TETHERS AS DEBRIS: HYDROCODE SIMULATION OF IMPACTS OF TETHER FRAGMENTS ON PLANAR AEROSPACE MATERIALS

Steven W. Evans, Ph.D.
NASA Marshall Space Flight Center, Huntsville, Alabama, United States
steve.evans@msfc.nasa.gov

ABSTRACT

Tethers promise to find use in a variety of space applications. Despite being narrow objects, their great lengths result in them having large total areas, and so tethers are quite susceptible to being severed by orbital debris. Extensive work has been done designing tethers that resist severs by small debris objects, and hence have longer working lives. It is from this perspective that most recent work has considered the tether – debris question. The potential of intact tethers, or severed tether fragments, *as debris* to pose a significant collision risk to other spacecraft has been less well studied. Understanding the consequences of such encounters is important in assessing the risks to other spacecraft posed by tethers. In this paper I discuss the damage that two types of tethers may produce on planar aerospace materials, as revealed by hyper-velocity impact simulations using the SPHC hydrodynamic code. Tether types considered include a single nylon line and a complex design including metal wires. Target materials considered include the aluminum plates typically used in debris shielding, and solar panels.

INTRODUCTION

Studies of orbital debris and of tethers have been active fields for the past several years [1,2,3,4]. The vast majority of previous work was done from the perspective of tether vulnerability to severance by debris impacts, rather than the effects of tethers *as debris* on other spacecraft. Consequently, considerable effort has been expended designing tethers that can suffer impacts and continue to function [5,6,7]. However, my interest has been on the hazard tethers may pose to other spacecraft.

When only polymer tethers were being designed and used, the question of the damage they might inflict on other vehicles during a collision accident was not considered important – after all, these were strings, dental floss, what harm could they do to aluminum plates, glass panes, or the like? Now conducting tethers, including metal wire components, are being designed and built, so that their effectiveness in electrodynamic propulsion can be evaluated. Metal wires are clearly more dangerous than polymer lines in hypervelocity collisions with other objects.

Owing to the difficulty of accelerating tether samples against planar targets in a two-stage light gas gun or other hypervelocity accelerator facility, I decided to model impacts of tether fragments using a hydrodynamic code whose simulation results had been validated by test.

SEDS EXPERIENCE

SEDS-2

My attention was first drawn to tether issues during 1994 when I did some orbital lifetime calculations for the Small Expendable Deployer System Project's second flight (SEDS-2) [8]. SEDS-2 rode as a secondary payload on the second stage of a Delta II flight in March 1994. After the Delta's upper stages and primary payload had departed from the second stage, the SEDS deployer kicked off an endmass toward the nadir, controlled the rate of tether deployment, and stopped the deployment after 20 km of tether had spooled out.

The flight configuration then consisted of the Delta II second stage (tipped down about 60 degrees from local horizontal), 20 km of tether, and an instrumented endmass (an aluminum box of 8x12x16-inches). The SEDS tether was a flat braid of Spectra 1000™ with a width of 0.75 mm, giving the 20-km length an approximate geometric area of 15m^2. Considering the variation in atmospheric density along the length of the tether, I computed its effective area to be almost 19.5 m^2 – more than twice the Delta II second stage's projected area of about 8.7 m^2.

The lifetime I predicted for this configuration was about 28 days. In actuality, the endmass and roughly 12 km of tether separated from the upper stage some on mission day 5. The cause of the separation was assumed at the time to be severance of the tether by impact of a meteoroid or piece of orbital debris.

SEDS-3

SEDS-3 was proposed as a secondary payload on a space shuttle mission, during which momentum transfer was to be used to loft the deployed endmass into a higher orbit [9], requiring a tether cut at the shuttle end. Once the endmass had reached apogee, it was to cut the tether also, which would go into a lower orbit and rapidly reenter. There was a concern that if the tether was accidentally severed during the deployment, prior to either of the planned cuts, part of the tether [10] (and perhaps the endmass) could recontact the shuttle. I performed simulations at various points in the deployment sequence to address these recontact concerns [11]. This investigation further provoked my interest in the effect of collisions by tether fragments on other objects.

LIFETIMES AND SEVER ANALYSES

Concerns about the limitation of single-strand tether lifetimes by meteoroid and debris impacts have led to predictions of tether lifetimes against sever [7, 10, 12], estimation of collision rates [4, 13], and development, analysis, and testing of several mitigating designs [5, 14]. These designs can employ multiple strands to serve as alternate tension paths, broad ribbons or tapes to prevent total sever by most debris impacts, or other approaches [6, 15]. One aspect of the analyses of tether lifetimes against impact sever is the characterization of the impactor size required to sever a strand [7, 12], typically expected to be between 0.1 and 0.4 the strand diameter.

Clearly, tethers can be severed by meteoroid and debris impacts, so a question arises as to the hazard such free tether fragments pose to other spacecraft [4, 13]. This hazard will be a function of orbital lifetime. Tethers are more affected by atmospheric drag than other classes of space objects, due to their large ballistic coefficients, β, given by:

$$\beta = C_D A / M \qquad (1)$$

where C_D is the drag coefficient, A is the cross sectional area, and M is the mass. The cross sectional area of a tether is very large, since, even though it may have small diameter, d, it tends to have great length, L. Consequently, tether β's are large.

Warnock and Cochran [3] performed analyses of orbital lifetimes for initially radially-oriented tethers and tethered satellites. They ran simulations of tethers orbiting about an oblate Earth with an oblate, rotating atmosphere, and considered atmospheric drag, gravitational forces, and tension forces in the tethers. Their tethers were assumed to be cylindrical in cross section, and made of Kevlar™ 29. They found that for cylindrical tethers of a given length starting at a given altitude, larger-diameter tethers had longer lifetimes than small ones: the ballistic coefficients decreased, because the tether's mass is proportional to d^2, while the drag is proportional to d. "*Consequently, a large diameter tether dissipates less orbital energy, per unit mass per unit time, than a small diameter tether, and will therefore have a longer orbital lifetime.*"

Considering length effects, they found that "*… a long tether, closely aligned with the local vertical, will encounter the more dense portions of the atmosphere earlier in its lifetime than will a short tether in a similar configuration. Thus, a long tether will dissipate orbital energy sooner, and have a shorter orbital lifetime, than will its short counterpart.*" For this reason, short tether fragments generated by hypervelocity collisions are of more concern as debris objects than long, intact tethers. Also, fragments of high-density-material tethers, e.g., conducting metal wires, are more of a concern, since they will have longer lifetimes, and will be much more effective penetrators than low-density forms.

The initial altitudes studied by Warnock and Cochran were in the range of 400 to 500 km. The corresponding lifetime values for 20-km tethers were rather short, ranging from a few hours to not quite ten days. I have calculated lifetimes for a 10 km long, 2 mm diameter tether having linear density of 3 g/m by a less-rigorous method than Warnock and Cochran, and results for 28.5-degree inclination orbits are shown in Figure 1. For tethers to constitute long-term collision hazards, their initial altitudes will have to be considerably higher, or the tethers must be considerably shorter or more dense than Warnock and Cochran's examples.

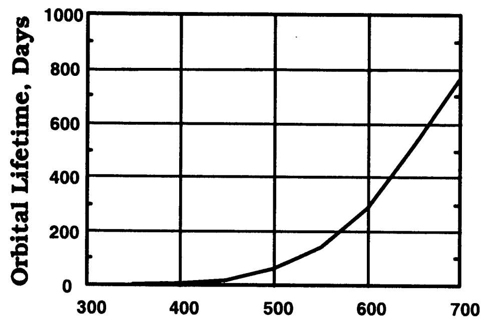

Figure 1. Estimated tether orbital lifetimes.

Concerns about tethers as debris objects are beginning to be addressed. NASA issued Orbital Debris Mitigation Guidelines [16] which included a section on tether debris hazard calculations. In addition, the Inter-Agency Space Debris Coordinating Committee, functioning under the auspices of the United Nations Committee for the Peaceful Uses of Outer Space, is preparing a Protection Manual [17] with respect to orbital debris, and it includes a section on protecting tethers from destruction by debris and on the hazards tethers may pose as debris.

SPHC

In addition to other kinds of analysis, hydrocode simulations have been used to examine the effect of hypervelocity impacts on tethers [18]. One particular computational method, known as Smooth Particle Hydrodynamics (SPH), was developed by Lucy [19], Monaghan [20], and Stellingwerf [21], and used in a variety of applications, from stellar astrophysics to impact studies. The version of SPH written for the C programming language (SPHC) has been in development by Stellingwerf [22] since the late 1990's. It formed the basis for the SPHINX hydrocode package used at Los Alamos National Laboratory. SPHC has been used in tether debris simulation analysis and the results verified by tests [23]. SPHC is structured so that momentum and energy conservation laws are tightly maintained. Equations of state and strength models appropriate to the various materials one may use (e.g. Mie-Gruneisen solids, liquid water, or perfect gas) are available, as well as a standard set of materials, with the appropriate material properties. This code was the tool I selected to simulate hypervelocity impacts of tether fragments on planar aerospace materials.

SCENARIO DEVELOPMENT

Tether Types

I selected two types of tethers to use in my impact simulations, a single nylon line, and a multi-element design consisting of a nylon core with a metal wire over-layer. The latter bears some resemblance to the conducting segment of the ProSEDS Project tether [24], which is scheduled to fly some time in late 2002.

Target Types

Planar material targets included a single aluminum plate, a solar panel (modeled as two thin glass layers backed by a layer of Kapton™), and spaced aluminum plates reminiscent of a metal multi-shock shield [2].

Closing velocity

The closing velocity between a tether fragment and its target were based on assumption of circular orbits at ~400 km altitude, having an orbital speed of 7.8 km/s. Depending on approach geometry, the closing velocity could be anywhere between a few meters per second and 15.6 km/s. I selected an approach direction of 60 degrees off the target's velocity vector. As shown in Figure 2, this corresponds to a minor peak in the debris approach direction distribution at this altitude (for an orbit inclination of 51.6 degrees) [1]. The closing velocity for the tether fragment was 13.51 km/s.

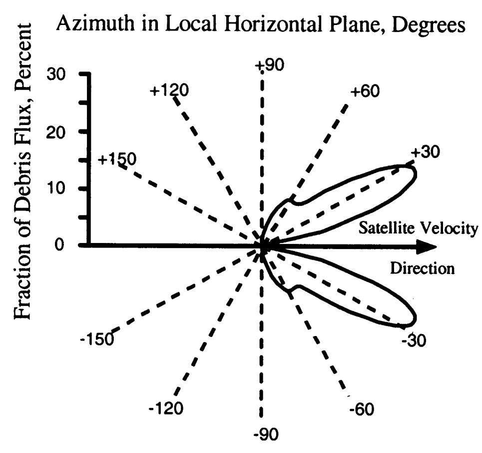

Figure 2. Orbital debris approach direction distribution in local horizontal plane.

SIMULATION RESULTS

Single-line Tether vs. Aluminum Plate

The first case considers a single-strand tether impacting an aluminum plate. The tether was modeled as a rectangular nylon strip with dimensions 0.75mm X 0.30 mm X 2.309 cm. The target was modeled as a 2cm X 2cm X 3mm plate of Al 6061-T6. The tether strip was rotated 50 degrees about its long axis, and tilted 30 degrees away from parallel to the target face plane. Figure 3. shows the pre-collision configuration. Figure 4. shows a snapshot at 4 μs into the collision.

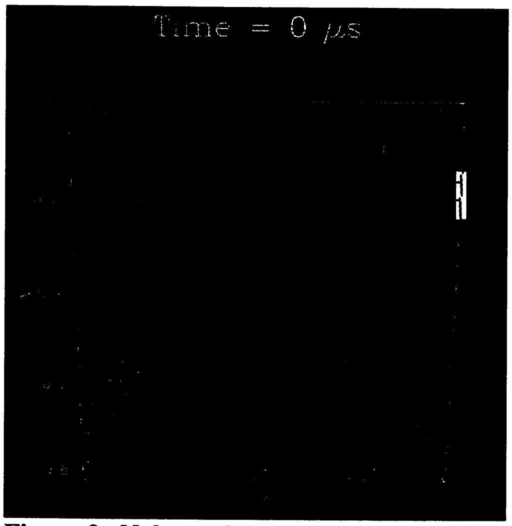

Figure 3. Nylon tether on aluminum plate scenario – initial set-up.

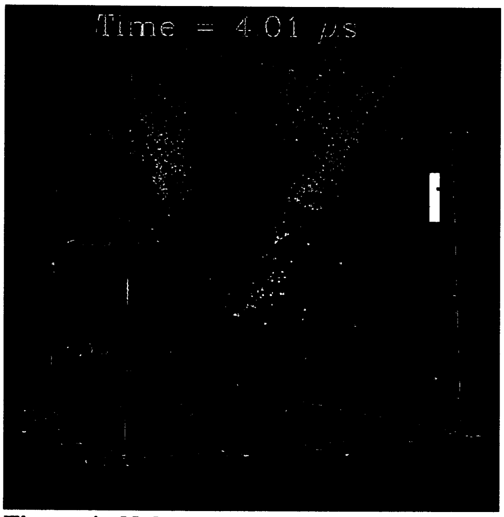

Figure 4. Nylon tether shattering aluminum plate, 4 μs into the collision.

The nylon tether clearly shattered the aluminum plate. Figure 4 is color-coded on material phase. Dull green indicates intact solids (aluminum); light blue indicates yielding solids; dark blue indicates fractured solids (aluminum); bright green to yellow indicate liquids (aluminum and nylon); orange and red indicate vapor (nylon). At 1.17 g/cm^3, the nylon strip had a kinetic energy of 554.72 joules. Although it was completely destroyed in the collision, the nylon strip imparted most of its kinetic energy to the aluminum during the collision, which was sufficient to shatter the plate. Fragments leaving the back surface of the plate were moving at approximately 3 km/s. If this plate were the bumper layer of a Whipple shield, the backwall would suffer hypervelocity impacts of bumper debris.

Single-line Tether vs. Solar Panel

The next target was a simulated solar panel, comprised of two layers of glass each 0.2 mm thick backed by Kapton^{TM} 0.6 mm thick. Adhesive tensions between the layers were set to half the internal tensions of the layers in an effort to model delamination conditions. As one would expect from the aluminum impact results, the nylon strip had no problem completely severing the solar panel target, as shown in Figure 5.

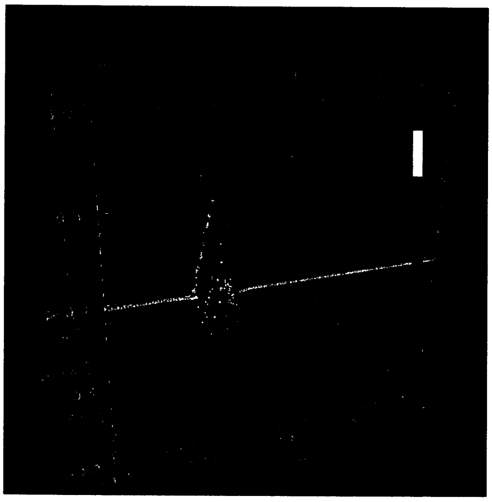

Figure 5. Nylon tether vs. solar panel, 1.1 μs into the collision.

Here the image is color coded on 'region' meaning the different types of material. Dark blue is the nylon; dull green is the top glass layer; yellow is the second glass layer; and red is the Kapton^{TM} layer.

During high velocity impacts, polymer tethers can be expected to produce severe damage on thin planar materials regardless of composition.

Conducting Tether vs. Spaced Aluminum Plates

The final tether configuration consisted of a 2 mm nylon core surrounded by seven 0.32 mm copper wires. The fragment is approximately 2.6 mm in diameter and 2 cm long. This is similar to the ProSEDS conducting tether, which will have a core composed of six strands of 390-denier Kevlar™ 49 twisted into a line, surrounded by seven 0.32 mm coated aluminum wires twisted in the reverse sense to remove torsion from the completed tether. Because of the difference in density between copper and aluminum, my simulation overstates the penetration capabilities of a conducting tether, compared with the ProSEDS configuration.

As my target configuration, I modeled two 3 mm thick Al 1350-O plates spaced to have 1.7 cm between the back of the first plate and the front of the second one.

Figure 6 shows the pre-collision set-up, and is color coded on 'region': blue is copper, green is nylon, and red is aluminum.

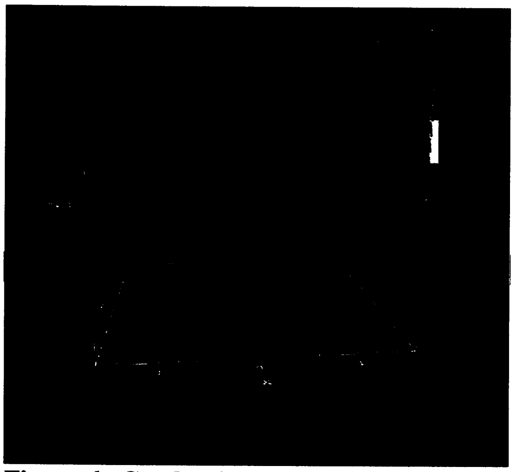

Figure 6. Conducting tether vs. plates set-up.

Figure 7, colored on phase, shows penetration of the first aluminum layer, and impact of high-temperature nylon and copper vapor on the second plate at 2 μs into the collision. Figure 8, also colored on phase, shows penetration of the second plate by aluminum and copper debris at 8 μs.

All the nylon has vaporized, and the copper has either liquified or vaporized. The remainder of the kinetic energy of the impactor not put into phase changes has been transferred to the aluminum, which is expanding into a debris cloud. Penetration of the second aluminum plate is accomplished by aluminum particle impact aided by pressure loading from the vaporized nylon and copper.

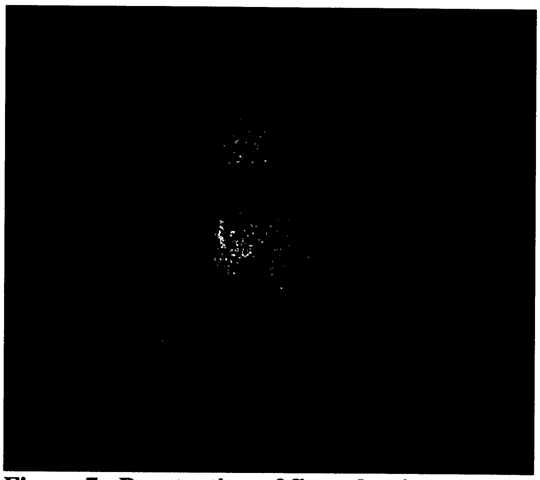

Figure 7. Penetration of first aluminum layer.

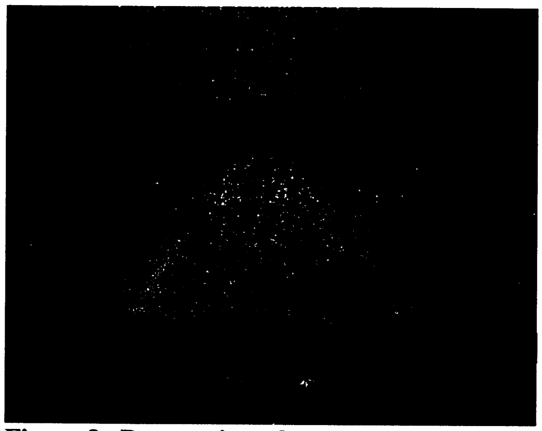

Figure 8. Penetration of second aluminum layer.

Debris fragments leaving the back of the second plate are aluminum moving in excess of 4 km/s. If these aluminum plates were part of a multi-shock spaced aluminum plate shield, any back-wall behind them would suffer hypervelocity impact by aluminum debris cloud fragments.

CONCLUSION

My work with SPHC on the 'tethers as debris' problem is only beginning. In future I plan to make comparisons with other authors' work on projectile shape effects [25], and projectile impact angle, density, and energy effects [26] on the penetration of plates and development of ballistic limit relations. I plan to improve my tether models to more closely reflect their as-built characteristics. Despite their small thicknesses and the frequent use of low density materials in their manufacture, uncontrolled tethers and tether fragments can do a lot of damage to other spacecraft. Low altitude tethers, such as the various incarnations of SEDS, pose minimal risk to other spacecraft due to their short lifetimes on orbit. However, higher altitude tether missions, especially those including metallic conducting elements, pose a much greater damage risk due to their longer lifetimes on orbit and the greater penetrating ability of their components.

REFERENCES

[1] *Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development,* NASA TM 4527, B.J. Anderson, ed., 1994.

[2] Christiansen, E.L., J.H. Kerr,"Ballistic Limit Equations for Spacecraft Shielding," *The International Journal of Impact Engineering*, **26**, 93 – 104, Pergamon, 2001.

[3] Warnock, T.W., J.E. Cochran, Jr.,"Orbital Lifetime of Tethered Satellites," *The Journal of the Astronautical Sciences*, Vol. 41, No. 2, pp. 165 – 188, April – June 1993.

[4] Matney, M., D. Kessler, N. Johnson, "Calculation of Collision Probabilities for Space Tethers," IAA-00-IAA-6.5.02, 51st International Astronautical Congress, 2 – 6 Oct. 2000, Rio de Janeiro, Brazil.

[5] Hoyt, R.P., R.L. Forward, "Failsafe Multistrand Tether SEDS Technology," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 2, pp. 1151 – 1159, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[6] Kustas, F.M., F.J. Jarossy, L.L. Burgess, "Design Considerations for a Long-Lifetime Space Tether," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 1, pp. 577 – 590, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[7] Beech, M., P.C. Toulmin, "Tether Survivability: SEDS-2 as a Diagnostic Tool," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 2, pp. 1233 – 1241, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[8] Evans, S.W., "Comparison of predicted and actual orbital lifetimes for the SEDS-2 mission," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 2., pp. 837 – 845, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[9] Harrison, J.K., "SEDS/SEDSAT Project Overview," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 1, pp. 85 – 93, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[10] Welzyn, K.J., J.H. Robinson, "Severed Tether Dynamics and Probability," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 3, pp. 1353 – 1366, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[11] Evans, S.W., "Post Deployment Recontact Issues for the SEDS/SEDSAT Mission," AAS Paper 96-203, AAS/AIAA Space Flight Mechanics Meeting, Austin, TX, February 1996.

[12] Christiansen, E., J. Kerr, private communication, 2001.

[13] Cooke, W.J., et al., "Tether Survivability and Collision Avoidance: Is LEO the Right Place for Tethered Systems?," Space Technology Applications International Forum (STAIF), Albuquerque, NM, 2001.

[14] Angrilli, F., et al., "Effects of Debris Damage on New Long-Life Tethers," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 2, pp. 1171 – 1179, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[15] Burgess, L.L., F.M. Kustas, F.J. Jarossy, "A Space Tether Experiment (STEX)," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 1, pp. 181 – 191, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[16] *NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris*, NSS 1740.14, NASA Office of Safety and Mission Assurance, August 1995.

[17] *Orbital Debris Protection Manual*, Chpt. 3, Inter-Agency Space Debris Coordination Committee, in preparation.

[18] Hayashida, K.B., J.H. Robinson, S.A. Hill, "Micro-Meteoroid and Orbital Debris Damage Analyses on SEDS Tether," *Proceedings of the Fourth International Conference on Tethers in Space*, Vol. 2, pp. 847 – 858, Smithsonian Institution, Washington, DC, April 10 – 14, 1995.

[19] Lucy, L., "A Numerical Approach to Testing the Fission Hypothesis," *Astronomical Journal*, Vol. 82, p. 1013, 1977.

[20] Monaghan, J.J., "An Introduction to SPH," *Computational Physics Communications*, Vol. 48, p. 89, 1988.

[21] Stellingwerf, R.F., "Smooth Particle Hydrodynamics," *Advances in the Free-Lagrange Method*, Trease, Fritts, and Crowley, eds., Springer Verlag, p. 239, 1990.

[22] SPHC Smooth Particle Hydrodynamics Code, Version 6.11, Stellingwerf Consulting, Los Alamos, NM, 2002.

[23] *STEP-AIRSEDS M/OD Hypervelocity Tether Impact Report*, TMTC-SA-PB-MODTESTv1.0, The Michigan Technic Corp., 2001.

[24] Curtis, L., et al., "Development of the Flight Tether for ProSEDS," STAIF, Albuquerque, NM, 2001.

[25] Cour-Palais, B., "The Shape Effect of Non-Spherical Projectiles in Hypervelocity Impacts," *The International Journal of Impact Engineering*, **26**, 129 – 143, Pergamon, 2001.

[26] Lamontagne, G., et al., "Projectile Density, Impact Angle and Energy Effects on Hypervelocity Impact Damage to Carbon Fibre/Peek Composites," *The International Journal of Impact Engineering*, **26**, 381 – 398.