Endurance Tests of Graphite Orificed Hollow Cathodes

IEPC-2009-022

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

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Abstract: This paper describes the present status of endurance tests of graphite orificed hollow cathodes at the Japan Aerospace Exploration Agency (JAXA). Discharge and neutralizer cathodes have been developed for JAXA's xenon ion engines. In order to achieve long life with stable performance, the keeper disk, orifice plate, and cathode tube in these cathodes are made of high-density graphite. An endurance test of the discharge cathode was started in March 2006 in a discharge chamber without beam extraction. Cumulative operation time reached 25,800 hours in August 2009 and there have been no signs of performance deterioration so far. An endurance test of the neutralizer cathode was started in June 2008 and has accumulated 9,300 hours of operation.

Nomenclature

J_A	=	anode current
J_b	=	beam current
J_d	=	discharge current
J_g	=	grid current
J_h	=	heater current
J_k	=	keeper current
J_{nh}	=	neutralizer heater current
J_{nk}	=	neutralizer keeper current
m_c	=	cathode flow rate
m_d	=	distributor flow rate
m_{nc}	=	neutralizer cathode flow rate
V_A	=	anode voltage
V_c	=	coupling voltage
V_d	=	discharge voltage
V_h	=	heater voltage
V_k	=	keeper voltage

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V_{nh} = neutralizer heater voltage
V_{nk} = neutralizer keeper voltage

I. Introduction

ORIFICED hollow cathodes are mature electron sources which feature high electron emission capability and long life. Many ion engines and Hall thrusters have adopted the hollow cathode for plasma generation and beam neutralization. The International Space Station also uses the hollow cathodes to relieve undesirable spacecraft charging. Although the long-term operational capability of the hollow cathodes has been demonstrated in many studies, some erosion problems of the electrodes have been reported.[1-5] In a 5,000-hour endurance test[1] of JAXA's 150-mN ion engine,[6] a certain level of erosion was observed on the keeper disk and orifice plate of the discharge cathode, and it was suggested that this erosion caused the engine's performance to change. Another endurance test[2] of a hollow cathode also showed that the orifice plate eroded with time and that this might change its operating characteristics.

To acquire longer life with less performance degradation, we have developed graphite orificed hollow cathodes for main discharge and ion beam neutralization. Endurance tests of the discharge and neutralizer cathodes were started in March 2006 and June 2008, respectively. This paper describes the present status of these tests.

II. Graphite Orificed Hollow Cathodes

Figure 1 shows a schematic of a graphite orificed hollow cathode[7] in which the keeper disk, orifice plate, and cathode tube are made of high density graphite. The orifice plate and cathode tube form a single piece as shown in Fig. 1, while the cathode insert is composed of porous tungsten impregnated with a mixture of barium oxide, calcium oxide, and aluminum oxide.

Figure 2 shows the graphite orificed hollow cathodes developed for main discharge and beam neutralization. The discharge cathode incorporates a support cylinder, the tip of which is made of graphite to avoid erosion problems. The design maximum emission currents of the discharge and neutralizer cathodes are 21 A and 4 A, respectively.

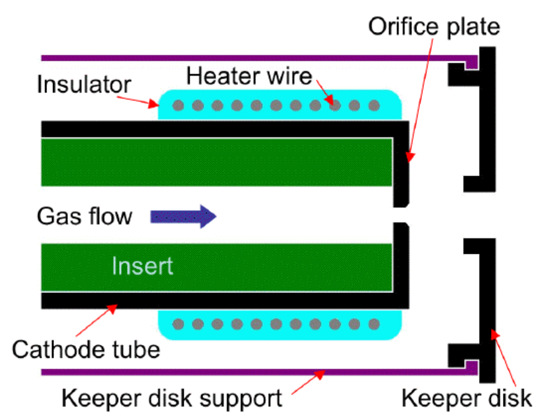


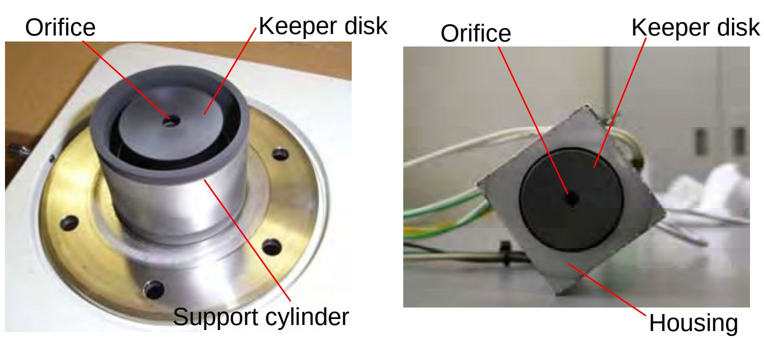
Figure 1. Schematic of graphite orificed hollow cathode. *Black colored parts (keeper disk, orifice plate, and cathode tube) are made of graphite.*

III. Discharge Cathode Endurance Test

An endurance test of the discharge cathode was started in March 2006 using a simulator of JAXA's 150-mN thruster. The cathode had accumulated 25,800 hours of operation as of August 2009.

A. Apparatus

Figure 3 shows a schematic of the test apparatus. The cathode is operated in a discharge chamber[8] to simulate thruster operating conditions. The geometrical and magnetic configurations of the discharge chamber are almost the same as those of the actual thruster. The temperature around the xenon flow controllers is kept constant by Peltier cooling and heating in order to avoid flow fluctuation due to temperature variation. Currents and voltages are sampled automatically at one-minute intervals by a data acquisition system. If an abnormal pressure or temperature condition is detected, cathode operation is halted automatically. The tank pressure



(a) Discharge cathode (b) Neutralizer cathode

Figure 2. Photograph of graphite orificed hollow cathodes. *(a) Discharge cathode, (b) Neutralizer cathode.*

during the cathode operation is maintained at approximately 5 x 10^{-3} Pa for N_2 by a 10,000-l/s cryogenic pump.

A front view of the discharge chamber during operation is shown in Fig. 4. The gridded area is restricted to a horizontal band to reduce xenon consumption.

B. Operation

Table 1 shows typical operating parameters for the endurance test and those of the 150-mN thruster. The discharge voltage and current and cathode flow rate in the endurance test are almost identical to those in thruster operation. The grid current of 3.2 A in the endurance test is reasonable compared with a beam current of 2.9 A during thruster operation. Therefore, it is expected that the conditions of the discharge plasma and neutral gases in the discharge chamber during the endurance test are comparable to those during thruster operation. The operating conditions have not been changed during the test except for short-duration measurements of current-voltage characteristics carried out every half year. In the cathode ignition sequences, a keeper open voltage of 200 V and an anode open voltage of 37 V are first applied, then the cathode is heated with a heater current of 10.5 or 12 A. Heater power is cut immediately after ignition occurs.

Figure 5 shows the electrical current distribution for the conditions shown in Table 1. Because the grid current of 3.2 A is derived from ion production in the discharge chamber, the electron emission current from the cathode is 12.9 A.

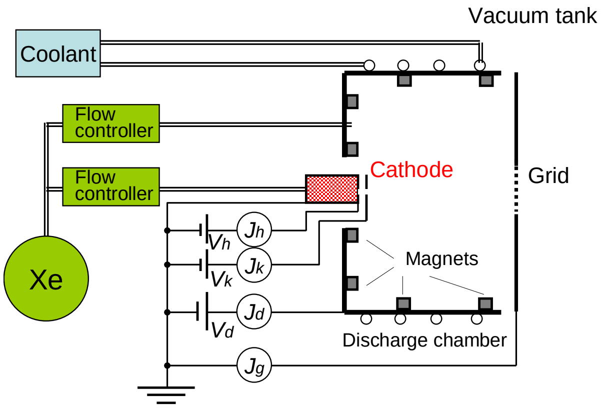


Figure 3. Test apparatus for discharge cathode endurance test.

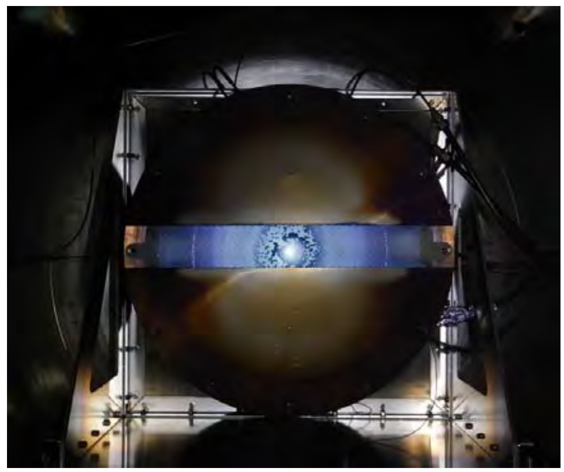


Figure 4. Front view of discharge chamber during cathode operation. *Discharge luminescence is visible through band-shaped grid area.*

Table 1. Nominal endurance test conditions compared with thruster operation.

	Endurance test	Thruster
*Beam current, J_b, A	-	2.9
*Grid current, J_g, A	3.2	-
Discharge current, J_d, A	15.1	15
*Discharge voltage, V_d, V	29	30
Keeper current, J_k, A	1.0	1.0
*Keeper voltage, V_k, V	8.5	7.4
Cathode flow rate, m_c, Aeq	0.25	0.23
Distributor flow rate, m_d, Aeq	0.05	2.97

* Measured values (typical)

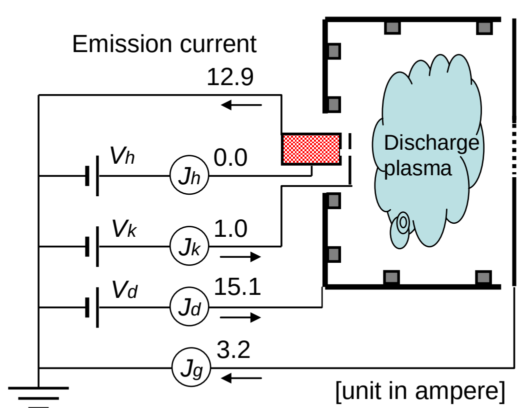


Figure 5. Current distribution in nominal operation.

C. Present Status

The discharge cathode endurance test was started in March 2006. The cumulative operation time and voltage variations during the test are shown in Fig. 6. The test had accumulated 25,800 hours of operation as of August 2009 and is still in progress. The rate of operation has been approximately 85%. The test has been interrupted approximately 50 times so far, 80% of these interruptions being intentional and 20% accidental. The most important event so far has been a change in the grid material from stainless steel to molybdenum in August 2006.[9] Since this event, there have been no modifications to the test apparatus.

Figure 6 indicates that the discharge and keeper voltages have been almost stable at approximately 30 V and 8 V, respectively, throughout the test and there have been no gradual voltage increases due to cathode deterioration. The glitches in the voltages are caused by transient phenomena in which the voltages rise for a short interval after ignition sequences as described later.

Although voltage variations have not been large so far, the discharge voltage behavior is different before and after the grid exchange in August 2006. Before this event, the discharge voltage had been rising gradually for 5 months from 30 to 32 V. The reason for this trend was an increase in the gas conductance of the stainless steel grid

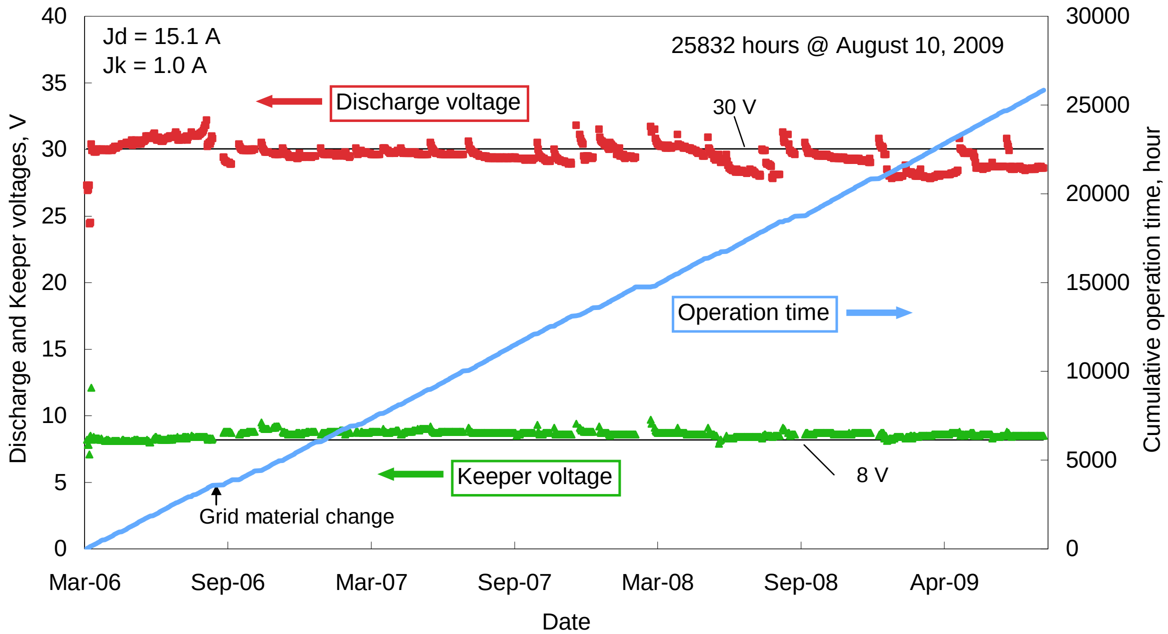


Figure 6. Discharge and keeper voltages and cumulative operation time in endurance test of discharge cathode from March 2006 to August 2009.

due to erosion.[9] The grid was therefore exchanged with one made of molybdenum. After the exchange, the discharge voltage became stable or rather showed a decreasing trend as shown in Fig. 6. This decreasing trend can be explained by examining the close-up front view of the grid shown in Fig. 7, taken in July 2009. Some grid apertures around the central area have become filled with material and the ratio of the filled area to the total perforated area is approximately 8%. This deposition caused an 8% decrease in gas conductance and increased gas pressure in the discharge chamber, leading to a reduced discharge voltage. The nature of the deposited material is unknown at present and analysis

Figure 7. Close-up view of central area of grid during operation in July 2009. *Filled apertures are distributed randomly around central area.*

will be conducted after the endurance test has been completed.

The keeper voltage has been fairly stable as shown in Fig. 6, and there have been no signs of cathode degradation such as depletion or contamination of the impregnated insert. Microscopic examinations of the electrodes in October 2006 and December 2007 revealed that the diameter of the orifice had increased by approximately 10% during the first several thousand hours of operation, but subsequent enlargement has been negligible.[9] This result might indicate that the shape of the orifice became adapted to the operating conditions after several thousand hours and this change was completed in the early stage of the endurance test. Microscopic examination also showed no erosion on the keeper disk.

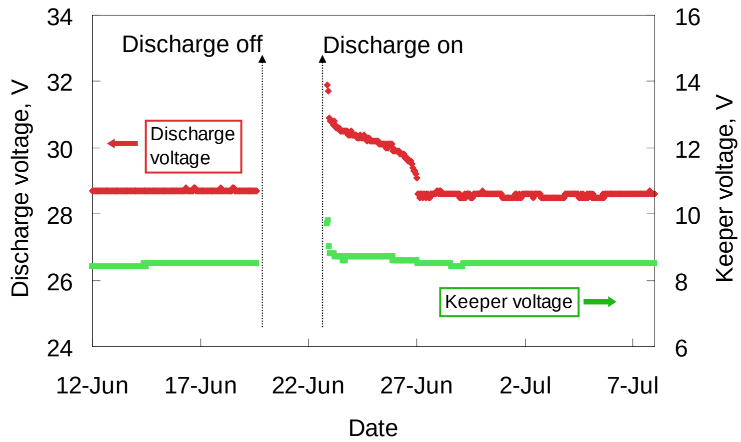


Figure 8. Short-term variations of discharge and keeper voltages before and after ignition from June to July 2009.

Figure 8 shows the short-term variations of the discharge and keeper voltages before and after ignition. The voltages rise just after ignition but return to their previous values approximately 100 hours after. This transient phenomenon is the reason for the glitches shown in Fig. 6. In this case, the test support apparatus was shut down during the interruption due to a scheduled power outage and the tank pressure rose to several tens of Pascals because of the release of trapped gases from a cryogenic pump. Ignition after interruptions without a halt in pumping requires less time to become stable, while ignition after atmosphere exposure needs longer to stabilize. In no cases were there any notable voltage changes before and after interruptions, so it is thought that the interruptions have limited effect on cathode degradation.

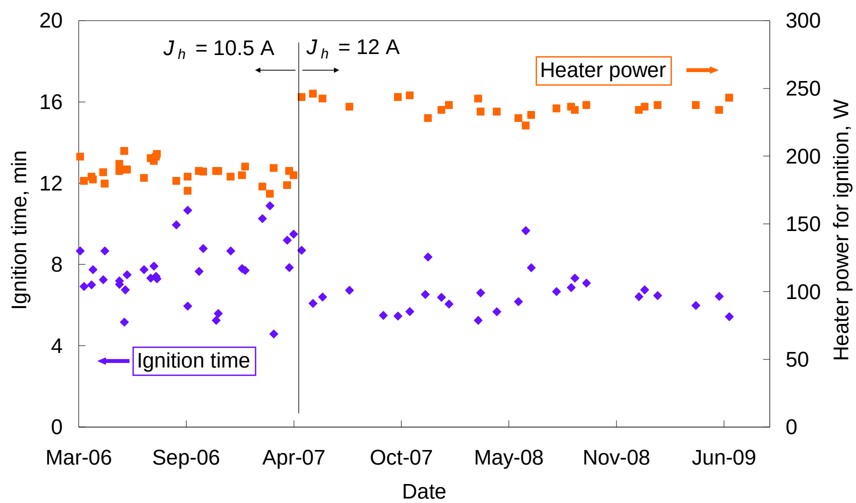


Figure 9. Required time and power for ignition in discharge cathode endurance test.

The heating time required for ignition is an indicator of the cathode's condition. Figure 9 shows ignition time and heater power for the past 50 ignition sequences in the endurance test. The ignition time includes one minute of heater current ramp-up. The heater current was changed from 10.5 to 12 A in April 2007 to prevent cathode overheating during long ignition times. As shown in Fig. 9, ignition time has varied widely, but shows no increasing trend. Average ignition times before and after the heater current was changed are 8 minutes and 6 minutes, respectively. The heater power for ignition has been almost constant since the heater current increase. No signs of cathode degradation can be observed from these ignition characteristics.

IV. Neutralizer Cathode Endurance Test

The neutralizer cathode endurance test was started in June 2008 and reached 9,300 hours cumulative operation in August 2009.

A. Apparatus and Operation

The neutralizer test is being conducted in a triode configuration as shown in Fig. 10. The anode plate is fixed at a distance of 70 mm from the cathode keeper disk. The data acquisition and fail-safe systems are similar to those of the discharge cathode test. The tank pressure during the neutralizer operation has been maintained at approximately 3 x 10^{-3} Pa for N_2 by a 12,000-l/s cryogenic pump.

Table 2 shows typical operating parameters during the endurance test compared with those of 2.9 A ion beam neutralization operation.[10] The coupling voltage is a potential difference between the neutralizer cathode and the facility ground or ambient plasma during thruster operation and is to be compared with the anode voltage in the endurance test. The table indicates that the endurance test simulates the neutralizer operating conditions during real thruster operation. The test conditions have not been changed except for short-duration measurements of current-voltage characteristics. Figure 11 shows the discharge luminescence of the neutralizer in the typical operating conditions shown in Table 2.

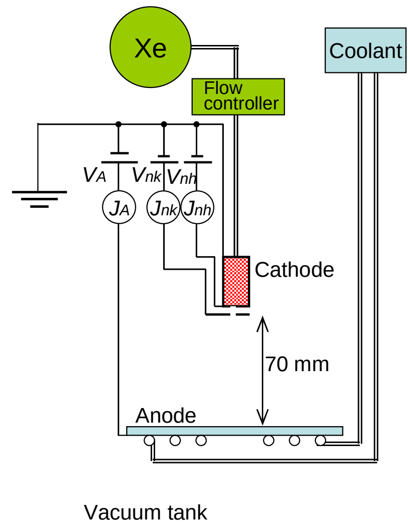


Figure 10. Test apparatus for neutralizer cathode endurance test.

Table 2. Nominal neutralizer endurance test conditions compared with thruster operation.

	Endurance test	Thruster
*Beam current, J_b, A	-	2.9
*Coupling voltage, V_c, V	-	25
Anode current, J_A, A	2.9	-
*Anode voltage, V_A, V	31	-
Keeper current, J_{nk}, A	1.0	1.0
*Keeper voltage, V_{nk}, V	16	20
Cathode flow rate, m_{nc}, Aeq	0.2	0.2

* Measured values (typical)

B. Present Status

The endurance test of the neutralizer cathode was started in June 2008. The cumulative operation time and variation of voltages during the test are shown in Fig. 12. The test had accumulated 9,300 hours of operation as of August 2009, with a rate of operation of approximately 91% and 13 ignition sequences so far.

Figure 12 indicates that the anode and keeper voltages have been almost constant at approximately 31 V and 16 V, respectively, throughout the test with no gradual increase due to performance deterioration. A notable difference between this neutralizer test and the discharge cathode test is the behavior of the keeper voltage after ignition. In the discharge cathode, both the discharge and keeper voltages stabilize within about 4 days after ignition, while the keeper voltage in the neutralizer test can take a month or more to stabilize. This might imply that the surface condition of the insert changes more slowly after ignition.

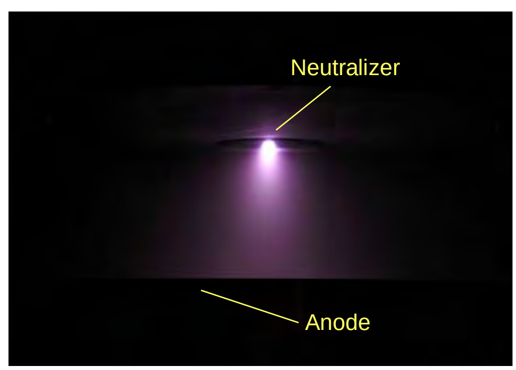


Figure 11. Discharge luminescence in neutralizer cathode endurance test.

V. Conclusion

An endurance test of a discharge hollow cathode designed for JAXA's xenon ion engines is being conducted. The keeper disk, orifice plate, and cathode tube of the discharge cathode are made of graphite to give a long life. The test had accumulated 25,800 hours of operation as of August 2009, and no signs of cathode degradation have been observed from the operating voltages and ignition performance. An endurance test of a graphite neutralizer hollow cathode was also started in June 2008, and cumulative operation time had reached 9,300 hours as of August 2009. Both these endurance tests are in progress and will be continued until a fatal problem occurs.

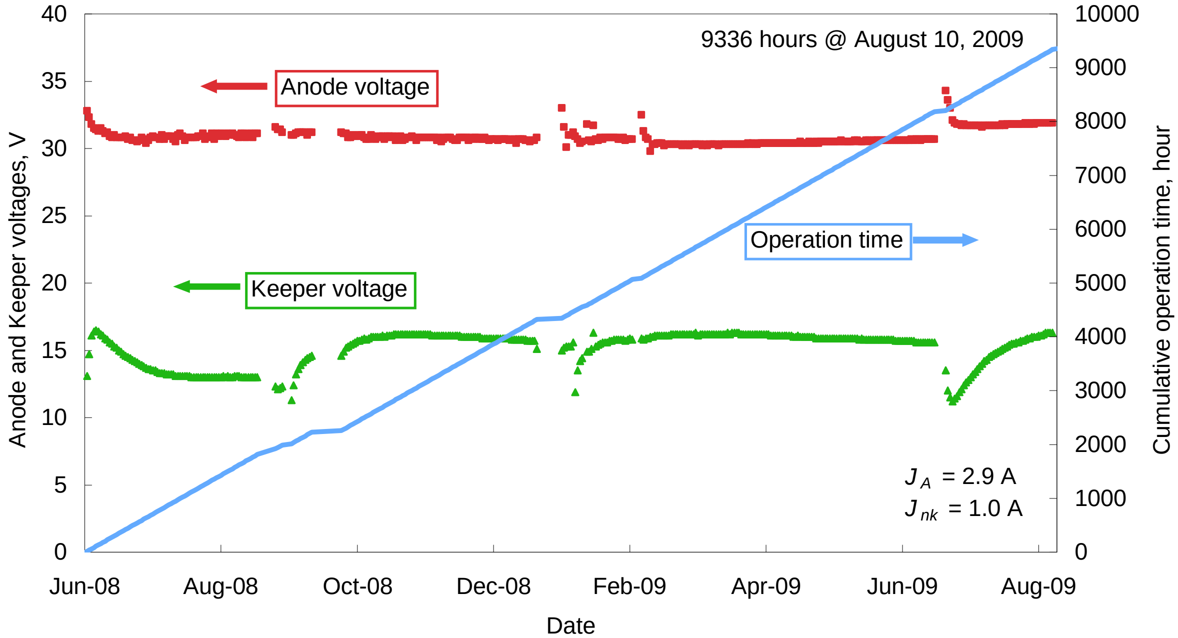


Figure 12. Anode and keeper voltages and cumulative operation time in neutralizer cathode endurance test from June 2008 to August 2009.

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