Electric Sail Tether Deployment System for CubeSats

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***Abstract*—An Electric Sail (E-Sail) propulsion system consists of long, thin tethers - positively-charged wires extending radially and symmetrically outward from a spacecraft. Tethers must be biased using a high-voltage power supply to ensure that the solar wind produces thrust. While the E-Sail concept shows great promise for flying heliopause missions with higher characteristic acceleration than solar sails, there are significant technical challenges related to deploying and controlling multiple tethers. A typical full-scale design involves a hub and spoke arrangement of 10 to 100 tethers, each 20 km long. In the last 20 years, there have been multiple space mission failures due to tether deployment and control issues, and most configurations involved a single tether.**

This paper describes an effort to develop and test a simple yet robust single-tether deployment system for a two-6U CubeSat configuration. The project included the following:
a) Tether dynamic modeling/simulation
b) E-Sail single-tether prototype development and testing
c) Space environmental effects testing to identify best materials for further development.
These three areas of investigation were needed to provide technical rationale for an E-Sail flight demonstration mission that is expected to be proposed for the 2022 timeframe.

The project team used an "agile" engineering approach in which E-Sail single-tether prototype designs were iteratively developed and tested to solve problems and identify design improvements. The agile approach was ideal for this low Technology Readiness Level (TRL) project because tether deployer development involved many unknowns in prototype development that could only be discovered through iterative cycles of construction and testing.

Extensive modeling and simulation were accomplished for three types of tether deployment:
a) Stage 1: propulsive separation with one 6U fixed
b) Stage 2: propulsive spin-up with one 6U fixed
c) Stage 3: propulsive spin-up with both 6Us free
Simulation results were valuable for understanding the propulsive and braking forces needed for controlled tether deployment.

This paper describes the evolution, insights, and test/performance data related to the resultant single-tether two-6U E-Sail test article which has been demonstrated in a test laboratory. The development effort suggests near-term work needed to achieve a useful flight demonstration, and provides ideas for how multiple-tether deployment systems might evolve going forward. A planned next-generation E-Sail prototype will include autonomous propulsive tether deployment while monitoring tether tension, location on the floor, distance between tether ends, acceleration, velocity, and propellant used.

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1. INTRODUCTION

The Electric Sail (E-Sail) propulsion system concept consists of positively-charged long thin wires extending radially outward from a central spacecraft. The wires or tethers must be biased using a high-voltage power supply such that thrust is produced due to the solar wind. The E-Sail concept shows great promise for achieving missions to the heliopause with higher performance (characteristic acceleration) than solar sail concepts. However, the E-Sail concept has significant technical challenges related to the deployment and control of numerous long thin wires or tethers.

The difficulty of deploying multiple tethers such that they do not tangle or touch each other is obvious, considering that a typical full-scale E-Sail design involves the use of tens to one hundred 20-km-long tethers in a hub-and-spoke architecture (Ref. 1 and Fig. 1). Additionally, there have been multiple mission failures involving tether deployment and control over the past 20 years. This project addresses the challenge of E-Sail tether deployment through development and testing of a robust and simple tether deployment system.

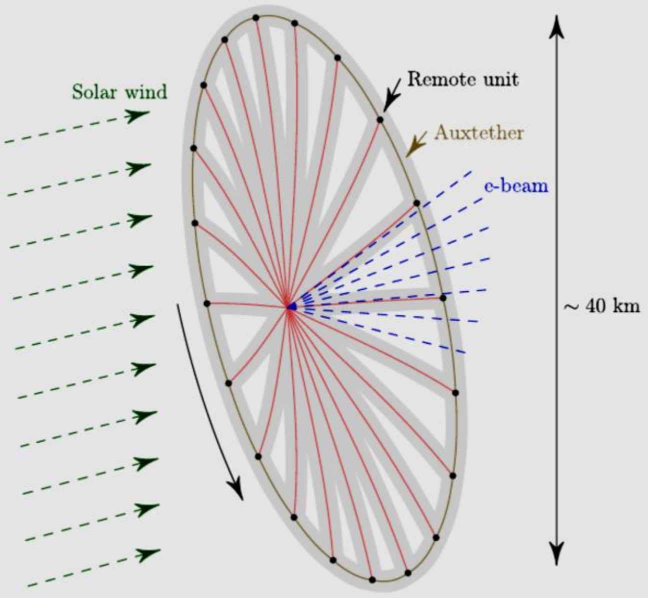


Figure 1. Electric Sail propulsion system concept (Ref. 1)

The approach followed in this project to develop a robust tether deployment system was to start with a single-tether, two-6U CubeSat configuration developed for a potential NASA Technology Demonstration Mission (TDM) project (Fig. 2). This paper describes (1) tether dynamic modeling/simulation by project partner Tennessee Tech University, (2) E-Sail single-tether prototype development and testing in the NASA Marshall Space Flight Center (MSFC) Flight Robotics Lab, and (3) space environmental effects testing of tether materials to help identify best materials for a demonstration mission. These three areas of work were needed to address technical challenges and work toward a flight demonstration mission for E-Sail.

An innovative agile engineering approach was utilized by the project team, where E-Sail single-tether prototype designs were iteratively developed through testing to solve problems and identify design improvements. The agile approach was ideal for this low Technology Readiness Level (TRL) project, since there were many unknowns in prototype tether deployer development that could only be discovered through iterative cycles of construction and testing. This approach has been successfully used in software development and low-TRL hardware development programs in government and industry.

2. TETHER DEPLOYMENT MODELING AND SIMULATION

Extensive tether deployment modeling and simulation were accomplished by project partner Tennessee Tech University, for the following cases for the single-tether, two-6U CubeSat E-Sail configuration:

- Stage 1: propulsive separation with one 6U fixed
- Stage 2: propulsive spin-up with one 6U fixed
- Stage 3: propulsive spin-up with both 6Us free

The tether would be propulsively deployed via cold gas thrusters from each CubeSat. When the system nears full deployment, thrusters on each CubeSat would deliver the radial component of thrust to begin the spin-up of the system and then pull the remaining tether out of the canister while keeping the tether in tension.

The simulations performed variation of deployment speed, tether tension, maximum angular velocity, and tether length at spin-up initialization. The propulsive force was 4.5N in all cases. Some of the simulation cases included frictional restraint applied to the tether during deployment by a brake device provided by project partner Tethers Unlimited, Inc.

Representative simulation results are presented in this section. Results were valuable for understanding the propulsive and braking forces needed for controlled tether deployment.

Stage 1: Propulsive separation with one 6U fixed

Stage 1 deployment time of 30 sec without abrupt (snatch) loading was the goal; case shown in Fig. 3 for 0.5 m/s and quadratic braking best achieved the goal.

Stage 2: Propulsive spin-up with one 6U fixed

For Stage 2, the maximum angular velocity achieved in 10 sec without abrupt (snatch) loading was the goal. The case in Fig. 4 for spin-up initiation at full deployment length and maximum angular velocity of 0.25 rad/sec best met the goal.

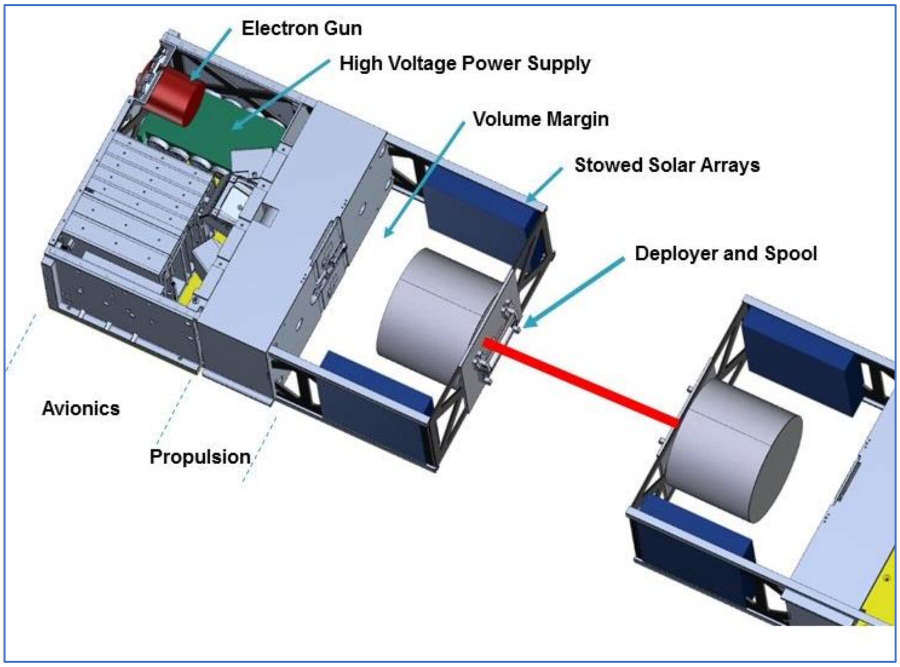


Figure 2. Single-tether, two-6U CubeSat E-Sail configuration (Ref. 2)

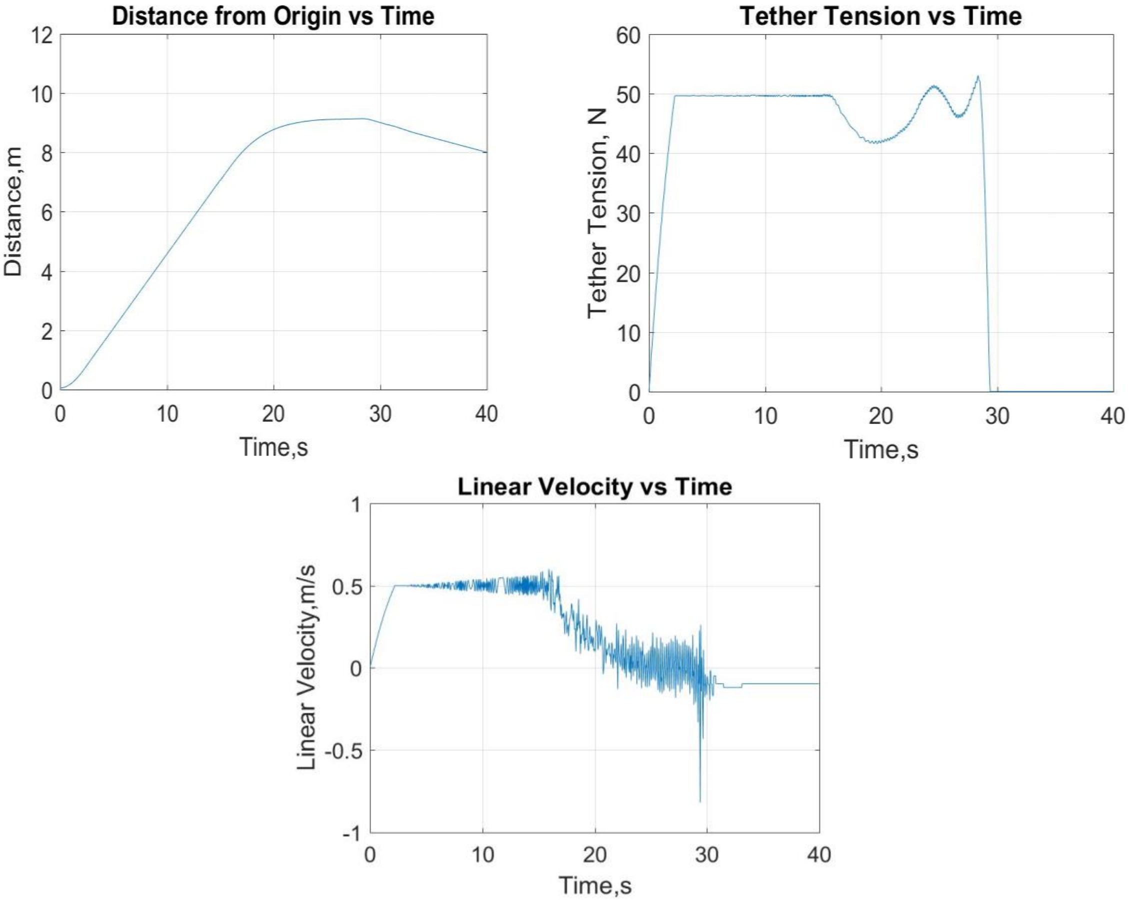


Figure 3. Stage 1 (propulsive separation with one 6U fixed) simulation results for tether deployment

Stage 3: Propulsive spin-up with both 6Us free

For Stage 3, the maximum angular velocity achieved in 10 sec without abrupt (snatch) loading was the goal. The case below for spin-up initiation at full deployment length and maximum angular velocity of 0.25 rad/sec best met the goal.

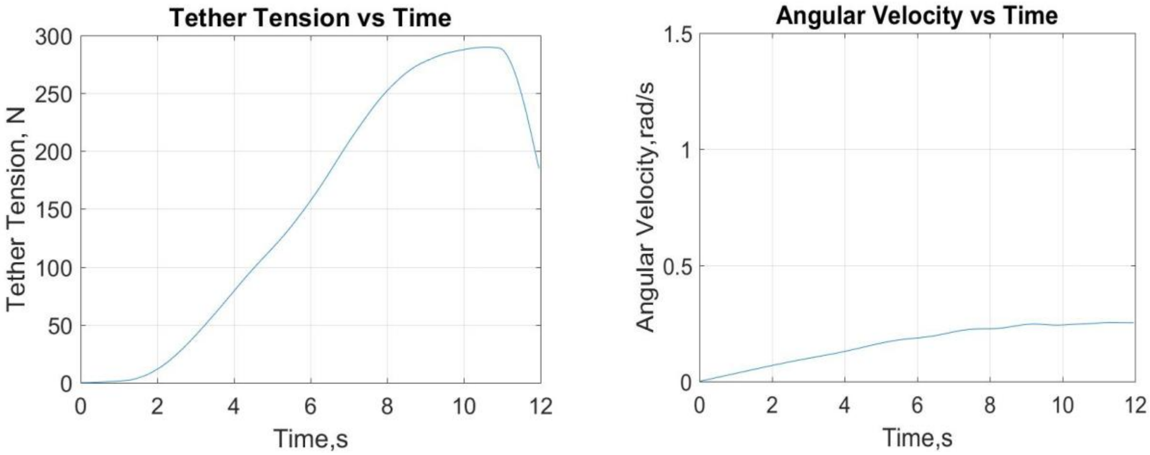


Figure 4. Stage 2 (propulsive spin-up with one 6U fixed) simulation results for tether deployment

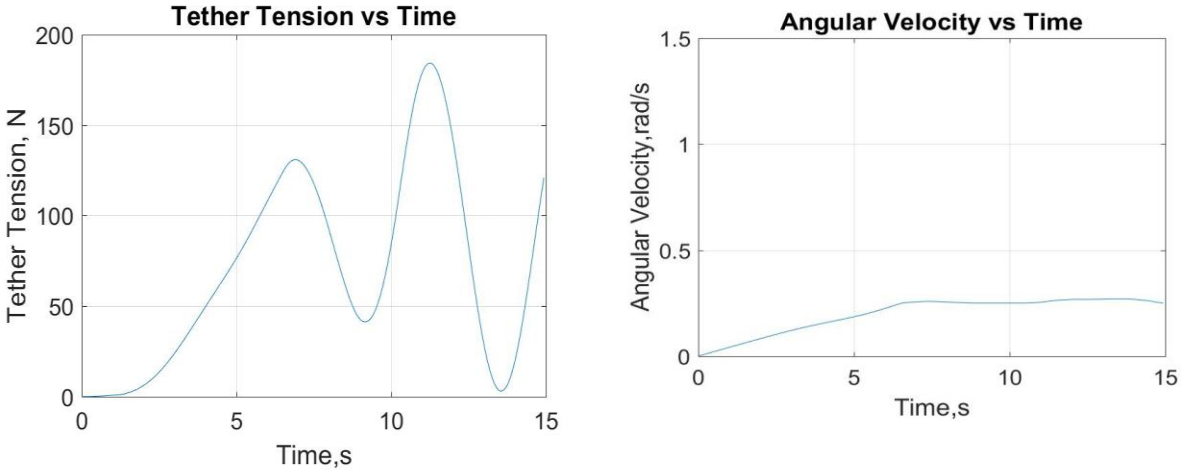


Figure 5: Stage 3 (propulsive spin-up with both 6Us free) simulation results for tether deployment

3. E-SAIL SINGLE-TETHER PROTOTYPE DEVELOPMENT AND TESTING

The project team accomplished breadboard prototype construction, assembly, and testing, utilizing an innovative agile engineering approach, where E-Sail single-tether prototype designs (Fig. 6) were iteratively developed through testing to solve problems and identify design improvements.

The team started with a simple mockup and progressed iteratively to advanced prototypes with tether deployer and brake, propulsion system, electrical components, and navigation components. Accomplishments included 3D printing of the prototype 6U frames, propulsion system (cold gas thruster) design using computational fluid dynamics (CFD) and computer aided design (CAD) tools, electrical design, software development, and overall system integration.

Demonstration testing of the breadboard prototype was successfully accomplished in the MSFC Flight Robotics Lab. The team continued to utilize an agile engineering approach to make improvements to the breadboard prototype based on test results:

- Added battery powered pumps to increase testing time on the Flight Robotics Lab floor compared to CO2 tanks alone
- Added a control bar to 6U prototype to prevent rotation of prototype during tether deployment

Testing of the breadboard prototype is shown in Fig. 7.

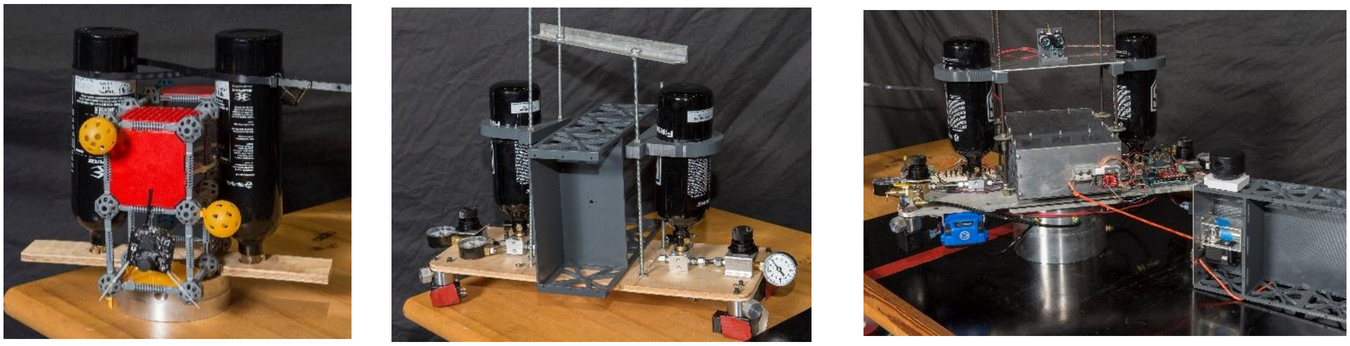


Figure 6. E-Sail prototype test articles (left to right: initial mockup, intermediate article, and improved design)

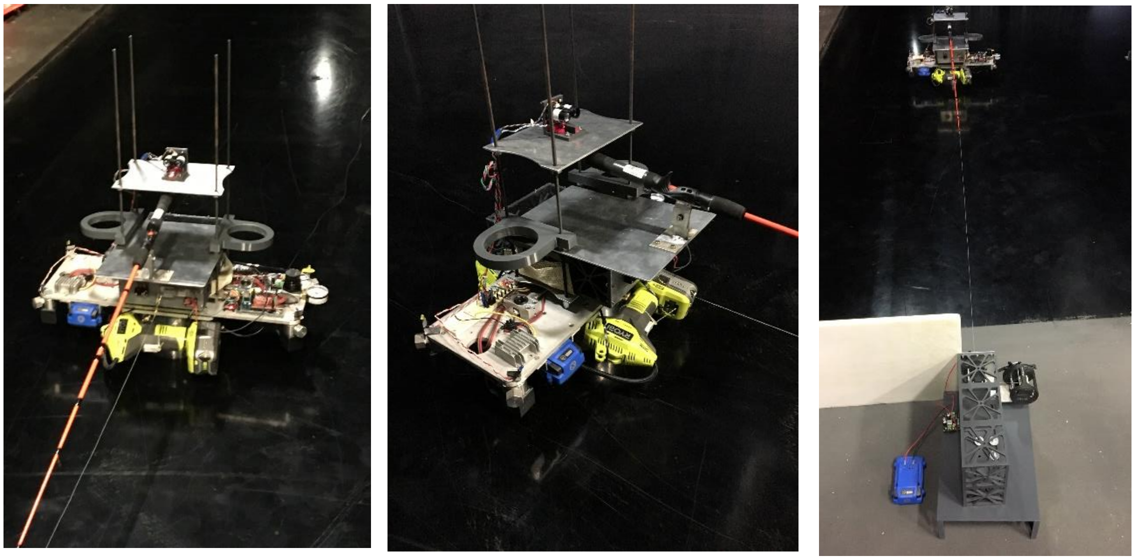


Figure 7. Demonstration testing of the E-Sail breadboard prototype in the MSFC Flight Robotics Lab

4. SPACE ENVIRONMENTAL TESTING OF TETHER MATERIALS

The next area of work for E-Sail accomplished in this project was space environmental testing of tether materials. The objective of the tether materials study was to understand which materials would be conductive enough to meet the requirement of the proposed E-sail propulsion system. The project objective would be met by measuring electron current collection by the material in a flowing plasma environment and comparing those results to the current collection of a stainless steel tether sample. It is known that stainless steel is a good conductor without the risk of an oxide layer, and any differences between the two samples would be attributed to the material resistivity and not the plasma. The test setup in the vacuum chamber is shown in Fig. 8, and the tether materials tested are shown in Fig. 9.

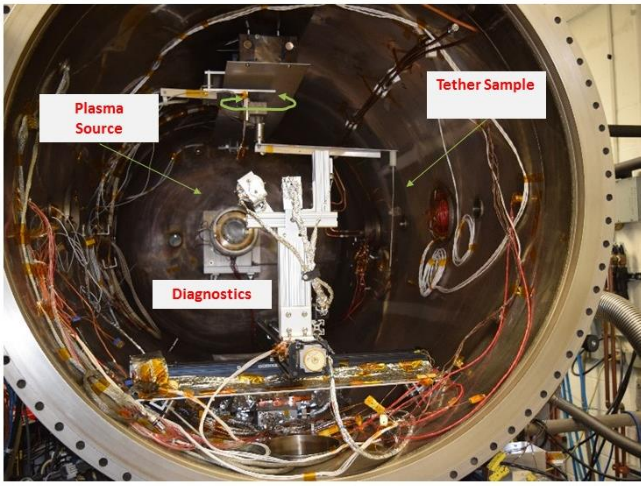
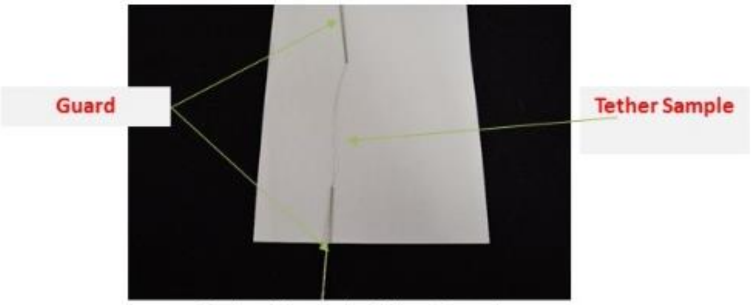


Figure 8. Tether materials test setup in space environmental effects chamber

Stainless Steel (SS) Reference Material

Amberstrand Tether Sample



Carbon Nanotube Tether Sample

Figure 9. Tether materials tested in space environmental effects chamber

Three different tether materials were tested:

- Stainless Steel (Plasma Reference)
- Amberstrand-Z-66-Ag silver-clad Zylon material
- Carbon nanotube tether

The test approach was to measure electron current collection to tether material at three different ion flow velocities, measure electron current collection while varying a positive bias from 0V to 400V, normalize electron current collection data to the random thermal electron current calculated based on the plasma properties measured using the Langmuir Probe (eliminate error based on the tether collection area (i.e. diameter and length)), and normalize the applied tether bias using the electron temperature measured with the Langmuir Probe (eliminate error from plasma source variations).

Electron collection tests on the three different potential tether materials were completed, and results of the study showed no difference in electron collection between stainless steel and Amberstrand while biased in a plasma. Based on these tests, Amberstand is an excellent tether candidate for an E-sail propulsion system because it has excellent conductivity in a plasma. The data comparison for Amberstrand and stainless steel is shown in Figure 10.

5. SUMMARY

This paper described successful developmental efforts for a single-tether Electric Sail deployment system for a future flight demonstration mission. Work included (1) tether deployment modeling and simulation for propulsive linear and spin-up separation, (2) single-tether prototype development and testing through an iterative agile engineering approach, and (3) space environmental testing of tether materials.

Results showed that engineering development of the E-Sail tether deployment system can be completed in the near term for a single-tether flight demonstration, that the agile approach works well for maturing low-TRL hardware, and that Amberstrand has great potential for use as the E-Sail tether material.

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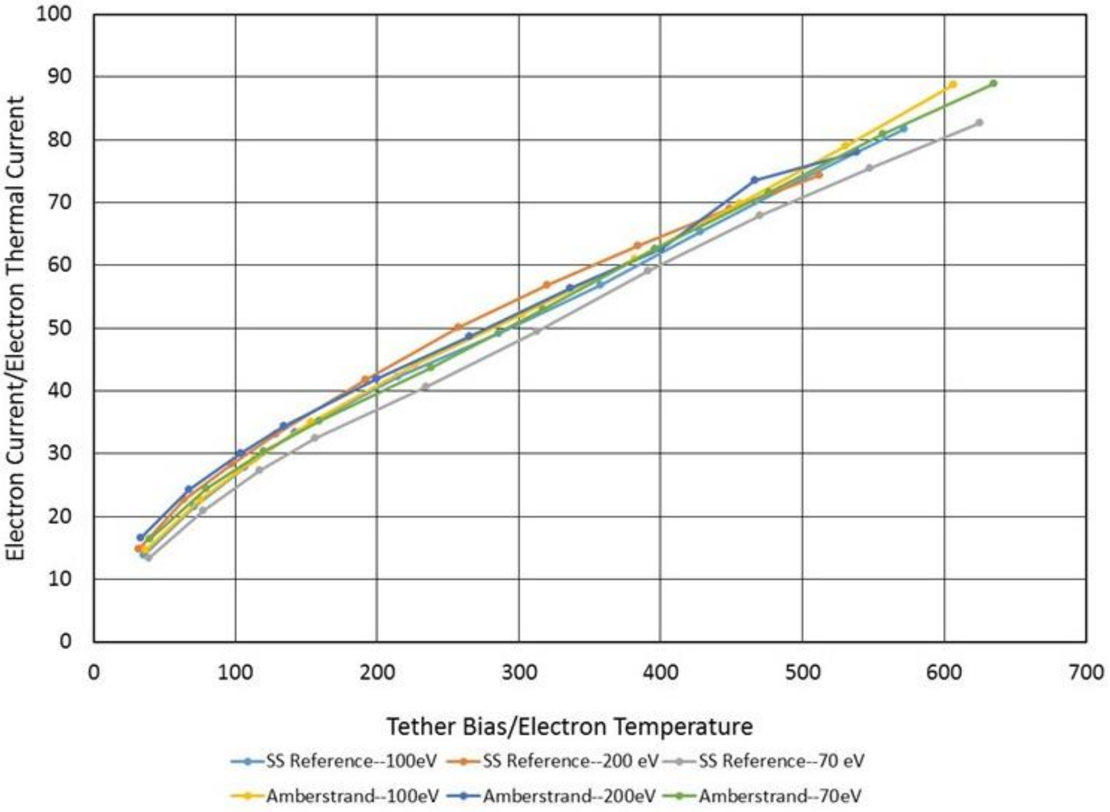

Figure 10. Tether materials test results for Amberstrand and stainless steel (SS)