Hollow Cathode Life Test for the Next-Generation Ion Engine in JAXA

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Abstract: An overview and current status of a hollow-cathode-life test for the next-generation ion engines in the Japan Aerospace Exploration Agency are described. Key features of this hollow cathode are 1) electron-emission capability of over 20 A, which corresponds to the ion-engine operation at the 200-mN thrust level, and 2) graphite parts adopted for anti-erosion. The objectives of this life test are to demonstrate the durability of the cathode and to prove the effectiveness of the graphite parts. The test is being conducted using a discharge chamber in order to simulate the conditions in the real thruster operation. Cumulative cathode-operation time reached 11,000 hours at the end of August 2007, and the test is successfully in progress. The degradation in performance has hardly been found from the changes in discharge and keeper voltages and start-up period.

Nomenclature

J_d = discharge current
J_g = grid current
J_h = heater current (for ignition)
J_k = keeper current
V_d = discharge voltage
V_k = keeper voltage
m_c = cathode flow rate
m_d = distributor flow rate

I. Introduction

THE Institute of Aerospace Technology in the Japan Aerospace Exploration Agency (JAXA/IAT) has been developing next-generation ion engines,[1] which covers a wide thrust range up to 200 mN. Promising applications of the thrusters are station keeping of heavy and long-life geostationary satellites, the orbit insertion of geostationary satellites, large-scaled ambitious science missions, and drag compensation of very low altitude satellites. Figure 1 shows a breadboard model of the next-generation ion engine, whose beam extraction diameter is 35 cm. The thruster has already achieved very high performance over the wide thrust range from 80 to 200 mN as summarized in Table 1, therefore, current efforts are directed to the evaluation of reliability and endurance

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performance. The most important factors that determine the lifetime of ion engines are ion optics and cathodes. Although lives of hollow cathodes are generally longer than those of ion extraction electrodes, it is necessary to demonstrate the durability of hollow cathodes for future ambitions missions.

Figure 1. Breadboard model of JAXA next-generation ion engine.

Major life-limiting factors of hollow cathodes are categorized into following three points: A) Depletion or contamination of an impregnated cathode, B) Erosion of a keeper disk or an orifice plate, and C) Short-circuit or disconnection of a heater wire. On the each life-limiting factor, many meaningful studies have been reported in these several years, e.g., 30,000-hour life-test of DS1 spare engine,[2] modeling of depletion of impregnated materials,[3] development of a reservoir hollow cathode,[4] plasma measurement nearby cathodes,[5] and life test of a heater.[6] These studies are very interesting and meaningful, however, it is difficult to estimate the durability of our own devices from the extension of these studies because thermal and electrical design differs. Therefore, we started the life test of a discharge hollow cathode of the next-generation ion engine in March 2006. In this paper, current status of the life test is described.

Table 1. Typical performance of JAXA Next-generation ion engine.

Thrust, mN	Specific impulse, s	Ion prod. cost, W/A	Propellant util. effi., %	Thruster effi., %	Input power, kW
81	3440	132	90.2	74.5	1.83
151	3480	117	90.0	76.7	3.36
181	3490	115	90.1	77.2	4.00
201	3490	110	90.0	77.5	4.45
210	3500	110	90.2	77.7	4.64

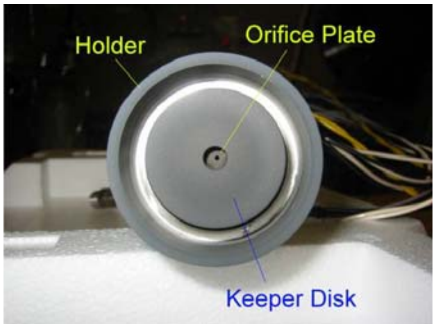
* Without the consideration of beam divergence and multiply charged ions.

II. Graphite Hollow Cathode

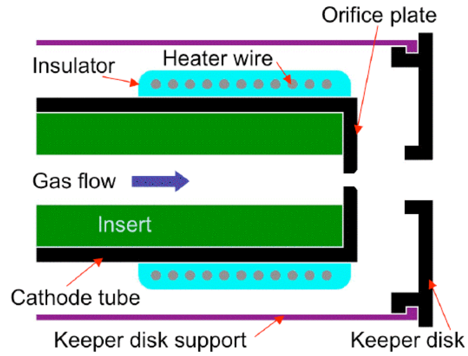
Several types of discharge cathodes had been developed in JAXA for the next-generation ion engines. A 5,000-hour endurance test[7] of the thruster had been performed using one of those cathodes with conventional metal electrodes, and it was confirmed that the cathode possessed sufficient durability. However, severe erosion of the orifice plate and the keeper disk was observed in the test, and it was suggested that the electrode erosion caused performance degradation of the cathode.

In order to suppress the performance degradation for longer operation period, materials with less erosion rate is more desirable to be used as an orifice plate and a keeper disk. Graphite is a suitable material for them because its sputtering yield is small enough under ionized-xenon bombardment with energy lower than 60 eV.[8]

A graphite discharge cathode[9] shown in Fig. 2 was finally developed after try and error efforts. In this cathode, the keeper disk, orifice plate, and cathode tube are made of graphite called "high density graphite." In building hollow cathodes, the machinability of material constrains the dimensions and shapes. Certain configurations cannot be formed with graphite even though it could be formed with metals because, e.g., forming a thin tube with graphite is very difficult. The graphite hollow cathodes used in this research were not the same in shapes as the metal hollow cathodes ever used on this account. In addition, connecting graphite parts with other metal parts needed some sophisticated techniques. The cathode insert is composed of a porous tungsten body impregnated with barium oxide. The cathode can emit a current up to 21 A, which corresponds to 200-mN thrust operation of the next-generation ion engines.



(a) Front view



(b) Schematic drawing

Figure 2. Graphite hollow cathode.

Using graphite for orifice plates and cathode tubes had been hesitated because carbon carburized tungsten at high temperatures to produce tungsten carbide. Despite such a threat, any problems have not been found in our pre-life tests. A typical temperature of the orifice plate measured with a two-color pyrometer in these tests was less than 1000 °C at a steady run and this is low enough to avoid the reaction.

III. Test Apparatus

The most important point of the life test is to operate the cathode in the conditions equivalent to those in the real thruster. In order to meet this requirement, the cathode is operated in a discharge chamber whose geometrical and magnetic conditions are almost the same as those of the real thruster. The discharge chamber is shown in Fig. 3. The chamber possesses a propellant manifold as the thruster has for setting a chamber pressure flexibly. A water-cooling pipe is wound around the chamber because there is no special treatment for radiative cooling.

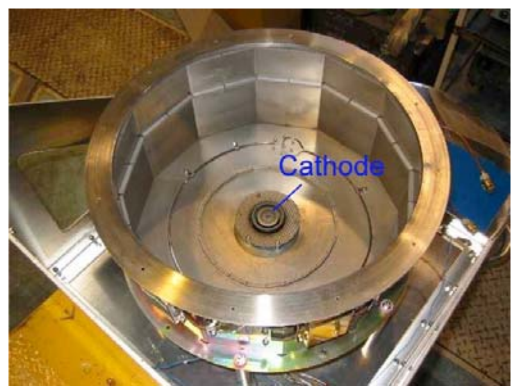


Figure 3. Discharge chamber for life test.

Figure 4 shows a grid and mask set on the downstream side of the discharge chamber. More than 70% of the grid area is masked to reduce the gas conductance, thus, to reduce xenon consumption. The masking area ratio was adjusted to obtain suitable operating conditions. The grid, which was used initially, was made of stainless steel, however, it was exchanged to molybdenum one in August 2006 because the grid erosion became serious as described later. The grid shown in Fig. 4 is the one made of stainless steel.

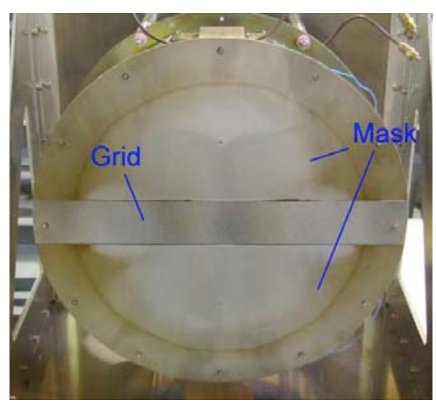


Figure 4. Grid and mask on discharge chamber.

The testing configuration is shown in Fig. 5. A discharge current, discharge voltage, keeper current, keeper voltage, cathode flow rate, distributor flow rate, pressure in vacuum tank, and temperature in cathode base are automatically acquired every minute using a data acquisition system. A grid current is measured with an analog ammeter once a day. When the extraordinary pressure or temperature is detected, the cathode operation is halted automatically.

The test is conducted in a vacuum tank, whose diameter and length are 0.9 m and 1.5 m, respectively. The tank pressure is almost constant at 5 x 10^{-3} Pa for N_2 throughout the cathode operation. Temperature around xenon flow controllers is kept constant at 25 °C to avoid fluctuation of the flow rate due to temperature change.

IV. Cathode Operation

In order to simulate the cathode operating conditions in the real thruster, the discharge voltage, discharge current, and cathode flow rate in the life test should be similar to those in the thruster operation. In this life test, these three parameters are adjusted by selecting appropriate masking area ratio of the grid and the cathode axial position. Table 2 shows typical operating and measured parameters in the life test. The discharge voltage, discharge current, and cathode flow rate in the table are almost equivalent to those for 150-mN-thrust operation of the next-generation ion engine. In addition, a grid current of 3.2 A in this test is reasonable because the summation of a beam current and drain current in the thruster operation with 150-mN-thrust levels is close to this value.

In a cathode ignition sequence, a keeper open voltage of 250 V and an anode open voltage of 37 V are applied at first, and the cathode is heated with a heater current of 10.5 A. The heater power is cut immediately after the ignition.

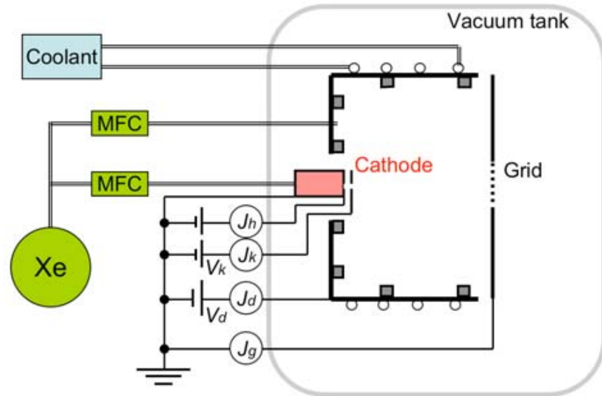


Figure 5. Configuration of life test.

Table 2. Typical operating parameters in life test.

Discharge current, J_d	15.0 A
Discharge voltage, V_d	29.7 V *
Keeper current, J_k	1.0 A
Keeper voltage, V_k	8.8 V *
Grid current, J_g	3.2 A *
Cathode flow rate, m_c	250 mAeq
Distributor flow rate, m_d	50 mAeq
Propellant	Xenon

* Measured values.

V. Life Test

The life test of the discharge cathode had started in March 2006, and the cumulative operation time reached 11,000 h at the end of August 2007. The test is still going on. Figure 6 shows the cumulative operation time and important events, which were accompanied by exposure to atmosphere. Flat sections of the plot designate interruption periods of the cathode operation. The rate of operation has been 84% so far.

The number of intentional and unexpected interruption has been 21 and 5, respectively. Major reasons for the intentional interruptions were xenon-bottle changing, planned outages, maintenance of peripherals, and maintenance of the discharge chamber. Causes for the unexpected interruption were failures of cryogenic pumps and blackouts due to thunderbolts.

The stainless steel grid, which was initially installed, was changed to the molybdenum one due to erosion in August 2006 as described later. In November 2006, the vacuum tank was opened to remove a flake that caused

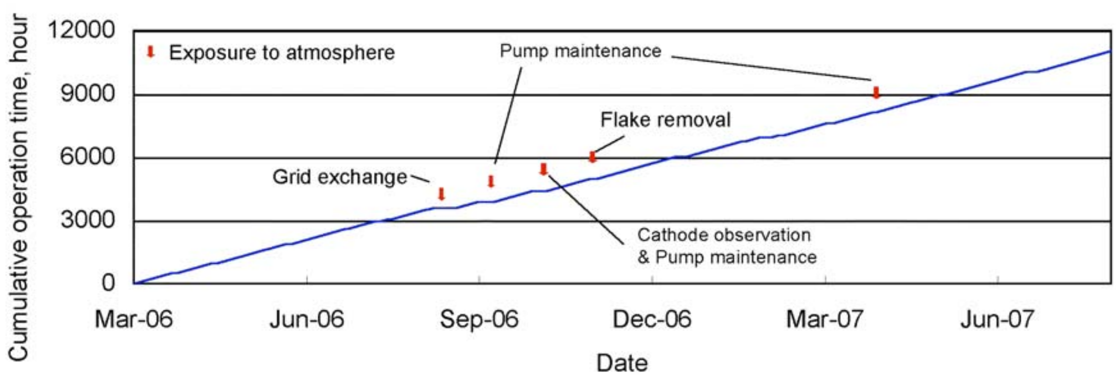


Figure 6. Cumulative operation time and important events.

short-circuit between the anode and the grid. Exposure of the cathode to atmosphere has been 5 times so far including these two events.

Discharge luminescence through the masked grid is shown in Fig. 7. The hollow cathode is located on the most luminous part in the central region.

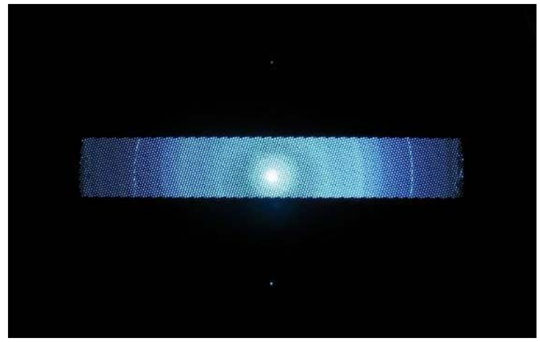


Figure 7. Discharge luminescence through masked grid.

A. Discharge Voltage

The variation of the discharge voltage in the life test is shown in Fig. 8. Although the discharge voltage has been always around 30 V, its behavior is clearly different before and after the interruption in August 2006.

Before this interruption, the discharge voltage had risen gradually for 5 months, and then rose sharply. The reason for this undesirable behavior is the increase in gas conductance through the grid due to the grid erosion. Since the stainless steel grid, whose sputtering yield is very high, was used in this period, the grid holes had been enlarged gradually with ion bombardment. This hole-enlargement caused the increase in gas conductance through the grid, thus, the decrease in the discharge-chamber pressure. Finally, a large hole with a diameter of about 1.5 cm appeared in the central part of the grid, and the discharge voltage showed abrupt increase simultaneously as shown in Fig. 8. After this trouble, the grid was exchanged to the new one made of molybdenum.

The discharge voltage after this grid exchange has been constant and stable around 29.7 V on the contrary to the initial behavior. This result indicates that the voltage increase described above was not attributable to the cathode problem but the problem on the grid. Some irregular voltage drops in Fig. 8 mean the transient responses from high voltage conditions after the ignitions. It usually takes a week for the voltage to become stable. Exposure of the cathode to atmosphere usually accompanied large voltage drops. No severe erosion was observed on the molybdenum grid at the flake removal operation in November 2006. The behavior of the discharge voltage after August 2006 indicates that the molybdenum grid has not been damaged seriously.

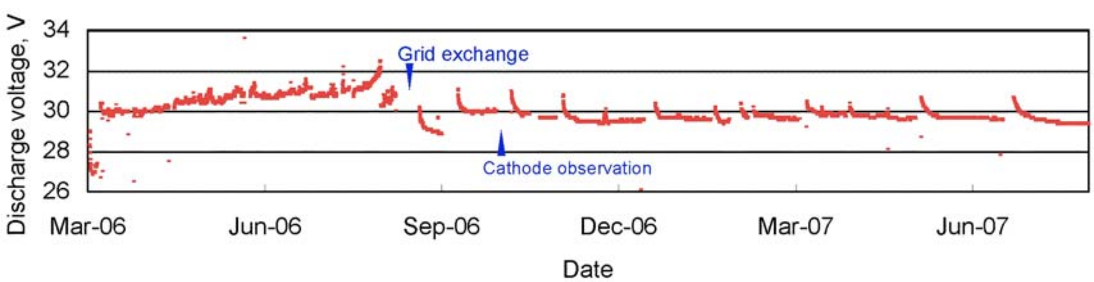


Figure 8. Discharge voltage variation.

B. Keeper Voltage

Figure 9 shows the variation of the keeper voltage in the life test. As the same as the discussions on the discharge voltage, the characteristics of the keeper voltage differ before and after the grid exchange.

The keeper voltage gradually increased up to 8.4 V before the grid exchange and jumped up to 8.8 V just after the exchange. After the several times of exposure events including this grid exchange, the voltage became stable around 8.8 V. The fluctuation of the voltage is a transient behavior following the ignition events. These results indicate that exposure to atmosphere affected the condition of the cathode insert, and the keeper voltage rose to keep the nominal electron emission. In other words, degradation of the insert, orifice plate and keeper disk due to long-term operation has been at negligible levels so far. The remarkable high voltage in October 2006 was due to long exposure of the cathode to air because of the cathode observation procedure.

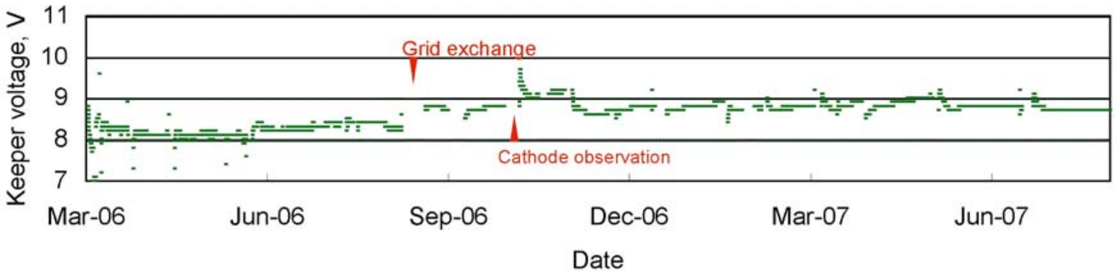


Figure 9. Keeper voltage variation.

C. Performance Curve

The relationship between the discharge voltage and current has been obtained every several months. Figure 10 shows the discharge voltages plotted against the discharge current from 10 to 20 A. The results of five measurements from March 2006 to July 2007 are shown in the figure. At each measurement, the cathode worked stably over the range of the discharge current.

The discharge voltage in the beginning showed the lowest value throughout the range, especially in the high current region, however, the difference is not so significant. The reason for the highest voltage appeared in May 2006 would be the increase in the open area fraction of the stainless steel grid as described above. No sign of performance degradation of the cathode due to the long-term operation is found from this figure.

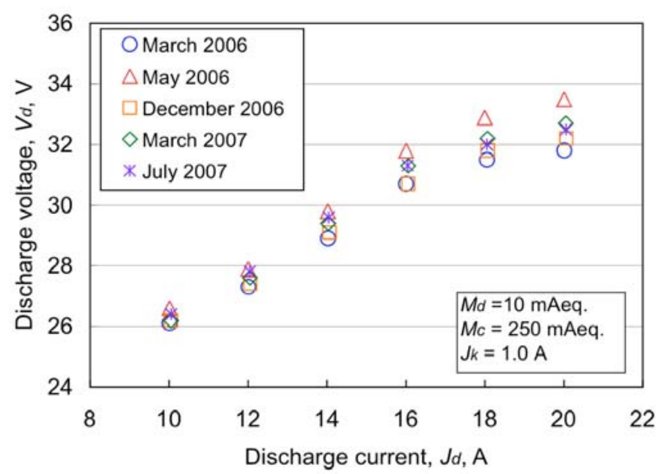


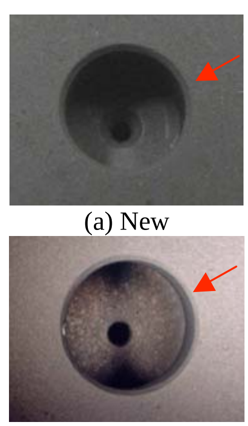
Figure 10. Discharge voltages plotted against discharge current from March 2006 to July 2007.

D. Keeper Disk and Orifice Plate

A keeper disk and an orifice plate of the hollow cathode are made of graphite. Confirming the durability of these parts is one of the important objectives of this life test. Figures 11 and 12 show the downstream faces of the keeper disks and the orifice plates respectively: (a) for before use and (b) for after 4400-hour operation. Note that the electrodes compared here are not the same ones but its initial shapes are equivalent to each other.

As shown in Fig. 11, no signs of the erosion cannot be observed on the keeper disk. Since severe erosion problems on keeper disks had been reported in some endurance tests,[2,7] the adoption of graphite could be a perfect solution to the keeper erosion problem.

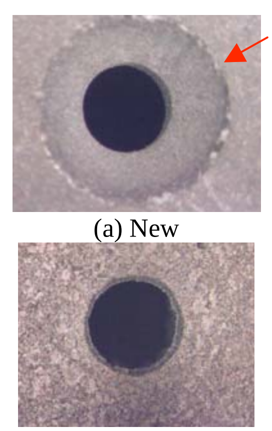
Figure 12 illustrates, on the other hand, that the orifice plate had been



(a) New

(b) After 4400-hour operation

Figure 11. Keeper disk.



(a) New

(b) After 4400-hour operation

Figure 12. Orifice plate.

eroded to a certain degree through the 4400-hour operation. One of the major shape changes is the enlargement of the orifice, which became larger by less than 10%. Another observed change is the erosion of the downstream surface. The shoulder of the taper on the periphery cannot be observed after the 4400-hour operation. In addition, the surface looks rough after the operation. The falling-off of carbon filler, which was impregnated into the graphite body to build up high-density graphite, due to high temperatures or ion bombardment probably caused this appearance change.

These results point out that a certain degree of erosion of the orifice plate would be unavoidable even if graphite with excellent sputtering tolerance is used. However, this erosion problem might be not serious because the shape change would not continue permanently. We guess that the shape of an orifice plate would be adjusted to appropriate geometry to maintain appropriate plasma condition, and the adjustment would be finished after a certain period of the operation. In this life test, this shape-adjustment-phase would be finished before the interruption for the grid exchange. The voltage stability in Figs. 8 and 9 after the grid exchange supports this hypothesis.

Although it is desirable to observe the orifice plate periodically, detailed observation has not conducted after this photography since long exposure of the cathode to atmosphere may affect the insert condition as discussed on Fig. 9.

E. Ignition Characteristics

The time required for ignition is an indicator to discuss the degradation of the hollow cathode. The periods required in the past 33 ignitions are shown in Fig. 13. The keeper open voltage, anode open voltage, and heater current were 250 V, 37 V, and 10.5 A, respectively, in most of the ignition procedures. Cathode temperatures before heating were usually below 30 °C.

The ignition time varied widely and it is difficult to discuss the tendency, however, it seems that the required time became longer slightly as the operation time elapsed. A possible reason for this trend is insufficient insulation between the winding heaters.

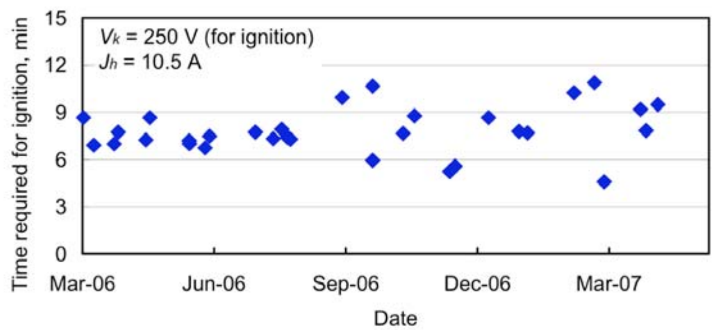


Figure 13. Variation of time required for ignition.

F. Carburization

One of the important objectives of this life test is to sweep away the fears of tungsten carburization. Since graphite is used for the orifice plate and the cathode tube in the hollow cathode, it had been worried that carbon carburized tungsten, which was the material of the insert body, at high temperatures to produce tungsten carbide.

Despite such fears, no problems concerning the carburization have been observed so far. A typical temperature of the orifice plate measured in pre-life-tests was less than 1000 °C and this is low enough to avoid the reaction. No carburization was also verified by the stable discharge and keeper voltages illustrated in Figs. 8 and 9.

VI. Conclusion

A life test of a discharge cathode made of graphite had started in March 2006. The cumulative operation time had reached 11,000 h at the end of August 2007, and the test is still going on. Variations of the discharge voltage, keeper voltage, and time required for ignition indicate that there has been no serious deterioration on the cathode performance. Although the cathode insert might have slight damage due to exposure to air, it stayed at permissible levels. No erosion has been observed on a graphite keeper disk. A graphite orifice plate was eroded slightly, however, it was conjectured that the shape-change had been terminated in an early phase of the test. No sign of tungsten carburization has been detected.

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