note that the eccentricity change rate will also vary during reboost. Figure 10 shows the apogee altitude increase.

*Thrust Efficiency:*

The thrust efficiency is shown in Figure 12. The graph shows that the thrust efficiency varies cyclically during each day; this variation is due to the fact that the Earth, and its magnetic field, are rotating inside the facility's orbit, and thus the angle between the geomagnetic field's axis and the orbit plane varies once per day. In addition, not readily apparent on this timescale, the thrust efficiency varies with altitude and with the angle of the tether relative to local vertical. Over this one day period, the average thrust efficiency is 40 μN/W (thrust efficiency calculated using the power input to the electrodynamic tether).

*Reboost Time:*

Since the rate of semimajor axis increase varies during the reboost operation, the best way to estimate the time needed to reboost the orbit is to assume that the rate at which the orbital energy of the system is increased is relatively constant during the reboost period. To reboost the orbit from 391x6105 km to 407x8445 km, the electrodynamic system must restore 54 GJ of energy to the tether facility's orbit. In the 2-day simulation, the electrodynamic thrusting restored the facility's orbital energy at a rate of 2.7 GJ/day, as illustrated in Figure 11.

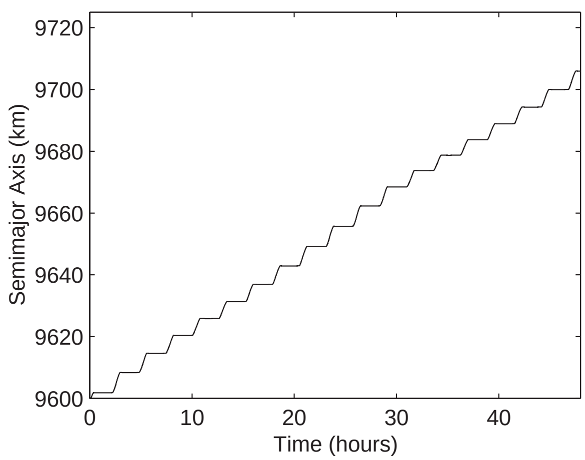



**Figure 8.** Semimajor axis during the first two days of the reboost operation.

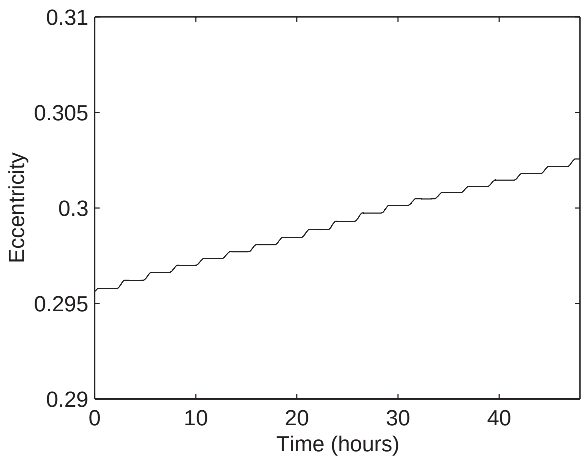



**Figure 9.** Orbit eccentricity.

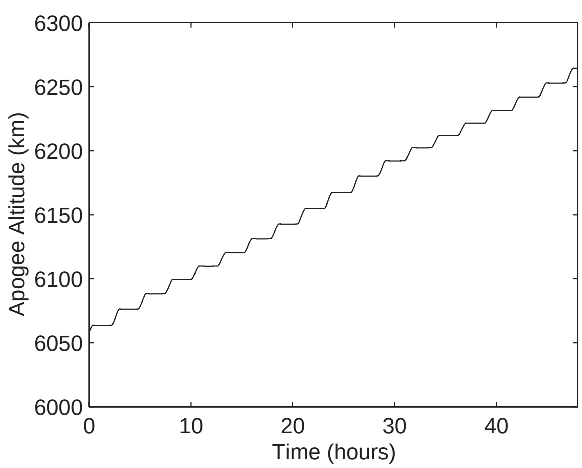



**Figure 10.** Apogee altitude

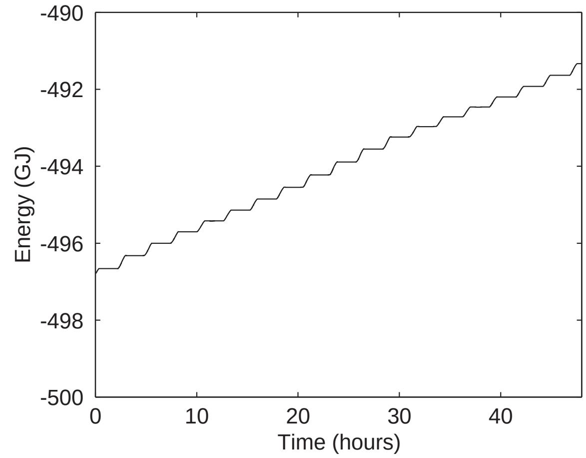



**Figure 11.** Orbital Energy.

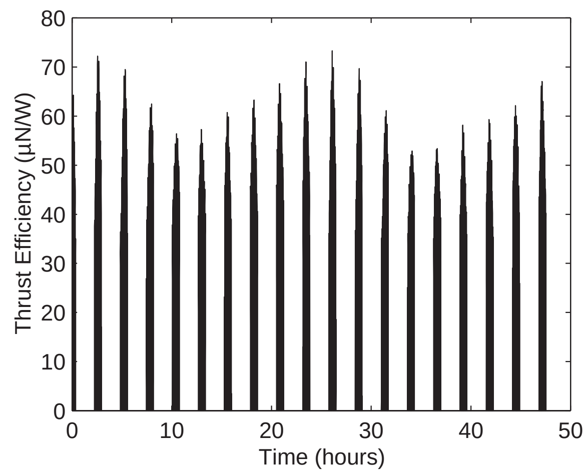



**Figure 12.** Thrust efficiency.

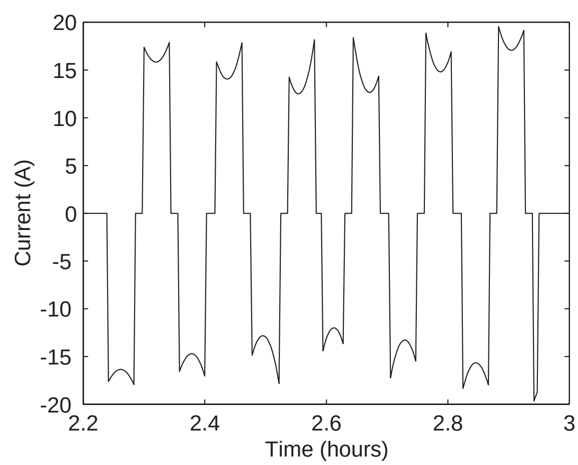



**Figure 13.** Current driven through the electrodynamic tether during a perigee pass.

*Energy System:*

The tether current during one of the perigee passes is shown in Figure 13. The charge level of the energy storage system (batteries or flywheels) over the two days is shown in Figure 14. With the solar power sup ply generating 150 kW during the portions of the orbit that the tether facility is illuminated, and processed through the batteries at an efficiency of 88%, the sys tem maintains its energy balance and the depth of charge does not exceed 20%.

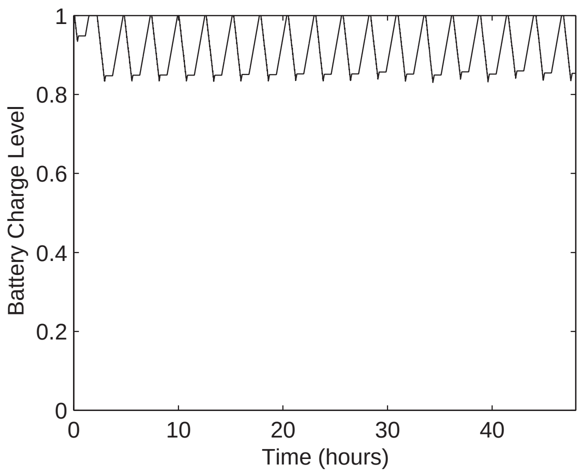



**Figure 14.** Battery charge level.

*Analysis:*

The simulated system, which had 150 kW of solar panel power and thrusted at 450 kW during perigee passes, would reboost the orbit energy within approxi mately 20 days. To achieve the 30 day reboost desired for the LEO⇒GTO Tether Boost Facility, we thus need a lower solar panel power of approximately 100 kW. Thrusting would be performed at 300 kW during peri gee passes, and tether current levels would be roughly 15 A.

## Summary

We have presented an orbital design and system-concept level definition for a tether facility capable of boosting 2,500 kg payloads from LEO to GTO once every 30 days. The entire tether facility is sized to enable an operational capability to be deployed with a single Delta-IV-H launch. The system is designed in a modular fashion so that its capacity can be increased with additional launches. The tether facility can also boost 1000 kg payloads to lunar transfer orbits, and will serve as the first building block of an Earth-Moon-Mars Tether Transportation Architecture. The tether facility will utilize electrodynamic tether propulsion to restore its orbit after each payload boost operation. Using numerical modeling we have validated the orbital design of the system and investigated methods for performing electrodynamic reboost of the station.


### Acknowledgments

This research was supported by Phase I and Phase II grants from NASA's Institute for Advanced Concepts. The author wishes to acknowledge important contributions by Robert Forward of TUI and Michal Bangham, John Grant, Brian Tillotson, Beth Fleming, John Blumer, Ben Donahue, Bill Klus, and Harvey Willenberg of the Boeing Company, as well as valuable discussions with Kirk Sorensen of NASA/MSFC.


### References


1. Hoyt, R.P. Uphoff, C.W., "Cislunar Tether Transport System", *J. Spacecraft and Rockets*, 37(2), March-April 2000, pp. 177-186.
2. Hoyt, R.P., "Cislunar Tether Transport System", Tethers Unlimited, Inc. Final Report on NASA Institute for Advanced Concepts Phase I Contract 07600-011, May 1999. Downloadable from *www.niac.usra.edu.*
3. Forward, R.L., Nordley, G., "MERITT: Mars-Earth Rapid Interplanetary Tether Transport System – Initial Feasibility Study," AIAA Paper 99-2151, *35th Joint Propulsion Conference,* Los Angeles, CA, 20-24 June 1999.
4. Carroll, J.A, *Preliminary Design of a 1 km/sec Tether Transport Facility*, March 1991, Tether Applications Final Report on NASA Contract NASW-4461 with NASA/HQ.
5. Hoyt, R.P., "Tether System for Exchanging Payloads Between Low Earth Orbit and the Lunar Surface," AIAA Paper 97-2794, *33rd AIAA/ASME/ ASE/ASEE Joint Propulsion Conference,* Seattle, WA, 6-9 July 1997.
6. Forward, R.L., "Tether Transport from LEO to the Lunar Surface," AIAA paper 91-2322, *27th AIAA/ASME/ ASE/ASEE Joint Propulsion Conference*, July 1991.
7. Bangham, M, Lorenzini, E., Vestal, L. *Tether Transport System Study*, NASA TP-1998-206959.
8. *Failure Resistant Multiline Tether*, Robert L. Forward and Robert P. Hoyt, PCT/US97/05840, filed 22 April 1997.
9. Forward, R.L., Hoyt, R.P., "Failsafe Multiline Hoytether Lifetimes," AIAA paper 95-2890*31st AIAA/SAE/ASME/ASEE Joint Propulsion Conference,* San Diego, CA, July 1995.