# POTENTIAL LAUNCH COST SAVINGS OF A TETHER TRANSPORT FACILITY

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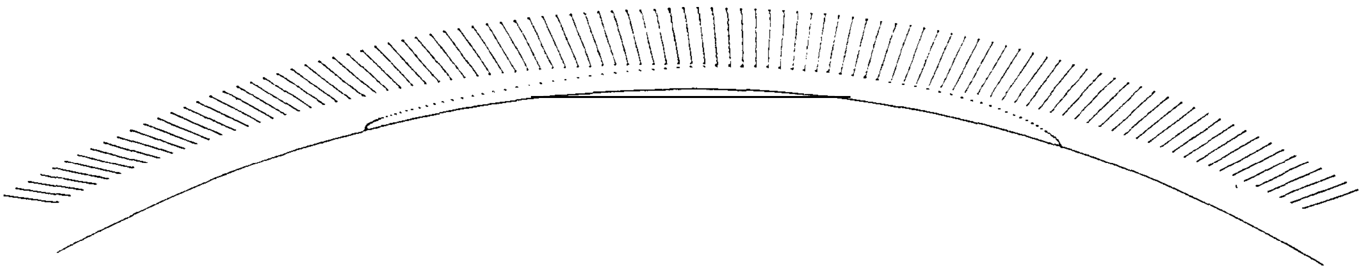

Figure 1. SST0 launch, sub-orbital payload handoff to baseline 290 km long tether, and lifting reentry. Drawn with Earth and tether to scale, with tether and launch vehicle location shown every 10 seconds (right to left).

## Abstract

A system design is presented for a tether transport facility capable of reducing the required launch vehicle **D**V from Earth to Low Earth Orbit (LEO) by 1.2 km/s. Sized to handle a 5 ton payload, it uses a 5 ton barely spinning tether 290 km long, and a 150 ton facility at an altitude of 420 km. The tether can capture a sub-orbital payload at 130 km altitude, either delivering it to the facility or providing an additional super-orbital boost of 1.1 km/s from a 600 km perigee orbit. A replacement tether can be delivered as a single payload. The total facility mass must be at least -30 times the design payload to ensure an adequate facility perigee after payload capture. Capture 1.2 km/s below orbit velocity increases vehicle mass at Main Engine Cut Off (MECO) by 30%. For SST0 vehicles having payloads of 10-20% of MECO mass, sub-orbital capture can increase vehicle payload by 150-300%. Other sizes of facilities in LEO are also discussed, including a much more ambitious 3.4 km/s tether that may complement gas gun launchers well. Finally, a technology development program is laid out, detailing tasks needed to evaluate the tether option in the ten to fifteen year time frame being examined in this paper.

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## Introduction

Space tethers capable of significant reduction in launch costs have been proposed for many years. Because of the ambitious nature of these concepts and the lack actual flight experience with tethers, these ideas have been justifiably excluded from near-term space systems planning. However, recent successful flight tests of three smaller-scale space tethers, combined with the current interest in launch vehicle design options including SSTOs, makes it timely to re-examine the relevance of ambitious tether concepts and their potential impact on launch costs to Low Earth Orbit and beyond.

As discussed in NASA's Tethers in Space Handbook (Penzo, 1989), space tethers have many interesting applications, both propulsive and non-propulsive. Their value here is their ability to exchange momentum between two masses in orbit. Springs are often used for this purpose when only a small velocity change (**D**V) is needed. The advantage of tethers over springs is that tethers can easily provide "strokes" a million times longer than springs. In addition, tethers weigh far less than springs for equal **D**V. These factors allow tethers to provide very large **D**Vs with low accelerations and low system mass. Since the net momentum change is zero, no propellant need be expended. (If the **D**V on one of the two end masses is undesired, it can be cancelled by chemical or electric propulsion, or by tether operations in the opposite direction.)

In this paper, we focus on a fairly ambitious tether transport node that may significantly increase launch vehicle payload to LEO and beyond. Such systems may have an important role to play coming decades, provided we start relevant work now.

## History

Tethers were first proposed by Tsiolkovsky (1895) as a propulsion method in space. Isaacs et al (1966) made a brief analysis of a space elevator in a geostationary orbit with the lower section fixed to the earth. Moravec (1977) analyzed a non-synchronous spinning tether, which avoids some of the problems of the long hanging version. Carroll (1983, 1984) noted the advantages of swinging and barely spinning systems. Other key tether proponents include Mario Grossi, the late Guiseppe Colombo, Ivan Bekey, Georg von Tiesenhausen, and Chris Rupp.

The first flight experiment with a long tether was the Tethered Satellite System (TSS) mission, flown on the Space Shuttle in 1992. A late design change resulted in a bolt interfering with the levelwind mechanism, so only 250 m of the 20 km tether was deployed. The tether and satellite were retrieved, and a reflight is planned in 1996. Besides many scientific experiments, TSS will investigate deployment and retrieval of a long, thick tether, an important milestone in showing the ability to control tethers.

The first successful orbital flight tests of a long tether system were SEDS-1 & 2, which tested the simple deploy-only Small Expendable Deployer System. SEDS was proposed by one of the authors (Carroll) at Energy Science Laboratories in 1983, and developed under NASA Small Business Innovation Research and follow-on funding from NASA Marshall Space Flight Center. Also involved in SEDS-1 & 2 were NASA Langley (payload instrumentation), NASA Goddard (integration & telemetry), McDonnell Douglas (launch vehicle provider), and the Air Force (primary payload). Tether Applications continued the project following a split-off from Energy Science Labs.

SEDS-1 was launched as a Delta/GPS secondary payload on March 29, 1993. The 20 km tether deployed properly and was cut at the right time, deboosting a 26 kg endmass into an accurate re-entry that was videotaped from the ground. SEDS-2 was launched March 9, 1994, on the last GPS Block 2 mission. SEDS-2 used feedback braking starting early in deployment. This limited the residual swing in the tether after deployment to $4^{o}$. The tether was left attached to the Delta after deployment. The tether suffered a cut (probably by a micrometeoroid) about 3.7 days after deployment. The remaining 7 km tether survived with no apparent further cuts until re-entry on May 7, 1994. The tether, shown in Figure 2 before the cut, was an easy naked eye object when viewed in a dark sky with good sun angle. More details on SEDS are given by Carroll and Oldson (1995).

Several other tether flights are well along in hardware fabrication and flight planning. The Naval Research Lab's Tether Physics and Survivability experiment (TiPS) should launch in 1996. It will deploy two tether experiments with 4 km long SEDS tethers 2 mm in diameter. In 1997 SEDS-3 will boost the SEDSAT micro-sat from the Shuttle into a higher, longer-lived orbit. Additional projects are in planning or early development in the US and Europe.

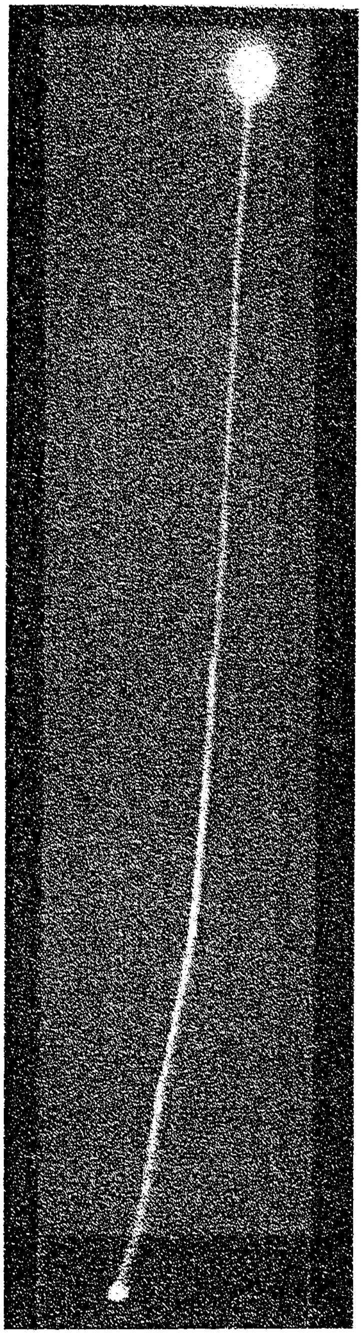

Figure 2. SEDS 2 tether in orbit with Delta 2nd stage at top and endmass at bottom, March 1994.

## Transport Facility Sizing

If both tether and rocket propulsion are available, the best combination will depend on tether and propellant mass, and also on support equipment mass, the cost or value of momentum transfer at the facility end, safety, reliability, and the idiosyncrasies of the two options. Just designing for minimum tether plus propellant mass is far simpler, shows key trends, and often gives representative answers. For modest DVs, rocket propellant mass scales with DV, while tether mass scales with the square of the DV. For small DVs, tethers alone should be used. For larger ones, the tether plus propellant mass is minimized if the ratio of marginal tether impulse to marginal tether system mass is equal to the propellant Isp. For single-use tethers, that occurs near 300 m/s tether DV. Typically the best operation for such a tether is a low-tension deployment, wide swing, and release near the vertical. In LEO this operation provides 4 m/s per km of tether length, so tethers up to -75 km long can often justify themselves even if they cannot be reused.

If the tether is reusable, then the optimum tether DV increases. But once the tether outweighs the payload, tether mass grows with the exponential of the square of the DV. Then the optimum tether DV grows -logarithmically with the expected number of uses. Table I below lists typical tether parameters for various intensities of use. The table assumes Spectra 1000 is used at 220 ksi maximum fiber stress (safety factor = 2). The reusable tethers assume a tether-tip mass -20% as massive as the payload for dynamics and operational reasons. Long and massive tethers require a 3:l spin:orbit spin rate to eliminate instabilities due to l/r non-linearities, while the 1.2 km/s tether can use a slower 2:l spin. A 2:l spin results in 1 tether pass through nadir each orbit. This allows the facility to drop into a lower-perigee after capturing a payload, without dragging the tether in the atmosphere. This allows a far lower facility/payload mass ratio than 3:l spins allow.

Frequent traffic justifies larger DVs, so LEO will be the first place for ambitious tether transport nodes. A LEO node can transfer payloads between sub-orbital, orbital, and super-orbital trajectories, and once in operation may be able to capture most traffic to its orbit inclination. Note also that as traffic patterns mature, the return traffic fraction grows. This not only increases tether throughput but also helps facility momentum balance. This reduces the need for high-Isp propulsion on the facility.

| Size | ΔV km/s | Mode | Length (km) | Tether taper | # tether uses to justify | Tether/ payload mass | Host/ payload mass | Key operation enabled |
|---|---|---|---|---|---|---|---|---|
| Small | 0.1 | hang/ swing | 25-50 | 1:1 | 1 | CO.01 | Any | Deorbit, capture w/c circularize |
| Medium | 1.2 | 2:1 spin | 290 | 1.4:1 | 10 | 1 | >30: 1 | soft suborbital reentry |
| Large | 3.4 | 3:1 spin | 760 | 16:1 | 500 | **50** | >500: 1 | Earth/moor transport, escape |

**Table I.** Summary of "natural" sizes of tether systems in LEO.

## Natural Sizes for LEO Tether Transport Nodes

Table 1 shows the key characteristics of three tether systems sized to enable useful operations. The least ambitious of the three can deboost payloads and launch vehicles into shallow reentry trajectories from the node, and can also capture them from typical direct-insertion trajectories. Both operations involve vehicle perigees near 0 km. For hanging tethers, the required tether length is 1/7 of the host facility's altitude; for swinging tethers, the length is -half that.

Larger **D**Vs cause increasingly steep and hard reentries after release or a missed capture. However, if the tether reaches all the way down to ~100-130 km altitude, then the suborbital payload starts reentry soon after release, before it can build up much vertical velocity. In order for the facility to have reasonably low drag, the tether needs to be >250 km long. A hanging tether would have high drag, heating, and atomic oxygen exposure, so a swinging or spinning tether that spends little time near nadir is needed. Simulations of both show that the baseline 2:1 spinning system has a very attractive combination of features. which are described in detail later.

The baseline tether length of 290 km can provide a 1.2 km/s sub-orbital **D**V, plus a 1.1 km/s super-orbital **D**V. These **D**Vs can be increased by raising the facility altitude and increasing the tether length. However the tether mass, l/r non-linearities, and difficulty of control increase rapidly. Based on work to date, by the time 2 km/s **D**Vs are desired, a faster 3:1 spin appears necessary. The faster spin has three undesirable features:

1. Tether drag increases if facility perigee drops;
2. Deployment & retrieval take more time & power;
3. Payload release near the horizontal no longer allows low-**D**V rendezvous with the host.

The first point strongly drives system requirements, because it requires a combination of high facility mass and winch power, or high-thrust high-Isp propulsion, or pairing of capture/release operations. On the other hand, simulations show 3:1 tether dynamics stable even for **D**V>3 km/s. This allows payloads to be captured at 60% of orbital velocity and slung to the moon or escape. Such high **D**Vs also enable a new option for facility momentum balance: catching moonrocks. Simulations of lunar-orbiting facilities show that a 3:1 spin rate allows transfer of payloads between the surface and trans-earth injection despite very large l/r non-linearities.

## Baseline Tether Transport Facility Design

The facility design presented here is an updated version of work in 1990-1991 under NASA Contract NASW-4461 (Carroll. 1991). The work was summarized in a JPL conference paper by Carroll (1992). The major change to the specific facility design since this initial work is the winch design. More details can be found in the two references.

Figure 1 (page 1) shows a sketch of the baseline 290 km long tether facility capturing a payload from a suborbital launch vehicle. The heavy facility mass is at an altitude of 420 km, resulting in a capture altitude of 130 km. The launch vehicle never hangs on to the tether, which would greatly increase the required tether and facility mass. Instead, it hands the payload off to a “smart” tether tip device, then immediately drops away on a reentry trajectory. The trajectory shown is for an SST0 with 3-gee throttling. MECO occurs 308 seconds after launch, and payload handoff 100 seconds later. If L/D = 1, the vehicle will land 3630 km east of the launch point, 1100 seconds after launch. Various pairs of launch/landing sites are possible, including West/East coast of the U.S., Hawaii/Calif., West/East coast of Australia, and West/East Mediterranean.

The total mass of the winch and other tether-specific hardware on the facility is estimated at -5 tons, plus the 1 ton endmass capture hardware and the 5 ton tether. An additional 145 tons of ballast mass are needed, but this can be supplied by used External Tanks, other surplus sources of mass, or facility payloads dedicated to other purposes.

## Selection of 12 km/s **D**V

Natural sizing for various tether systems in LEO has already been discussed, and a 1.2 km/s AV system emerges as a logical choice for the first ambitious tether system, because the tether is the minimum “long” tether that allows soft reentries. A 1.2 km/s design **D**V has other justifications. It is high enough to allow major launch cost savings, as shown later. It is a small enough **D**V to keep the tether mass less than the design payload mass, thus allowing launch of complete replacement tethers on a single mission. The ballast mass, while large (-5 External Tanks), is within the range of realistic Earth deployed systems. The size is also small enough to allow a stable barely spinning tether, which has several important advantages.

## Barely Spinning Tether

We have baselined a barely spinning tether, meaning a tether which is spinning once per orbit in its own local vertical reference frame, or twice per orbit relative to an inertial frame. Figure 3 on the next page is a drawing of the tether and the Earth to scale, with a capture occurring at the top as indicated, followed by the beginning of retrieval.

A barely spinning tether system has several important advantages over either a hanging tether or a rapidly spinning tether system. First, the risk of micrometeoroid cuts is lower for a barely spinning tether than either a hanging tether or a faster spinning tether. A barely spinning tether, for the same **D**V as a hanging tether, is half the length, thicker, and has 4 times the expected lifetime against cuts. The barely spinning tether is also 10% lighter than the hanging tether and 30% lighter than a shorter, equal-**D**V faster spinning tether. A short, heavy fast-spinning tether does have less risk per unit time, but it cannot easily be retrieved between uses, so its overall risk of cut will be higher than the barely spinning system unless the tether system is used very frequently.

Another major advantage of a barely spuming tether is the ease of deployment and retrieval. The barely spinning tether (which spins slowest when it moves through the horizontal) has nearly the same total energy as the initial undeployed system. Thus, the energy dissipation required during deployment and the energy input needed during retrieval are close to a minimum. A hanging tether requires 10 times more energy to be dissipated or added. Since minimizing the exposure risk is highly desirable, the easiest system to deploy and retrieve is best.

The barely spinning system also tolerates the unavoidable altitude loss and drag much better than either hanging or rapidly spinning systems. By proper phasing of the once per orbit tether swing (in the local vertical reference frame), the tether can be kept above the facility at perigee when drag would otherwise be unacceptable. This allows much larger facility altitude changes and hence a much smaller facility mass for a given design payload, or conversely, a much larger design payload for a given facility mass.

A final advantage of barely spinning tethers is that they allow quick payload retrieval and docking to the facility without requiring tether retrieval. The method is to capture the payload above or below the facility, swing it almost to the horizontal, and release it. Proper release timing puts the payload onto a low-**D**V rendezvous trajectory with the facility one orbit later. (Due to its finite mass, the facility is itself on a “short tether” from the center of mass of the whole system.) This operation can be reversed by releasing the payload at the right time, maneuvering it to rendezvous with the tether tip near the horizontal, catching the tip, and releasing 1/4 or 3/4 orbit later, to return to Earth or boost into a higher orbit.

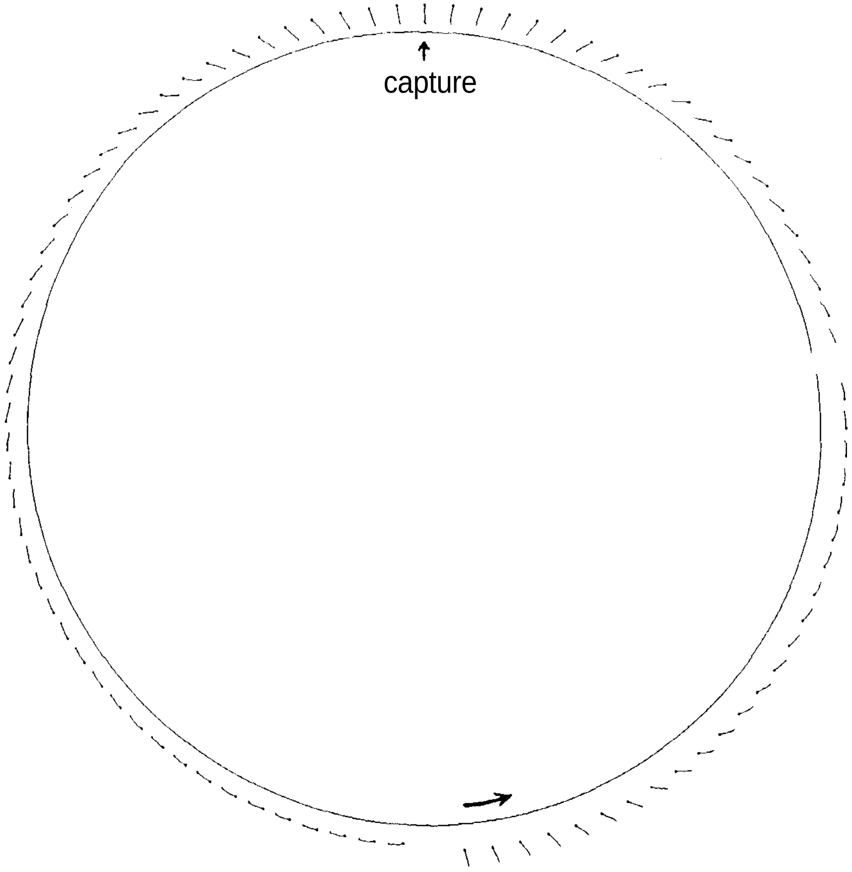

**Figure 3.** Tether dynamics every minute during sub-orbital capture (to scale with Earth)

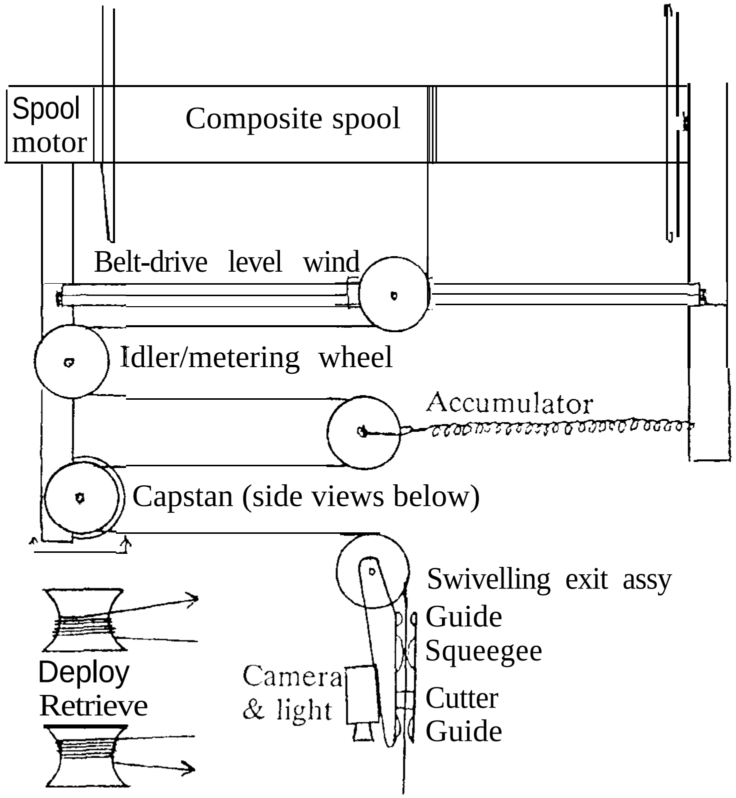

**Figure 4.** High speed, high tension capstan drive winch design

## Tether Design

Our baseline 290 km tether tapers from 5.5 mm in diameter at the facility end to 4.9 mm diameter 30 km from the payload end. Beyond that it increases back toward 5.5 mm, to accommodate a Teflon jacket to protect against atomic oxygen, and to reduce loads near the tip to compensate for atmospheric heating. The tether is braided Spectra 1000, the material and construction used on the two SEDS flights. Spectra is a high strength oriented polyethylene fiber made by Allied Fibers. It has a density of 0.97 g/cm$^3$ and a short-term tensile strength of 420 ksi. The Spectra is loaded to a peak stress of 220 ksi shortly after capture of a sub-orbital payload.

We estimate that the baseline tether will be cut by micrometeoroids roughly once per month. The risk due to debris could be higher, but most of that risk is due to tracked objects, which can be avoided. Micrometeoroid risks are a key driver on operating scenarios and operating costs. Fast deployment and retrieval between uses is highly desirable, unless multiple operations are planned within a day or two of each other. The relationship between tether diameter and micrometeoroid cut risk is critical for selecting the best facility size. Based on an analysis of SEDS-2 flight data, and using a risk multiplier of 4 to account for the much higher loading of this tether vs. SEDS, the mean time before cut for a highly-loaded Spectra tether with a diameter D. (in mm) is:

$$\text{Mean life in km-yr} = (D.+0.3\text{mm})^3 / 4$$

Based on this, a 290 km tether averaging 5.3 mm in diameter has a mean life of 55 days. For smaller tethers sized for l-2 ton design payloads, the average diameter is 2.4-3.4 mm, and the mean life is 6-16 days. Such tethers would have trouble paying for themselves before they are cut, even if retrieved between uses. On the other hand, they could pay for themselves in one use if the real purpose is to test the transport node concept at low cost. The shuttle or even a 30-ton External Tank could serve as the facility mass. The winch could be integrated into a cross-bay carrier shorter and lighter than that used for the TSS.

At the other extreme, SST0 designs discussed later have -50 ton payloads when used in a Single-Stage-To-Tether (SSTT) mode. A tether for such a payload is 17 mm in diameter, and the life is 4 years. Here the risk of cut is less of an issue and partial retrieval for drag reduction may be more of a driver.

## Winch Design

The winch and storage reel is the core of the main facility. We propose use of a traction winch. This uses a driven capstan separate from the storage reel, to decouple the reel from outboard loads. This allows use of a far lighter reel, and eliminates crushing damage to tether deep within the winding. The winch must handle 290 km of variable-diameter tether weighing 4700 kg. The original reel design (Carroll, 1991) is 0.5 x 1.5 x 4.0 m (core dia x flange dia x core length). Test windings of braided Spectra made at 1% of the tether's breaking strength show that the winding has enough solidity to stay in place at peak winding speeds, and the inner layers can deform enough as outer layers are added to limit loads on the reel to ~ 1% of those calculated from the conservative "hydrostatic approximation." Figure 4 on the previous page shows a sketch of the current design.

The 1991 design used multiple individually driven sheaves. This minimizes tether slippage on the sheaves, but it results in many tether bend/straighten cycles that cause sliding and wear inside the tether. A single multi-turn capstan results in both axial and transverse slippage, but reduces internal tether wear. This design has been used to deploy large kites on multi-kilometer tethers, and works very reliably and smoothly if the sheaves on either side of the capstan are positioned properly. Deployment and retrieval require speeds up to 25 m/s, at tensions up to 27 kiloNewtons. Total cyclic energy storage requirement is 52 kWh during the first hour of retrieval, plus 11 kWh for the load-relief maneuver described below.

## Capture and Release Transients

If the tether is at equilibrium before capture, then it will stretch after capture, overshoot the new equilibrium length, and cause a peak load 70% higher than the post-capture equilibrium. This strongly drives tether and system size. An anticipatory reeling maneuver can reduce peak loads to within a few % of the equilibrium post-capture load. The strategy is to reel in enough tether to cancel out any post-capture sag, in the time required for a tensile wave to travel from the reel to the payload (when capture occurs) and back to the reel. This requires reeling at 38 m/s for 46 seconds, starting 23 seconds before capture. The ideal reeling profile is a square wave, but reel-motor torque limits require velocity ramps taking 7 seconds. Simulations show that the 7-second velocity ramps introduce only minor increases in peak load.

This maneuver is the design driver for capstan and reel speed, reel motor torque, and power demand. The net power required is 665 kW, or about 900 kW at 75% motor/controller efficiency. The total energy required is only 11 kWh. Despite the high speed and high torques, motors sized for steady-state reeling can handle the overloads associated with this maneuver due to its brevity.

A more serious problem is anticipating the moment of capture. This requires a combination of accurate relative trajectory sensing in a predictable environment (using GPS + proximity sensors), plus prompt, reliable, and safe capture hardware (which is discussed in the next section).

An alternative is to use a propulsive burn to cancel out the payloads downward velocity at the equilibrium position. This requires a **D**V of 61 m/s, which requires, at an Isp of 450, a propellant mass equal to 6 to 7% of the payload increase provided by the capture. A combination of non-anticipatory reeling and thrust is also an option. The preloading option has the highest benefit, but other options exist if anticipatory reeling is a problem.

Release of the payload does not involve high stress on the tether. The main concern is avoiding slack tether. A reverse operation to the capture reeling, in effect pre-unloading, can be done if required to minimize the recoil of the tether.

### Rendezvous and Capture Hardware

The requirement for accurate rendezvous of the payload and tether tip and prompt, reliable, safe capture is clearly a major task. A detailed study of rendezvous at a lower **D**V has been done by Stuart (1987), and should be usable in this case with appropriate scaling. The task appears tractable with current guidance, navigation and computer hardware and software. The issue of prompt, reliable, and safe capture, especially with a manned launch vehicle, is also critical. The current concept is to put the capture hardware at the end of an inflated membrane boom. The light boom can be maneuvered quickly, and boom contact with the vehicle need not cause problems. The capture hardware itself may use industrial grade Velcro, as did the winning entry in a 1990 MIT contest sponsored by Carroll. The winning design reliably made strong captures at first contact, using a probe that could be dropped 30 cm onto a raw egg without breaking it.

### Deployment Strategy

Deployment begins with spring ejection or a small thrust maneuver. Once the endmass clears the facility by a few meters, it makes an oblique burn to increase the deployment rate enough to tolerate a minimum tension of 10 Newtons. Gravity-gradient effects eventually take over and increase the deployment rate. This continues until deployment speeds reach -25 m/s. At this time, 50 to 60 km of tether are deployed. Deployment is then stopped, and the tether allowed to swing towards the vertical.

As it approaches the vertical, a few kilometers of tether are retrieved to pump enough energy into the system to cause it to exceed the libration limit and become a barely spinning system. Once initiated, the once per orbit spin must be maintained by adding spin angular momentum to the system as length increases. This requires periods of retrieval near the vertical, with the deployment done near the horizontal. The result is a net average tilted dipole moment, which interacts with the gravity gradient to increase the spin angular momentum. At the same time, the total orbital angular momentum decreases. The total time required for deployment is about 5 orbits plus the initial 2 hours for the initial non-spinning deployment, for a total deployment time of about 10 hours.

### Retrieval Strategy

Most of the retrieval is done simply by reversing the deployment strategy of correctly phased deploy & retrieve episodes. Now, we must retrieve near the horizontal and redeploy near the vertical to keep the spin rate from increasing. As tether length and tension decrease, any transverse tether dynamics are amplified, especially with no payload at the tip. Retrieval of the 1 ton “smart tip” and tether is shown in Figure 5, using a local vertical/horizontal reference frame. The images were made using REELSIM, a tether simulation program written by Carroll.

By orbit (and rotation) #7 in Figure 5, the transverse tether dynamics have become focused into a travelling kink in the tether. This is a generic problem with light tethers during retrieval. Propulsive burns at the tether tip when the kink reaches the tip appear to solve the problem at low cost, at least for a 1.2 km/s tether. This option is shown with numbers 7A and 8A in Figure 5. Additional work is desirable to study the problem and improve the control strategy.

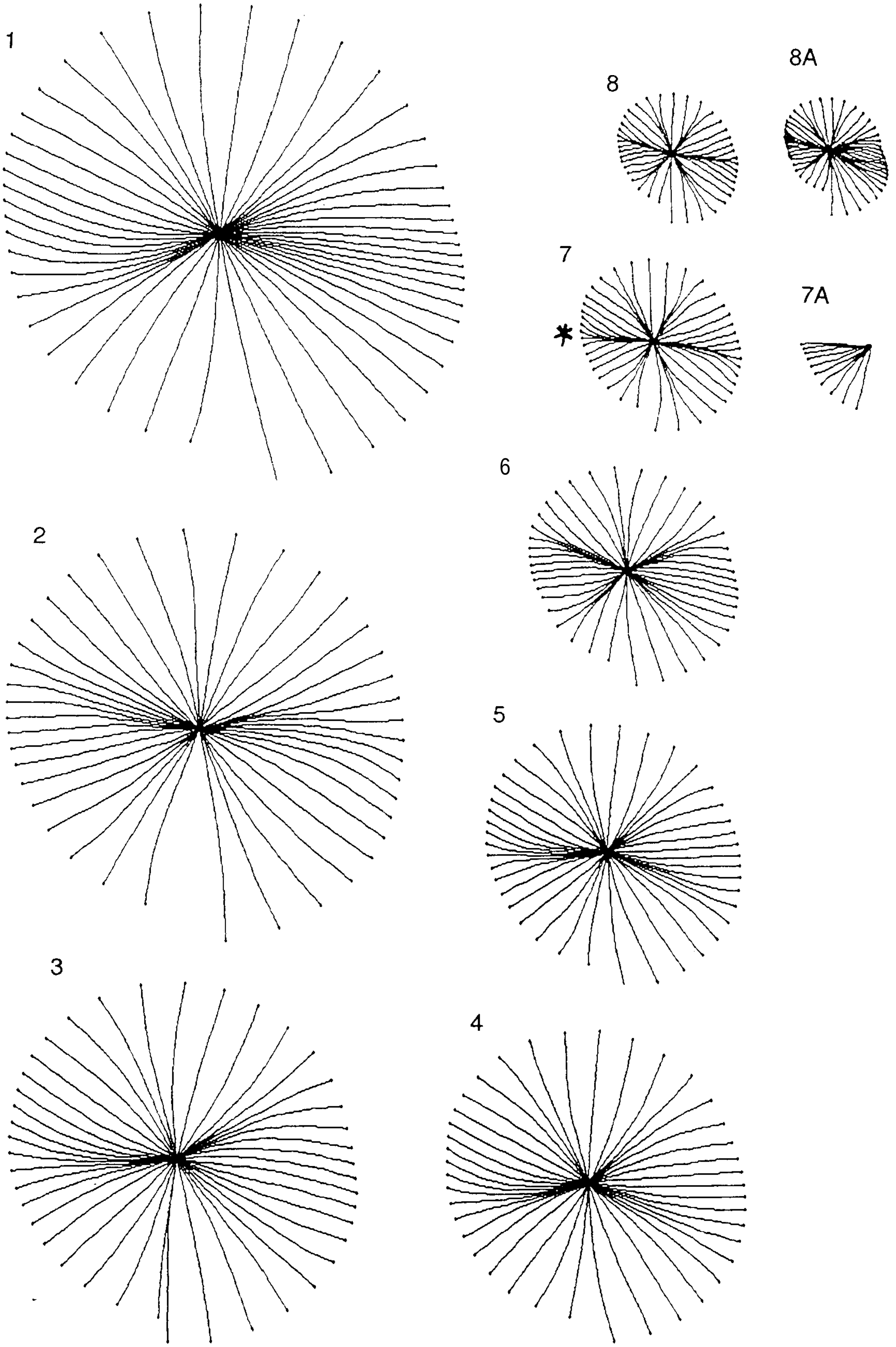

**Figure 5.** Multiple exposure picture of tether retrieval with 1 tonne endmass, every 2 minutes.

### Reboost

Momentum is conserved (Newton!). The net impulse transferred to boosted payloads is balanced by an equal and opposite deboost impulse to the facility. This can be cancelled out either by deboosting "return traffic" (which may become comparable, in a mature environment), or by some form of high Isp propulsion. In low inclinations, the reboost requirements might best be satisfied by an electrodynamic tether; however, we will also consider reboost by ion engines, as a more conservative, inclination-independent option.

Assuming the traffic imbalance is equivalent to capturing 2 sub-orbital payloads per month and retrieving them to the facility, a total of 1.2E7 kg-m/s of momentum make-up is required. This can be done with about 6 Newtons thrust at a 75% duty factor. An electrodynamic reboost system would require about 60 kW and negligible propellant, while an ion engine at an Isp of 6000 s would require about 250 kW and 200 kg of propellant per month, or 2% of delivered payload mass. Hence reboost power requirements exceed retrieval power requirements, except during the capture load-relief maneuver. Total energy use is strongly dominated by reboost, enough so that energy storage system sizing will be driven more by a need to operate ion-engines through day-night cycles, than by storage required for energy recovered by regenerative braking during deployment episodes.

If we assume a specific power of 0.25 kW/kg for complete solar arrays, about 1 ton of solar cells, with an area of about 1000 $m^2$, is needed for ion engine reboost. Batteries capable of running the ion engines for a 36-minute eclipse will add roughly another 4 tons. Hence the power system will weigh roughly as much as the tether. Power systems of this scale may justify other options (solar dynamic, flywheel storage, etc.), and system trades are needed to better define and optimize the power system.

### Other Facility Uses

An orbiting transport facility that requires a mass 10X greater than the "tether-system mass" of tether, winch, and power supply will only make sense in two situations: either traffic is high enough to justify the high "balance-of-system mass", or the balance of system mass serves other needs that benefit from or at least tolerate the tether operations. Such a facility sounds like a space station, but one whose design is driven by different issues from the current station.

The facility could serve as a propellant depot, allowing transport of propellants on volume limited payload flights where extra mass capacity exists. Besides greatly enhancing payload to LEO or beyond, the facility can take advantage of the significant difference between "-3 sigma" capability and average residuals including gases. It could serve as a refueling and repair station for a reusable upper stage. It could also perform many of the zero gravity experiments being proposed for the Space Station. Since it would probably be in a 28.5" inclination orbit, the cost of access would be less. If the tether transport facility requires 250 kW power at 75% duty cycle to provide a net + 1.2 km/s boost of 2 5-ton payloads per month (or 120 tons/year), then 250 kW will be available at 25% duty cycle for other experiments. The facility may not require a permanent human presence, but the reduced cost of getting there and the variety of useful tasks to be done there may quickly make this facility the primary manned presence in low earth orbit.

## Impact on Launch Costs

This section discusses the potential payload increases available from a I.2 km/s tether node when used with various vehicles now under study. For the analysis, detailed mass breakdowns were not available for some vehicles. But enough has been published on a wide enough range of vehicles to allow some general conclusions to be reached on typical payload increases. A detailed cost savings analysis is not possible now, so we present payload increases as a useful substitute.

Five vehicles were selected for analysis: the OSC/Rockwell X-34, the Rockwell X-33, the Black Horse, the SSTO-R from Access to Space, and the Space Shuttle.

x-34: The X-34 is a current project to develop a two stage vehicle using an air launch from a large subsonic jet airplane (Anon., 1995). The first stage is winged, and is reused after gliding back to a runway landing. The second stage is expendable. The X-34 is being built by a joint venture company formed by Rockwell and Orbital Sciences Corporation, with a mix of NASA and company funding. The goal is an orbital flight in 1998. A choice between two variants, the 34A and B, has not yet been made. The A version has a 1,200 lb payload, and is launched from an L-1011, while the B version has a 2,500 lb payload and is air launched from a 747. The A version is used for our analysis. It has a GLOW of 76,300 lb. The initial mass of the second stage is 11,200 lb. To calculate the final total mass of the second stage, we used the published stage ΔV of 13,600 ft/s, plus a 600 ft/s circularization burn, and a oxygen/kerosene Isp of 355 s., giving a final stage mass of about 3,200 lb.

X-33: The X-33 is an SST0 vehicle with a much larger payload than the X-34. Three teams are currently competing on the project, Lockheed-Martin, Rockwell, and McDonnell-Douglas/Boeing. Enough data on the Rockwell design was given by Smith and Asker (1995) to include it in our comparison. It has a payload of 15,000 to 40,000 lbs. We use the larger payload in our analysis, and assume it is for a 28” inclination 185-km parking orbit for upper stage release. The empty weight of the vehicle is 186,000 lbs. Since the RS-2100 engine (SSME derivative) is listed as a possible engine, we use the SSME Isp of 455 seconds. GLOW is given as 1.9 million lbs.

Space Shuttle: For the Space Shuttle, we use the following masses: GLOW of 4.5 million lb., 180 klb orbiter, 60 klb ET, 54 klb payload, and 13 klb ET residual propellants. The SSME Isp of 455 s is used. In addition, the space shuttle can also use a much smaller facility sized for 5-ton payloads, in a hanging low-ΔV mode using 60 km of the 290 km tether. In this mode, the available ΔV is 120 m/s at the start of the mission (replacing the circularization burn) and another 120 m/s at the end of the mission (replacing the deboost burn, and restoring the facility to its original altitude). If the saved OMS propellant can be off-loaded to the facility, ~ 10 tons of OMS propellant (including a -2 ton flight performance reserve) may be made available for other facility users.

Black Horse: The Black Horse concept (Zubrin and Clapp, 1994) is the largest of a suite of proposed winged rocket vehicles using aerial propellant transfer to augment performance to orbit. It uses the non-cryogenic propellants JP-5 and hydrogen peroxide, with an assumed Isp of 335 s for the vacuum performance of the high altitude engine. Use of storable propellants makes it unusual among proposed SSTOs. The empty vehicle mass is 15.4 klb, and the payload mass is 1.0 klb.

SSTO-R: The SSTO-R design is the baseline pure rocket design of the NASA Access to Space study, as reported by Bekey (1994) and in somewhat more detail in a summary report by NASA (1994). A family of progressively higher performance vehicles using incremental technical improvements is presented for a SST0 design. The baseline design in the report is used here, with a 41 klb payload and a 160 klb vehicle, and Isp of 455 s. The baseline uses a weight growth margin of 15%, which implies substantially larger payload capacity if the actual weight growth during development is less. The benefits of the tether are reduced as the payload mass fraction increases.

## Vehicle Mass Analysis

The mass analysis for the vehicles is straightforward at the “spreadsheet” level. The tether transport node ΔV of 1.2 km/s is used to directly decrease the amount of propellant required. (No credit is taken for eliminating the deboost ΔV.) The incremental propellant mass ratio is given by:

$$R_{prop} = e^{\Delta V / g I_{sp}} - 1$$

Where g is the standard conversion factor (9.8 m/s$^2$) and Isp is specific impulse in seconds. This gives the fractional amount of propellant saved, relative to the original mass of payload plus inert mass. We now assume that all of this propellant mass saved is used to increase the payload capacity. The increase of payload, relative to original payload, is given by the ratio: $R_{prop}/F_{pay}$. The new payload mass is the old payload mass multiplied by the ratio plus 1:

$$New\ M_{pay} = M_{pay}\left(1 + \frac{R_{prop}}{F_{pay}}\right)$$

Presented in this manner, the effects of the propellant and tether ΔV are decoupled from the question of vehicle inert mass and payload mass. Table II (next page) show the analysis for the 5 vehicles discussed, with the augmented payload shown on the last line. Although payload mass fraction and Isp are both comparably important in theory, the payload mass fraction varies far more than Isp (and is also far more uncertain for yet-to-be-built vehicles). Hence the greatest increase in payload is found for vehicles such as the Black Horse that have the lowest payload mass fraction.

One class of vehicles is not represented in this table: vehicles with zero or negative payload on their own, but significant payload in the “single-stage-to-tether” (SSTT) mode. Such vehicles allow use of lower cost hardware. And the SSTT mode may justify completing development of an “overweight” SSTO.

| Vehicle | Rockwell x-33 | SSTO-R | X-34A | Shuttle | Black Horse |
|---|---|---|---|---|---|
| Configuration | VTHL<br>SST0 | VTHL<br>SST0 | Air launch<br>TSTO | VTHL<br>1.5 stage | Air launch<br>SST0 |
| GLOW (klb) | 1900 | 1960 | 76.3 | 4500 | 184.25 |
| Propellant | $O_2/H_2$ | $O_2/H_2$/RP | $O_2$/J P-4 | $O_2/H_2$ | $H_20_2$/J P-5 |
| Final Isp (s) | 455 | 455 | 355 | 455 | 335 |
| $/flight (M) | 40? | 41 | 4 | 500? | ?? |
| $R_{prop}$ | .3086 | .3086 | .3447 | .3086 | .4409 |
| $M_{inert}$ (klb) | 186 | 160 | 2.0 | 253 | 15.4 |
| $M_{pay}$(klb) | 40 | 41 | 1.2 | 54 | 1.0 |
| $F_{pay}$ | .1770 | .2040 | .3750 | .1759 | .0610 |
| $R_{prop}/F_{pay}$ | 1.744 | 1.513 | .919 | 1.754 | 7.229 |
| New $M_{pay}$ (klb) | 110 | 103 | 2.3 | 149 | 8.2 |

**Table II.** Summary of launch vehicle parameters and tether assisted payload increases.

We assume that payload mass can be swapped one for one with propellant mass. If the increased payload is propellant that can be transferred and used for other purposes, this is appropriate. Directly increasing payload by offloading propellant from the tanks probably reduces the benefits by 10%; more if the “enhanced” payload exceeds the available payload bay volume or structural limits. Taking full advantage of the tether facility may require vehicle redesign, with smaller tanks, a larger payload bay, and mechanisms for quick payload release after payload capture. It may be feasible to do this with no mass penalty with the bulky oxygen/hydrogen vehicles, but this may be optimistic for hydrocarbon-fueled vehicles. For SST0 vehicles now under study as the primary large launch vehicle in the near future, the benefit may be to halve the cost per pound to orbit, even with a substantial charge for tether replacement and operations. However, because of the high cost of starting a tether transport facility, it makes more sense initially to size it around the baseline 5 ton payload, depending on which vehicles actually get built and can be modified to use the enhanced payload capacity.

### New Tether Materials

The performance of an ambitious tether systems depends strongly on the strength to weight ratio, so it is useful to look at promising new materials. One candidate is poly (p-phenylene benzobisoxoazole), PBO, a rigid rod polymer studied by the Air Force Materials Lab in the 1970’s (Humphrey and Vedula, 1995), and by Dow Chemical Co. from 1984 to 1994. Fiber bundles tested by Dow had strengths of 4.94 GPa (716 ksi), with a density of 1.56 g/cm$^3$. Currently, only Toyobo is working on PBO. Its strength-to-weight ratio is comparable to Spectra, but less work has been done on it so it may have more room for improvement. Another factor is that its higher strength at elevated temperatures allows sub-orbital captures at 10-20 km lower altitudes than Spectra. This allows softer reentries.

A second option is enhancing Spectra or its European equivalent, Dyneema. Their strength increases with the amount of elongation imposed on the fiber during processing, and the decision to stop at current values is a matter of economics. DSM personnel say that if there was enough market (-100 tons/year), they could improve the strength/weight ratio of Dyneema by 30 to 40% by further elongation.

## Gas Guns and Tethers

On a somewhat longer time scale, ambitious tethers and gas guns may have a very important complementary role to play in low cost launch of bulk materials. The gas gun needs to be on the equator to launch repetitively into one orbit plane. It also needs to be on the west side of a mountain, sloping up to the east. Hunter and Hyde (1989) give details of a gas gun design that is a good match with the 3.4 km/s tether. They use a two stage gas gun, with the first stage of air/methane combustion driving a massive piston, compressing the second stage hydrogen gas, which in turn accelerates a projectile. They explored muzzle velocities from 4-8 km/s and selected a nominal muzzle velocity of 5.8 km/s, with about a 1 km/s loss as the projectile transits the atmosphere. The total mass accelerated to this speed (payload, solid rocket, and sabot), is 1.76 tons.

We recently explored capturing gun-launched payloads with the 3.4 km/s tether, and were surprised by the results. For capture at 110 km by a vertical tether, a gun elevation angle of 13° is required. This low angle makes drag a serious issue. But raising the gun elevation seems not to help, because it requires either off-vertical catches or (better) vertical-tether capture at a higher altitude. If the drag DV is 10% of muzzle velocity, the best capture altitude is about 150 km; for higher losses, higher capture altitudes are better. For an equatorial launch site, the required muzzle velocity is 4.6 km/s plus drag losses, within the 5.8 km/s nominal design capability.

Hunter and Hyde give an estimated capital cost of $0.5 billion. We assume an amortization rate of 20% is required, giving a $lOOM/yr capital cost. Operational costs are assumed to be $5OM/yr for 3600 launches of 1.76 tons each, or 6120 tons/yr. This gives a cost of about $25/kg, or about $ll/lb. While these numbers are highly speculative, a launch system requiring no chemical rockets is fundamentally appealing as a path to very low cost bulk transport to LEO, and the two systems naturally complement each other. Combined with the assumed access to lunar materials implicit in the 3.4 km/s tether node, we can see the core of a very low cost space transportation infrastructure. We hope these visions of what *might occur will* inspire enough near term research to enable these options in the longer term.

## Conclusions and Recommendations

Ambitious tether systems have a potentially large role to play in transport to LEO. The 1.2 km/s system discussed appears to be technically feasible and could potentially reduce launch costs significantly, even with modest launch rates. However, several near term and long term topics need more research and development to allow evaluation and deployment of the tether transport node in the ten to fifteen year time frame.

### Near Term Tasks

1. Better characterization and understanding of micrometeoroid risk and damage as a function of tether material, size, geometry, and load.
2. Development of damage tolerant tethers and hardware for their deployment and retrieval.
3. Reliable capture using baseline “Velcro” and inflatable boom, along with alternate concepts.
4. High speed tether reeling tests.
5. Better characterization of tether atomic oxygen and ultraviolet degradation.
6. Improved thruster-assisted tether retrieval strategies with a light tip mass.
7. Simulation of upper limit of performance possible with a barely spinning tether.
8. More detailed tether facility design.
9. A small proof-of-concept design, which can fly as a Shuttle payload

### Longer Term Tasks

1. Launch vehicle redesign issues related to using the tether assist, including fast payload transfer, rendezvous, reentry heat loads, propellant combinations, and effect of trading propellant for payload.
2. Re-examination of option of taking Shuttle External Tanks to orbit for various uses, including tether transport node ballast mass.
3. Analysis of overall cost and benefit of a transport node in LEO.
4. Effect of lunar material on the transport node.
5. Gas gun design and synergism with high DV tether.
6. Electrodynamic tethers as viable propulsion and energy storage method in LEO.
7. R&D on stronger tether materials.

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