PLASMA INTERACTIONS WITH A NEGATIVE BIASED ELECTRODYNAMIC TETHER

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Abstract

The ProSEDS conductive tether design incorporates two distinct types of tethers from a plasma interaction viewpoint. The 200 m closest to the Delta II spacecraft is insulated from the plasma, and the remaining 4800 m is semi-bare. This latter portion is considered semi-bare because a conductive coating, which is designed to collect electrons from the plasma, was applied to the wires to regulate the overall tether temperature. Because the tether has both insulating and conductive tether sections, a transition point exists between the two that forms a triple point with the space plasma. Also, insulated tethers can arc to the space plasma if the insulation is weakened or breached by pinholes caused by either improper handling or small meteoroid and orbital debris strikes. Because electrodynamic tethers are typically long, they have a high probability of these impacts. The particles, which strike the tether, may not have sufficient size to severe the tether, but they can easily penetrate the tether insulation producing a plasma discharge to the ambient plasma.

Samples of both the ProSEDS tether transition region and the insulated tether section with various size of pinholes were placed into the MSFC plasma chamber and biased to typical ProSEDS open circuit tether potentials (-500 V to –1600 V). The results of the testing showed that the transition region of the tether (i.e. the triple point) arced to the ambient plasma at –900 V, and the tethers damaged by a pinhole or simulated debris strike arced to the plasma between –700 V and –900 V. Specific design steps were taken to eliminate the triple point issue in the ProSEDS tether design and make it ready for flight. To reduce the pinhole arcing risk, ProSEDS mission operations were changed to eliminate the high negative potential on the insulated tether. The results of the testing campaign and the design changes implemented to ensure a successful flight are described.

Introduction

ProSEDS is an electrodynamic (ED) tether mission designed to fly as a secondary payload on a DELTA II Global Positioning System (GPS) satellite, and demonstrate electrodynamic thrust as a potential propellant less propulsion application. After the primary GPS payload is placed in its orbit, the Delta II second stage fires to place ProSEDS in a near circular orbit with an altitude of about 275 km. The Delta II will then begin the ProSEDS mission by turning on the ProSEDS computer, which will control the payload for the remainder of the mission. The signal to release the endmass and deploy the tether comes from the Delta II once the stage has established the correct orientation. After the tether has been deployed ProSEDS will begin what is expected to be approximately a 1-day mission.

ProSEDS consists of two separate hardware platforms, the Instrument Panel (IP) hardware and the Deployer side hardware. Both of these platforms are diametrically opposing each other around the Delta II bellyband. The IP hardware consists of a 10 A rated hollow cathode plasma contactor, primary battery, secondary battery, Power Distribution Box (PDB), a Langmuir Probe Spacecraft Potential (LPSP) electronics box, Differential Ion Flux Probe with Mass (DIFP/M) electronics box, and transmitter. The LPSP and DIFP/M probes are mounted on the Delta II struts[1]. The Deployer side hardware consists of an on-board computer called the Data System Electronic Box (DSEB), tether and deployer hardware, both a GPS receiver and antenna, and a student built endmass. The deployer hardware includes the tether canister, which housed the tether, brake mechanism, and the High Voltage Control and Monitor (HVCM) box to switch the tether in and out of the electrical circuit. The deployer side hardware closely resembles the design of the old Small Expendable Deployer System (SEDS)[2].

ProSEDS on orbit operation is to begin with the tether deployment and slowly bring the instruments on-line after tether deployment. Once the entire payload is operating, the primary mission would begin and last about five orbits due to primary battery life. These first five orbits ensure ProSEDS of at least five orbits of data, which is sufficient to meet all primary objectives established for the experiment. After the five orbits, the extended phase begins. The extended mission phase operates off the secondary battery, and during this time ProSEDS attempts to regulate the charge of the secondary battery using the current collected by the tether. During normal operation, the system is designed to both open and close the tether circuit to collect background plasma data. This data is needed for further model development of ED tether propulsion.

The ProSEDS tether, shown in Figure 1, is a 15 km long tether, and consists of a non-conductive ballast tether and a conductive ED tether. The ballast tether is attached to the endmass using a 20 m Kevlar leader designed to withstand the exhaust plume of the Delta II motor firing. The Kevlar leader is attached to the 10 km non-conductive Dyneema section, which is designed with sufficient length to overcome the friction force generated by the ED tether as it exits the deployer canister. The non-conductive tether is attached to the conductive tether using a special Kevlar to Dyneema splice. This splice is designed to prevent the metallic wire of the conductive tether from coming in contact with the Dyneema due to its low melting point.

The conductive tether has two distinct sections that have unique purposes during the mission. The conductive tether is designed to collect the ionospheric electrons on the semi-bare portion of the tether to evaluate the effectiveness of the bare tether current collection, which was proposed by Sanmartin[3]. The insulating tether enables the ProSEDS scientists to open circuit the tether and measure the tether open circuit tether voltage. Computer simulations of the 5000 m ED tether, which include its late mission dynamics, have predicted the maximum open circuit tether voltage to be almost –1400 V.[4] This prediction is to be verified using on orbit data.

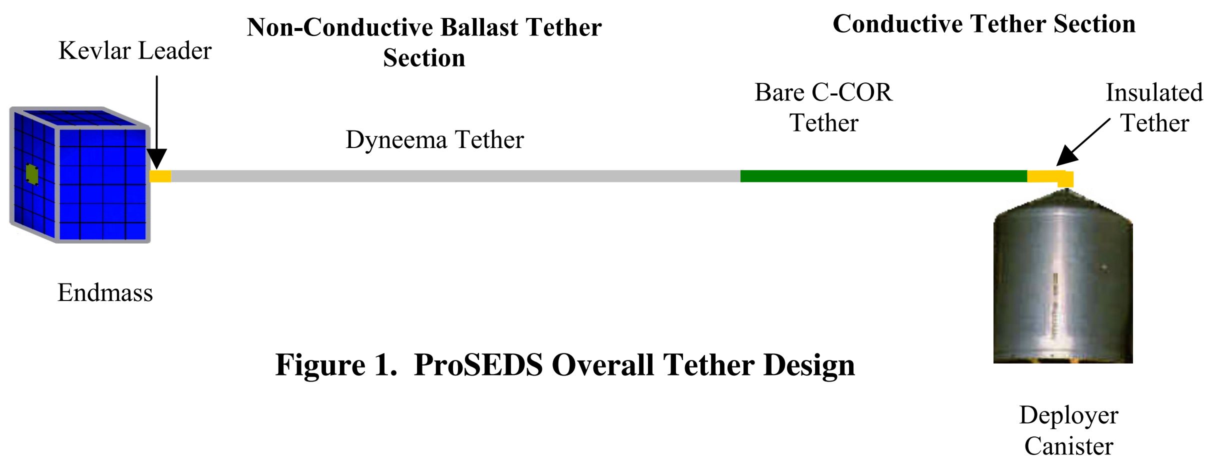

Figure 1. ProSEDS Overall Tether Design

The conductive tether consists of a 4800 m semi-bare tether and a 200 m insulated section. The entire conductive tether is made up of seven individually coated 28 AWG aluminum wires. The coating used for the semi-bare tether is an electrically conductive atomic oxygen resistant polymer, conductive colorless oxygen resistant (C-COR), specifically designed for the ProSEDS mission. The insulating coating consists of two distinct layers, triton oxygen resistant (TOR) and polyimide.[5,6] TOR is an atomic oxygen resistant polymer, which protects the main dielectric layer, the polyimide. Finally, the insulated tether is then over braided with Kevlar for abrasion protection during tether deployment.

An independent high voltage assessment of the entire ProSEDS system was performed early on in the program.[7] In that assessment two items of concern specifically related to the tether were identified. The items were: 1) The triple point at the junction between the bare and insulated tether, and 2) The triple point produced at the junction between the bare and the non-conducting tether interface. Also, early on in the ProSEDS tether design, the importance of maintaining the integrity of the insulating coating was recognized based on past history with TSS-1R where a breach in the insulation led to an electrical discharge event which severed the tether.[8] During all testing and handling with the flight tethers every effort was taken to maintain and verify the insulation integrity using a spark test. The two triple points identified in the high voltage assessment are located at two very different points on the tethers both physically and electrically. The first triple point, which is at the transition between the semi-bare tether and the insulated tether, is located very close to the Delta II, and it will see very high negative potentials during tether open circuit. Whereas the second triple point is located at the end farthest from the Delta II stage, and during open circuit it will experience mostly high positive voltages.

The three potential tether interactions with the LEO plasma were investigated in plasma chamber testing at MSFC, and where problems existed design changes were implemented. The plasma chamber tests focused on the transition between the semi-bare conductive tether and the insulated tether and on the effects of pinholes in the insulated tether. The transition between the conductive tether and non-conductive tether does not experience negative potentials, so it was not tested at these potentials. However, a single test was done at positive potentials on the transition between the conductive and non-conductive tethers. The results of these investigations are discussed, and the required design changes described.

Plasma Test Chamber Set-Up

The ProSEDS tether sections were placed in a 1.2 m diameter and 3 m long cryo-pumped vacuum system. The chamber was capable of a base pressure in the low 10^{-6} Torr, and mid 10^{-5} Torr with the hollow cathode plasma source running. A photograph of the internal chamber set-up for these tests is shown in Figure 2. The hollow cathode source can operate on any noble gas, but for these tests argon was used except for one test that utilized nitrogen. The plasma source is designed to deliver cool diffuse plasma to the sample location with an electron temperature of 0.5 to 2 eV and plasma density of $5x10^5$ to $2x10^6$ cm^{-3}. The plasma chamber contained a spherical Langmuir probe with an overall diameter of 2.5 cm to verify plasma conditions before and after testing.

A 2 m long tether sample was placed in the plasma chamber diagonally across the vessel so that the center of the sample under test was directly in line with the hollow cathode plasma source about a meter away. Later a second sample was added to the setup by placing one sample eight inches below the other sample. In this case, both samples were equally spaced from the centerline of the hollow cathode source. One sample was allowed to float while not under test eliminating it from interacting with the other sample during testing. The 2 m long tether sample was supported by a specially designed sample holder, which was insulated from ground and allowed the tether to make electrical contact to a high voltage power supply. The electrical contact required a Faraday cage to prevent plasma from coming in contact with the connection because the electrical connection produced its own triple point with the plasma.

The overall electrical circuit for studying the effects of the tether in a plasma is shown in Figure 3. The tether sample was connected to the high voltage power supply through a high power 250 Ω load resistor. The load resistor was used to simulate the resistance of the tether. However, the load resistor was divided into five resistive segments of 50 Ω each in an attempt to more closely simulate the distributed tether resistance. The power supply was controlled manually from the front panel, and a separate data acquisition computer recorded both tether current and voltage data during the test via the analog output on the back of the power supply.

The procedure for testing each tether sample was the same with the ultimate goal of meeting the design requirement of –1800 V. The –1800 V limit was determined based on the worst case open circuit tether voltage (~ -1400 V) and providing a small 30% factor of safety.

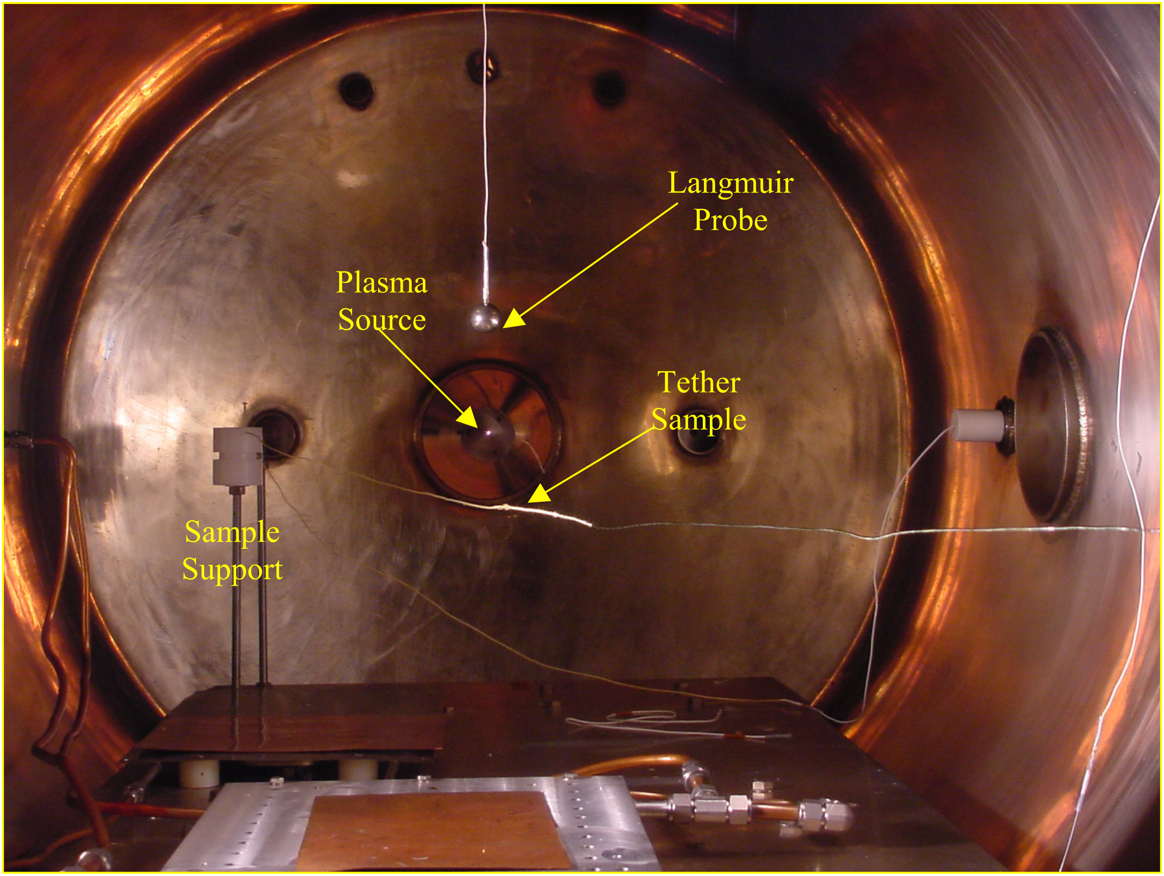

Figure 2. ProSEDS High Voltage Plasma Interactions Internal Chamber Set-Up

The sample or samples were placed in the plasma chamber and pumped down overnight to ensure a good hard vacuum. Starting chamber pressures were typically around 1-2 x10^{-6} Torr. Each test was started by turning on the plasma source and allowing it to come to thermal equilibrium. The voltage was set at -100 V and held for at least two minutes. The tether voltage was decreased in -100 V increments until the sample either arced to the plasma or passed the –1800 V limit.

Triple Point at The Semi-Bare Conductive Tether and Insulated Tether Transition

The most volatile triple point condition was found to be at the transition between the semi-bare (C-COR coated) conductive tether and insulated tether transition splice because this tranisition will experience the highest negtaive potentials. That particular transition is shown in the schematic in Figure 4. At this transition the tether is being transitioned from the conductive C-COR coated wire to the insulated wire by cold welding or butt welding the two diffent coated wires together and the central Kevlar core is changing size. The butt welding process is a process that joins two aluminum wires together without any heating. This is accomplished by using an off-the-shelf product that cold flows the aluminum wire together. This process worked extremely well because the coatings were relatively thin (~0.01 mm to 0.03 mm) compared to the wire diameter (0.32 mm), and the butt weld joints turned out to be stronger than the virgin aluminum wire. The butt welds were staggered over 7-10 cm to ensure that the butt welds would lay nicely in the tether volume. However, a by product of the cold welding process were sharp aluminum flanges that circled the butt welds. Every attempt was made to remove these flanges using a special cutting tool. Yet it was still difficult to make sure the joint was perfectly smooth. Also, a transition in the Kevlar core was necessitated by differences in the diameters of the two wire types (.i.e. 0.34 mm for the bare conductive wire and 0.39 mm for the insulated wire). This required a Kevlar coresplice which took place about 60-80 cm from the location of the butt welds. In order to protect the entire transition region the Kevlar overbraid, which was initally designed to protect the insulated wire, was extended over the region containing both the butt welds and the coresplice.

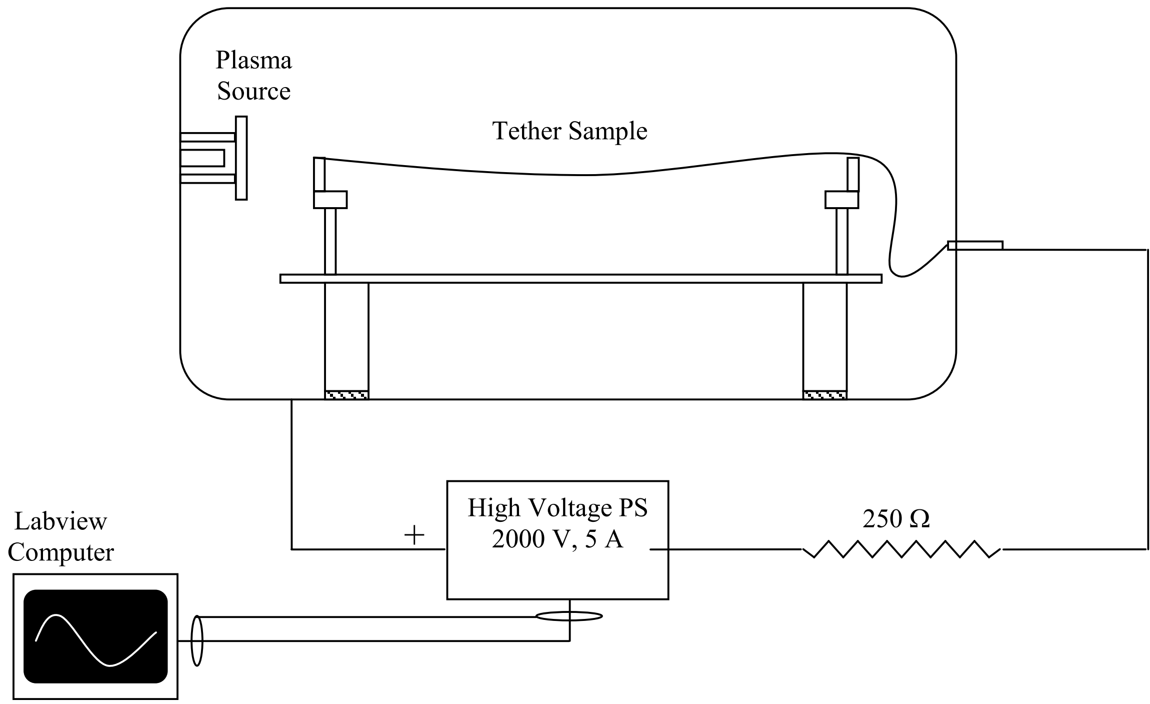

Figure 3. Tether High Voltage Test Schematic

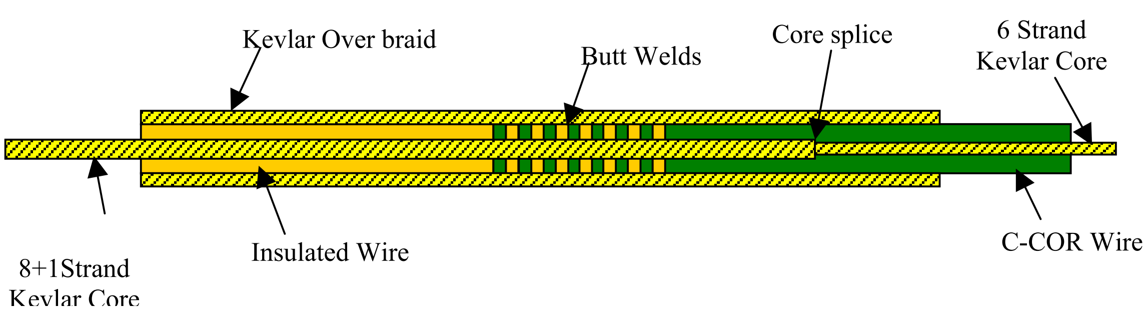

Figure 4. ProSEDS as Designed Conductive Tether to Insulated Transition

During the fabrication of the three ProSEDS flight tethers (F1, F2, and F3) extra conductive to insulated tether splices were made for post process testing. Some were used for strength testing while others were used for plasma testing. One of the samples created during the F2 processing was specifically used for triple point evaluation. The F2 transition sample was placed into the plasma chamber and the standard procedure followed. At –900 V bias the sample initiated ~3.5 A discharge which sustained for about 20 s. At that point the tether separated and the charged end landed against the chamber wall and continued to discharge until the power supply was turned off. Figure 5 shows the data collected during this test. The blue circle data points represent the power supply voltage in kilovolts and the square red data points represent the current draw from the power supply. It is believe that the large current from the arc is being fed from the power supply in the lab, but is being limited by the power resistor in line with the supply. However, the electrical circuit as close to reality as possible and on-orbit currents of this magnitude with an operating plasma contactor were predicted. Post-test evaluation showed that the arc was initiated at the triple point caused by the plasma interface with the conductive tether transition region. Figure 6 is a photograph of the intense plasma discharge started and sustained when the triple point ignited in the plasma chamber.

Once it was demonstrated the ProSEDS tether design had a triple point design problem, several materials and potential solutions were tested to find a solution that eliminated the problem. The solutions focused on two particular areas. The first area of concern was to eliminate the sharp electric field change at the triple point by adding semi-conductive materials over that transition region, and the second area of concern was to focus on the sharp butt weld flanges. Four different materials, Aracon (i.e. nickel plated Kevlar), carbon loaded Kapton®, carbon loaded cotton, and Aerodag-G graphite spray, were tested as potential semiconductor material candidates. These materials were chosen because they met the basic requirements which were the material had to be easy to apply to the tethers, it had to be conductive, and it could not react adversely with the existing tether materials.

The results of the plasma chamber tests on the material design changes on the ProSEDS conductive tether triple point are detailed in Table 1. Of the materials detailed in Table 1 only one material, Aerodag-G, successfully passed the plasma chamber test at -1800 V. Aracon® did show surprising improvement over the initial transition design. The other materials did not show significant improvement or even made the situation worse.

The second problem of softening the butt weld flanges was done by attempting to wrap Teflon tape around the butt welds then over wrapping the entire 7-10 cm long transition with a contiguous Teflon tape wrap. This type of design successfully passed initial plasma chamber testing. However, when the transition region was put through a simulated deployment test, the cold weld flanges punctured through the Teflon exacerbating the problem (see Table 1). The final solution was to add the Aerodag-G spray to both underneath and on top of the over braid and to shorten the length of the over braid. Then Aerodag-G was applied from the over braid beyond the butt welds into the C-COR region. Figure 7 depicts the new conductive tether transition region, which eliminated the triple point from the tether design. The integrity of the transition was verified by completing both five simulated tether deployments and exposure to 6 days of on orbit atomic oxygen. Each of these samples was then subjected to a successful plasma chamber tests.

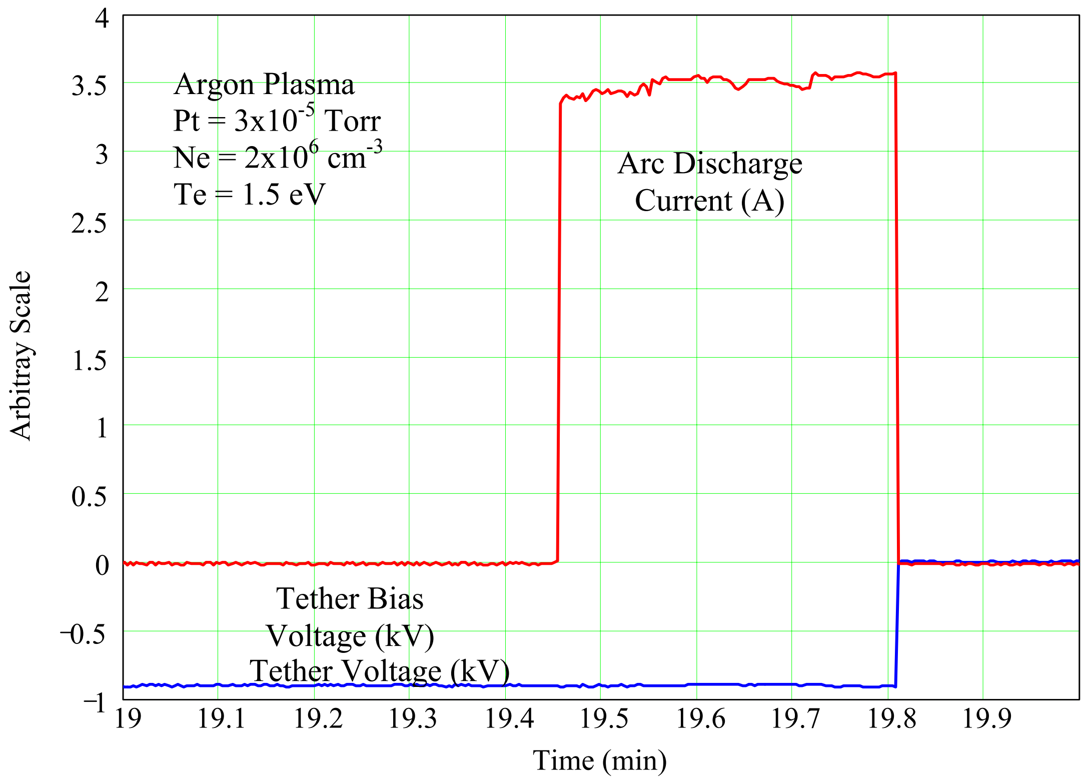

Figure 5. Current and Voltage Data Due to ProSEDS Conductive Tether Triple Point Discharge

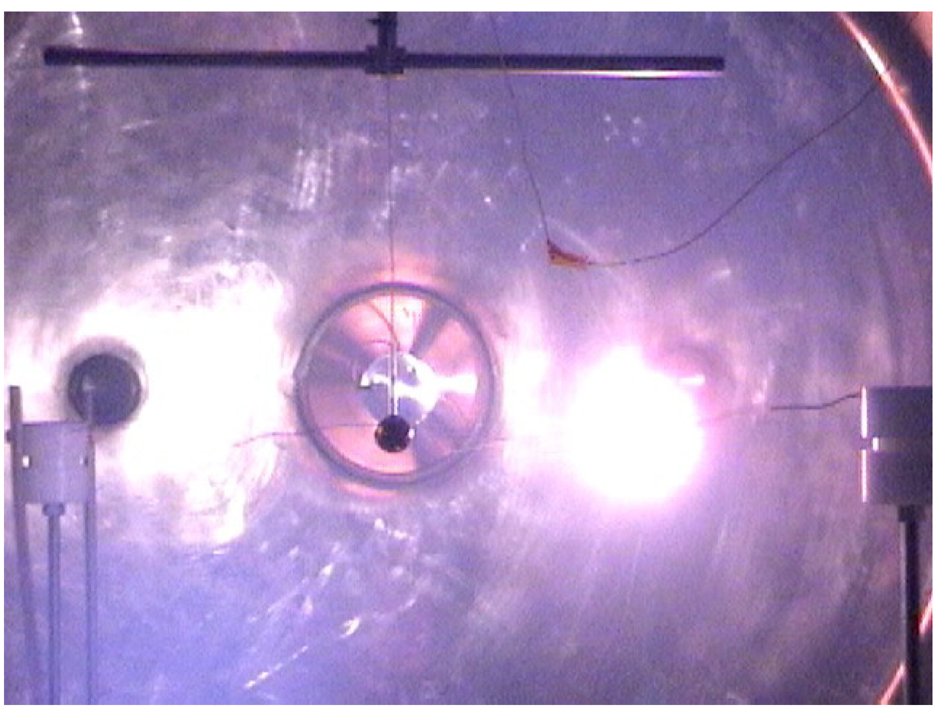

Figure 6. Photograph of ProSEDS Conductive Tether Undergoing Plasma Discharge

Table 1. ProSEDS Tether Triple Point Test Summary

Sample Description	Breakdown Voltage (V)	Chamber Pressure (Torr)	Test Summary
F2 Sample Transition	-900 V	$4x10^{-5}$	The failure occurred at the intersection of the conductive C-COR and Kevlar over braid.
F2 Simulated Tether Transition w/ Aracon®	-1500 V	$5x10^{-5}$	The sampled failed at -1500 V, about 1” from the end of the Metal clad Kevlar.
F2 Simulated Tether Transition w/ carbon loaded cotton fibers	-1000 V	$4x10^{-5}$	The sample failed at -1000 V, but began arcing at -700 V.
F2 Simulated Tether Transition w/ Teflon tape wrap on butt-welds	-1400	$5x10^{-5}$	The sample failed at –1400 V
F2 Simulated Tether Transition w/ carbon loaded Kapton (resistance of 18 kΩ).	-500	$5x10^{-5}$	The sample failed at –500 V
F2 Simulated Tether Transition w/ Aerodag-G and Teflon Tape on Butt-Welds	-1800+	$6x10^{-5}$	The sample passed the design voltage at –1800 V
F2 Simulated Tether Transition w/ Aerodag-G and Teflon Tape on Butt-Welds After simulated tether deployment	-1000	$6x10^{-5}$	The sample began arcing as early as –1000V.
F2 Simulated Tether Transition w/Aerodag-G	-1800+	$6x10^{-5}$	The sample passed the design voltage at –1800 V
F2 Simulated Tether Transition w/Aerodag-G which had undergone 5 simulated deployments	-1800+	$6x10^{-5}$	The sample passed the design voltage at –1800 V
F2 Simulated Tether Transition w/Aerodag-G which had been exposed to 6 days atomic oxygen exposure	-1800+	$6x10^{-5}$	The sample passed the design voltage at –1800 V

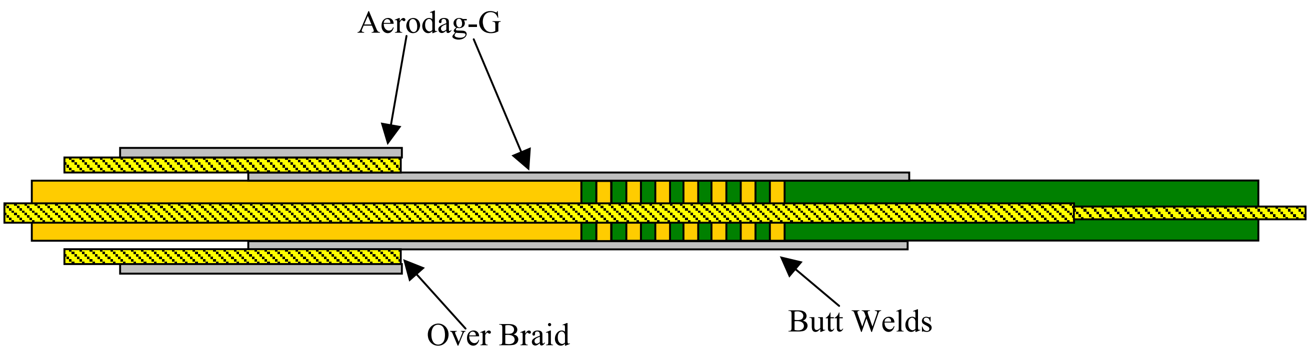

Figure 7. ProSEDS Tether Triple Point Mitigation Design

Plasma Interactions with Pinholes in ProSEDS Insulated Tether

Several tests were conducted on the insulated ED tether to investigate the interactions between small nicks in the tether caused by either ground handling or micrometeoroid and orbital debris impacts and the ambient plasma. Various methods were used to try and simulate the damage caused by either ground handling or debris impacts. It was recognized from the start that if damage was caused on the ground, it would manifest itself as a tiny insulation nick either caused by a cut or cracking of the insulation. However, an orbital debris impact could potentially do more damage by exposing completely severed wire strands. Every attempt was made to quantify the effects of these two different scenarios. Plasma chamber testing was done on both samples with small cuts and samples with wires that have been intentionally cut. This range of damage should bound the potential problem for ProSEDS. During the plasma chamber testing only negative bias potentials were applied, because the insulated section is located in a region where high negative potentials are expected.

The results of this investigation are detailed in Table 2. The main objective was to determine if the ProSEDS tether was at risk to an arcing event. A small cut was made in the insulation of a tether sample, which was verified with a digital multi meter (DMM) during the procedure. The sample was placed in the plasma chamber and biased using the standard procedure. The initial test did not show a problem, but there was some question as to weather the cut closed after the knife was removed, so a spark test at 3000 V was performed. The spark test is a standard test found in all electric cable manufacturers to look for holes in the insulation before shipping the product. During a spark test the wire is passed through a bead electrode, which is biased at the corresponding voltage. When a fault is present, an arc is produced. Because of the arc generated, the spark test is a destructive type test. The spark test verified the cut in the insulation. This sample was tested in the plasma chamber and a breakdown threshold of –900 V was measured. The difference between these two test results is likely the damage done by the spark test which likely enlarged the nick. The results of this tested verified that a nick in the tether insulation could cause a problem, but it did depend on the size of the nick.

Several methods were attempted to simulate the effects of orbital debris impacts short of having an actual impact test done. The method that was repeated on various samples was simply cutting the wires and either leaving the wire inside the over braid or pulling the cut end outside. It was thought that during a debris strike the wire outside the over braid was a more plausible scenario as the over braid would likely be damaged during the impact. All simulated orbital debris tests where at least one wire was cut experienced electrical breakdown between -700 V and -1300 V. Because the insulated tether is expected to be at this potential during most open circuit periods, the ProSEDS tether has a design problem. Solutions to this problems could be design changes or to eliminate the open circuit period. Before any changes were made to either the tether design or ProSEDS operation, one last test was done to see if the chamber pressure of mid 10^{-5} Torr had a significant effect on the voltage breakdown thresholds. A test at mid 10^{-6} Torr pressures was proposed to determine the overall effect.

Table 2. ProSEDS Insulated Tether Pinhole Test Summary

Sample Description	Breakdown Voltage (V)	Chamber Pressure (Torr)	Test Summary
Small Pinhole in Insulated Tether, verified with DMM.	-1800+	$5x10^{-5}$	Sample passed the design voltage of –1800 V.
Insulated tether with Small pinhole arced at 3000 V in the spark tester several times.	-900 V	$5x10^{-5}$	At –900 V the sample broke down and burned the tether in half.
Insulated tether with knife cut; Aerodag applied along the length of the sample.	-700 V	$5x10^{-5}$	At –700 V the sample broke down and burned the tether in half.
Simulated debris hit; two wires intentionally cut.	-700 V	$5x10^{-5}$	At –700 V the sample failed.
A piece of insulated tether with two of the seven strands of wires intentionally cut.	-800 V	$6x10^{-6}$	The sample discharged at –800 V drawing a current of 1.5 A based on the supply current limit.

A titanium sublimation pump was added to the chamber to add extra pumping capacity of the neutral gas. In order to make the most efficient use of the titanium pump, the plasma source working gas was switched to nitrogen. When a piece of insulated tether, which had two of the seven strands cut, was placed in the plasma chamber and tested, the sample broke down at -800 V. When compared to the previous sample which had two wires cut yet the chamber pressure was mid 10^{-5} Torr, the breakdown voltage was only –100 V better. The results of this test indicated that a potential failure mode existed when an orbital debris hit the tether cutting at least one wire. A calculation of the probability that an orbital debris particle large enough to sever a single wire in the short 200 m insulated tether was done, and the probability that the insulated tether could sustain an arc inducing debris impact was about 13% per day[9]. This probability was higher than the accepted probability of 4 % per day that the entire tether will sustain a debris impact to sever the tether.

The potential corrections to the insulated tether centered on either changing the overall tether design or the ProSEDS operational scenario. Because the changes to the tether design were going to be extremely costly in terms of cost and schedule, the operational timeline was changed. Initially, the tether was going to be in open circuit mode every 30 s the entire mission. Due to the potential debris induced arc event, the operational timeline was changed to allow open circuit mode every 30 s for only the first five orbits. After that point in time, the tether would no longer be allowed to enter the open circuit mode. The proposed operational change allowed scientists some time to collect needed data, though it reduced the total data set. The operational change reduced the probability of a debris particle impact large enough to cause an electrical breakdown to about 4% per day. This level of risk was equivalent to the risk accepted by the project early in the design phase.

ProSEDS Conductive Tether to Non-Conductive Tether Transition

The ProSEDS conductive tether to non-conductive tether transition did not show as volatile nature as the other transition. This is because this transition is biased at high positive potentials during open circuit. Because of the negative voltage potential did not exist, only a high positive potential was considered. The transition was placed into the plasma chamber and tested following the standard procedure, and it did not demonstrate any problems from 0 to +1500 V.

Summary

The ProSEDS tether design includes an insulated tether and a semi-bare conductive tether. The transition between the two creates a triple point with the ambient plasma. Plasma chamber testing of this transition region demonstrated electrical breakdown of -900 V, which was below the -1400 V design potential. Four semi-conductive materials were evaluated for use in reducing the electric field change at this point. Once the Aerodag-G spray was incorporated into the tether design, the tether passed all plasma chamber tests eliminating the triple point concern. The new tether design also passed both simulated deployment tests and six days on orbit of simulated atomic oxygen exposure. The ProSEDS insulated tether samples, which contained simulated orbital debris damage experienced plasma discharge between -700 V and -800 V. The cost of changing the tether design forced an operational change that eliminated the tether open circuit mode after the first five orbits. Finally, no plasma effects were measured at the remaining triple point at the conductive tether to non-conductive tether transition because it will only experience high positive tether potentials.

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