

Observation and Analysis of Graphite Hollow Cathode after 45,000-Hour Life Test

IEPC-2013-364

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013*

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Abstract: Discharge characteristics during a 45,660 h life test and destructive analysis results after the life test of a discharge hollow cathode developed in the Japan Aerospace Exploration Agency (JAXA) are described. The discharge and keeper voltages had remained almost stable at about 30 and 8 V respectively throughout the life test and there were no gradual voltage increases due to cathode deterioration. The eroded depths of the keeper and orifice plate due to ion bombardment were approximately 0.2 mm, respectively. In addition, there was no chemical reaction between the graphite and insert materials. These results show that adopting graphite may be a good solution to solve the problem of erosion of the keeper disk and orifice plate. The insert inner surface was clean within 7 mm from the downstream edge, where many pores were found. Either no tungsten crystallite was deposited or no poisoning layer was formed. We think that this clean surface was one of the main reasons for the extended stable operation. The measured temperature at the downstream end of the insert under the discharge condition was 1,120 °C in the additional experiment using a similar cathode. In addition, a heat calculation showed the temperature varied between both ends of the insert inside was 77 K. This clean surface can be secured due to the low operating temperature and small temperature difference. Through a life test and destructive analyses, we confirmed that this hollow cathode had sufficient surplus life capability.

Nomenclature

V_d	= discharge voltage
J_d	= discharge current
V_k	= keeper voltage
J_k	= keeper current
LDS	= laser displacement sensor
SEM	= scanning electron microscopy
EDX	= energy-dispersive X-ray analysis
XRD	= X-ray diffraction
EPMA	= electron probe micro analysis

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I. Introduction

HOLLOW cathodes are mature electron sources, featuring high electron emission capability and long life. Accordingly, many ion thrusters and Hall thrusters have adopted the hollow cathode for plasma generation and beam neutralization, and the International Space Station also uses hollow cathodes to relieve undesirable spacecraft charging. Their long lives were demonstrated by NASA LeRC¹ and JPL² at around 30,000 h. In the NASA LeRC case, the degradation of the cathode insert was life-limiting, while in the JPL case, although the cathode survived a run of 30,472 h, its keeper electrode had been eliminated by erosion far before the end of the run. Although the loss of the keeper electrode does not directly lead to the end of the cathode life, it is undesirable for many reasons. In addition, the erosion of the keeper electrode against ion bombardment can be reduced by switching the material from metal to graphite, which is highly tolerant of ion impingement³.

Conversely, the orifice plate of the hollow cathode is also bombarded by ions and eroded. The wear exerted on the orifice plate may limit its lifespan, which can be effectively mitigated by thickening the orifice plate. However, an excessively thick plate will impair thruster performance. Selecting adequate thickness is thus problematic, and a change in orifice diameter, which follows an undesirable change in the thruster operating point, is inevitable. JAXA decided to use graphite as the orifice material; both to ensure it would last beyond 30,000 h with certainty and avoid changing the operating point. Life testing of a discharge cathode, with a graphite orifice plate, started in March 2006 to validate its life, since which time the testing status has been reported⁴⁻⁸.

Destructive analyses are needed to evaluate the quantitative damage to the hollow cathode after extended operation and estimate the remaining lifetime. Server-Verhey performed destructive analyses of an insert of the hollow cathode which failed at a 28,000 h life test. He demonstrated that the main life-limiting phenomena were (1) tungsten deposition, (2) Ba-containing layer formation, and (3) tungstate formation¹. Sengupta et al. performed physical and chemical analyses of impregnated-cathode assemblies from an ion thruster life test operated for 30,472 h. They demonstrated that (1) the keeper electrode plate was removed due to ion sputtering from the discharge plasma, (2) no tungstates or other oxide/poisoning layers were detected over the entire emitter surface, (3) substantial W crystallite deposition was apparent at the downstream end, and (4) the insert experienced temperature-dependent barium oxide depletion within the matrix. However it is estimated that 25,000 h of operation remained². Thanks to their efforts, many researchers were able to recognize the behavior in the life of hollow cathodes operating in the gas discharge.

A chemical reaction between carbon and other materials should be noted from analyses of the graphite hollow cathode after an extended life test, which resemble those for the metal cathodes. The insert of this graphite hollow cathode is constructed with a W matrix and an emitting material (BaO, CaO, Al₂O₃), while the orifice plate and cathode tube are made of graphite. Accordingly, both chemical reactions between (1) emitter material and carbon, and (2) tungsten and carbon were focused on the analyses in addition to erosion due to ion bombardment.

II. Hollow cathode operation and performance

Figure 1 shows a graphite-orificed hollow cathode developed in JAXA, which was originally designed to generate a 150-mN-class ion thruster, and the nominal discharge current (J_d) is 15 A. Figure 2 shows a schematic view of this hollow cathode, the keeper disk, orifice plate, and cathode tube of which are made of high-density graphite to extend the life. Graphite is preferred for these components due to its low sputtering yield. The insert is a porous tungsten (W) matrix impregnated with a compound mixture of barium oxide, calcium oxide, and alumina (BaO-CaO-Al₂O₃) with a molar ratio of 4:1:1.

In the life test, the cathode was operated in a discharge chamber without beam extraction. Geometrical and magnetic conditions of the chamber are almost the same as those of JAXA's 150-mN thruster. The gridded area of the dummy-screen-electrode is restricted to simulate the discharge condition in the beam extraction operation with a reduced xenon flow rate. The cathode was operated at a fixed discharge current (J_d) of 15 A and a keeper current (J_k) of 1 A except for short-term operations used to obtain current-voltage characteristics.

The cumulative operation time and voltage variations during the test are shown in Fig. 3. The test was started in March 2006 and had accumulated 45,660 h of operation as of June 2012 when it was intentionally terminated. It should be noted that the life test was concluded prior to hollow cathode failure, meaning the 45,660 h duration represents the maximum demonstrated life but not the end of life for the hollow cathode. Figure 3 indicates that the discharge and keeper voltages remained almost stable at approximately 30 and 8 V, respectively, throughout the test and there were no gradual voltage increases due to cathode deterioration.

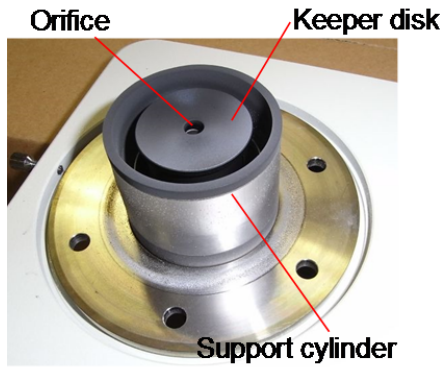


Figure 1. Graphite hollow cathode for main plasma discharge in ion thruster.

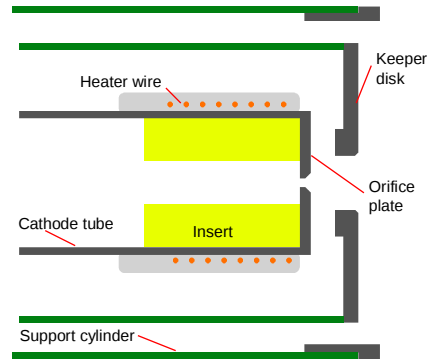


Figure 2. Schematic of graphite discharge cathode. Keeper disk, orifice plate, and cathode tube are made of graphite.

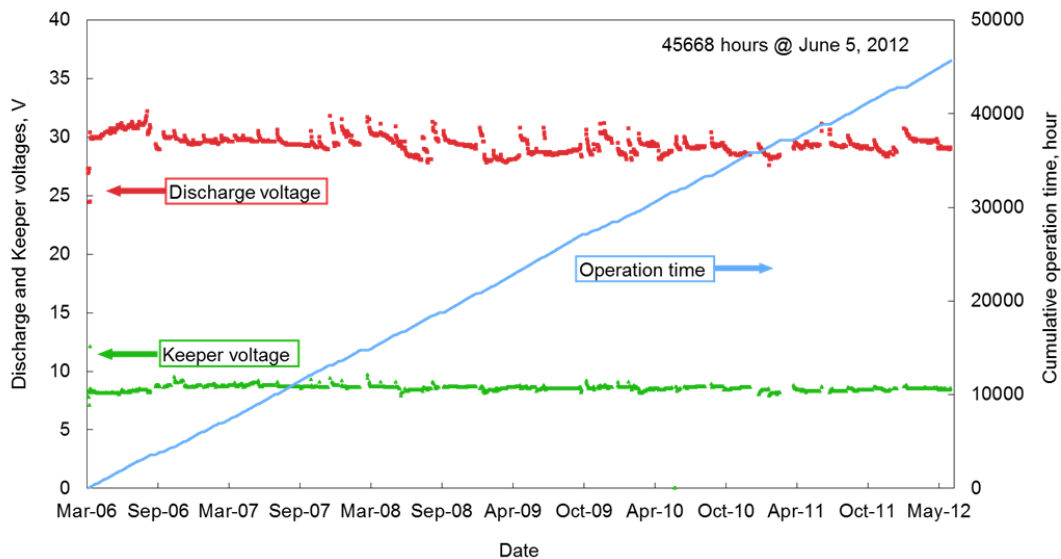


Figure 3. Cumulative operation time and voltage variations during 45,660-hour life test.

III. Destructive analysis

A. Keeper disk

Close-up views of the downstream surface of the keeper disk after the life test are shown in Fig. 4. Microscopic observations were conducted five times in the life test, before operation and after 4,400, 13,100, 31,600 and 45,660 h of operation. As shown in Fig. 4, almost no signs of erosion were observed on the keeper disk. To verify this observation result, the geometry of the keeper surface was measured using a laser displacement sensor (LDS) after

45,660 h of operation. The measured geometry is shown in Fig. 5 as red dots with the initial shape as black solid lines. This measurement indicated that the keeper surface was slightly eroded adjacent to the aperture but not near the periphery. The erosion in the most eroded area was less than 0.2 mm after 45,660 h of operation, which shows that adopting graphite may solve the problem of keeper disks eroding.

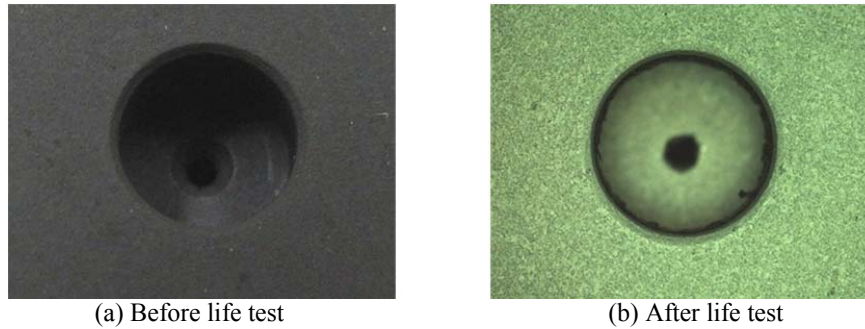


Figure 4. Downstream surface of keeper disk before and after 45,660-hour life test.

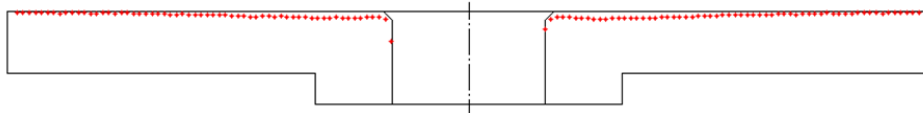


Figure 5. Keeper disk geometry measured by laser displacement sensor (LDS) after 45,660-hour operation.

B. Orifice plate

Figure 6 shows a scanning electron microscopy (SEM) image of the downstream surface of the orifice plate after the life test. The orifice diameter expanded by approximately 10% over the initial condition. A cross-sectional view of the orifice plate after the life test is shown in Fig. 7 as blue dots with the initial shape as black solid lines. This view was measured by an optical 3D surface metrology system: Infinite Focus®, Alicona. The maximum eroded depth of the downstream side was about 0.2 mm, which was close to that of the upstream side. The orifice plate remained thick enough.

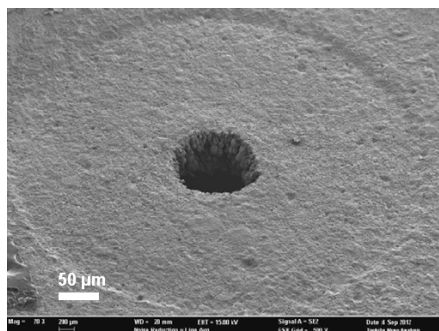


Figure 6. Downstream surface of orifice plate after 45,660-hour life test.



Figure 7. Orifice plate geometry measured by optical 3D surface metrology system after 45,660-hour life test.

C. Insert

The cathode insert was halved along the axis, and observed by optical microscopy, scanning electron microscopy (SEM), energy-dispersive X-ray analysis (EDX), electron probe micro analysis (EPMA), and X-ray diffraction (XRD).

(C-1) Outer diameter surface of the insert

The cathode insert was easily extracted from the cathode tube, to which it did not adhere. Figure 8 shows an SEM photograph of the outer diameter surface of the insert, which was clean and had almost no BaO deposition. The insert is constructed with tungsten and an emitter ($\text{BaO}, \text{CaO}, \text{Al}_2\text{O}_3$), while the cathode tube is made of graphite. Based on the SEM photograph, the insert did not react chemically and physically with the cathode tube. These results show that using graphite would be appropriate for the orifice plate and cathode tube.

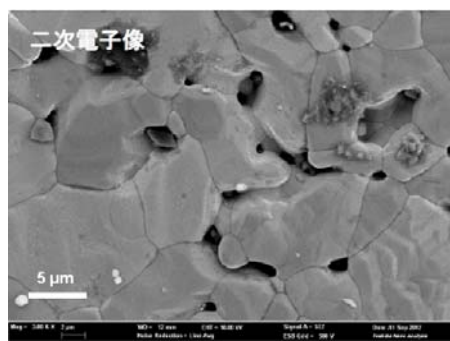


Figure 8. Outer diameter surface of insert after 45,660-hour life test.

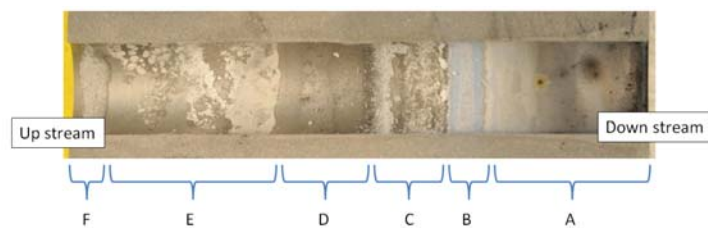


Figure 9. Close-up view of inside wall of insert after 45,660-hour life test.

(C-2) Inner diameter surface of the insert

Figure 9 shows a close-up view of the inner diameter surface after the life test, characterized by six zones along the axis, the inside of each of which was uniform. These zones were named A to F and are shown in typical SEM photographs in Fig. 10. Their features are as follows:

- Zone A: Around 7 mm in length along the axis. The shape of the porous tungsten surface was flat due to ion bombardment compared with the original surface and a few emitter particles comprising Ba, Al, and O were detected by EDX on the surface, although minute and only a few micro meters in size. No tungsten crystallite deposition, tungstates, or other poisoning layers were detected on this zone. Many pores of the porous tungsten existed on the surface. Therefore the entire length of this zone would have contributed to electron emission.
- Zone B: The length along the axis was 1.5 mm. The pores on the surface were covered with a ca. 42-μm-thick layer of an indeterminate substance, containing emitter ingredients comprising Ba, Ca, Al and O. BaCaWO_6 was detected in these ingredients by XRD and this zone would have not contributed to electron emission.
- Zone C: The length along the axis was 3 mm. The surface pores were covered with a ca. 23-μm-thick layer of an indeterminate substance, containing emitter ingredients comprising Ba, Ca, Al and O.
- Zone D: The length along the axis was 4.5 mm. No tungstates or other oxide/poisoning layers were detected on this surface. Since surface pores of porous tungsten were present, this zone would have contributed to electron emission.

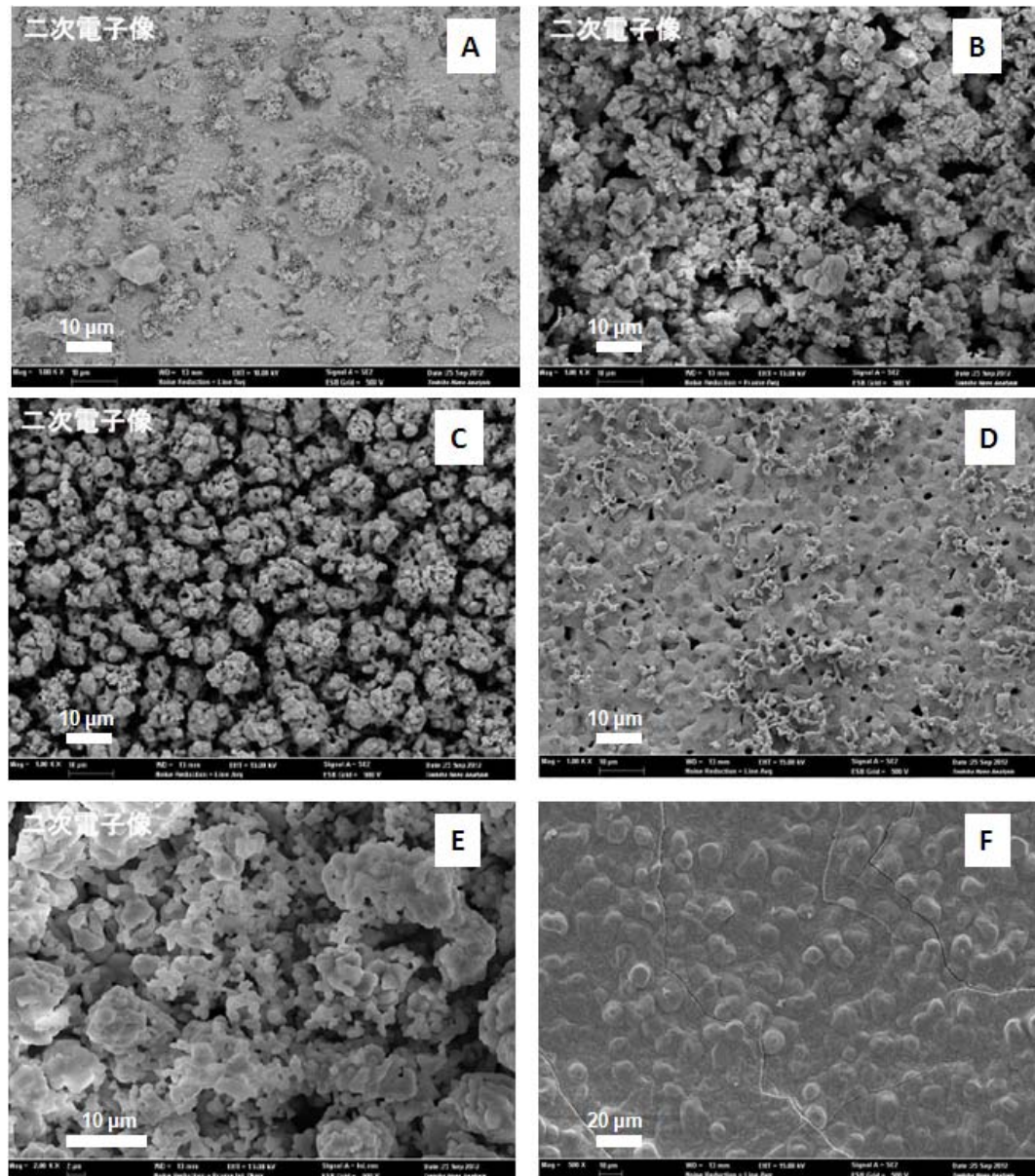


Figure 10. SEM photographs of inside wall surface of insert after 45,660-hour life test.

- Zone E: The length along the axis was 7.5 mm. The surface pores were covered with a ca. 20-μm-thick layer of an indeterminate substance, containing emitter ingredients comprising Ba, Ca, Al and O.
- Zone F: The length along the axis was 1.5 mm. The surface pores were covered with a ca. 10-μm-thick layer of an indeterminate substance, containing emitter ingredients comprising Ba, Ca, Al and O. This layer had some cracks, propagated by surface tension during the phase transition from liquid to solid. Since no pores were found in this area, this zone would not have contributed to electron emissions.

(C-3) Depletion of Ba

The emitter impregnated in the porous tungsten matrix evaporates from the surface. Since impregnant depletion occurs near the surface, the depleted depth increases with lifetime. We can roughly predict the remaining insert lifetime by measuring this depleted depth. EPMA was used to provide a semi-quantitative measure of impregnant depletion. Figure 11 shows the depleted depth as a function of axial distance from the orifice plate. The depleted depth at 1 mm from the orifice plate was 470 μm , showing a non-linear decrease with axial distance. At 7 mm upstream from the orifice plate, the depletion depth was about 0 μm . The depleted depth of 470 μm is smaller than the insert thickness.

Shroff et al. investigated the cathode life as a function of the Ba evaporation rate for the impregnated cathodes during an extended test and established an empirical relationship between the depleted depth and lifetime, whereby the Ba depleted depth was proportional to the square root of time⁹. Using this relation, the estimated Ba drying up time of our insert is hundreds of thousands of hours.

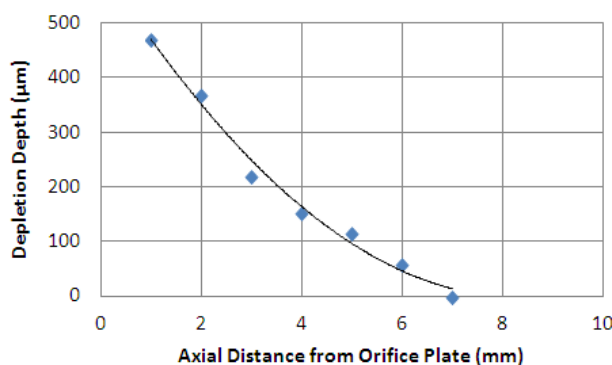


Figure 11. Impregnant depletion depth as a function of axial distance from the orifice plate for the insert.

D. Heater

A heater is one of the key components of the hollow cathode. Regarding the heater, we observed (1) a change in the electrical resistance of the heater coil, (2) deformation of the heater coil, (3) a chemical reaction between the heater wire and the insulating material, (4) peeling of the heater wire with the insulating material, (5) a chemical reaction between the insulating material and the cathode tube and (6) peeling of the insulating material with the cathode tube. Moreover, we confirmed that there was no problem affecting the hollow cathode characteristics.

IV. Discussion

A. The merit in choosing graphite as the keeper and orifice plate materials

Doerner et al. measured the sputtering yields of molybdenum and carbon against low energy xenon ion bombardment¹⁰. The sputtering yields of molybdenum at energy of 50 eV were 0.003 and 0.006 atoms/ion, while that of carbon was 0.0002 atoms/ion which was 15-30 times smaller than that of molybdenum. Carbon yields below 50 V are unknown, while the carbon yield at 30 V is expected to be several orders of magnitude lower than those at 50 V. Conversely, the molybdenum yield at 30V is about one tenth of those at 50V. Based on the difference in sputtering yields, the carbon keeper was not heavily eroded under conditions which would cause a molybdenum keeper electrode to disappear. No chemical reaction occurred between graphite and tungsten or barium oxide, the cathode tube and insert materials, while the portion where the outer insert surface contacted the graphite directly showed no trace of any carbon and tungsten reaction. Nor was any compound, including carbon, found in an abnormal quantity on the inner diameter surface of the insert. Accordingly, from a chemical reaction perspective, the use of graphite for the orifice plate and cathode tube is not problematic.

B. Emission domain of the insert inside having been sufficiently secured

The insert inner surface was clean, within 7 mm from the downstream edge (Zone A) and included many pores as shown in Fig. 12. Either no tungsten crystallite was deposited or no poisoning layer was formed. We think that this clean surface was one of the main reasons for the long-term stable operation. To keep Zone A in such good condition, the temperature of the insert should be sufficiently low. Though the insert temperature was not measured during the life test, we estimated it by measuring the insert temperature using another cathode and calculating the temperature distribution by numerical analysis.

The insert temperature was measured in triode testing using another hollow cathode of the same type. Thermocouples (Pt/Pt-Rh) were attached to the downstream end of the insert as shown in Fig. 13. Figure 14 shows the measured temperature, which was 1,120 °C at a discharge current of 15 A.

The insert temperature distribution under discharge condition was calculated using Thermal DeskTop® thermal analysis software. After modeling the hollow cathode assembly, and heat sources with power equivalent to discharge power were attached to the surfaces of the insert and orifice plate. The calculation results based on an insert downstream end temperature of 1,120 °C are shown in Fig. 15. The temperature difference between both ends of the insert was 77 K, while that in Zone A was 22 K.

Polk et al. measured the temperature distribution in a hollow cathode, which is the same as the Space Station Plasma Contactor cathode¹¹. They reported that the insert temperature at the downstream edge was 1,180 °C and the temperature difference between both edges was 200 K where $J_d = 12$ A. Compared with these results, the temperature of the downstream edge of our cathode is low and the temperature difference is also small. The expanded emission area due to this small temperature difference meant a lower maximum temperature. We attribute this clean surface to the low operating temperature and small temperature difference.

Conversely, the clear partitioning inside the wall of the insert in six area along the axis was considered attributable to (a) temperature distribution, and/or (b) plasma discharge mode. However, it is unclear how the inside wall surface was clearly partitioned in the six areas.

C. Life estimation

We estimated the life of our hollow cathode. The main factor dictating the life of the hollow cathode assembly, as mentioned above, was erosion of the orifice plate. The eroded depth of the orifice plate on each side was 0.2 mm respectively at 45,660 h. The remainder is 0.6 mm because the thickness of the orifice plate is designed to be 1 mm. The estimated remaining life is 67,500 h if we assume the eroded depth is proportional to time.

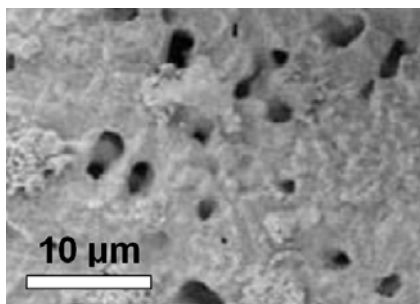


Figure 12. Inside diameter surface of “Zone A” of insert after 45,660-hour life test.

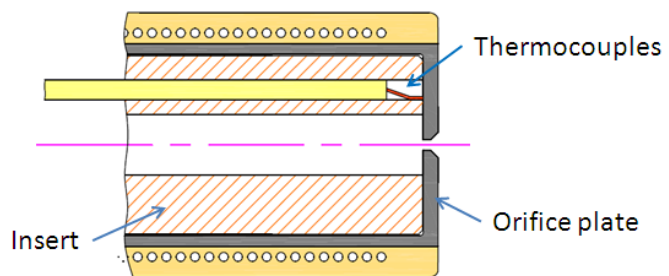


Figure 13. Cross-section of graphite discharge cathode showing thermocouple location in insert.

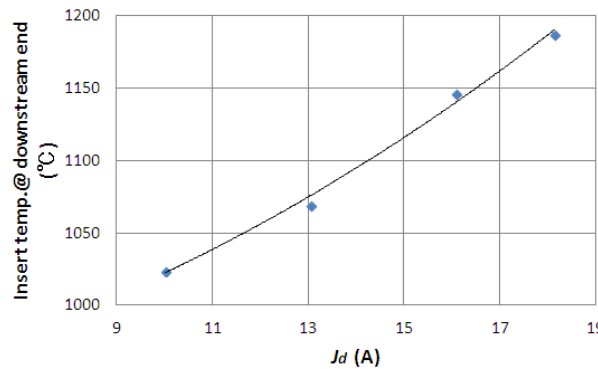


Figure 14. Measured insert temperature at downstream end vs. discharge current(J_d).

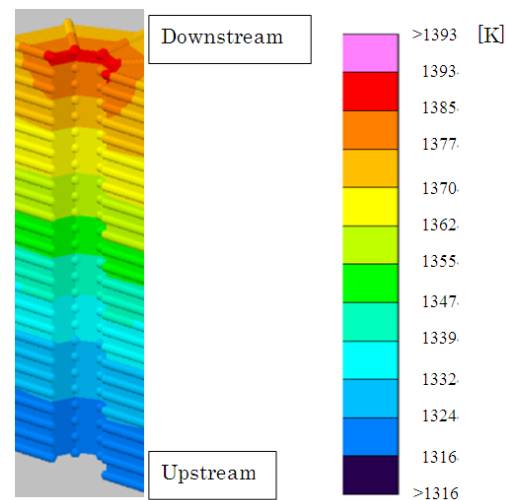


Figure 15. Calculated temperature distribution of the insert.

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