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Life Test of a Xenon Hollow Cathode for a Space Plasma Contactor

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A plasma contacting device using a hollow cathode for plasma production has been baselined for use on the Space Station. This application will require reliable, continuous operation of the cathode at electron emission currents of between 0.75 and 10 A for two years (17,500 hours). In order to validate life-time capability, a hollow cathode, operated in a diode configuration, has been tested for more than 8600 hours of stable discharge operation as of March 30, 1994. The cathode is operated at a steady-state emission current of 12.0 A and a fixed xenon flow rate of 4.5 sccm. Discharge voltage and cathode temperature have remained relatively stable at approximately 12.9 V and 1260 °C during the test. The test has experienced 7 shutdowns to date. In all instances, the cathode was reignited at about 42 V and resumed stable operation. This test represents the longest demonstration of stable operation of high current (>1A) xenon hollow cathodes reported to date.

Introduction

The decision to baseline a plasma contacting device on the Space Station was reached recently.[1] This plasma contactor will provide a connection to the surrounding space plasma and effectively prevent a build-up of potentially deleterious electrical charge on the Space Station.[2] Operational requirements for the plasma contactor are to provide a neutralization current between 0.75 to 10.0 A of electron current over approximately one-third of the 90 minute orbital period for up to two years. To meet these requirements, a reliable, long-life electron emitter for the plasma contactor is needed.

A hollow cathode-based configuration was selected as the electron emitter due to its successful application for over 25 years for ion thruster plasma production and beam neutralization in domestic[3,4] and foreign[5,6,7] ion propulsion research and flight programs. Mercury was used extensively as the ionizing propellant, and long-life operation of cathodes with mercury expellant has been demonstrated.[8,9] However, due to spacecraft operational and environmental concerns, an alternative to mercury was sought.

Since 1980, inert gases have become the propellant of choice for electrostatic ion thrusters, though there is not an equivalent experience base relative to mercury. Additionally, the extended-testing experience gained with the inert gases in the past 14 years includes several instances of performance degradation and cathode failure. These failures included cathode orifice erosion,[10,11,12] cathode body tube fracturing and swelling,[13] and degradation of performance and internal surfaces of the hollow cathode.[14,15,16]

The extended (>1,000 hours) test experience with inert gas hollow cathodes reported has been limited to a few tests. First, a xenon ion propulsion subsystem was operated at 1.4 kW for 4,350 hours.[11] The main discharge hollow cathode was operated at an emission current of 6.3 A. The orifice of the main cathode closed at approximately 700 hours into the wear-test. This cathode was then replaced with a larger-orificed cathode. The new main discharge cathode was used for the remainder of the test and exhibited negligible orifice change.[17]

Second, a 5000 hour steady-state test of a xenon hollow cathode in an ion thruster simulator was conducted at an emission current of 25 A.[16] In this test, the discharge voltage and ignition voltages changed significantly during the course of the test. The cathode orifice size also increased during the test and substantial material deposition formed on the cathode insert surface. In addition, the cathode insert's average brightness temperature at the electron emission region was 1500 °C as measured with an optical pyrometer. This operating temperature for the insert is considerably higher than recommended for these devices.[18]

Finally, a 1,960-hour cyclic life-test of 14-cm xenon ion thrusters has been reported.[19] This thruster incorporated hollow cathodes for the main discharge and neutralizer that emitted approximately 3.7 A and 0.5 A, respectively. The orifice was eroded during the life-test, resulting in increased area. The neutralizer cathode experienced ignition difficulties during the life-test and, by cycle 210, the neutralizer insert and keeper electrode had to be replaced.

Because of the lack of prior successful extended test experience with inert gas hollow cathodes, several extended tests were performed as part of a program initiated at NASA-LeRC in 1989.[15,20] For hollow cathodes operated on xenon, a suspected cause of the observed degradation is contamination by oxygen and oxygen-bearing compounds that attacks the cathode surfaces, particularly the sensitive insert surfaces. There are three probable sources for oxygen contamination. The expellant gases (Xe, Kr, Ar) have residual contamination left over from the gas extraction process. Feed-system materials and components evolve contaminants either through leakage or by outgassing from internal surfaces. Excessive oxygen release from the cathode insert can occur if proper precautions are not taken. As part of this program, procedures were implemented and expellant feed-system fidelity improved to alleviate oxygen contamination. These changes resulted in improved cathode performance and reduced degradation of the internal cathode surfaces.[15,20,21] This test series has been expanded to meet the requirements of the Space Station plasma contactor application. This paper will report the status of an on-going life-test of a xenon hollow cathode operating at a steady-state emission current of 12.0 A in a planar diode configuration. For further details on the experiment set-up, the reader is directed to Reference 21.

Experimental Apparatus

Cathode Configuration

The hollow cathode consists of a molybdenum-compound tube with a tungsten orifice plate electron-beam welded to one end. A small orifice with a chamfer on the downstream surface was electron-discharge machined into this plate. The insert, a porous sintered tungsten cylinder impregnated with barium-calcium-aluminate salts ($4BaO{\cdot}CaO{\cdot}Al_2O_3$), was placed in the downstream end of the tube. A helical-wound sheathed heater used for cathode activation and ignition was friction-fitted on the outside of the body tube over the region occupied by the insert.[22]

The wear-test is being conducted with a planar anode, as shown in Figure 1. The cathode is mounted on centerline of the test-port. The anode is a molybdenum plate also mounted on test-port centerline, positioned downstream from the plane of the cathode orifice plate. The anode plate is isolated from ground potential surfaces.

Test Facility

The wear-test is being performed in a cryogenically-pumped bell-jar with a xenon pumping capacity of 2100 L/sec. The facility had a base pressure of approximately 1.0×10^{-5} Pa and an operating pressure of 1.2×10^{-2} Pa at the test conditions.

Test Procedures

Table I lists the procedures employed to prepare the hollow cathode and the facility for operation. Further details of the procedures can be found in Reference 21.

Wear-test Performance

Wear-test Setpoint

The target operating set point is a steady-state emission current of 12.0 A and a xenon flow rate of 7.5 Pa-l/s (4.5 sccm or 0.41 mg/s). This emission current value was the projected highest current requirement from the plasma contactor unit (PCU) on the Space Station.[2] Table 2 includes the initial and nominal values of each parameter.

Wear-test Chronology

The parameters of greatest interest are the discharge voltage and the cathode temperature. Figure 2 shows the behavior of the discharge voltage as a function of test time. Two types of voltage variations have been observed. First, the discharge voltage exhibited long-term changes that took place over hundreds of hours, as can be seen in Figure 2, but which did not continue to rise or fall appreciably. At the time of this presentation, the discharge voltage had achieved a nominal operating value of 12.9 V ± 0.6 V after 8600 hours of operation. Second, variations occurred on a daily period due to changes in xenon flow rate. These flow rate changes are nominally ±5% and are believed to be the result of daily variations in ambient temperature, changes in the xenon pressure behavior in the feed-line, and the resolution limits of the flow metering valve.

Cathode tip temperature as a function of test time are shown in Figure 3. The cathode's brightness temperature, as measured with a disappearing filament pyrometer which incorporates an emissivity correction of 0.39, exhibited similar long-term changes as the discharge voltage, however, none of these changes were monotonic. The average cathode tip temperature was measured to be 1260 °C ± 50 °C.

Parametric Characterization

Cathode operation has been characterized over the course of the test by measuring the discharge voltage and cathode temperature under variation of emission current. Figure 4 shows the behavior of the discharge voltage as a function of emission current. All data were taken at a fixed xenon flow rate of 7.5 Pa-l/s. As can be seen, the discharge voltage behavior has remained relatively constant throughout the test. Table 3 shows the chronology of the data sets indicated in Figure 4.

Figures 5 show the cathode tip brightness temperature behavior as a function of emission current at a fixed xenon flow rate of 7.5 Pa-L/s measured the disappearing filament pyrometer, respectively. The behavior of the cathode tip temperature is approximately the same over the course of the wear-test. As with discharge voltage, the different data sets were taken at the times noted in Table 3.

Ignition Characteristics

In all instances, the discharge has been established or re-established using the steady-state applied voltages of the discharge supply, without having to resort to a high voltage pulse. The voltage was raised gradually until breakdown occurred. Table 3 lists the required ignition voltages over the course of the test. The average ignition voltage is 42.2 V during the nine discharge starts to date.

Wear-test Shutdowns

Seven test shutdowns have occurred to date. The chronology of the shutdowns along with the suspected or known causes is listed in Table 3.

Discussion of Performance

In preparation for this wear-test, numerous modifications and procedures were implemented to mitigate oxygen contamination of the cathode. The test configuration incorporated all the system improvements used in an earlier, successful, 500-hour hollow cathode wear-test.[19] These improvements included active purification of the xenon expellant stream, pre-test feed-system bake-out to remove interior surface contaminants, and use of ultra high vacuum fittings, valves, and transducers in the expellant feed-system. Feed-system integrity was maintained throughout the wear-test.

The behaviors of three parameters were of primary interest. First, the discharge voltage has remained at a nominal value of 12.9 V $\pm$ 0.6 V for over 8600 hours. Additionally, the discharge voltage-emission current characteristic remained approximately constant. For a given emission current, the discharge voltage varied by 3.0 V or less at all conditions measured.

Second, the average cathode tip brightness temperature is approximately 1260 °C, as measured by the disappearing filament pyrometer. Variations in cathode tip temperature were less than 50 °C over the course of 8600 hours of testing.

Finally, cathode ignition voltages have remained constant at 42.2 V $\pm$ 1.0 V during the several restarts that have occurred during this test. Increased ignition voltages have been associated with deteriorating cathode condition in previous extended tests.[14-16, 19] Consequently, the stable ignition voltage suggests that the internal cathode condition has remained relatively unchanged during this test. Further analyses of the cathode condition will wait until completion of the wear-test.

Summary Remarks

A hollow cathode has operated successfully for more than 8600 hours in a planar diode configuration at a steady-state emission current of 12.0 A and xenon flow rate of 7.5 Pa-l/s. The cathode has operated at a nominal discharge voltage of 12.9 V and an average cathode tip temperature of 1260 °C. The cathode has experienced 7 shutdowns during the wear-test. In all cases, pre-shutdown performance recovered after reactivation and reignition. The cathode has ignited at an average voltage of 42.2 V in seven instances over the course of the wear-test.

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Table 1 Test Procedures Employed

Procedure	Objective	Parameter Measured	Frequency
Feed-system Bake-out	Removal of oxygen & water vapor from feed-system interior surfaces	Feed-line pressure	After exposure to ambient conditions
Feed-system Leak-rate Testing	Verify integrity of feed-system	Feed-line leakage rate	After alteration of feed-system
Feed-system Purging	Removal of oxygen & water vapor from feed-system interior surfaces	N/A	Prior to restart
Cathode Activation	Prepare cathode insert surface for low work function emission	Activated according to prescribed schedule	Prior to restart after exposure to any atmospheric components

Table 2 Wear-test Operating Parameters

Parameter	Initial Value	Nominal Value	Continuously Monitored? (Y/N)
Discharge Voltage, V	11.0	12.8	Yes
Discharge Current, A	12.0	12.0	Yes
Xenon Flow Rate, Pa-L/s (sccm)	7.5 (4.5)	7.5 (4.5)	No
Cathode Tip Brightness Temperature - Disappearing Filament Pyrometer, °C, emissivity correction = 0.39	1350	1256	Yes

Table 3 Shutdown Occurrences

Shutdown Occurrence	Time, hours	Cause	Modifications	Restart Ignition Voltage	Parametric Data Taken
0	0	Start of Test	N/A	43.5	√
1	1467	Faulty sensor	Modified power system interlocks. Changed out Xe bottle	45.0	√
2	2089	Building power loss	None	40.5	
3	2639	Faulty sensor	None	39.5	
4	3121	Xe supply change-out	Xe bottle changed.	44.0	√
5	4772	Xe supply change-out	Xe bottle changed	43.0	
6	5410	Building power loss	None	42.0	
7	6947	Building power loss	None	39.0	
8	7331	Xe supply change-out	Xe bottle changed	38.8	

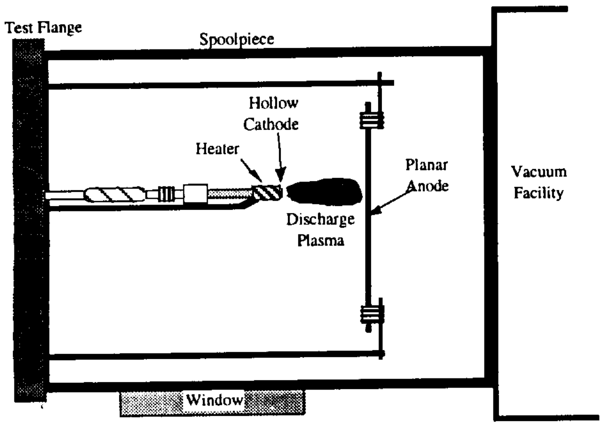

Fig. 1 Schematic of wear-test cathode/anode test configuration.

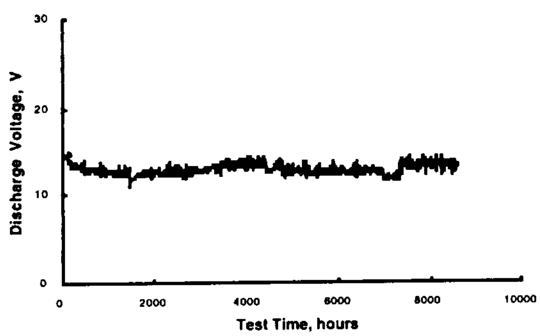

Fig. 2 Discharge voltage over course of wear-test. Emission current and xenon flow rate were fixed at 12.0 A and 7.5 Pa-l/s, respectively.

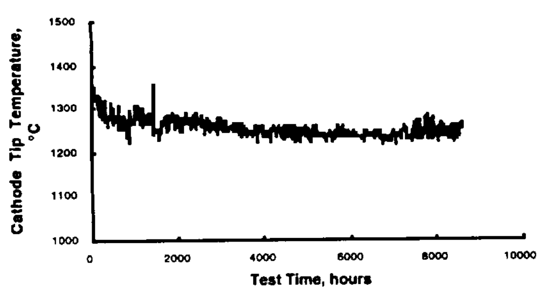

Fig. 3 Cathode tip brightness temperature over course of wear-test. Temperature was measured with a disappearing filament pyrometer sighting the cathode orifice plate incorporating an emissivity correction of 0.39. Emission current and xenon flow rate were fixed at 12.0 A and 7.5 Pa-l/s, respectively.

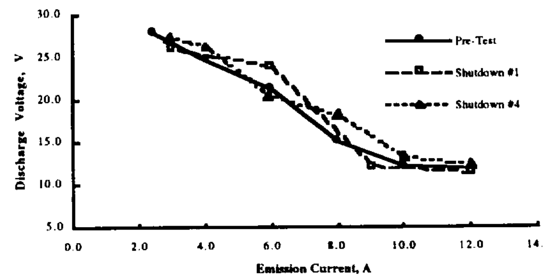

Fig. 4 Discharge voltage versus emission current. All data taken at a fixed xenon flow of 7.5 Pa-l/s. Data sets represent cathode performance after different restarts over the course of the test.

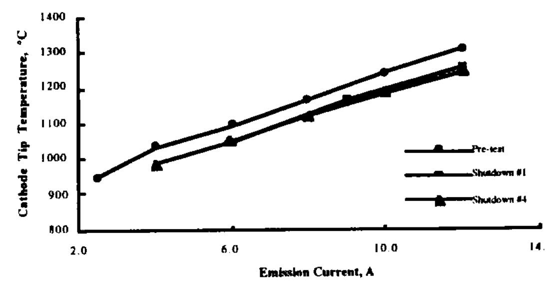

Fig. 5 Cathode tip temperatures versus emission current. All data were taken at a fixed xenon flow rate of 7.5 Pa-l/s. Temperatures were measured with a disappearing filament pyrometer, which incorporated a surface emissivity value of 0.39.

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13. ABSTRACT *(Maximum 200 words)*

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