DESIGN CONCEPT FOR A REUSABLE/PROPELLANTLESS MXER TETHER SPACE TRANSPORTATION SYSTEM†

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ABSTRACT

The Momentum Exchange/Electrodynamic Reboost (MXER) tether facility is a transformational concept that significantly reduces the fuel requirements (and associated costs) in transferring payloads above low earth orbit (LEO). Facility reboost is accomplished without propellant by driving current against a voltage created by a conducting tether's interaction with the Earth's magnetic field (electrodynamic reboost). This system can be used for transferring a variety of payloads (scientific, cargo, and human space vehicles) to multiple destinations including geosynchronous transfer orbit, the Moon or Mars. MXER technology advancement requires development in two key areas: survivable, high tensile strength non-conducting tethers and reliable, lightweight payload catch/release mechanisms. Fundamental requirements associated with the MXER non-conducting strength tether and catch mechanism designs will be presented. Key requirements for the tether design include high specific-strength (tensile strength/material density), material survivability to the space environment (atomic oxygen and ultraviolet radiation), and structural survivability to micrometeoroid/orbital debris (MM/OD) impacts. The driving mechanism key requirements include low mass-to-capture-volume ratio, positional and velocity error tolerance, and operational reliability. Preliminary tether and catch mechanism design criteria are presented, which have been used as guidelines to "screen" and down-select initial concepts. Candidate tether materials and protective coatings are summarized along with their performance in simulated space environments (*e.g.*, oxygen plasma, thermal cycling). A candidate catch mechanism design concept is presented along with examples of demonstration hardware.

INTRODUCTION

Since the concept of the Momentum Exchange Electrodynamic Reboost (MXER) tether has been described in detail by other presenters at this conference, this paper will not repeat such material. From our perspective, the salient features of such a tether system include a required service lifetime of ten years in an elliptical orbit (450 x 6500 km) with adverse atomic oxygen (AO), ultraviolet (UV), micrometeoroid/orbital debris (MMOD), and thermal environments. The specified tether length of 110 km and the centrifugal forces associated with the spinning nature of the system led us to research the highest strength non-metallic materials currently reasonably available, such as Vectran®✦ and Zylon®♦ PBO (p-phenylene-2,6-benzobisoxazole).

A second feature of our work under this contract required the design and scale model testing of capture systems to effect the instantaneous acquisition of a payload satellite by the rotating, orbiting MXER system. One of these systems, the so-called "umbrella" system will be further described herein.

RESULTS AND DISCUSSION

STRENGTH TETHERS

Under subcontract from Lockheed Martin, the Cortland Cable Company, of Cortland, NY, procured the materials of interest in filament form, and built up subassembly braids with isolated break-strengths of approxi-

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† This effort was performed under contract number NNM04AA99C from the NASA Marshall Space Flight Center.
‡ Deceased.
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mately 15,000 pounds from there. We were unable to obtain a supply of M5®♥, and did not really try to obtain carbon nanotube reinforced materials at this time.

REQUIREMENTS FOR HIGH STRENGTH TETHER

Key requirements for the MXER high-strength tether include the following items:

1) high specific-strength (strength/density) at end-of-life (EOL),
2) material survivability after exposure to the anticipated operational space environment, and
3) tether deployability.

STRENGTH REQUIREMENT

Within each of these qualitative general-area requirements are a more defined, specific set of requirements. For example, dynamics analysis performed for a baseline tether mission that consisted of an orbit transfer of a payload with two metric tonnes mass, resulted in the estimate of a required load capability of ~172 MPa (25ksi) for the strength tether. In order to be conservative, we applied a safety factor of 2, thus requiring a load capability of 345 MPa (50ksi). To increase the efficiency of the tether, the use of the highest-strength material available is desirable. This results in the specification of the smallest number of braids or tape elements, which also reduces the overall mass of the tether system. Another inherent measure of tether efficiency is the specific strength or strength/density ratio; thus a material with very high strength and low density is optimum.

MATERIAL SURVIVABILITY IN SPACE ENVIRONMENT

Survivability of the tether material in the operational space environment, without inducing excessive degradation, is also a key requirement. The anticipated space environments that the tether will experience include: 1) atomic oxygen (atomic oxygen fluence is highest at lower (*e.g.*, 500 km) earth orbits) (ref. 1), 2) ultraviolet (UV) radiation, 3) structural survivability to micrometeoroid / orbital debris (MM/OD) impacts, 4) vacuum exposure and thermal cycling (from earth-shadowed and direct solar irradiance) effects, and 5) synergistic effects from these combined space environments.

Atomic oxygen degradation of polymeric materials has been documented from terrestrial laboratory exposures in simulated atomic oxygen sources, as well as measured from actual space flight experiments (*e.g.*, LDEF – the Long Duration Exposure Facility) (Reference 1). Discoloration and change in optical properties, oxidation, mass loss, and loss in strength has been observed, with more damaging effects on polymers. In general, pure metals, fluorinated materials, and coatings of metals/oxides have shown the greatest resistance to atomic oxygen degradation. Ultraviolet radiation is another potentially damaging space environment that has been studied over the years. Cross-linking of polymers, resulting in material strength reductions has been reported for a variety of polymer materials (ref. 1). Even metal-coated polymers (*e.g.*, aluminized Kapton™) has exhibited reduction in material strength, but the degradation was significantly reduced for the metal-coated polymers compared to bare Kapton™.

Micrometeoroid and orbital debris presents another aggressive space environment that the strength tether must survive. Impact with MM/OD particles can result in reduction in the cross-sectional area of the strength members and reduced load carrying capacity or even complete strength member rupture. Conservative use of predictive analytical models includes the selection of a critical particle size of 1/3 to ½ of the strength member diameter as the particle size that will result in complete strength member rupture (ref. 2). Generally, orbital debris is more of a stressing environment since it is more common in lower earth orbits and the size-number density relation is roughly inverse with larger number density for smaller size particles. In contrast, micrometeoroids are more common at the higher orbital altitudes of highly elliptical orbits.

Vacuum exposure and thermal cycling from exposure to earth-shadowed and direct sunlight periods area also stressing environments. High vacuum conditions can outgas material from polymers, resulting in material loss, strength degradation, and also provide a source of contamination. Thermal cycling from alternate exposures to earth-shadowed (at far side of elliptical orbit) and direct sunlight periods of the orbit can significantly lower or raise the tether temperature, depending on the tether outer surface optical properties. Surfaces with high

♥ Registered trademark of Magellan Systems International, Ltd., Richmond, VA.

emittance, common for thicker oxide and some ceramic coatings reduce the peak temperature experienced during direct sunlight exposure. This is important for certain polymeric tether material candidates (*e.g.*, polyethylene) which have lower melting temperatures, which in certain cases have rather low upper use temperatures.

Synergistic combination of these space environments can have degrading effects on polymeric material properties, and in certain cases even accelerate the property degradation.

TETHER DESIGN CRITERIA

Criteria used in the evaluation and ranking of candidate tether designs include the three first tier criteria: 1)technical/performance, 2) manufacturability, and 3) cost. Table 1 shows these first-tier criteria along with more specific, second-tier criteria within each group. For example, within the technical/performance criterion, mechanical properties, space environment resistance, and deployability were considered as important factors to ensure the tether design would satisfy MXER mission requirements.

Manufacturability included fabrication, inspection, repair, and testing criteria, all of which factor into the ability to successfully and reliably manufacture a long-length MXER tether.

Cost, while not as important as either the technical or manufacturing criteria, includes cost for raw material, fabrication/manufacturing costs, and transportation costs.

Criterion	Definition
Technical/Performance	The technical & performance capability of the tether design to meet the MXER mission requirements.
- Raw Matl Strength/Mass (BOL)	The strength/mass ratio at beginning of life of the tether strength member raw material.
- Finished Tether Strength/Mass (EOL)	The strength/mass ratio at end of life of the finished MXER tether.
- Deployability	The ability to deploy the MXER tether for its in-space operational mission.
- Combined Environment Resistance	The ability of the finished MXER tether to withstand degradation due to MMOD, UV and ionizing radiation environments.
- AO Resistance	The ability of the finished MXER tether to withstand degradation due to the atomic oxygen (AO) environment.
Manufacturability	The ability to build, inspect, repair and test the MXER tether in multi-kilometer lengths.
- Build	The ability to build the MXER tether (includes automated and manual processes).
- Inspect	The ability to inspect the MXER tether during the build and test operations (includes automated and manual processes).
- Repair	The ability to repair any component within the tether during build or test operations, including a full tether repair at a single point.
- Test	The ability to test the MXER tether, including breakstrength, combined environments, AO resistance and thermal cycling.
Cost	The material, fabrication and transportation costs for manufacturing the MXER tether.
- Material	The raw material costs for the MXER tether.
- Fabrication	The fabrication costs (labor, tooling, facilities, testing) for the MXER tether.
- Transportation	The transportation costs (special handling/environments) for the MXER tether during production.

Table 1. Tether Design Criteria Used for Evaluation/Ranking of Candidate Designs

Using the Analytical Hierarchy Process (AHP) to evaluate specific tether designs (and also mechanism designs), we performed pair-wise rankings of the evaluation criteria listed in Table 1. From this process, technical / performance was rated as 0.65 (or 65%), followed by manufacturability at 0.25, and cost at 0.10. In other words, it was determined that the technical / performance first tier criteria was evaluated at 65% of the overall importance, followed by manufacturability at 35% and so on. Within each first tier criteria were second-tier and third-tier criteria, which also were ranked using the pair-wise ranking method. The overall results of the breakdown of the first and second tier ranking criteria are shown in Figure 1. From this ranking criteria tree, it can be observed that the first tier technical/performance criteria had five second-tier subset criteria, with the pair-wise ranking resulting in EOL tether strength/mass ratio having the highest weighted rank of 0.41, followed by deployability at 0.28, and combined space environment resistance at 0.21, etc. Multiplying the first tier criteria ranking by the second tier ranking resulted in the overall weighted score for the specific evaluation criteria; these values are listed in Table 2. Note that the EOL strength/mass ratio had the absolute highest weight of 0.27, followed by deployability at 0.18, etc. Also observe that the top six criteria accounted for ~85% of the total weighted criteria for the tether, thus these 6 criteria were viewed as the criteria of highest importance.

The next step in the AHP methodology was to rank the performance of candidate tether designs (from 5: very good to 1: poor) against the weighted evaluation criteria listed in Table 2, and then multiply the whole number rankings by these weighted criteria. The resultant scores were summed to produce an overall score for the candidate tether design.

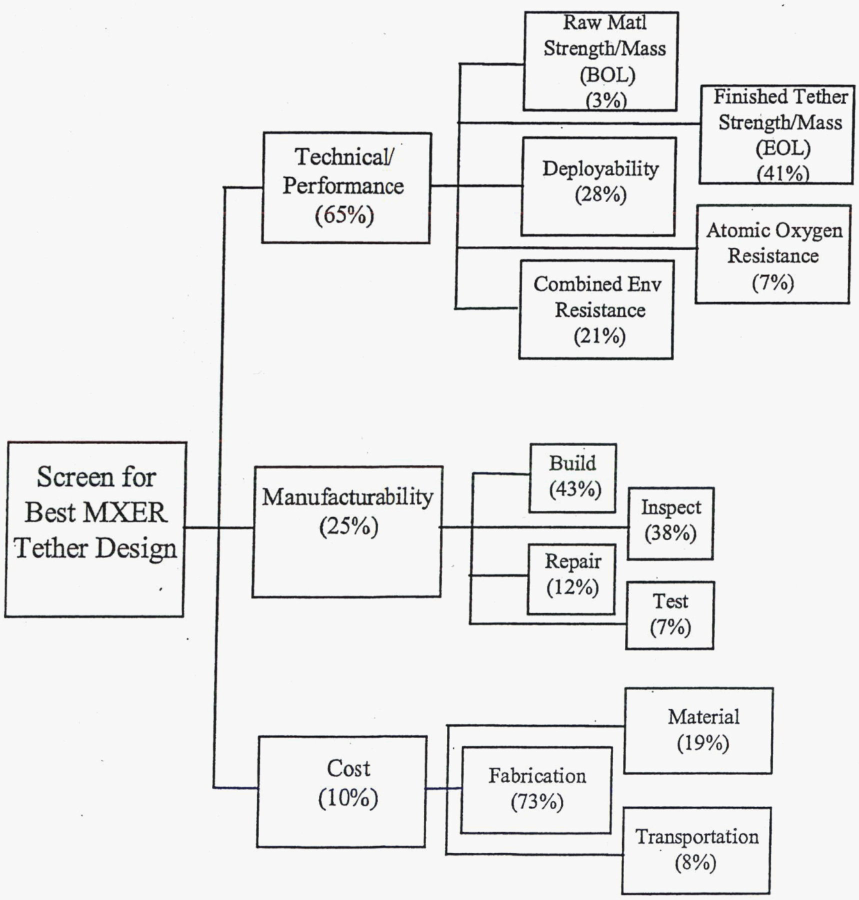


Figure 1. Breakdown of AHP Ranking Criteria With Relative Weights of Each First and Second Tier Ranking Criterion

Criteria	Absolute Importance
1) EOL Finished Str/Mass	0.269
2) Deployability	0.180
3) Comb Env Res	0.136
4) Build	0.107
5) Inspect	0.095
6) Fab Cost	0.070
7) AO Res	0.049
8) Repair	0.029
9) BOL Matl Str/Mass	0.021
10) Test	0.019
11) Matl Cost	0.018
12) Transp Cost	0.008

These Categories Represent ~ 85% Of Total Weight (criteria 1–6)

Table 2. Tether Specific Design Criteria And Relative Weight of Each Criterion

CANDIDATE TETHER DESIGNS

Candidate tether designs that were considered in the AHP ranking methodology included the general categories of interconnected multistrand braid tether and a continuous-width taper or ribbon tether. From preliminary tether material (*e.g.*, Spectra®, Zylon® PBO, Kevlar®, Vectran®) property review and sample testing / evaluations, a series of candidate tether designs was formulated for both multistrand and tape-tether configurations. Using the AHP ranking methodology listed above, we down-selected the highest ranked tether designs, which are listed in Table 3. Zylon PBO was selected as the strength member, since it offers the highest specific strength of the candidate tether materials. Starting with filaments of the selected materials, appropriately-sized braids were fabricated, and further combined into higher-level tether assemblies, such as the wide, flat laminated tape and the multistrand interconnected tethers described below. A novel technique for maintaining the alignment of the strands on a multi-strand, interconnected parallel tether undergoing lamination was developed and utilized.

However, Zylon does have its limitations as well, including aging effects from UV exposure and sensitivity to moisture pickup resulting in strength reduction.

For the multistrand architecture, this consisted of interconnected (by stitching to reduce the likelihood of slippage) PBO Zylon braids protected by physical vapor deposited Al overcoated with aluminum oxide (Al_2O_3). The purpose of these coatings are to provide protection of the PBO to atomic oxygen attack and UV degradation and also to increase the emittance of the Al (by the Al_2O_3 top coating). This PBO coating protection concept has been demonstrated by DRLI on both smaller length (*e.g.*, 17.8 cm (7 in)) braids and more recently on much longer length braids (*e.g.*, 60 m). For this longer length, Cortland Cable Company (CCC) has developed a stitching methodology to periodically interconnect the braids. From our ranking criteria, this concept offered the highest rank for the multistrand concept due to the following: 1) lightest weight, 2) flexible for stowage and deployment, and 3) interconnected to enable load transfer in the event of MM/OD impact, which increases its survivability.

Technical issues that would need to be addressed before full-scale demonstration include: 1) attaining full coating coverage of the entire braid structure, whether coating is applied to individual braids for subsequent interconnection or coating of the interconnected tether structure; 2) possibility of coating removal when wrapped tightly around a stowage drum or during deployment; and 3) demonstration of UV survivability of the bilayer coating on the PBO braid. The PVD coating process is inherently limited by line-of-sight restrictions imposed by the sputtering process. However, use of opposed sputtering sources or an array of three sources with angles

Tether Design	Maturity	Advantages / Technical Risks
Multistrand **Interconnected (Stitched) Zylon Braids w. Al/Al_2O_3 PVD Coating**	**Tether Demo. by CCC** **Coating Demo. by DRLI**	**+ Highest Rank, Lightweight** **+ Flexible for Stowage, Deploy** **+ Interconnect for Survivability** **– Complete Coating Coverage** **– Coating Removal During Drum Wrap ?** **– UV Protected ?**
Tape, Ribbon **Zylon (Stitched) in PET / PE Bicomponent Facesht w. Al/Al_2O_3**	**Tether Demo. by CCC** **Coating Demo. by SwRI on Small Piece**	**+ Flat Surface ofFacesht for Better Coating Coverage** **+ Ensured Separation of Braids** **+ No Entanglement During Assy., Deployment** **– Heavier Than Multistrand** **– Drag Issue ?; Cutouts** **– Thermal Limits for Facesht.**

PE –Polyethylene; PET– Polyester; DRLI– Deposition Research Lab.,SwRI – Southwest Research Institute

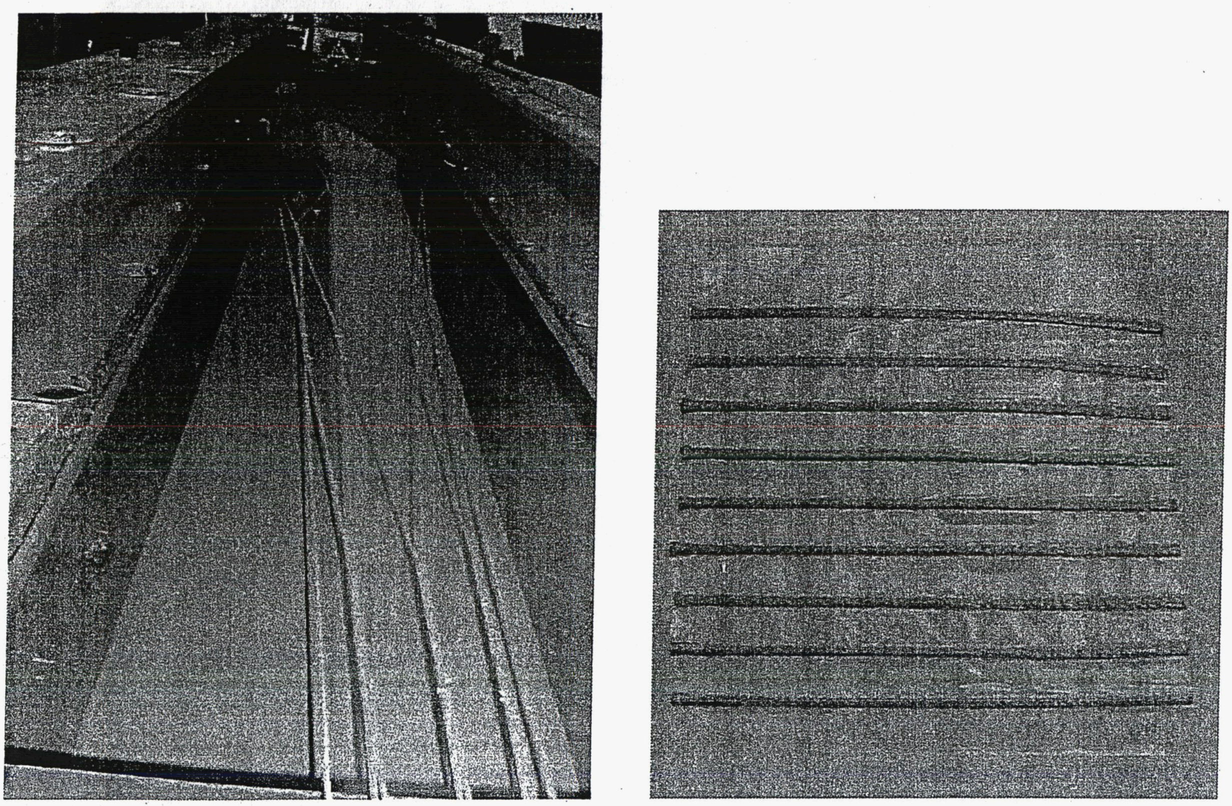
Table 3. Summary of Final Tether Designs

between normals of 120° would alleviate this concern. This would be ideal for coating an assembled tether. Alternately, processing of individual braids by passing through a hollow sputtering cathode would ensure good coverage of all exposed braid surfaces. Length-wise compression of the braids does offer the possibility to obtain some penetrating coating coverage, especially when the braid is subsequently loaded into tension in use.

For the tape tether concept, our highest rank design consists of PBO Zylon braids that are laminated between polymer facesheets consisting of a bilayer of polyester (PET) (outer) with a lower-melting point polyethylene (PE) inner surface. Cortland Cable Company investigated the best spacing distance between the PBO braids that results in good bonding and isolation of the braids. In a similar manner to the multistrand concept, duplex coating with Al and Al_2O_3 was performed for space environment protection. But in this case, the flat surface of the lamination provides a better surface for subsequent coating adhesion and coverage. This has been demonstrated by DRLI on small length (~17.8 cm (7 in)) and most recently by SwRI on a longer length (~76.2 cm (30 in)) sample. Besides the advantages of better coating coverage and separation of braids, there will be no entanglement of the braids during mandrel wrapping or deployment. Potential limitations for this tape concept include: 1) increased weight compared to the interconnected multistrand; 2) drag issues from the continuous tape; and 3) thermal limitations from the PE portion of the facesheets. Cut-outs address the drag issue, while high emittance surface reduces temperature.

Figure 2a shows a demo example of the multistrand interconnected braid tether. The photograph shows a long length of the interconnected braid tether, with periodic stitch interconnection positions. Effective design of the interconnection methodology will require finite element modeling (FEM) to enable specification of the cross-member angle with the axial load-bearing braids, type and length of interconnection stitching, behavior of multistrand configuration upon rupture of a single braid, *etc.* Location of the stitch interconnections will be recommended by the MM/OD analysis, which has been used to predict the fraction of impacts per unit length. Assuming a selected safety factor, the specification of the interconnection spacing is then possible. For example, from initial MM/OD analysis, it was predicted that a single impact with a braid would occur over a span of ~55.6 m. Therefore for contingency, adding interconnections at fractions of this length would increase the safety factor to braid rupture. We lacked the capability to properly test samples of the necessary length of tens of meters to experimentally validate this concept.

Figure 2b shows a best effort by CCC to fabricate a tape tether configuration. Cortland Cable studied the best spacing distance between braids to ensure lamination for the tape tether concept. For the 6966 braid, a somewhat tighter, more circular braid, it was observed that a 2.54 cm (1 in) spacing was required to ensure good lamination of the PET/PE bicomponent facesheets between the braids (Figure 2b). Decreasing this spacing to 1.91 cm (0.75 in) was not as effective as only the inner-most region of the facesheets are bonded together.



a) ***b)***

Figure 2. Photographs of: a) Long Length of Interconnected Tether and b) Tape Tether Configurations Fabricated by Cortland Cable Company.

CANDIDATE TETHER MATERIAL TEST DATA

Candidate tether materials were tested under different simulated space environments, including: 1) oxygen asher (mixed plasma of oxygen atoms and ions) and 2) thermal cycling simulating the temperature swings anticipated during an elliptical orbit. In addition, coated braids were subjected to tape peel and mandrel-bend tests to assess relative coating adhesion as well as mechanical break strength tests on as-coated and thermally-cycled material.

In general, it was observed that Spectra™ could not tolerate very high oxygen plasma asher power levels or long-time exposures, as induced temperatures degraded the polyethylene material. In contrast, bare Zylon and coated PBO survived higher power levels and a bilayer alumina/Al coated (by PVD) provided the best oxygen erosion resistance.

Thermal cycling (from ~200°C to +30°C) was applied to PVD-coated and interconnected PBO braids to assess length change, mass loss, and also provide specimens for mechanical break strength measurements. Interconnected braids exhibited length shortening for 2 of the 3 groups of 7, while mass loss was measured for all of the 3 groups of 7. However the magnitude of the length changes and mass losses were very low, e.g., a maximum shortening of 0.2% for one group of 7 interconnected braids and a maximum mass loss of 0.28%. For the 3 tape tether articles, both shortening and mass loss were measured, but once again the magnitudes of the length change and mass loss were very low again. So it appears the fairly extreme thermal cycling did not have a significant effect on changes in tether article length or mass. Strength measurements after thermal cycling exhibited a minor effect on strength and displacement reduction, with a ~7.1% drop in strength for the interconnected double braids, and a ~6.8% reduction for the single braid tested with the load path directed through the interconnection. Such Zylon PBO coated by physical vapor deposition with a base layer of metallic aluminum and a second, outer, layer of aluminum oxide (Al_2O_3) appeared to offer adequate protection from the AO/UV environment of low earth orbit, and to have an appropriate α/ε ratio to limit the peak temperatures developed on-orbit to an acceptable upper limit. Regardless of optical properties, analysis showed that all tether configurations would reach temperatures of about minus 170° C on the lower limit (in earth eclipse). This raised concerns about embrittlement, and merits further investigation.

The tether concepts that were investigated under the current effort were "non-conducting," but we have not yet investigated whether the PVD aluminum base layer will result in any adverse conductive effects (*e.g.*, electrodynamic "drag" on the system as a whole) when applied as described.

"UMBRELLA" CAPTURE SYSTEM

The top level requirements for the capture system, of which this is one example, include:

- ❖ Local horizontal (*i.e.*, in the plane perpendicular to the nadir-zenith line) dispersions of 5 meters in any direction;
- ❖ Local vertical dispersions of ± 50 meters;
- ❖ The ability to release the payload within a few hundredths of a second of a desired time;
- ❖ Service life of ten years with a postulated 12 cycles per year;
- ❖ A "clean" interface to a wide variety of paying customer satellites; and
- ❖ Simple, low cost, reliable, *etc.*

Derived requirements include:

- ➢ No maintenance requirements (no moving parts) on the tether side of the interface;
- ➢ Safe disposition of the payload satellite side of the interface; and
- ➢ No impact loads transmitted between the MXER and the payload satellite.

The resultant concept consists of two assemblies:

- ❖ A "tennis racket" (TR), being a circular hoop ten meters in diameter, strung with an array of cross-wires, and attached to the tether in such a manner as to remain in the local horizontal plane; and
- ❖ The "package," containing the actual "umbrella" penetrator (UP) (See Figure 3), the interface to the payload, and other elements to be described in the following scenario.

From the payload perspective the relative motion of the approaching is almost "up & down" – nearly along the local vertical. Starting with the extended boom, stabilized by the payload, and with the UP "cocked," the TR descends over the UP (See Figure 4). As it descends, the UP collar is depressed, allowing the head to expand (as shown in Figure 3), preventing withdrawal from the TR. In virtually all cases, the TR keeps traveling down the probe. As it continues to push the collar, this further motion causes the bi-stem to commence retracting vigorously – in order to avoid compression loading of the bi-stem and/or impact with the payload.

When the retraction catches up with the TR, retraction stops and a ratchet engages, thereby transmitting the opposite direction acceleration to the payload.

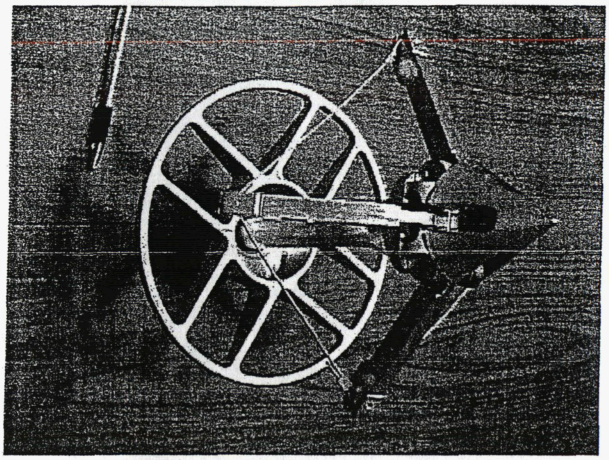


Figure 3. The UP scale model as fabricated.

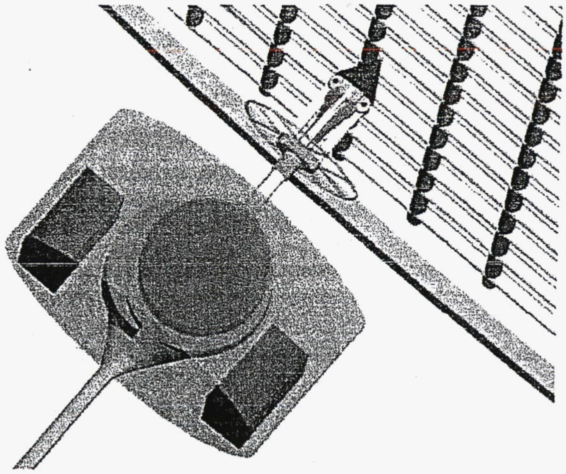


Figure 4. The overall UP system concept.

Approximately 180° of MXER rotation later, the entire "package" is (pyrotechnically) separated from the payload under payload command, thereby sending the payload on its way. An additional 90° of MXER rotation later (as estimated by a timer initiated simultaneously with the pyrotechnic release), the cable constraining the UP "arms" is pyrotechnically cut, releasing the now-useless "package" remnants. The release angle selected gives it a strong downward velocity, causing reentry in less than half a revolution. The TR is left undamaged, uncluttered, and ready for reuse after the MXER system has recovered its energy by electrodynamic recharge.

SUMMARY AND CONCLUSIONS

It was concluded that ultimate development and qualification of a coated multi-strand tether in support of an operational MXER system is feasible. The work described herein has significantly advanced the MXER system TRL towards the ultimate goal of deploying at least a flight demonstration system. The scale model "Umbrella Penetrator" capture device functioned as expected. The overall capture system needs additional development work, but can ultimately satisfy the demanding requirements placed on it. Taken together with the other work in the In-space Propulsion area, these accomplishments represent major progress towards the goal of propellantless, reusable propulsion of at least unmanned vehicles / satellites.

FUTURE WORK

Additional testing with newer high strength materials, such as M5® when it can be obtained, is warranted in order to enable the highest performance system. Existing samples of our current fabrications have been delivered to the NASA Marshall Space Flight Center for testing in their AO facility in order to cross check our work using the Lockheed Martin "asher" facility. Additionally, the entire area of MM/OD resistant electrically conductive tethers, as well as assuring that the existing Al/Al2O3 overcoated tethers do not cause electrodynamic drag due to unintended conductivity needs investigation.

ACKNOWLEDGMENTS

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Additionally, our subcontractor team member, the Cortland Cable Company, ably and enthusiastically represented by Mr. Douglas P. Bentley, was the enabling element in the strength tether portion of these studies. In turn, ***his suppliers***, including Deposition Research Laboratories, Inc., of St. Charles, MO, and Southwest Research Institute of San Antonio, TX, actually applied the coatings necessary to our evaluations.

REFERENCES

1) E. Silverman, "LEO Materials Selection Guide" in *Space Environmental Effects on Spacecraft*, NASA Contractor Report 4661, Part 1, Contract NAS1-19291, Prepared for LaRC, Aug. 1995., pp. 2-25.
2) W. Bohl, LMSSC personal communication, July 2005.