

An Experimental Study of Carbon Nanotube Field Emission Cathodes for Electrodynamic Tethers

IEPC-2005-104

Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005

Yasushi Okawa^{*}, Shoji Kitamura[†], Satomi Kawamoto[‡]
Japan Aerospace Exploration Agency, Chofu, Tokyo, 182-8522, Japan

Yasushi Iseki[§], Kiyoshi Hashimoto^{**}, and Etsuo Noda^{††}
Toshiba Corporation, Fuchu, Tokyo, 183-8511, Japan

Abstract: An experimental investigation of a carbon-nanotube field-emission cathode (FEC), which is suitable as an electron emitter in an electrodynamic tether propulsion system, was conducted. One of the important issues in the design of FEC is to suppress an electron flow to a gate electrode to avoid thermal deformation of the electrode and to reduce power loss. For meeting this requirement, we designed an FEC device having a masking plate on a cathode surface. A numerical simulation indicated that presence of the masking plate distorts the electric field adjacent to the cathode surface and a converged electron beam that does not impinge on the gate electrode is formed. Several FEC devices were fabricated based on the simulation results, and they were tested experimentally. Results indicated that no electron current flowed to the gate electrode when the gate electrode and the masking plate were assembled and aligned correctly. In addition, an endurance test showed that degradation of an emission current after 26-hour operation was less than 10%.

Nomenclature

J_a	=	Anode current
J_e	=	Emission current
J_g	=	Gate electrode current
V_a	=	Anode voltage
V_g	=	Gate electrode voltage

I. Introduction

It has been widely recognized that space debris is becoming a serious problem to our space activity. In order to keep safe in near-earth orbits, not only suppressing new debris production but also removing existing ones is necessary. Highly efficient propulsion systems are needed for this debris removal and electrodynamic tether (EDT)

^{*} Research Engineer, Advanced Space Technology Research Group, E-mail: okawa.yasushi@jaxa.jp.

[†] Director, ditto.

[‡] Research Engineer, ditto.

[§] Specialist, Power and Industrial Systems R & D Center.

^{**} Specialist, ditto.

^{††} Group Manager, ditto.

propulsion is one of the promising candidates because it needs neither propellant nor electric power in theory. In the Institute of Space Technology and Aeronautics, Japan Aerospace Exploration Agency (JAXA), research and development of an EDT propulsion system for the space debris mitigation has been started.¹ One of the important elements of the EDT system is an electron-emitting device at an end of the tether. The electron emitter should be operational with low power, lightweight, robust, and simple. This paper describes the current research and development status of carbon nanotube (CNT) field emission cathodes (FEC's), which have some attractive features as electron-emitting devices in the EDT system.

An EDT propulsion system essentially consists of a long electrically conductive tether and plasma contactors at both the ends for electron emission and collection. Figure 1 depicts a typical image of an EDT system and an electric potential profile along the tether. It is presumed that a bare tether is used as an electron collector in our system as shown in this figure. The EDT generates $J \times B$ force against the orbital motion by the interaction between the electric current through the tether and the geomagnetic field if electrons are emitted from an electron emitter and collected along the bare tether. Our target specifications² of the EDT system at present are 1) deorbit-only operation with a simple reel mechanism, 2) a conductive tether length of 5 km, 3) a maximum tether current of 3 A, and 4) an operational orbit is a low earth orbit with 30-deg inclination or a sun-synchronous one.

Tether potential with reference to plasma space potential is determined automatically depending on properties of the ambient plasma, the geomagnetic field, tether geometries, and contact impedance between the electron emitter and the plasma as shown in Fig. 1. Redundant potential difference can be consumed in an electric power generator and the power is distributed to other electric devices on-board. Since plasma parameters and tether attitude vary constantly, the electric potential profile and thus the tether current change drastically during the operation.^{2,3} The electron emitter has to be operated under this time-varying current condition.

There are various types of electron emitters for space use; thermionic cathodes, electron guns, hollow cathodes, FEC's, and others.^{4,5} In these options, FEC's are suitable for the EDT system because they need no consumables, no warming-up time, low electric power, and have mechanical robustness. Combining the FEC and the bare tether, a totally propellant-free debris deorbit system can be formed.

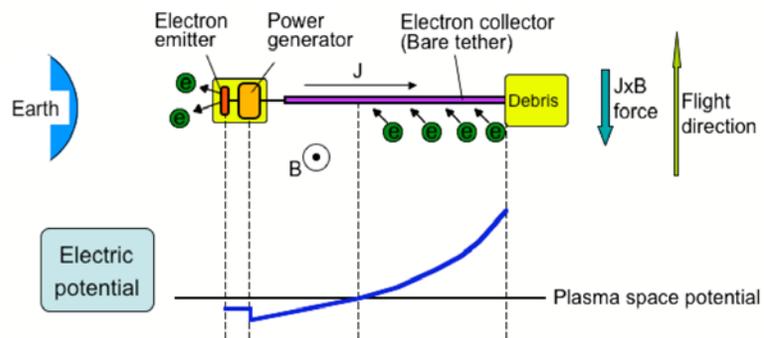


Figure 1. Typical image of EDT system and electric potential profile along tether.

II. Field Emission Cathodes Utilizing Carbon Nanotubes

Figure 2 shows a conceptual image of FEC operation in orbit. In an FEC device, electrons are extracted from a cathode surface by applying a strong electric field by a gate electrode, which is placed adjacent to the cathode. Required gate voltage depends on the separation distance between the cathode and the gate. Most extracted electrons flow into ambient plasma through the gate electrode when a negative potential difference of several tens of volts exists between the cathode and the space plasma as shown in Figs. 1 and 2.

There are various types of FEC's such as Spindt cathodes, cathodes using triple junction structure, and CNT cathodes, and what they have in common is that the cathode surfaces possess pointed extremities or edges in which the electric field is concentrated. In these options, CNT cathodes were selected as the first candidate as the electron emission device of our EDT system. The most important reason for this choice was

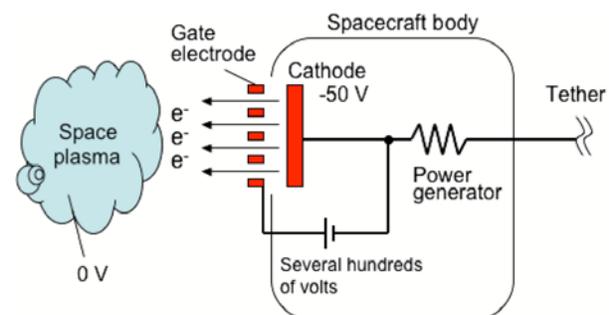


Figure 2. Conceptual image of FEC operation in EDT system.

that the CNT cathodes have high tolerance to electric breakdown and thus can be operated in lower vacuum condition in low earth orbits compared with other FEC's. It is also expected that the CNT cathodes have high tolerance to exposure to atomic oxygen. These features are probably attributable to its structure. The CNT cathode has a large quantity of nanotubes on the surface and the damage on a single nanotube does not degrade overall emission performance severely because other nanotubes nearby can replace the role of the damaged nanotube.⁶ Figure 3 shows a SEM image of one of the CNT cathodes we developed.

In our preliminary experiments,^{7,8} two types of CNT cathodes using multi-wall nanotubes were tested; CNT's made by thermal chemical vapor deposition (CVD-CNT) and ones by arc discharge process (arc-CNT). The electron extraction tests were conducted in diode mode in which a gate electrode was not used but an anode plate was placed adjacent to the CNT substrates. The test results showed that 1) an electron emission current of 120 mA was obtained from a 40-mm diameter CVD-CNT, and 2) a 2-mA electron current was extracted from a 4-mm diameter arc-CNT. The emission current densities of the CVD-CNT and the arc-CNT were approximately 8 and 16 mA/cm², respectively. From these current densities, the required area for 3-A electron emission is estimated as 19 x 19 cm for the CVD-CNT and 14 x 14 cm for the arc-CNT. These sizes are reasonable as the electron emission devices in EDT propulsion systems.

The experimental results, on the other hand, also indicated the durability problem of the CNT cathodes. In the CVD-CNT operation, the emission current decreased rapidly and it became a quarter of the initial value after 30 minutes. The emission current of the arc-CNT, on the other hand, declined gradually with time and it became constant at a half of the initial current after a 5-hours operation. The endurance performance of the arc-CNT cathode was much better than that of the CVD-CNT cathode therefore we decided to adopt arc-CNT cathodes in our current study even though the further improvement in durability was required.

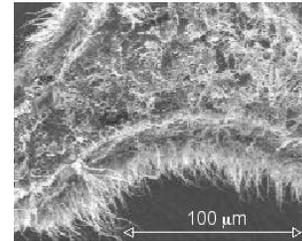


Figure 3. SEM image of carbon nanotubes bonded on metal substrate.

III. Carbon Nanotube Cathode with Gate Electrode

As shown in Fig. 2, the gate electrode is an essential element of the FEC device for on-orbit operation. The central aim of this study is to develop FEC devices with the gate electrodes and evaluate their performance. One of the important points in FEC design is suppressing an electron flow to the gate electrode to avoid thermal deformation of the electrode and to reduce power loss in the power processor shown in Fig. 2. For meeting this requirement, we developed a unique FEC design as described below.

In order to find the optimal electrode design, electron trajectory calculations were conducted using a particle-in-cell (PIC) code. In the calculations, a two-dimensional rectangular model was used for its simplicity. Figure 4 shows the calculation domains of two different FEC configurations, with and without a masking plate. Here, the "masking plate" denotes a conductive material, whose shape is similar to the gate electrode, attached on the cathode surface. A uniform electron emission of 10 mA/cm² from the cathode was assumed. Open area fraction of the gate electrode was set at 90%.

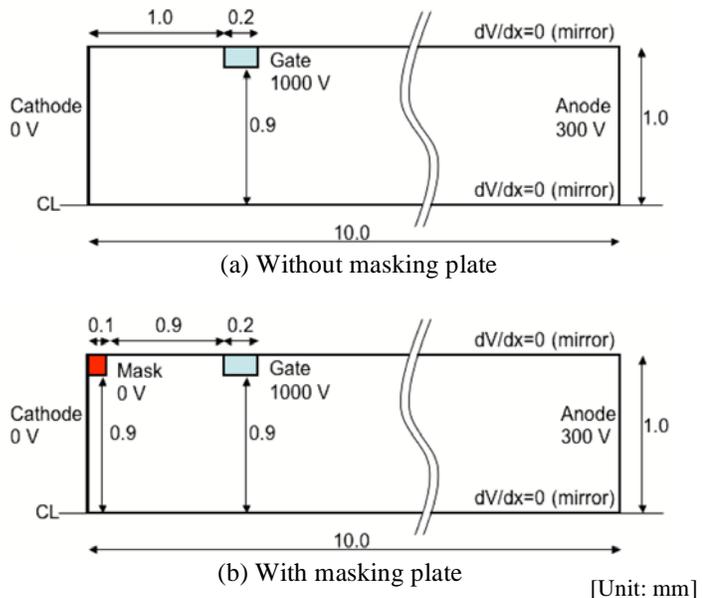


Figure 4. Calculation domains of electron trajectory simulation.

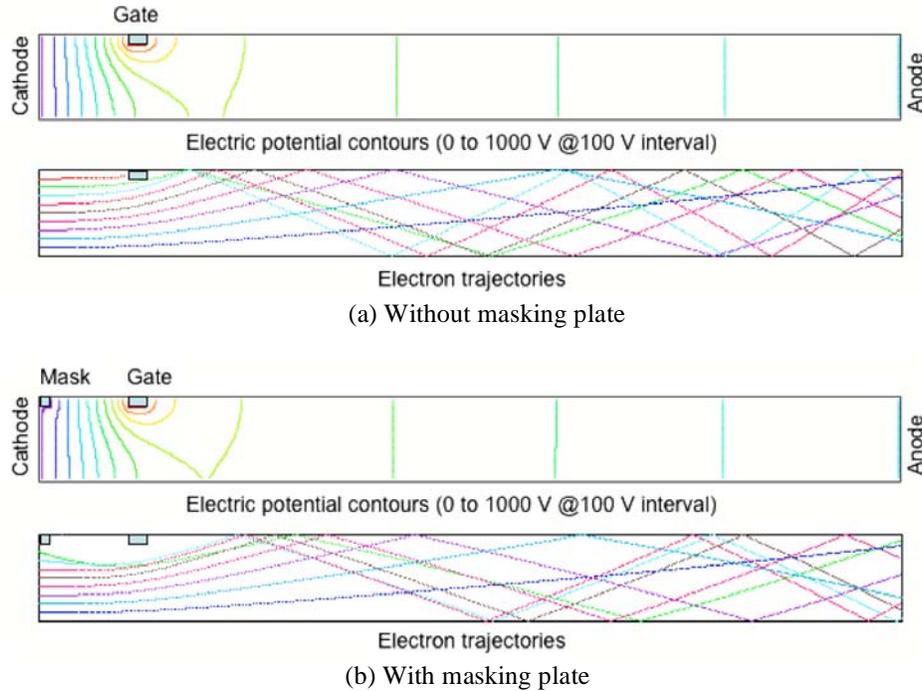


Figure 5. Electric potential contours and electron trajectories in the cases with and without masking plate.

Results of the calculations are shown and summarized in Fig. 5 and Table 1. Electric potential contours and electron trajectories in the cases with and without the masking plate are shown in Fig. 5. The figure and table indicate that the ratio of electron flow to the gate is approximately 15%, which is larger than the open area fraction of the gate, in the case without the masking plate. This is because the electric potential profile has diverged shape between the electrodes. In the case with the masking plate, on the other hand, no electrons flow to the gate because the electrons, which are extracted near the edge of the masking plate, are initially accelerated by the distorted electric field and they form a pinched electron beam. From this comparison, we decided to use the electrode design with the masking plate on the cathode.

The insertion of the masking plate, however, has an undesirable influence that is the decrease in electric field strength near the cathode. So, it is necessary to optimize the electrode geometries for efficient electron extraction. Figure 6 shows a calculation result of the relation between the electric field on the cathode surface and a radius position in the cases with various cathode sizes. Figure 6 illustrates that the electric field at the center of the hole increases with an increase in the aperture radius up to 0.8 mm owing to the shielding effect of the masking plate. When the aperture radius is larger than 1.0 mm, on the other hand, the electric field at the center decreases with increasing the radius and the electric field has dented shape. Considering these characteristics, an aperture radius of about 1.0 mm seems to be appropriate when the

Table 1. Emission current distribution to anode and gate electrode.

	without Mask	with Mask
Anode current	85%	100%
Gate current	15%	0%

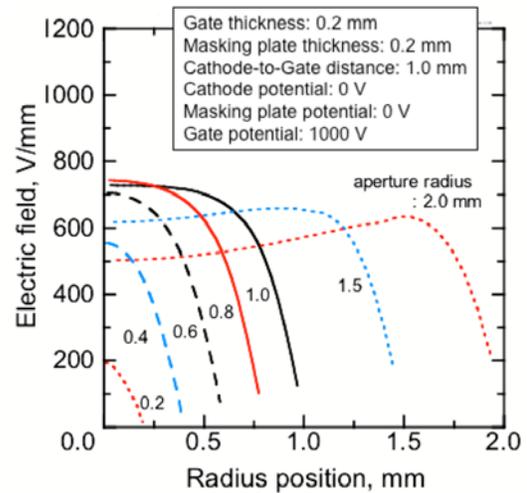


Figure 6. Electric field on cathode surface for various gate aperture radii. Gate and masking plate have same shape.

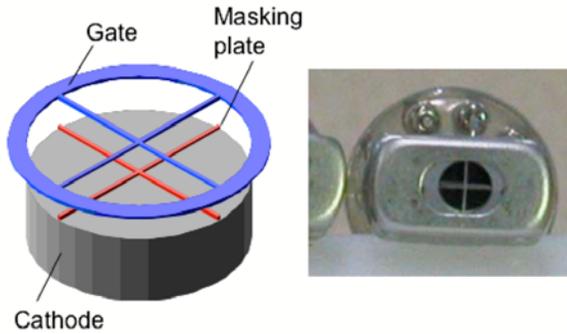


Figure 7. Carbon nanotube cathode with cross-shaped gate and masking plate.

Table 2. Dimensions of cathode assembly (Designed values).

Cathode diameter, mm	4.0
Cathode-to-gate distance, mm	0.6 - 0.65
Width of cross-shaped gate, mm	0.1
Thickness of cross-shaped gate, mm	0.1
Width of cross-shaped mask, mm	0.1
Thickness of cross-shaped mask, mm	0.1
Open area fraction of gate	0.94

cathode-to-gate separation distance is about 1.0 mm.

Depending on the discussion above, we fabricated the CNT cathode assemblies with gate electrodes and masking plates. The schematic drawing and photograph of one of the cathodes are shown in Fig. 7 and its dimensions are summarized in Table 2. This cathode assembly has a cross-shaped masking plate on a cathode surface as well as a gate electrode having the same shape. The main reason for the shape is its large open-area fraction, which is 93.6%. Although the sector aperture shape is not consistent with the geometries in the calculations above, those estimations are still valid in this sector model because their characteristic lengths are equivalent to each other.

IV. Electron Extraction Tests

Electron extraction tests using the CNT cathode shown in Fig. 7 were conducted to evaluate the effect of the masking plate insertion. The electric circuit of the tests is shown in Fig. 8. In this experiment, an anode voltage V_a was kept constant at 3 kV to exclude the influence of secondary electron emission from the anode. This relatively high anode voltage does not affect the electron trajectories near the cathode and gate because the electric field around the cathode device is dominated by its own potential. Electron emission current J_e and drain current to the gate J_g were measured using shunt resistances and digital multimeters. Pressure in the vacuum chamber during the operation was in the order of 10^{-4} Pa.

Figure 9 shows electron emission currents and gate currents plotted against the cathode-to-gate voltage V_g . Note that the emission current includes the gate current and anode current as shown in Fig. 8. Characteristics of the CNT having a mesh electrode as a gate are also drawn for comparison. Figure 10 shows the photograph of the cathode with the mesh gate, which has an open area fraction of 66%. The masking plate was not attached in this device. Figure 9 illustrates that the total emission current of the cathode having the mesh gate is larger than that of

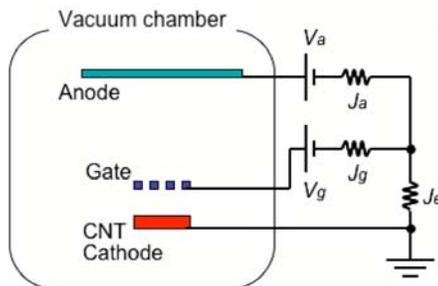


Figure 8. Electrical circuit of electron extraction test.

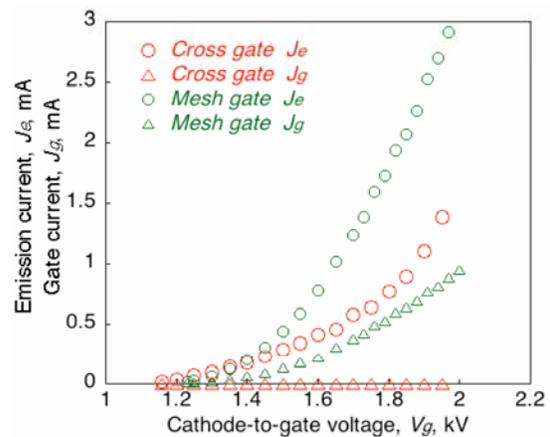


Figure 9. Electron emission characteristics of CNT cathodes with cross-shaped gate and mesh gate.

the cathode with the cross-shaped gate. The reason for this difference is that the electric field is stronger when the mesh gate is used because the leakage of the electric field through the aperture is smaller owing to its small radius and because there is no shielding effect of the masking plate.

Comparing the gate currents, on the other hand, the cathode with the cross-shaped gate is superior to that with the mesh gate. In the cross-shaped gate cathode, almost no electron current flows to the gate as expected by the numerical simulation shown in Fig. 5 and Table 1 while the mesh gate receives about 30% electrons of the total emission. This result indicates that the attachment of the masking plate is very effective to suppress the electron flow to the gate and to avoid the thermal deformation of the gate and extra power loss.

Although the effectiveness of the masking plate became clear by the comparison above, the manufacturing technique of the cathode assembly has not been sufficient. Figure 11 shows electron emission currents J_e and gate currents J_g plotted against the cathode-to-gate voltage V_g for five cathode samples having same structure. In this figure, the characteristics curves of the sample No. 4 correspond to those plotted in Fig. 9.

It is observed that the current-voltage characteristics of the samples differ considerably from each other. There is almost no gate current in the case of the sample No. 4, on the other hand, the other samples have measurable gate currents. Especially in the case of the sample No. 2, the gate current fraction to the emission current is approximately 10%, which is much higher than the gate area fraction of 6.4%. This excessive gate current indicates that electrons flowed not only to the cross-shaped part of the gate but also to the rim of the gate aperture. Since the misalignment of the masking plate and the gate electrode probably caused this undesirable current flow, improvement in the fabrication technique is necessary in near future. The differences in the threshold and inclination of the emission currents are probably attributable to the difference in the cathode-to-gate separation distance or CNT surface condition, therefore, we also need an effort to reduce the variations in this respect.

One of the important problems on CNT cathode development is the time-dependent degradation of the emission capability, which limits the lifetime of the device. Figure 12 shows the time variations in the emission and gate currents of one of the CNT cathodes shown in Fig. 7. In this measurement, the gate voltage was kept constant at about 2 kV after the emission current was raised gradually up to 1.9 mA. It is shown that the emission current after continuous 26-hour operation is approximately 1.7 mA, which is 90% of the initial value. The durability was considerably improved compared with our former study⁸ by changing a bonding method of CNT's on a substrate though it may still not be sufficient for future debris removal applications. Figure 12 also indicates that thermal deformation of the gate electrode did not occur in this endurance test because there was no unexpected change in the gate current.

There remain some issues to be investigated in order to develop CNT cathodes as the electron source of the EDT



Figure 10. CNT cathode with mesh gate.

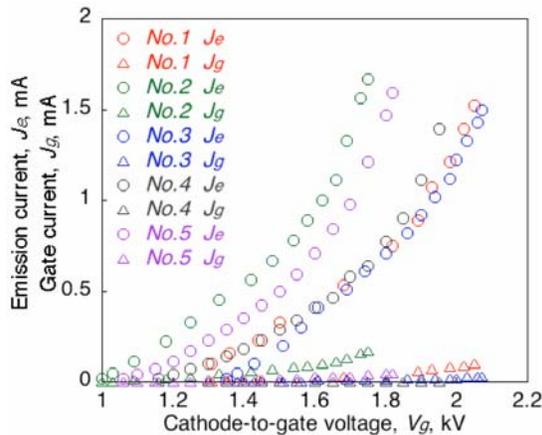


Figure 11. Electron emission characteristics of five CNT cathodes having cross-shaped gates.

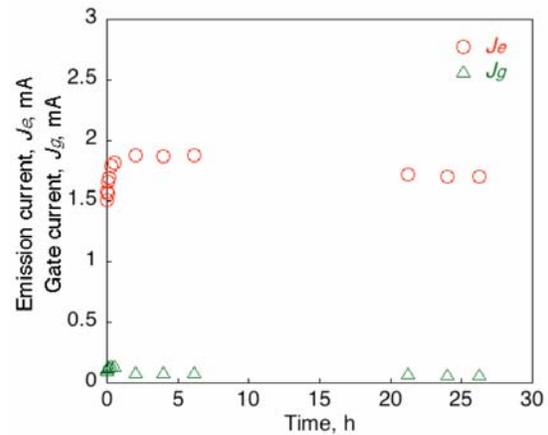


Figure 12. Variation of emission characteristics of CNT cathode in continuous 26-hour operation.

propulsion system. Lowering the gate voltage is one of the inevitable improvements to reduce extra power consumption and to avoid interference between the gate and ambient plasma. The CNT cathodes we developed require a gate voltage of several kilovolts to obtain sufficient electron emission at present and this cannot be accepted. Adding a shield electrode over the gate electrode may be effective to avoid the gate-plasma interference.

V. Conclusion

An experimental investigation of carbon nanotube cathodes having gate electrodes for electron extraction was conducted. To suppress an electron flow to the gate electrode, a thin masking plate, which deforms the electric field between the gate and cathode, was attached on the cathode. Geometrical parameters of the electrodes were optimized by numerical simulations. Results of electron extraction tests showed that the addition of the masking plate made a drain current to the gate electrode negligible when the each electrode was assembled appropriately. So, it is stated that the masking plate insertion has significant effect on performance enhancement of the carbon nanotube cathodes though the improvement in fabrication technique is necessary for performance stabilization. The endurance test of the cathode was also conducted and the degradation of an emission current after 26-hour operation was less than 10%.

References

- ¹ S. Kibe, S. Kawamoto, Y. Okawa, F. Terui, S. Nishida, and G. Gilardi, "R&D of the Active Removal System for Post-Mission Space Systems," 54th International Astronautical Congress, 2003, IAC-03-IAA.5.4.07.
- ² S. Kawamoto, Y. Okawa, S. Yoshimura, S. Nishida, A. Nakajima, S. Kitamura, M. Kyoku, and M. Cho, "Electrodynamic Tether Systems for Debris Removal," 9th Spacecraft Charging Technology Conference, 2005.
- ³ J. Vaughn, L. Curtis, B. Gilchrist, S. Bilen, and E. Lorenzini, "Review of the ProSEDS Electrodynamic Tether Mission Development," 40th Joint Propulsion Conference, 2004, AIAA-2004-3501.
- ⁴ K. Fuhrhop, D. Morris, and B. Gilchrist, "Electron Emission for Electrodynamic Tether Systems in Space," 40th Joint Propulsion Conference, 2004, AIAA-2004-3495.
- ⁵ M. Tajmar, "Survey on FEED Neutralizer Options," 38th Joint Propulsion Conference, 2002, AIAA-2002-4243.
- ⁶ C. Gasdaska, P. Falkos, V. Hruby, M. Robin, N. Demmons, R. McCormick, D. Spence, and J. Young, "Testing of Carbon Nanotube Field Emission Cathodes," 40th Joint Propulsion Conference, 2004, AIAA-2004-3427.
- ⁷ S. Kitamura, S. Nishida, Y. Iseki, and Y. Okawa, "Field Emitter array Cathodes for Electrodynamic Tether Propulsion," 55th International Astronautical Congress, 2004, IAC-04-IAF-S.4.09.
- ⁸ Y. Okawa, S. Kitamura, and Y. Iseki, "Preliminary Testing of Carbon-Nanotube Field Emission Cathodes for Electrodynamic Tethers," 9th Spacecraft Charging Technology Conference, 2005.