A Carbon Nanotube Field Emission Cathode for Electrodynamic Tether Systems

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Abstract: An electrodynamic tether (EDT) is an attractive candidate for deorbit propulsion of future active debris removal systems because of its simplicity and high efficiency in mass and power consumption. EDT needs an electron emission device for sending an electric current to the tether and the device should also be small, simple, and low powered. A field emission cathode (FEC) possesses some advantages on these requirements compared to other cathodes. One of the critical issues on FECs for EDT is the durability on low earth orbit (LEO). We performed a 1500-hour endurance test of a breadboard model of a carbon nanotube FEC at a constant emission current density of 5 mA/cm^2 and a tank pressure of 5 × 10^{-5} Pa. The extraction voltage increased from 700 to 1000 V and neither severe breakdown nor short-circuit were observed during the test. The life of the cathode was expected to be much longer than 1500 hours on orbit considering the difference in vacuum conditions between the endurance test and LEO.

I. Introduction

SPACE debris population has drastically grown in these decades. The collision event between Cosmos 2251 and Iridium 33 in February 2009 signaled that "Kessler Syndrome", which means that collisions between orbiting objects cause a cascade, is becoming realized. In recent years, space agencies have agreed that in order to remediate on-orbit environment, it is not enough to suppress new debris generation but remove existing on-orbit debris by active debris removal (ADR) systems. Some studies[1,2] have shown that removing large objects such as rocket upper stages and satellites on low earth orbit (LEO) is the most effective way to remediate the on-orbit environment from a long-term view.

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An ADR system needs propulsion for deorbiting and there are some candidates including solid or liquid chemical propulsion, electric propulsion, and advanced propulsion. In these candidates, an electrodynamic tether (EDT) is very attractive because of some features as follows. 1) EDT can be simple, small, and light-weight because it does not need propellant, tanks, and valves. 2) EDT can be attached space debris easily. Neither strong grabbing force nor center-of-mass alignment are required for the attachment because the thrust generated by EDT is small and distributed along the kilometers-long tether. In ordinary propulsion systems, the thrust axis should go through the center-of-mass of the debris object and attaching the propulsion system with keeping this alignment is difficult. 3) EDT does not need thrust vector control during the deorbiting operation because the thrust is automatically generated for reducing the orbit energy when electromotive force (EMF) is used in driving the tether current. From these points, we have selected EDT for deorbit propulsion of ADR systems and have been studying the critical components and the system.[3-5]

Figure 1 shows a conceptual image of EDT. A long conductive tether deployed in geomagnetic field on LEO induces EMF along the tether and an electric current is driven using EMF when electrons are emitted and collected at each end of the tether. The interaction between the geomagnetic field and the tether current generates J×B force against the orbital motion. There have been several EDT experiments on orbit or using sounding rockets[6-8] and its current driving principle has been proved, however, the thrust generation has not been demonstrated. In Japan Aerospace Exploration Agency (JAXA), we are preparing to realize the thrust generation demonstration of EDT in near future as a first step to build an ADR system. Bare tethers, tether reeling mechanisms, releasing mechanisms of an end mass, and electron emission devices are the most important elements for the EDT and we have been developing these components. This paper describes a selection of the electron emission device, details of a field emission cathode, and its endurance tests.

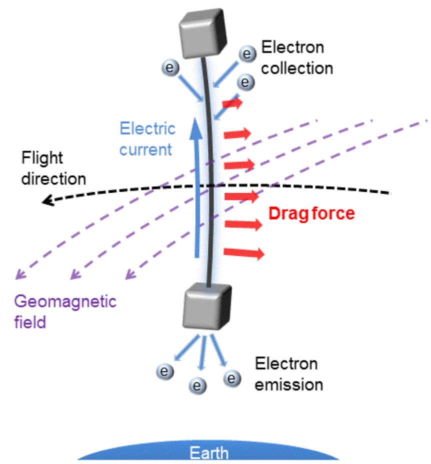

Figure 1. Conceptual image of electrodynamic tether (EDT).

II. Electron Emitter for EDT

In EDT systems, electron emission and collection at each end of the tether is indispensable for driving tether current and thus generating thrust. As an electron collector, a bare wire anode proposed by Sanmartin[9] is the most attractive because of its current collection capability and flexibility. This bare tether is a simple passive device. As an electron emitter, on the other hand, some active device is needed to send enough electric current for generating thrust for deorbiting large space debris.

Some candidates for the electron emitter for EDT are listed in Table 1. The most important characteristics for the electron emission device in EDT systems are small, light-weight, simple, and low power consumption. The EDT systems, which are attached to debris objects, should be simple and compact, therefore, the electron emission devices should also be. Another important feature for the electron emitter is low contact voltage between the emitter and space plasma. The EMF induced by the tether is distributed to a contact potential difference at the bare tether, an ohm resistance drop along the tether, some electrical loads in the circuit, and a contact potential difference at the emitter. Therefore, the low contact voltage at the emitter is desirable to use the EMF effectively. In addition, since the EMF and the tether current are drastically varied during the orbital motion, the electron emitter is better to follow these changes autonomously.

Table 1. Comparison of electron emitters for EDT.

	Advantages	Disadvantages
Field Emission Cathode	Small, Simple, Low power	Space charge limit, Not matured
Hollow Cathode	High current density, Matured	Tank and valves, Heat load
RF/ECR Cathode	High current density	Tank and valves, Not matured
Thermionic Cathode	Small, Simple, Matured	Space charge limit, Heat load
Passive Cathode (Photoemission, Ion collection)	Simple, No power	Large area, Low current density

In Table 1, a hollow cathode is superior to other devices in electron emission capability and flexibility. It provides high electron emission current density with low contact voltage due to space charge relaxation by internal plasma. In addition, no active current control is required even when the tether current and potential fluctuate drastically. However, the hollow cathode needs working gas and the feeding system for it. Tanks, valves and piping for gas feeding make the system heavy and complicated and this disadvantage might be critical for ADR systems. RF or ECR cathodes have similar advantages and disadvantages while the technologies have not been matured compared to hollow cathodes.

We expect that a field emission cathode (FEC) is the most attractive candidate for the EDT of future ADR systems because of its potential capabilities. As shown in Fig. 2, the FEC can emit electrons by simply applying strong electric field on pointed emitters. Since the FEC requires neither heating power nor working gases, the cathode system can be very simple. Although the emission current density to space plasma is limited by Child's law, an adequate emission current for generating deorbit thrust can be obtained from a realistic size of the emitter because three-dimensional diffusion of emitted electrons can be taken into account.[10] Power consumption per unit emission current is not small compared with hollow cathodes at present because of low efficiency of small high voltage converters, however, the power consumption will be reduced by improving the extraction voltage in near future.

Although thermionic cathodes are also good candidates in terms of simplicity, it requires high extraction voltage to overcome space charge limit as in FECs. Therefore, it is inferior to FECs because additional heater power is needed for electron production. Its heat load on spacecraft is another disadvantage of the thermionic cathodes. Some passive cathodes using ion collection or photoelectron emission seem to be applicable to micro-sized EDTs, however, its current level obtained is insufficient for deorbiting large debris objects.

Based on the trade-off study above, we have selected FECs as the most feasible candidate for the EDT systems.

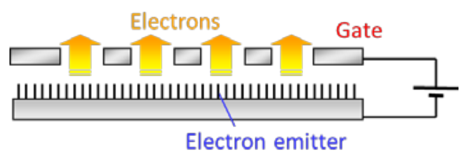

Figure 2. Conceptual image of field emission cathode (FEC).

III. Carbon Nanotube Field Emission Cathode

Various types of FECs for space application have been studied such as cathodes using thin film technologies as typified by Spindt cathode,[11] cathodes using triple junction structure,[12] regenerative cathodes,[13] and carbon nanotube (CNT) cathodes.[14] Some studies[15-17] have reported the comparison of these cathodes and there are merits and demerits in each type. In these options, CNT cathodes have been selected as the first candidate for the electron emission device of our EDT system. The most important reason for this choice is that the CNT cathodes have high tolerance to electric breakdown and thus can be operated in low vacuum condition in LEO environment compared with other FECs. This desirable feature is attributable to its structure and chemical stability. 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 one.

Figure 3 shows a breadboard model (BBM) of a CNT cathode, which is developed for applying to a near future EDT experiment. The BBM cathode consists of independent eight cathode units and each unit possesses 4-mm-diameter CNT sheet as an electron emitter. The cathode system becomes robust in this structure because a failure in one unit does not affect the operation of other units. On the other hand, since one high-voltage-converter supplies the extraction voltage for all the units, it is necessary to average the emission characteristics of each unit using some electronic devices when the variation of the emission characteristics cannot be neglected.

A schematic drawing of a single unit of the BBM cathode is shown in Fig. 4. The unit mainly consists of a CNT sheet, a mask electrode, a gate electrode, a base plate, and a shield case. The mask and gate possess slit apertures for electron extraction and are fabricated by photo-etching. The CNT sheet and mask are connected electrically each other. Since the current loss to the gate should be low enough to avoid excessive power consumption and thermal load, the mask is necessary for reducing the loss current. The mask not only covers unnecessary emitter areas but also distorts the electric field and makes the electron

Figure 3. Breadboard model (BBM) of carbon nanotube FEC.

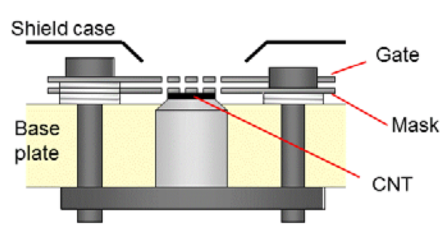

Figure 4. Schematic drawing of a single cathode unit of BBM.

trajectories converge.[18] Figure 5 shows a scanning electron microscope (SEM) image of the CNT sheet. Fluffy nanotubes are complexly intertwined and many tube tips are distributed randomly. These nanotubes are high purity multi-walled nanotubes made by a unique arc discharge process developed by JFE Engineering Corporation.[19] The diameter of nanotubes distributes around 10 nm and the thickness of the CNT layer is approximately 50 μm.

Key technological issues of the CNT cathode for the EDT systems are 1) reduction of the electron extraction voltage, 2) improvement in the electron extraction efficiency, 3) evaluation and improvement of the durability, and 4) development of hardware and software for appropriate current/voltage control. On the extraction efficiency, we have obtained a good prospect by adopting the mask structure as described above. Therefore, we are putting emphasis on the remaining three issues at the present time, and the endurance performance of the CNT cathode is the topic of this paper.

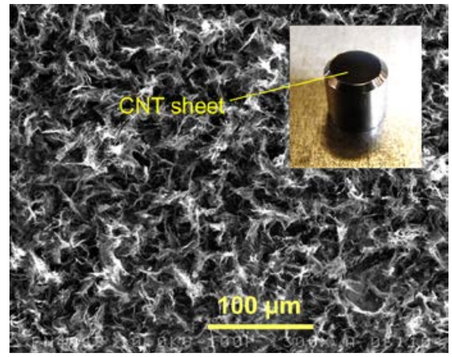

Figure 5. SEM image of surface of CNT sheet.

IV. Endurance Tests of CNT Cathode

Durability is one of the most important issues to evaluate the feasibility of CNT cathodes for EDT systems, which will be operated in LEO. In this section, results of endurance tests are shown after the discussion on the test environment.

A. Vacuum Condition in Endurance Test

Electron emission characteristics and durability of FECs strongly depend on the vacuum condition, in which the cathodes are operated.[20,21] In order to estimate the cathode durability on-orbit operation by the ground test, it is important to understand the difference between the ground test environment and the on-orbit environment.[22] Table 2 shows the environment comparison between them.

In the endurance tests, the cathode was operated in a rectangular chamber with the size of 660 × 450 × 450 mm. A turbo molecular pump (TMP) was used to maintain vacuum and the pressure was almost constant at 5×10^{-5} Pa during the cathode operation. Since neither gas feeding nor baking of the chamber surface was done for the test, this tank pressure was a result of the equilibrium between the pumping speed of the TMP and the desorption rate of H_2O from the chamber wall, therefore, population of H_2O was probably dominant in the vacuum tank. When the cathode was operated, some radicals and ions such as OH, O, H_2O^+ and OH^+ were produced and existed around the cathode by dissociation and ionization due to electron bombardment to residual H_2O molecules, therefore, the conditions for the cathode should be harsher than that when just H_2O flux was considered.

Pressure and Atomic Oxygen (AO) flux at three LEO altitudes are also shown in Table 2. The values at noon in solar maximum period are listed to assume the worst case. The AO flux is calculated from the thermal velocity, and the direction (ram or wake) of the cathode surface with reference to orbital motion is not taken into account. In our previous experiments, it was observed that the CNT sheet was eroded at almost the same rate as a polyimide film when AO impinged vertically with orbital velocity on the CNT sheet. Considering this result, the cathode surface is better to be parallel to the orbital motion, and in such a case, the AO flux can be estimated based on the thermal velocity. Although the population of He cannot be neglected in higher altitude such as 1000 km, the consideration of it is not necessary because rare gases do not affect the characteristics of CNT cathodes severely.[21,23]

From Table 2, the H_2O flux in the endurance test is two orders of magnitude larger than the AO flux on 600-km altitude and four orders larger than that on 1000-km altitude at noon in solar maximum period.

Table 2. Comparison of test environment in vacuum tank and LEO environment.

	This test	400-km alt.*	600-km alt.*	1000-km alt.*
Pressure, Pa	5.0×10^{-5}	6.2×10^{-6}	5.5×10^{-7}	2.2×10^{-8}
H_2O number density, m^{-3}	6.0×10^{15}	-	-	-
AO number density, m^{-3}	-	3.3×10^{14}	2.8×10^{13}	3.3×10^{11}
Temperature, K	300	1160	1160	1160
Thermal H_2O flux, $m^{-2}s^{-1}$	9.0×10^{17}	-	-	-
Thermal AO flux, $m^{-2}s^{-1}$	-	1.0×10^{17}	8.8×10^{15}	1.0×10^{14}

* Sloar maximum, Noon.

Since ADR systems with EDT will be mainly operated over the altitude of 650 km, in which spacecraft with ordinary area-to-mass-ratio cannot satisfy so called “25-year rule,” the vacuum condition in this endurance test is considerably damaging to the cathode compared to the LEO environment. In addition, it was reported that the deterioration of a carbon nanotube cathode in H_2O atmosphere is more serious than that in O_2 atmosphere.[21] Further consideration on the oxygen environment such as the difference between molecular and atomic oxygen is necessary for detailed evaluation.

B. Circuit and Cathode Settings

The electrical circuit in the endurance tests is shown in Fig. 6. Eight independent cathode units are operated by one DC-DC converter, which is connected to each emitter via a current sensing resistor and a current limit resistor. The current limit resistors are needed to adjust the electron emission currents of the eight units because there was a wide variety of emission characteristics. The resistances were chosen based on the initial characteristics of each cathode unit as described later. All the emission current, J_e, gate current, J_g, and shield current, J_s were measured by shunt resistors. As shown in Fig. 6, only CNT emitters were negatively biased and other parts (gate electrodes and shield case) were grounded in this endurance test, while the negative potential of the emitter would be less than 100 V on orbit operation, therefore, CNT deterioration by ion impingement would be overestimated in this test compared to that on orbit.

Figure 7 shows the cathode location in the vacuum tank. The distance between the CNT cathode and the facing tank wall, which has a role of anode, was approximately 370 mm.

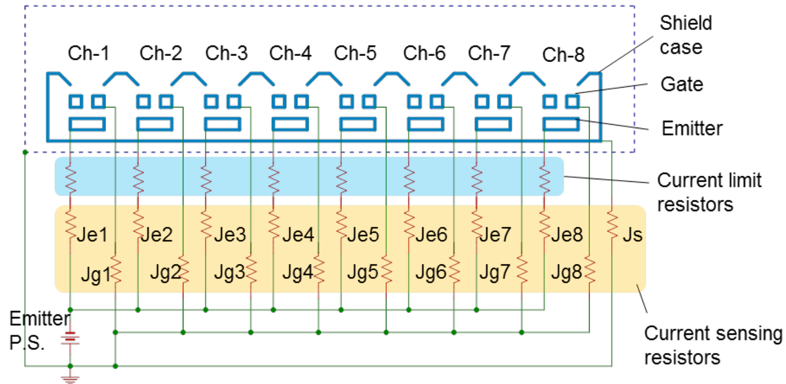

Figure 6. Electrical circuit for endurance tests.

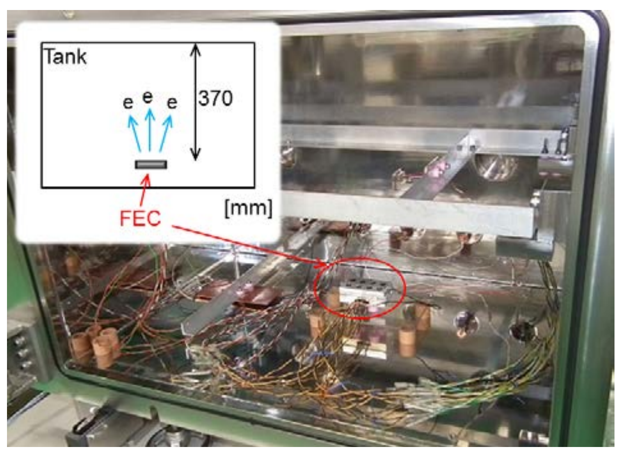

Figure 7. Cathode location in vacuum tank.

C. Initial Characteristics of Cathode

The initial current-voltage characteristics of each cathode unit before connecting the current limit resistors are shown in Fig. 8. The characteristics of emission current, J_e and loss current to gate, J_g of eight cathode units were obtained independently after 9-hour conditioning operation on each unit. Emission current density on the CNT sheet for 0.5-mA-emission is approximately 6.6 mA/cm^2 when the effective electron extraction area is assumed to be 60% of the total emitter area due to the existence of the mask on the CNT sheet.

Figure 8 shows that there was a wide variety of emission characteristics between the eight cathode units. A required voltage for 0.5-mA-emission in Ch-2 was only 320 V, on the other hand, that in Ch-4 was approximately 580 V. Extraction efficiency, which is the ratio of the electron current through the gate to the total emission current, also varied such as over 97% in Ch-5 and 63% in Ch-8. The reasons for these varieties probably are essential difference on electron emission characteristics of the CNT sheets and geometrical misalignment in electrode assembling such as misalignment in aperture axes and variation in electrode separation distances. The improvement in the assembling accuracy is an important issue to be solved in near future.

In order to utilize the capabilities of the eight cathode units effectively, the emission characteristics were adjusted using the current limit resistors by balancing the emitter voltages for 0.5-mA-emission. The current-voltage characteristics in simultaneous operation of all the eight units after this adjustment are shown in Fig. 9. By the adjustment, the inclination of total emission current became gentle compared with the characteristics shown in Fig. 8. Figure 10 shows the current-voltage curves of each cathode unit at the same experiment as shown in Fig. 9. The emission current curves of the better performance units such as Ch-2 became almost linear due to the large potential

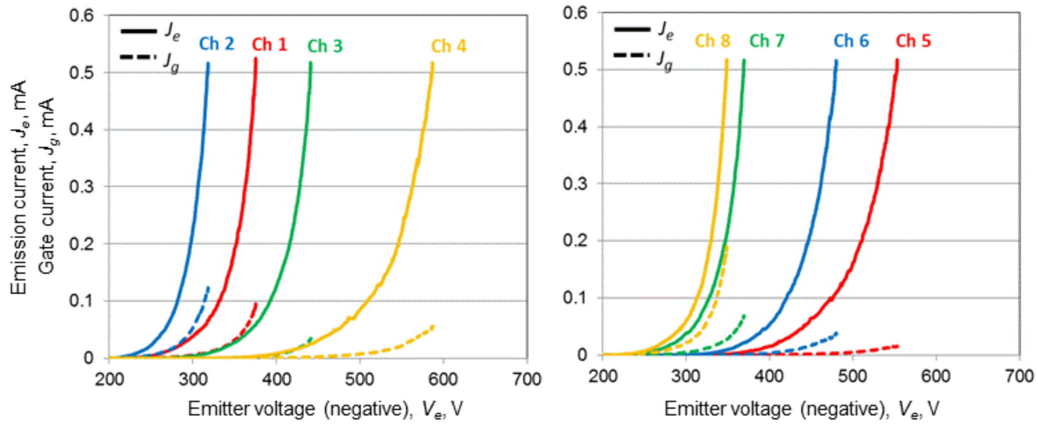

Figure 8. Initial current-voltage characteristics of each cathode unit. Ch-1 to 4 (left) and Ch-5 to 8 (right).

drops at the current limit resistors. For example, the potential drop for Ch-2 emitter when the emission current was 0.5 mA was approximately 280 V. Since the current limit resistances are the cause of the power loss intrinsically, it is preferable to reduce or control the resistances flexibly during the operation. Such a treatment is important to exploit the emission capability of each cathode unit effectively, especially for long term operation.

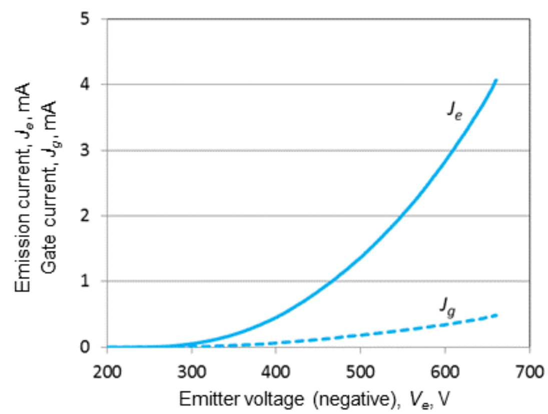

Figure 9. Current-voltage characteristics in simultaneous operation of all units after current level adjustment.

D. 50-hour Tests at Four Current Levels

After the adjustment of emission characteristics, 50-hour tests of the BBM cathode were conducted at the initial emission current of 1, 2, 3, and 4 mA. The emitter voltages were kept constant at each current setting. The total emission current and emitter voltage are plotted against the operation time in Fig. 11. Some irregular plots at the operation time of 80 and 180 hours are the results of stepwise current increase procedure after the interruption.

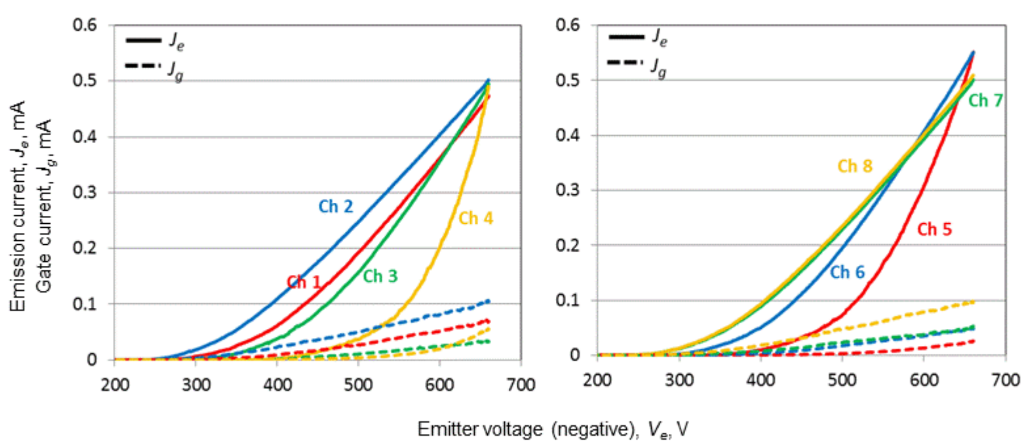

Figure 10. Current-voltage characteristics of each cathode unit in simultaneous operation of all units after current level adjustment. Ch-1 to 4 (left) and Ch-5 to 8 (right).

Figure 11 shows that the emission current decreased in time at all the current levels and the decline rate was higher in the larger current cases. Comparing the case with the initial current of 1 and 4 mA, for example, difference in the current decline rate was more than twice. Such a tendency, which is that the emission current deterioration depends on the current density in CNT cathodes, has been reported in some studies and the reason for this deterioration is thought to be resistive heating or chemical absorption of gases.[24,25] Figure 11 indicates that a certain level of performance degradation of CNT cathodes in long-term operation is not avoidable at these current density levels in a vacuum condition shown in Table 2. In other words, however, the life of the cathode can be extended by selecting lower current density levels. Since the present BBM has large redundant surface area, where is not used for electron extraction, as shown in Fig. 3, it is possible to reduce the redundant area by redesigning the structure and lower the equivalent current density of the device.

Figure 11 also illustrates that the fluctuation of the emission currents were small throughout the operation and severe instability with steps and spikes,[20] which are usually observed in carbon emitters, did not exist clearly. This stability is probably due to "ensemble averaging" effect,[26,27] i.e., the noise is statically reduced because the emission current is an integral of electrons emitted from many emission sites on the CNT sheets.

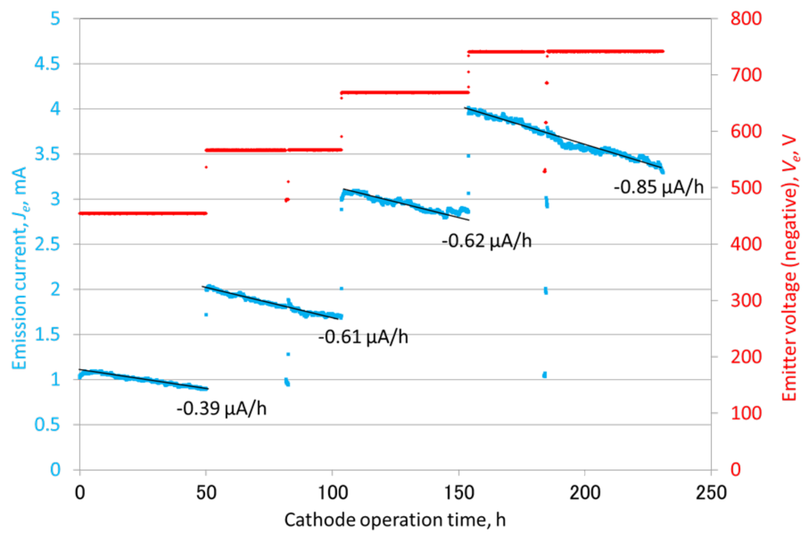

Figure 11. Emission current change in time in 50-hour tests at initial emission currents of 1, 2, 3, and 4 mA. Emitter voltages were kept constant at each initial current level.

E. 1500-hour Endurance Test at Constant Emission Current

A 1500-hour endurance test of the BBM cathode was conducted after the short term tests described above. The cathode was operated at the constant total emission current of 3 mA, which was selected assuming the application to an EDT experiment in near future. The emission current density on the CNT sheet was approximately 5 mA/cm^2 in this case.

Time dependent variation in the emitter voltage to keep the 3-mA electron emission is shown in Fig. 12. The test was terminated after 1533 hours intentionally because the emitter voltage exceeded 1000 V, which was the planned maximum voltage. There were twice interruptions, one was for obtaining the current-voltage characteristics at 420 hours and another was for a power outage of the facility at 700 hours. An incomplete short circuit occurred in Ch-8 at 300 hours and the emitter voltage decreased in short

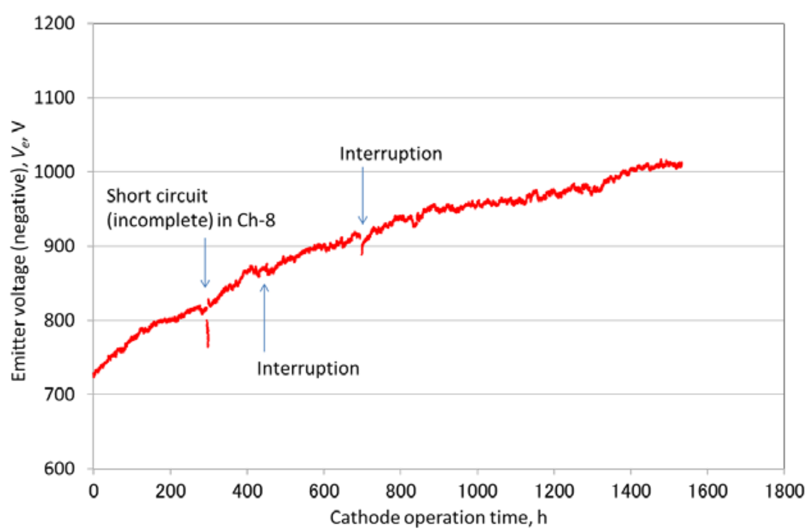

Figure 12. Time dependent variation in emitter voltage to maintain 3-mA electron emission in 1500-hour endurance test.

period of time. The glitch was recovered automatically after 4 hours and a reason for this transient failure seemed to be a flake between the electrodes, which might be burned out after 4 hours.

Figure 12 shows that the emitter voltage kept rising throughout the test and the voltage difference between the beginning and ending was approximately 300 V. The voltage increase rates were 400 mV/h in the beginning and 110 mV/h after 800 hours. Although the emitter voltage was not saturated completely, the slope became gentle as the operation time accumulated. In our previous 1000-hour endurance test using a similar cathode,[28] on the other hand, the voltage rising rate was approximately 80 mV/h throughout the test at an emission current density of 1.3 mA/cm^2. These results indicate that the degradation rate of the electron emission depends on the current density levels although the detailed characteristics of the deterioration vary in each experiment. From this it is suggested that the appropriate selection of the emission current level is important for satisfying the life requirement in the practical use of FECs on orbit.

Figure 12 indicates, from another point of view, that the BBM cathode possesses the life of 1500 hours in the ground test environment when the extraction voltage is limited to 1000 V. As compared in Table 2, since the vacuum environment in this endurance test is more damaging than that on LEO in EDT operation, it is expected that the cathode life is longer than 1500 hours on LEO. For detailed discussion of the cathode life, an on-orbit demonstration is necessary in near future.

Figure 13 shows the time dependent variation in the total gate current plotted against the operation time. The gate current decreased in time while the emission current was kept constant at 3 mA, and this is a preferable tendency because a large gate current causes the power loss in the processor and increase in heat load on the electrode assembly. This gate current reduction was probably attributable to the improvement in electron beam convergence through the gate aperture, which was caused by homonization of the emission sites on the

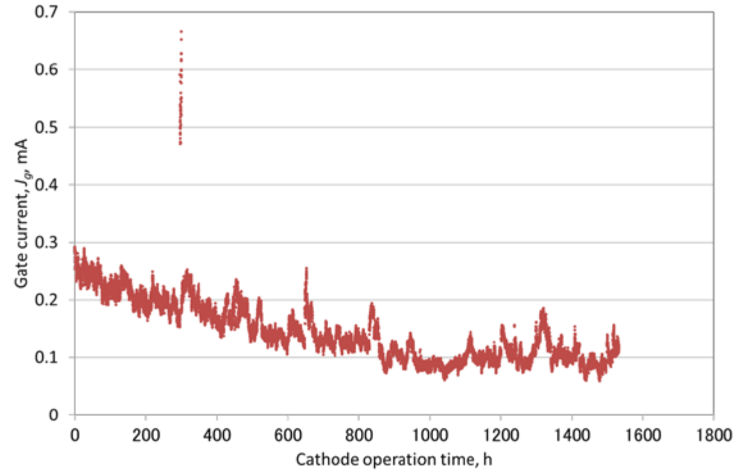

Figure 13. Time dependent variation in gate current in 1500-hour endurance test.

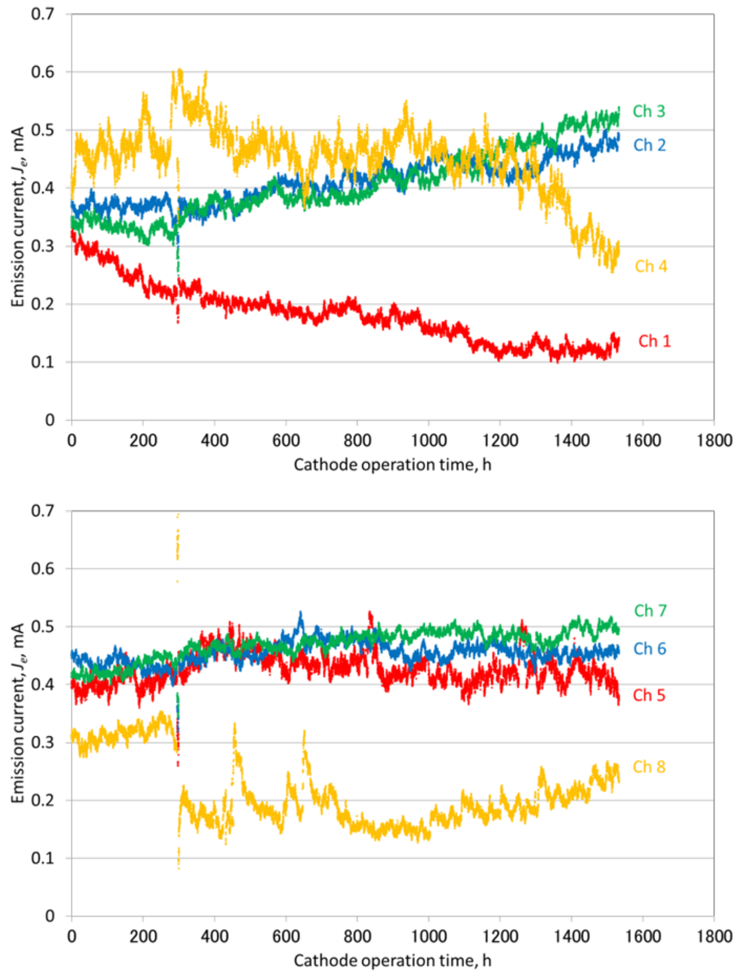

Figure 14. Time dependent variation in emission current at each cathode unit in 1500-hour endurance test. Ch-1 to 4 (Top) and Ch-5 to 8 (Bottom).

CNT sheet. Transient large currents at 300 hours were derived from the incomplete short circuit in Ch-8.

Time dependent variations in each emission current of Ch-1 to 8 are plotted in Fig. 14. Although summation of these currents were kept constant at 3 mA throughout the test, the each emission current varies vigorously. The emission currents of Ch-1, 4, and 8 degraded severely compared with other channels. The deterioration in Ch-8 was probably caused by some damage on the CNT sheet when the short circuit occurred at the operation time of 300 hours, on the other hand, the reasons for the degradation in Ch-1 and 4 are not clear. The emission currents of Ch-2, 3, 5, 6, and 7 were almost stable and gradually increased throughout the test, and these rises compensated the current decrease in Ch-1, 4, and 8. These results suggest that the progress of the performance degradation depends on the individual emitters, and the cathode with better initial characteristics is not necessarily better in endurance performance. Microscopic and chemical analyses are required for further discussion. In addition, development of the appropriate control circuit and logic are necessary in order to exploit the individual characteristics of the cathode units effectively.

V. Conclusion

Carbon nanotube field emission cathodes have been studied for applying to electrodynamic tethers, which are attractive candidates for deorbit propulsion of future active debris removal systems. A breadboard model of a carbon nanotube cathode possessing eight independent emission units was fabricated and tested for evaluating its endurance performance. In 50-hour tests at four emission current levels, it was shown that the performance degradation rate depends on the emission current density, and lowering the current density is effective to extend the cathode life. A 1500-hour endurance test was also conducted at the constant emission current density of 5 mA/cm^2, and neither severe breakdown nor short-circuit were observed during the test, while the extraction voltage increased from 700 to 1000 V. Comparison between the test environment and on-orbit one indicated that life of the cathode is probably much longer than 1500 hours in LEO environment.

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