12/9/94
E9246
CR|P

NASA Contractor Report 195402

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

Timothy R. Sarver-Verhey
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

November 1994

Prepared for
Lewis Research Center
Under Contract NAS3–25266

National Aeronautics and
Space Administration

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

Timothy R. Sarver-Verhey
Sverdrup Technology, Inc.
NASA Lewis Research Center Group
Brook Park, OH 44142

Abstract

Implementation of a hollow cathode plasma contactor for charge control on the Space Station has required validation of long-life hollow cathodes. A test series of hollow cathodes and hollow cathode plasma contactors was initiated as part of the plasma contactor development program. An on-going wear-test of a hollow cathode has demonstrated cathode operation in excess of 4700 hours with small changes in operating parameters. The discharge experienced 4 shutdowns during the test, all of which were due to test facility failures or expellant replenishment. In all cases, the cathode was reignited at approximately 42 volts and resumed typical operation. This test represents the longest demonstrated stable operation of a high current (>1 A) xenon hollow cathode 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 orbital period of approximately 90 minutes. 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 electric propulsion applications, a hollow cathode has typically consisted of a high-temperature metal tube with or without a restrictor at the downstream end. A low work function emitting insert is positioned in the tube. This emitter has been either a roll of tantalum foil coated with a barium-strontium compound or a porous tungsten cylinder insert impregnated with BaO-CaO-Al_2O_3-based compounds.[3] A heater mounted on the cathode tube is used to raise the temperature of the emitter to enhance electron emission for discharge ignition. The restrictor plate on the downstream end of the cathode tube increases the local pressure at the emitter which in turn reduces the voltage requirements for the electrical discharge. Once the discharge has been initiated and a stable discharge has been established, ion bombardment of the emitter sustains the temperature without use of the heater.

In the United States ion propulsion program, mercury vapor was used extensively in hollow cathodes, including those for the Space Electric Rocket Test (SERT) II,[4] the 8-cm ion thruster system,[5] the Ion Auxiliary Propulsion Subsystem (IAPS),[6] and the Solar Electric Propulsion Subsystem (SEPS)[7] development programs. Mercury was also the propellant used in the United Kingdom's thruster development program,[8] West Germany's Radio-frequency Ion Thruster (RIT-10) thruster development program,[9] and the Japanese ETS-III propulsion system development program.[10] 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. While long-life operation of cathodes with mercury expellant has been demonstrated,[11,12] there is not an equivalent experience base with inert gases. Additionally, the extended-testing experience gained with the inert gases in the past 13 years includes several instances of performance degradation and cathode failure. These failures included cathode orifice erosion,[13,14,15] cathode body tube fracturing and swelling,[16] and degradation of performance and internal surfaces of the hollow cathode.[17,18,19] Examples of body tube cracking and anomalous material formation are shown in Figures 1 and 2, respectively.

Before 1992, reports on extended testing of hollow cathodes operating on inert gases at emission currents of several amperes for longer than 1,000 hours were limited to two ion thruster life-tests. A xenon ion propulsion subsystem was operated at 1.4 kW for 4,350 hours.[14] The main discharge hollow cathode had an intermediate keeper electrode and operated at an emission current of 6.3 A. During the test, the main cathode discharge voltage decreased from an initial voltage of 28.5 V to a final voltage of 26.0 V.[20] The main cathode keeper voltage was relatively stable at a nominal voltage of 14.0 V, but had risen to approximately 16.5 V by the end of the test. The main discharge cathode orifice 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 change in orifice plate condition. The neutralizer operated at nominal keeper and coupling voltages of 18.0 and 24.0 V, respectively. These voltages exhibited variations of 11.0% and 11.5% respectively during the wear-test. The post-test condition of the neutralizer exhibited negligible changes.

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.[19] In that test, discharge voltage varied from a maximum of 21.0 volts to a minimum of 12.0. The nominal voltage was approximately 17.5 V. Additionally, the ignition voltage varied from a minimum of 18.0 V to a maximum of more than 900 V. The cathode orifice plate's brightness temperature rose from a minimum of 1100 °C at about 500 hours to a maximum temperature of 1250 °C by hour 4300. The average temperature of the cathode orifice plate over the course of the test was 1200 °C. The cathode insert's brightness temperature at the electron emission region demonstrated similar behavior during the life-test, but was found to have a substantially higher average temperature of 1500 °C. This operating temperature for the insert is considerably higher than recommended for these devices.[3] Finally, the cathode orifice size increased during the test and substantial material deposition formed on the cathode insert surface.

A series of ion thruster life-tests for the ETS-VI Ion Engine program being performed at the National Space Development Agency of Japan and Mitsubishi Electric Corporation has been reported.[21] These tests all used hollow cathodes operating at multi-ampere emission current levels and in steady-state and cyclic operating modes. However, no information on the performance and condition of the hollow cathodes tested is available, making it difficult to assess the success of the life-tests.

Recently, the results of a 1,960-hour cyclic life-test of 14-cm xenon ion thrusters were reported.[22] This thruster incorporated hollow cathodes for the main discharge and neutralizer that emitted approximately 3.7 A and 0.5 A, respectively. The discharge voltage of the main cathode varied from a low of 28.0 V to a maximum of 40.0 V with an average of approximately 35.0 V. In addition, the orifice size increased during the life-test by erosion. The neutralizer cathode experienced ignition difficulties during the life-test and, by cycle 210, the cathode insert and keeper electrode had to be replaced.

Because of the lack of 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.[18,23] For hollow cathodes operated on xenon, a suspected cause of the observed degradation is oxygen contamination that attacks the cathode surfaces, particularly the sensitive insert surfaces.[18,23] There are three probable sources for oxygen contamination. First, the expellant gases (Xe, Kr, Ar) have residual contamination left over from the gas extraction process. Second, feed-system materials and components evolve contaminants either through leakage or by outgassing from internal surfaces. Third, 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 minor degradation of the internal cathode surfaces. 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. The test apparatus and procedures are discussed next. The performance behavior and observed changes will then be presented.

Experimental Apparatus

Hollow Cathode

The hollow cathode, shown schematically in Figure 3, 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 hollow cathode is similar to a laboratory-model device that has been wear-tested extensively at NASA-LeRC for contamination studies and ion thruster testing,[18,23] however the orifice diameter was decreased to accommodate the lower emission current requirements. The insert, a porous sintered tungsten cylinder impregnated with $4BaO{\cdot}CaO{\cdot}Al_2O_3$, was placed in the downstream end of the tube. Refractory metal electrical leads, attached to the rear of the insert, were spot-welded to the interior of the upstream end of the body tube. These leads provided electrical contact and maintained the position of the insert in the body 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.[17] Several layers of metal foil were tightly wrapped around the heater and spot-welded in place to reduce radiated power losses.

Cathode-Anode Configuration

This wear-test is being conducted with a planar anode, as shown in Figure 4. The cathode is mounted on centerline of the test-port, supported by the ceramic insulator assembly that connected to the feed-system inlet. A compression fitting on the cathode (see Figure 3) joined the cathode assembly to the ceramic insulator assembly that thermally isolated it from the test assembly. The insulator and feed-line within the test-port are all 0.64 cm diameter tubing. The anode consists of a 20.3 cm diameter molybdenum plate mounted on test-port centerline with three support rods. It is positioned downstream from the plane of the cathode orifice plate. The anode plate is isolated from ground potential surfaces with three isolation mounts attached to the support rods. A small hole was drilled into the plate centerline to enable temperature measurement of the cathode orifice plate.

Xenon Expellant Feed-system

The expellant feed-system is shown schematically in Figure 5. The feed-line is 0.64 cm diameter stainless-steel tubing. All tubing connections used ultra high vacuum metal gasket seals, except where transducer installation required polymer o-ring fittings. A gas purifier was installed upstream of the flow monitoring and control devices. The internal pressure of the feed-line is 170 kPa (10 psig) upstream of the flow control valve. A bypass line upstream of the flow control valve sped evacuation of the feed-system when pumping down from atmosphere. Additionally, a second bypass line was added upstream of the gas purifier during a shut-down at hour 3119 to speed evacuation from that portion of the feed-system.

Xenon Expellant

Research grade xenon (99.999%) gas is used throughout the wear-test and parametric testing. According to vendor specifications for the xenon expellant, the total oxygen level (from O_2, H_2O, CO_2, and miscellaneous hydrocarbons) in the xenon is approximately 3.0 ppm. The xenon delivery pressure is 170 kPa (10 psig).

Power Supplies

Two power supplies operate the hollow cathode as shown in the electrical schematic in Figure 6. A 25 V, 15 A current-regulated supply provides the required power for the cathode heater during activation and starting. A 55 V, 20 A SCR-regulated power supply with a linear output stage provides the necessary voltage and current for both ignition and maintenance of the discharge. The cathode and all test-port surfaces are at facility ground while the anode plate is connected to the positive output of the discharge supply and electrically isolated from the test port. A 3 mH inductor was added to the discharge circuit to alleviate power supply noise.

Instrumentation

The static and dynamic behavior of the discharge voltage and current are monitored along with the xenon mass flow rate, the cathode temperatures, and facility and test port pressures (see Table I). The discharge voltage is measured both at the power supply and at the test flange to account for any line losses. The noise levels of the discharge voltage and emission current are measured at the test flange with a digital oscilloscope.

The cathode temperature is measured by two techniques. First, three type R (Pt-13%Rh/Pt) thermocouples were spot-welded to the external surface of the cathode body tube in the following locations: immediately upstream of the orifice plate weld, immediately upstream of the heater coils, and at the compression fitting connection to the thermal isolator (see Fig. 3). Metal foil was spot-welded over the thermocouple junctions at the two downstream locations to mitigate plasma interactions with the signals. Second, two pyrometric devices are sighted onto the cathode surfaces. An infrared thermometer is sighted onto the cathode body tube, immediately upstream of the orifice plate weld (nearly identical to the location of the downstream thermocouple). A disappearing filament optical pyrometer is sighted onto the cathode orifice plate from a window on the vacuum facility (see Fig. 7). A value of 0.39 is used for the surface emissivities parameters that is incorporated into both pyrometers. This value is a typical emissivity of a metallic, non-polished, tungsten surface at the projected operating temperatures.[24] The choice of the emissivity value is somewhat arbitrary because the exact surface condition of the sighted surfaces and the time-dependence of the surface condition are unknown.

Bayard-Alpert ion gauges monitored the facility and test-port pressures. A capacitance manometer measured expellant feed-system pressure during leak-rate tests. A thermal mass flowmeter measures the xenon flow rate. All monitored parameters listed in Table 1 are recorded at 5 and 15 minute intervals to a computer during the wear-test.

Vacuum Facility

The wear-test is being performed in a cryogenically-pumped bell-jar with a xenon pumping capacity of 2100 L/sec. The configuration of the test facility is shown schematically in Figure 7 and in the photograph in Figure 8. The hollow cathode is mounted in a 0.3 m diameter test port attached to the bell-jar. A 0.3 m diameter pneumatic gate valve provided isolation of the test-port during equipment changes. 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 described below.

Test Procedures

Mass Flowmeter Calibration

The mass flowmeter was calibrated before the test on xenon with a bubble flow calibrator.

Feed-system Bake-out

Before initiation of the wear-test and after each change-out of the xenon bottle, the expellant feed-system was heated to outgas the contaminants trapped on the interior tubing surfaces. Heat tape was wrapped over the feed-line and powered to raise the tubing temperature. All bypass lines were open to the facility vacuum to remove any gases evolved from the feed-line surfaces. The feed-system was baked out for a minimum of 24 hours and then cooled to ambient temperature before continuing.

Feed-system Evaluation

The contamination level within the expellant feed-system was characterized by pressure-rise testing. Pressure-rise tests consisted of evacuating the feed-system, then isolating the feed-line from the facility vacuum and monitoring the rise in pressure over time with the two pressure transducers discussed above. This pressure rise was attributed to leakage through the fittings and outgassing from the internal surfaces. The pressure change during the first several hours was neglected as a precaution against any outgassing contribution. The leak-rate of the feed-system was measured periodically throughout the wear-test to verify integrity. Similar to the wear-test results of Reference 23 performed in the same facility, the leak-rate test behavior had no significant outgassing contribution.

Feed-system Purging

Prior to cathode activation, the feed-system was evacuated for at least 12 hours. Xenon gas was purged continuously for a short period at the beginning of the hollow cathode activation.

Cathode Activation

The insert was activated once the test port was at a facility pressure of at least 1.3×10^{-4} Pa and feed-line pressure was below 1.0×10^{-2} Pa. The procedure used at NASA-LeRC was derived from an activation procedure developed during the SEPS program.[25] This multiple step procedure was similar to the procedure used in previous wear-tests.[18,23] The same activation procedure was performed after each of the 4 discharge shutdowns during the test where exposure of the cathode to atmospheric gases was suspected. After activation, a short, high-temperature pre-heat of the cathode was performed to enable low-voltage ignition of the discharge.

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] The xenon flow rate setting provided discharge stability and maintained the discharge voltage at less than 20.0 V, which was the upper limit of operation allowed by station requirements. Table 1 includes the initial and nominal values of each parameter.

Wear-test Chronology

The monitored parameters of greatest interest are the discharge voltage and the cathode temperatures. Figure 9 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 rose to a maximum voltage of approximately 15.1 V by hour 110 of the wear-test. The discharge voltage decreased to a minimum of 11.9 by hour 1950 after which it rose until hour 4400 where it peaked at approximately 13.8 V. The voltage then dropped again to approximately 12.8 V. At the time of this publication, the discharge voltage had achieved a nominal operating value of 13.0 V after 4770 hours of operation. Second, variations occurred on a daily period and were due to changes in xenon flow rate. These flow rate changes are typically about ±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. Insufficient data were available to accurately determine the cause of these changes. The behavior exhibited by discharge voltage at approximately hour 1500 was the result of a facility failure.

Cathode tube temperatures as a function of test time are shown in Figures 10 and 11. Figure 10 shows the temperature measurements from the three thermocouples attached to different locations on the cathode body tube. The temperatures at all three locations exhibit similar behavior as they each decreased monotonically during the test. The cathode tip temperature decreased by approximately 95 °C from the maximum temperature of 1115 °C at the beginning of this test to a minimum temperature of 1020 °C at the time of this report. T/Cs 2 and 3, mounted upstream of the cathode heater, exhibited approximate decreases of 50 and 23 °C, respectively. The 'noise' in all the temperature measurements is the result of the daily variations in xenon flow rate. Additionally, the temperature 'spike' indicated at approximately 1500 hours was the result of off-normal behavior that will be discussed in the wear-test shutdowns' section. Small temperature increases following cathode restarts occurred but these quickly fell to approximately the pre-shutdown temperatures.

Figure 11 shows the temperature behavior as measured by the two pyrometers. While the measurements by the two devices are significantly different, the temperature behaviors for both exhibit a monotonic decrease in temperature similar to the thermocouple data shown in Figure 10. Using the disappearing filament pyrometer, the cathode temperatures experienced a small decrease of approximately 100 °C during the test, from a maximum of 1350 °C to a nominal value of 1250 °C at the time of this report. The infrared thermometer measured a smaller decrease of 50 °C from a maximum temperature measurement of 1225 °C.

The pyrometer measurements of cathode temperature are used to substantiate the thermocouple measurements. However, these measurements are problematic due to the difficulty in accurately and consistently maintaining the sighted region of the cathode tube and orifice plate. From experience with these devices on this and earlier tests, the disappearing filament pyrometer had an uncertainty of ± 25 °C and the infrared thermometer had a sighting repeatability of ± 50 °C and a focusing repeatability of ± 50 °C. Additionally, the true surface emissivity of the surfaces measured are unknown. No compensation for changes in the surface emissivity during the wear-test due to changes in the surface condition is employed. Consequently, the pyrometer measurements are used only to verify the behavior of the cathode temperature as a function of time. The uncertainties noted above are not considered sufficient to invalidate the qualitative information obtained.

Ripple on the discharge voltage and emission current signals are monitored with an oscilloscope throughout the test. The behavior of the peak-to-peak ripple over the average signal magnitude is shown in Figure 12. As can be seen from the figure, the emission current level remains relatively constant at a nominal value of 0.12% during the test. The discharge voltage ripple is more erratic, but never exceeded 1% throughout the wear-test. The average voltage ripple is 0.72%. After the fourth shutdown at hour 3119, the voltage ripple stablized, as can be seen in Figure 12.

Parametric Characterization

Cathode operation has been characterized over the course of the test by measuring the discharge voltage and cathode temperatures under variation of emission current and xenon flow rate. Figure 13 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 (4.5 sccm or 0.41 mg/s). As can be seen, the discharge voltage behavior is relatively constant throughout the test. Variations are largest in the 6-9 A range. However, at the wear-test point of 12.0 A, voltages are within 7.6 % of each other. Table 2 shows the chronology of the data sets indicated in Figure 13. Not indicated in Table 2 is the initial data set which was taken before initiating the wear-test.

Figures 14(a) and 14(b) show the cathode tip temperature behavior as a function of emission current at a fixed xenon flow rate of 7.5 Pa-L/s measured with the type R thermocouple and the two pyrometers, respectively. In Figure 14(a), the behavior of all the data sets for the cathode tip thermocouple is approximately the same over the course of the wear-test as shown by the shape functions of the curves. However, the temperatures are decreasing with time which is consistent with the behavior exhibited in Figure 10.

In Figure 14(b), the cathode tip temperatures are measured with two optical pyrometers. The data sets for the infrared thermometer (open symbols) do not indicate the monotonic decrease in temperature with time as was exhibited by the thermocouple or the disappearing filament pyrometer. The data set of the thermometer taken after the first shutdown at hour 1467 indicated higher temperatures than any of the other data sets. This was believed to be largely due to sighting and focusing errors discussed above. Consequently, the accuracy of the infrared thermometer readings is suspect. The disappearing filament pyrometer data (closed symbols) exhibit approximately the same monotonic increase with emission current as shown by the thermocouple measurements of Figure 14(a). The higher temperatures of the disappearing filament pyrometer measurements relative to those of the infrared thermometer are attributed to the different measurement location and surface characteristics. As with discharge voltage, the different data sets have been taken over the course of the wear-test at times noted in Table 2.

Figure 15 shows the discharge voltage as a function of the xenon flow rate at three times during the test. Emission current is fixed at 12.0 A. The data exhibits the largest variation of approximately 16 % at flow rates below approximately 8.5 Pa-L/s. At the wear-test flow rate, there is a monotonic increase in discharge voltage from the pre-test data set to the data set taken at shutdown #4. The lowest flow rate tested was approximately 4.6 Pa-L/s (2.7 sccm), because the discharge rapidly became unstable at lower flow rates.

Figure 16(a) and 16(b) show the cathode tip temperatures versus xenon flow rate. All data are taken with a fixed emission current of 12.0 A. Fig. 16(a) shows the temperatures measured with the type R thermocouple at the cathode tip. The data sets demonstrate that cathode temperature is only slightly sensitive to xenon flow rate, with a rise in temperature of less than 50 °C for the pre-test data set when the flow rate varied from 5.0 Pa-L/s to 16.6 Pa-L/s. The other data sets showed even less change with flow rate. As can be seen, the cathode temperature is decreasing with time over the range of the flow rates examined, with the measured temperature changes being between 40 and 80 °C

The cathode temperature behavior measured by the disappearing filament pyrometer as a function of xenon flow rate generally agrees with the thermocouple results, as can be seen in Fig. 16(b). The disappearing filament pyrometer data sets exhibit similar trends as the thermocouple measurements of Figure 16(a), though temperatures were approximately 200 °C greater. The measured changes in cathode temperature are also slightly greater, being between 40 °C at the lowest flow rates and 100 °C at the highest flow.

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 is raised gradually until breakdown occurred. Table 3 lists he required ignition voltages over the course of the test. The average ignition voltage is 42.5 V during the 5 discharge starts to date.

Wear-test Shutdowns

Four test shutdowns have occurred to date. The chronology of the shutdowns along with the suspected or known causes is listed in Table 2. The first shutdown was believed to be the result of a faulty pressure sensor that caused an unintentional closing of the isolation valve between the test port and the facility. The discharge continued to operate for 10.5 hours within the test port as the local pressure rose to approximately 25 Pa. The discharge voltage and cathode tip thermocouple temperature rose to maximum values of 18.8 V and 1170 °C, respectively during this time. After this shutdown, the suspect sensor was replaced; a pressure interlock was added; the xenon bottle was changed out, and the cathode was reactivated and reignited. As can be seen in Figure 9, the discharge voltage was initially lower than before shutdown, but recovered quickly.

The second shutdown occurred as a result of power loss to the building and resulted in shutdown of discharge power supply and the vacuum facility. Afterwards, the cathode was reactivated and reignited. Cathode operation resumed with negligible change in discharge voltage and temperatures.

The third shutdown was again believed to be the result of a faulty pressure sensor and resulted from an unintentional closure of the main isolation valve. The discharge was immediately shut off as a result. Subsequently, the cathode was reactivated and reignited and resumed operation with negligible change in operating parameters.

The fourth shutdown was an intentional one to change out the Xe gas supply that was running low. After the gas bottle was changed and the feed-system slightly modified for pump-out, the cathode was again reactivated and reignited.

Discussion of Performance

In preparation for this wear-test, numerous modifications and procedures to mitigate oxygen contamination of the cathode were implemented. The test configuration incorporated all the system improvements used in an earlier, successful, 500-hour hollow cathode wear-test.[23] 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 are of primary interest. First, the discharge voltage has remained at a nominal value of 13.0 V for nearly 4800 hours. Additionally, the discharge voltage behavior under variation of emission current and xenon flow rate remained approximately constant. The discharge voltage varied by 3.0 V or less at all conditions measured.

Second, the average cathode tip temperature is approximately 1038 °C, as measured by the thermocouple. A temperature decrease of 100 °C occurred during the wear-test. The cathode behavior suggests that the same mechanism that occurred in a previous 500 hour wear-test was occurring to this cathode. In Reference 23, the cathode experienced a monotonic decrease in temperature that was hypothesized to have been the result of a small increase in the radiative emissivity of the cathode and cathode heater surfaces. This emissivity increase may have been the result of changes in the surface condition of the radiation shielding on the heater due to either coating or erosion of the surface. Deposited material found during post-test examination of the cathode and cathode heater surfaces supported this hypothesis. While it was not possible to examine the condition of the radiation shielding on the cathode under test, similar mechanisms for coating the foil are probably present, since the same facility was used, albeit with several changes since the last test. If so, these mechanisms are less active, as the cathode has experienced a comparable temperature change only over a much longer period.

The additional thermocouples and the two pyrometers are used to verify the behavior of the tip thermocouple. While significant differences in measured temperatures have been found using the three methods, the measured temperature behavior is approximately the same as the emission current or xenon flow rate has been varied. Maintaining the sighting locations of the pyrometers to accurately compare temperature measurements with thermocouple data is extremely difficult under the operational requirements of the wear-test.

Finally, cathode ignition voltages have remained nearly constant during the several restarts that have occurred during this test. Increased ignition voltages have been associated with deteriorating cathode condition in previous extended tests.[17-19, 22] Consequently, the stable ignition voltage suggests that the internal cathode condition has remained relatively constant 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 4700 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 (4.5 sccm). The cathode has operated at a nominal discharge voltage of 13.0 V and an average cathode tip temperature of 1038 °C. The cathode temperature decreased by approximately 100 °C during the wear-test. The temperature change may have resulted from an increase in the emissivities' of the radiating surfaces of the cathode. The cathode has experienced 4 shutdowns, both intentional and unintentional, during the wear-test. In all cases, pre-shutdown performance recovered after reactivation and reignition. The cathode has ignited at an average voltage of 42.5 V in five instances over the course of the wear-test. This wear-test of a xenon hollow cathode at high (> 1.0 A) emission current represents the longest reported test exceeding 1,000 hours that has not suffered from performance and life degradation due to cathode contamination.

Acknowledgments

The author would like to acknowledge the technical support of F.K Jent, J.R. Miller, G.R. Schneider, R.D. Buttler, C.D Schroeder, J.B. Naglowsky, and J.E. Parkes in execution of this wear-test. Additionally, thanks are extended to M.J. Patterson, G.C. Soulas, and Dr. R.M. Myers for assistance and input during the wear-test.

References

1 Moorehead, R.W., Deputy Director, Space Station Freedom Program and Operations, communication to Work Packages 1-4 Directors, dated April 3, 1992.

2 Patterson, M.J., et al.,"Plasma Contactor Technology for Space Station Freedom," AIAA Paper No. 93-2228, June 1993.

3 Kohl, W.H., *Handbook of Materials and Techniques for Vacuum Devices*, Reinhold, New York, 1967, pp. 491-496.

4 Kerslake, W.R. and Ignaczak, L.R., "Development and Flight History of SERT II Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 30, No. 3, May-June 1993, pp. 258-290.

5 Anon., "8-cm Mercury Ion Thruster System Technology," NASA TM X-71611, Oct. 1974.

6 Collet, C., and Power, J.L., "Qualification Test Results of IAPS 8cm Ion Thrusters," AIAA Paper No. 82-1954, Nov. 1982.

7 Anon., "30-cm Ion Thrust Subsystem Design Manual," NASA TM-79191, April 1980.

8 Stewart, D., "Life-testing of the UK T4A Thruster," AIAA Paper No. 76-1023, Nov. 1976.

9 Krulle, G., Zeyfang, E., and Voit-Nitschmann, R., "Recent Life and Performance Test Results Achieved Within the RIT-10 D & Q Program," AIAA Paper No. 78-678, April 1978.

10 Kitamura, S., et al., "ETS-III Ion Engine Flight Operations in the Extended Mission Period," *Journal of Propulsion and Power*, Vol. 2, No. 6, Nov.-Dec. 1986, pp. 513-520.

11 Collett, C., "Thruster Endurance Test," NASA CR-135011, May 1976.

12 Bechtel, R.T., Trump, G.E., and James, E.J., "Results of the Mission Profile Life Test," AIAA Paper No. 82-1905, Nov. 1982.

13 Ramsey, W.D., "12-cm Multi-cusp Ion Thruster Inert Gas Performance," NASA CR-168208, July 1984.

[14] Beattie, J.R., Matossian, J.N., and Robson, R.R., "Status of Xenon Ion Propulsion Technology," AIAA Paper No. 87-1003, May 1987.

[15] Brophy, J.R. and Garner, C.E., "Tests of High Current Hollow Cathodes for Ion Engines," AIAA Paper No. 88-2913, July 1988.

[16] Rawlin, V.K., "Internal Erosion Rates of a 10 kW Xenon Ion Thruster," AIAA Paper No. 88-2912, July 1988.

[17] Patterson, M.J. and Verhey, T.R., "5-kW Xenon Ion Thruster Life-test," AIAA Paper No. 90-2543, July, 1990.

[18] Sarver-Verhey, T.R. and Patterson, M.J., "Microanalysis of Extended-Test Xenon Hollow Cathodes," AIAA Paper No. 91-2123, June 1991.

[19] Brophy, J.R. and Garner, C.E., "A 5,000 hour Xenon Hollow Cathode Life Test," AIAA Paper No. 91-2122, June 1991.

[20] Beattie, J.R., Private Communication, Hughes Research Laboratories, Malibu, CA, August 1993.

[21] Yoshikawa, T., "Electric Propulsion Research and Development in Japan," IEPC Paper No. 91-004, October 1991.

[22] Kitamura, S., Miyazaki, K., and Hayakawa, Y., "Cyclic Test of a 14 cn Diameter Ring-Cusp Xenon Ion Thruster," AIAA Paper No. 92-2146, July 1992.

[23] Sarver-Verhey, T.R., "Extended-Testing of Xenon Ion Thruster Hollow Cathodes," AIAA Paper No. 92-3204, (NASA CR 189227), July 1992.

[24] Reick, G.D., *Tungsten and Its Compounds*, Pergamon Press, Oxford, 1967, pp. 22-23.

[25] DePauw, J.F., "30 cm Thruster Cathode Activation," NASA Tech Ready Information Memo No. 13, NASA Lewis Research Center, Dec. 1977.

Table 1 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 Temperature, °C	1100	1050	Yes
Cathode Tip Temperature - Disappearing Filament Pyrometer, °C	1350	1270	Yes
Cathode Body Temperature, °C	845	816	Yes
Cathode Base Temperature, °C	369	361	Yes
Discharge Current Noise, % P-P	0.09	0.72	No
Discharge Voltage Noise, % P-P	0.06	0.11	No

Table 2 Shutdown Occurrences

Shutdown Occurrence	Test Time, hours	Cause	Modifications	Parameters Measured?
1	1467	Gate valve closure due to faulty sensor	Modified power system interlocks. Changed out Xe bottle	Yes
2	2089	Building power loss	None	No
3	2639	Gate-valve closure due to faulty sensor	None	No
4	3119	Xe supply required replenishment	Xe bottle changed. Feed-system modified to allow feed-line evacuation.	Yes
5	4770	Xe supply required replenishment	Xe bottle changed	Yes

Table 3 Ignition Behavior

Ignition Occurence	Voltage, V
Initial Start-up	43.5
Shutdown #1	45.0
Shutdown #2	40.5
Shutdown #3	39.5
Shutdown #4	44.0

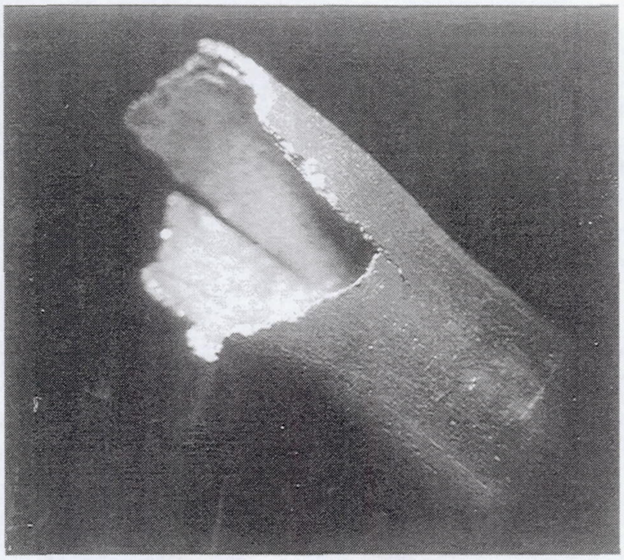


Figure 1 Photograph of cracked tantalum cathode body tube which was damaged during a 567 hour ion thruster extended test.[16]

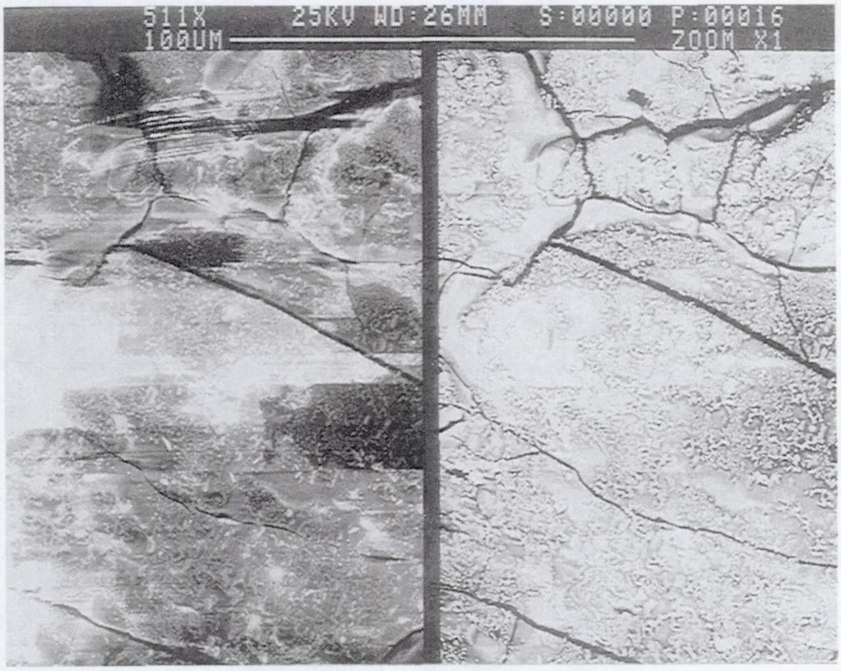


Figure 2 Photograph of an amorphous barium-oxide material formed on cathode electron emitting insert surface during a 500 hour test.[18] Left side of photo is a secondary electron emission image of the insert surface, right side is a backscattered electron emission image of the same surface.

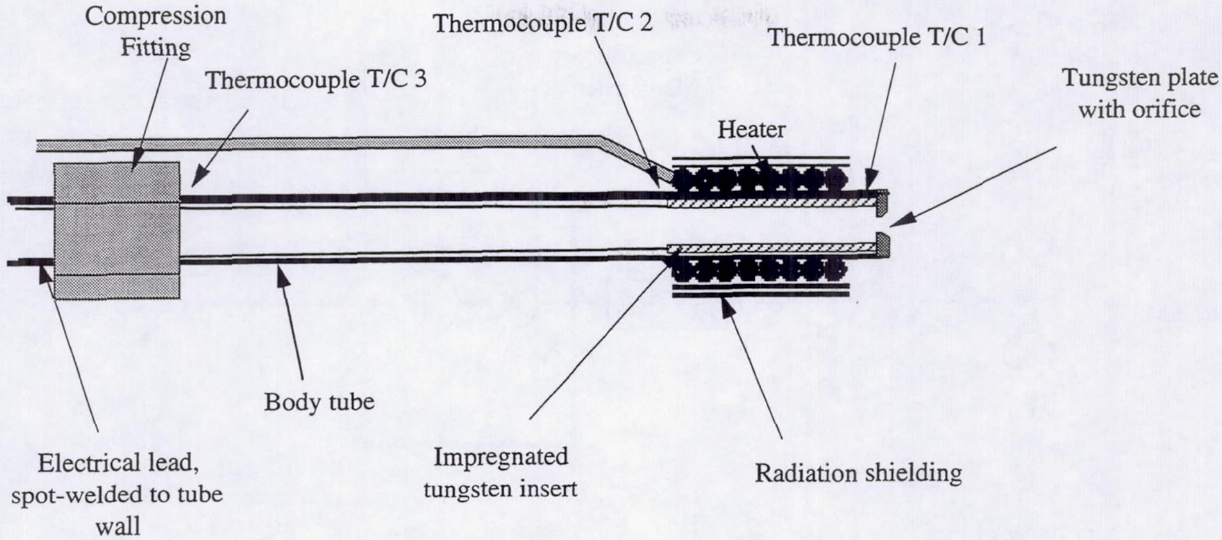


Figure 3 Schematic of wear-test hollow cathode

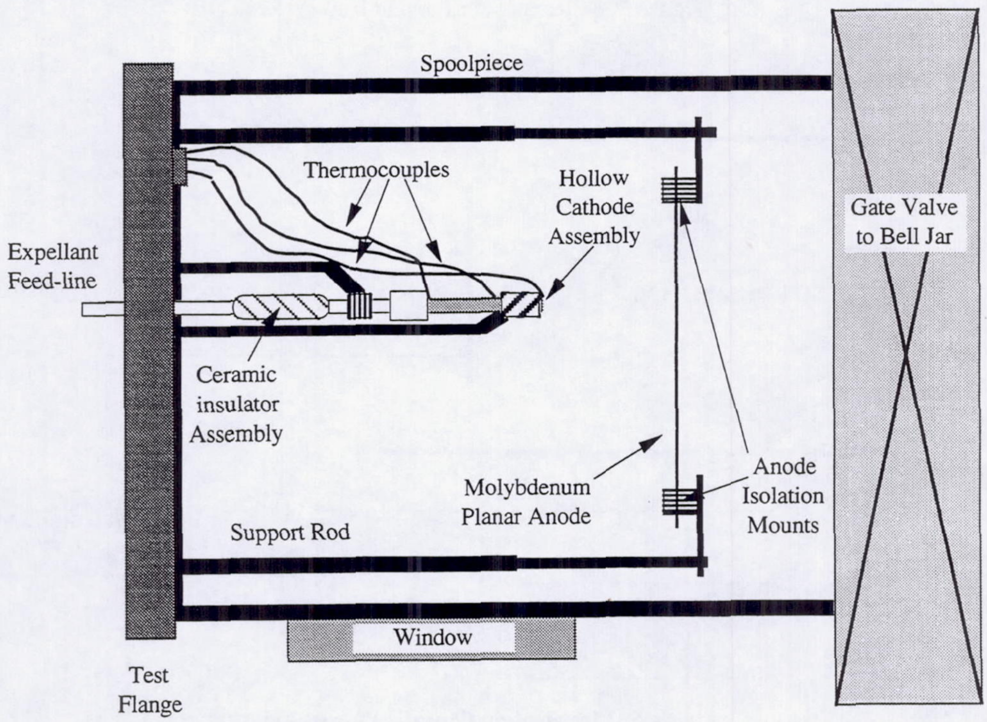


Figure 4 Schematic of wear-test cathode/anode test configuration.

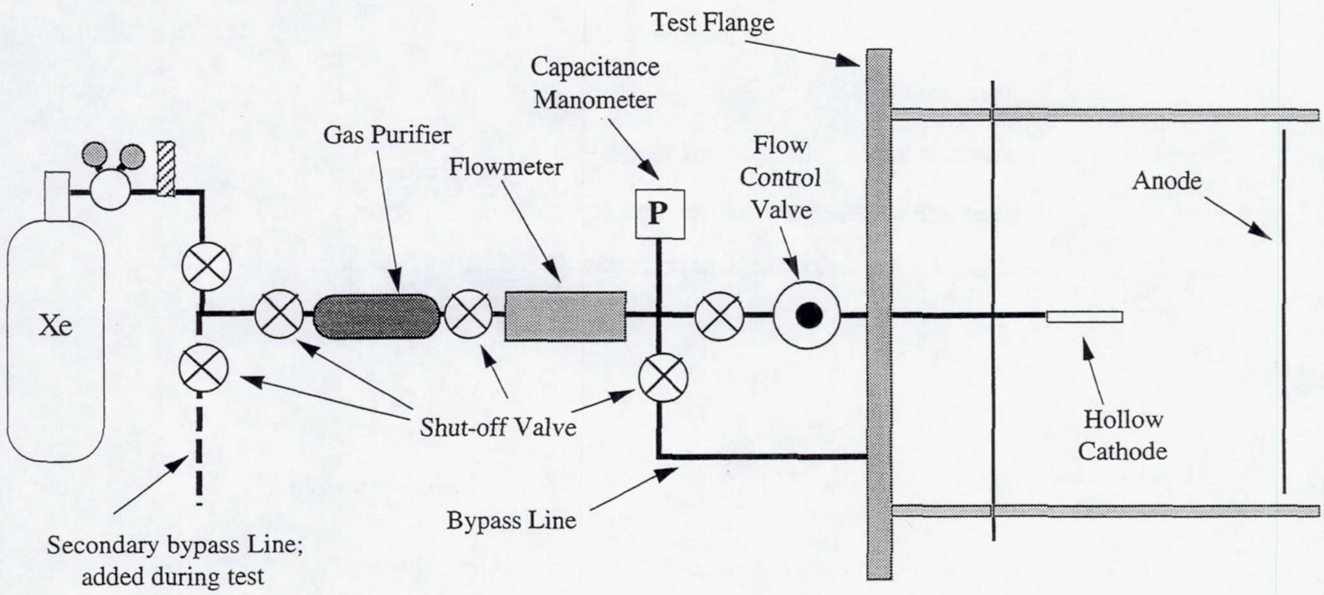


Figure 5 Schematic of expellant feed-system

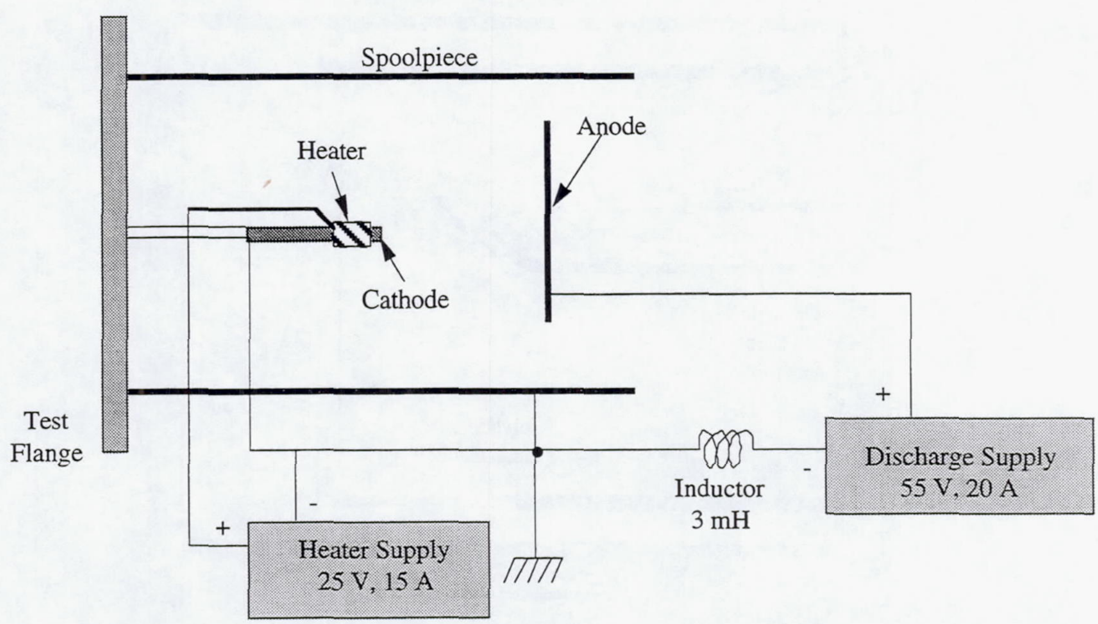


Figure 6 Electrical configuration for wear-test.

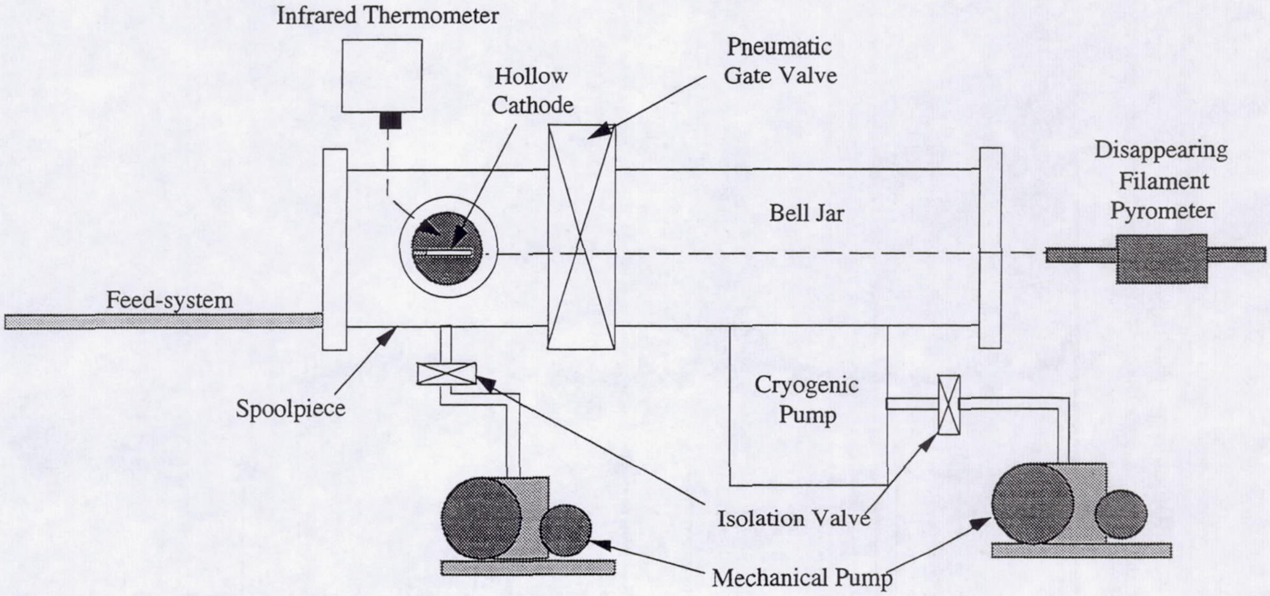


Figure 7 Schematic of vacuum facility and test article.

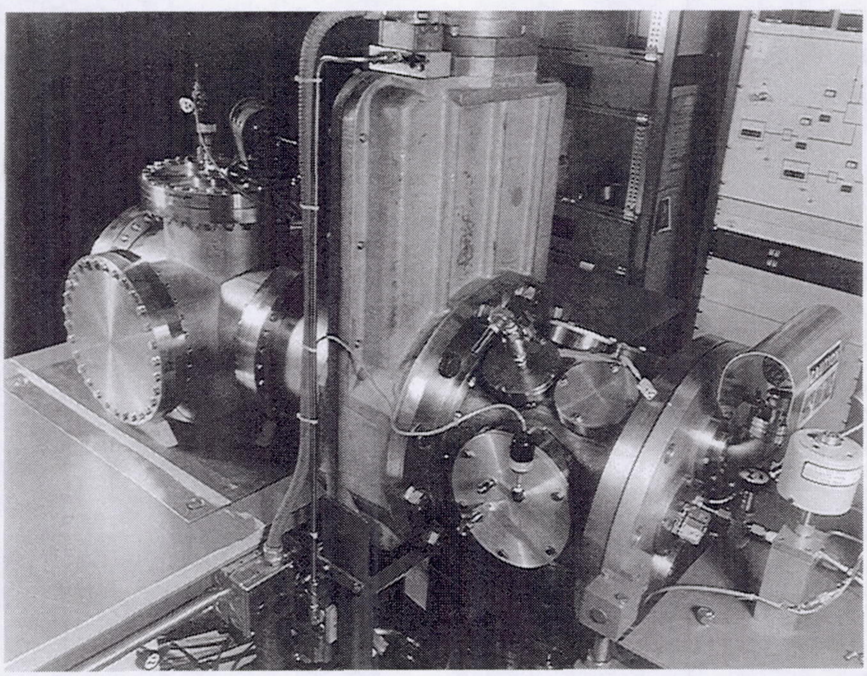


Figure 8 Photograph of cryo-pumped vacuum facility and test-port. Test-port is on right side of photograph.

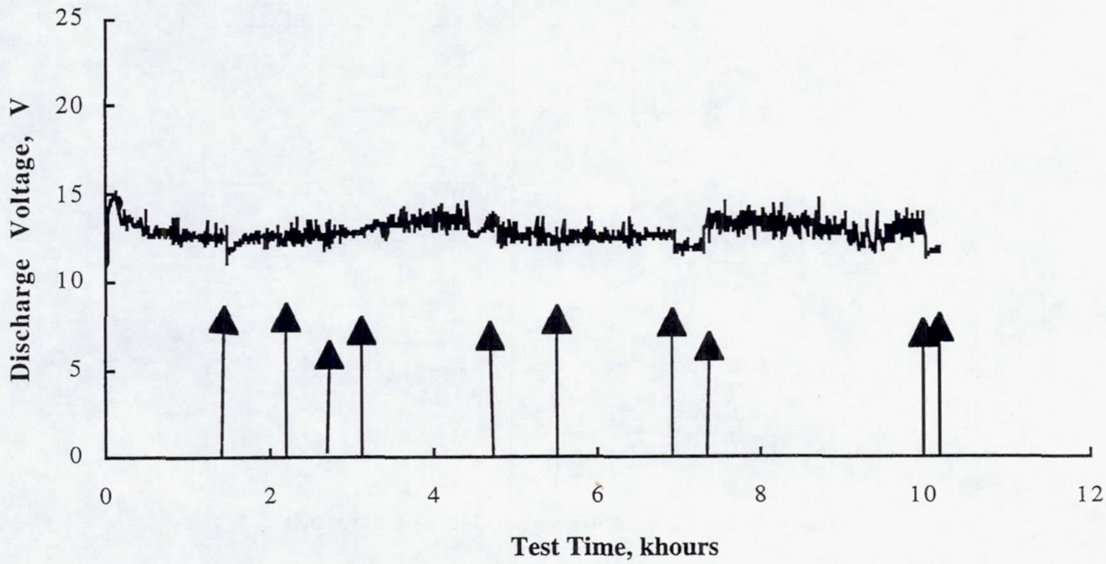


Figure 9 Discharge voltage over course of wear-test. Emission current and xenon flow rate were fixed at 12.0 A and 7.5 Pa-L/s, respectively. The vertical arrows indicate the wear-test shutdown occurences.

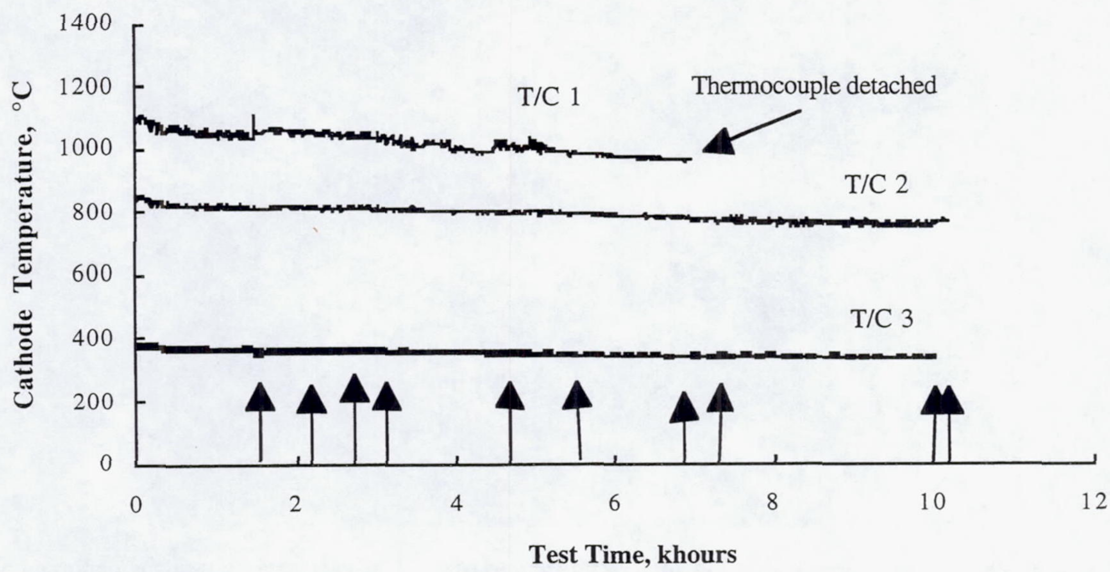


Figure 10 Cathode temperatures over course of wear-test. Temperatures indicated are measured with three type R (Pt/13%Rh-Pt) thermocouples spot-welded to cathode tube. Emission current and xenon flow rate were fixed at 12.0 A and 7.5 Pa-L/s, respectively. The vertical arrows indicate the wear-test shutdown occurences.

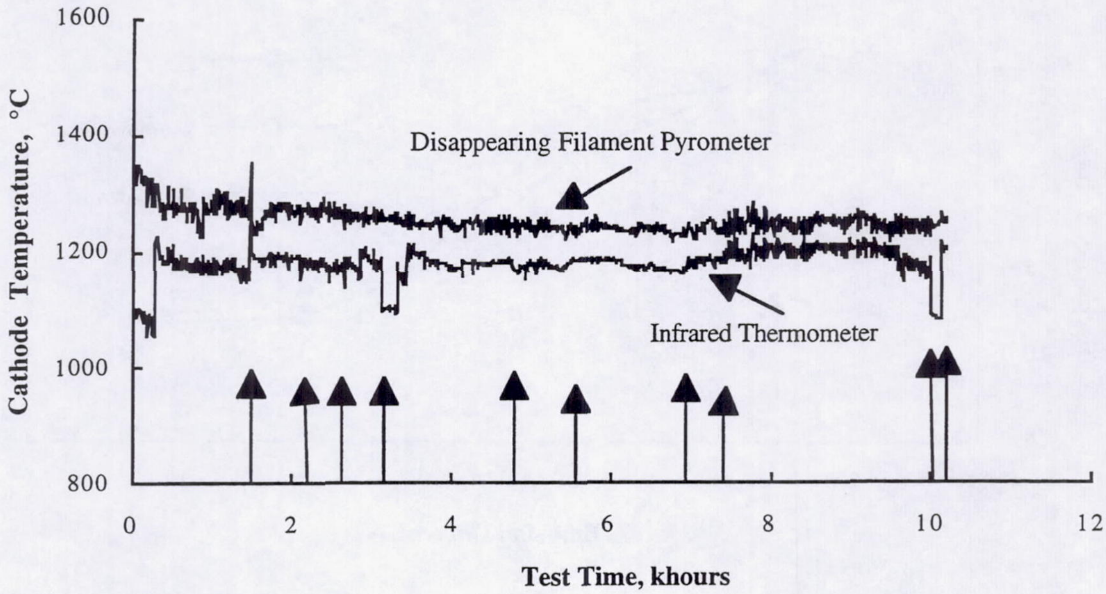


Figure 11 Cathode temperature over the course of the wear-test. Measurements taken with two optical pyrometers. Emission current and xenon flow rate were fixed at 12.0 A and 7.5 Pa-L/s, respectively. The vertical arrows indicate the wear-test shutdown occurences.

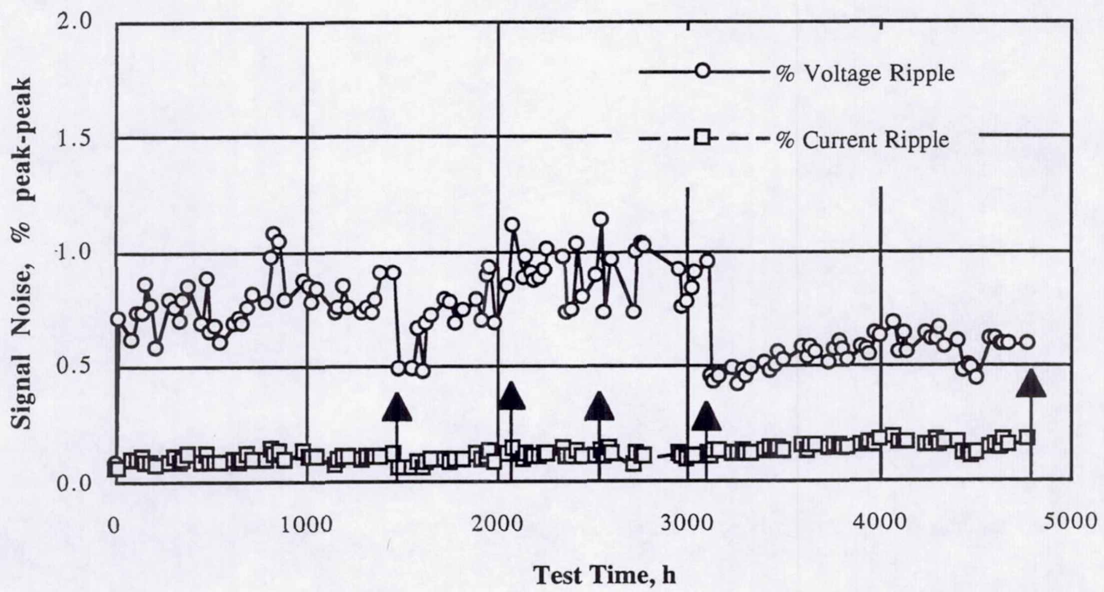


Figure 12 Discharge voltage and emission current noise over the course of the wear-test. Noise is defined as the peak-to-peak magnitude divided by the signal. Emission current and xenon flow rate were fixed at 12.0 A and 7.5 Pa-L/s, respectively. The vertical arrows indicate the wear-test shutdown occurences.

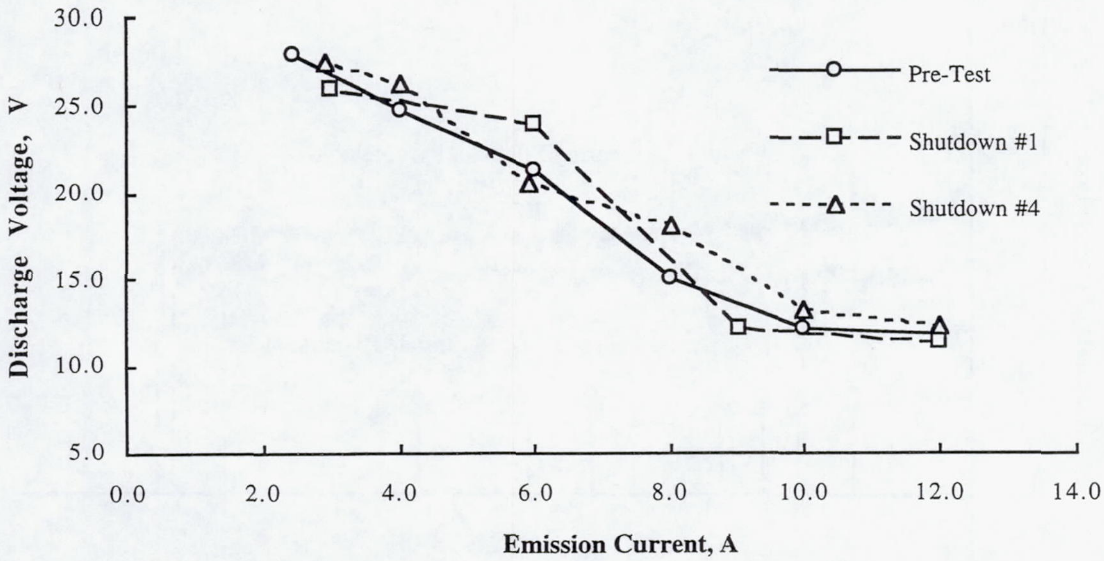
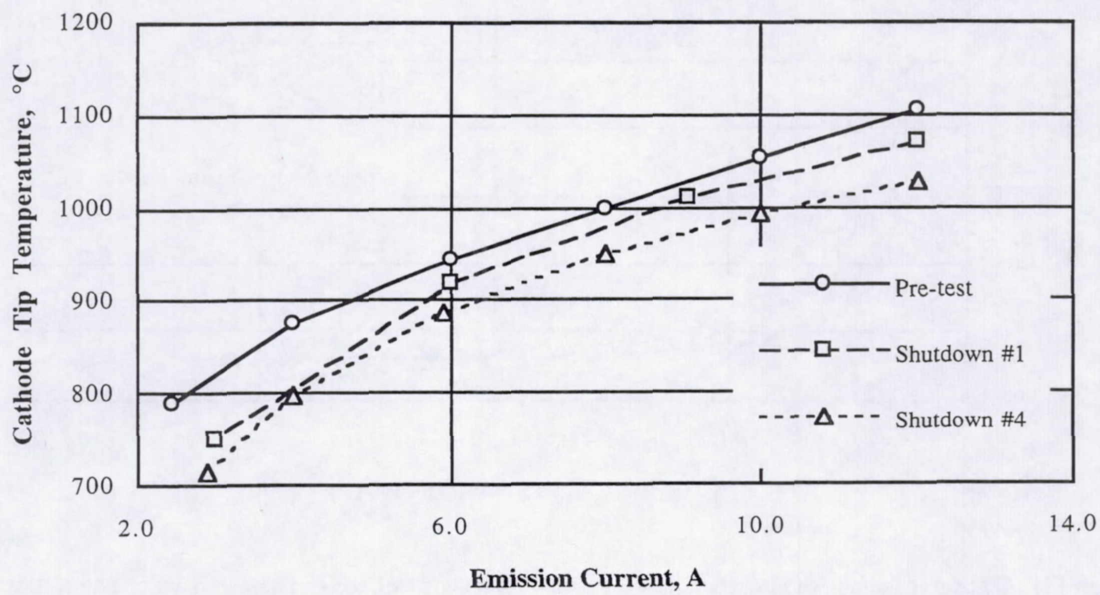
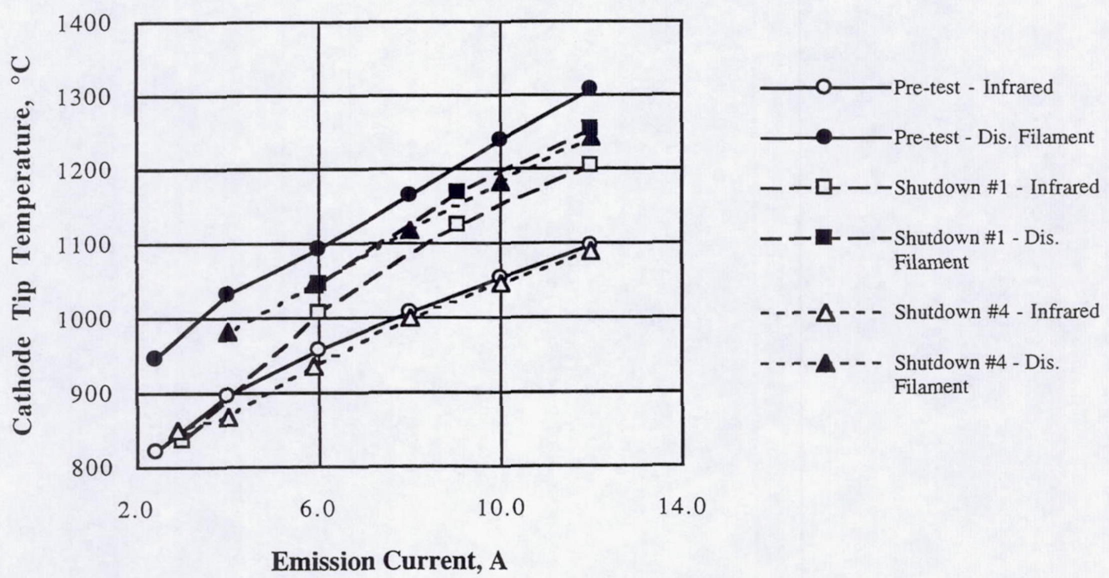


Figure 13 Discharge voltage versus emission current. All data taken at a fixed xenon flow of 7.5 Pa-L/s. Data sets repesent cathode performance after different restarts over the course of the test.



(a) Cathode Temperatures measured with Type R thermocouple.



(b) Cathode temperatures measuresd with two optical pyrometers.

Figure 14 Cathode tip temperatures versus emission current. All data were taken at a fixed xenon flow rate of 7.5 Pa-L/s. In part a), data shown is from a type R thermocouple spot-welded onto the cathode body tube near the cathode tip. In part b), the temperatures were measured with an infrared thermometer and a disappearring filament pyrometer, both of which incorporated a surface emissivity value of 0.39.

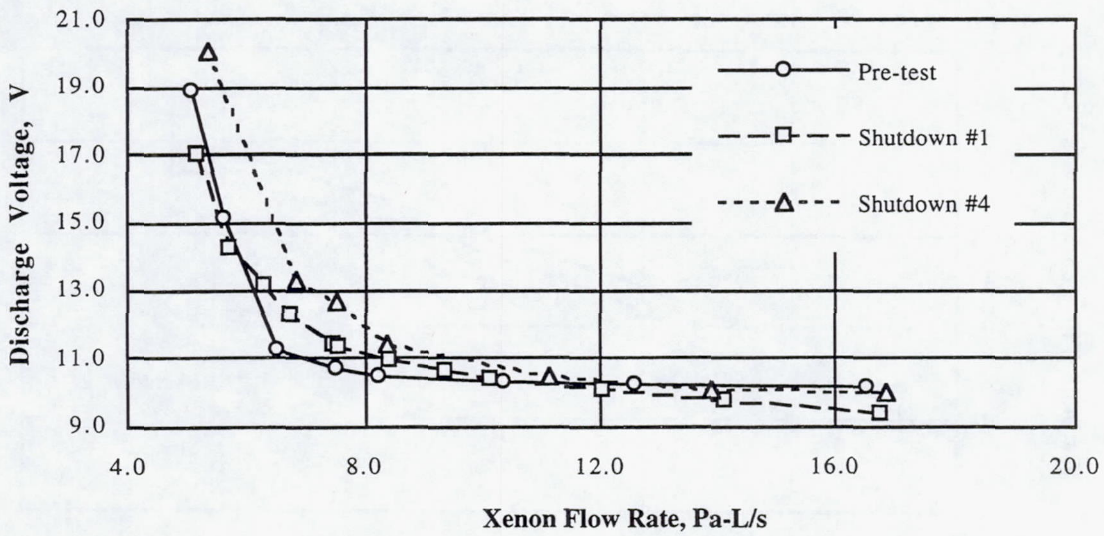
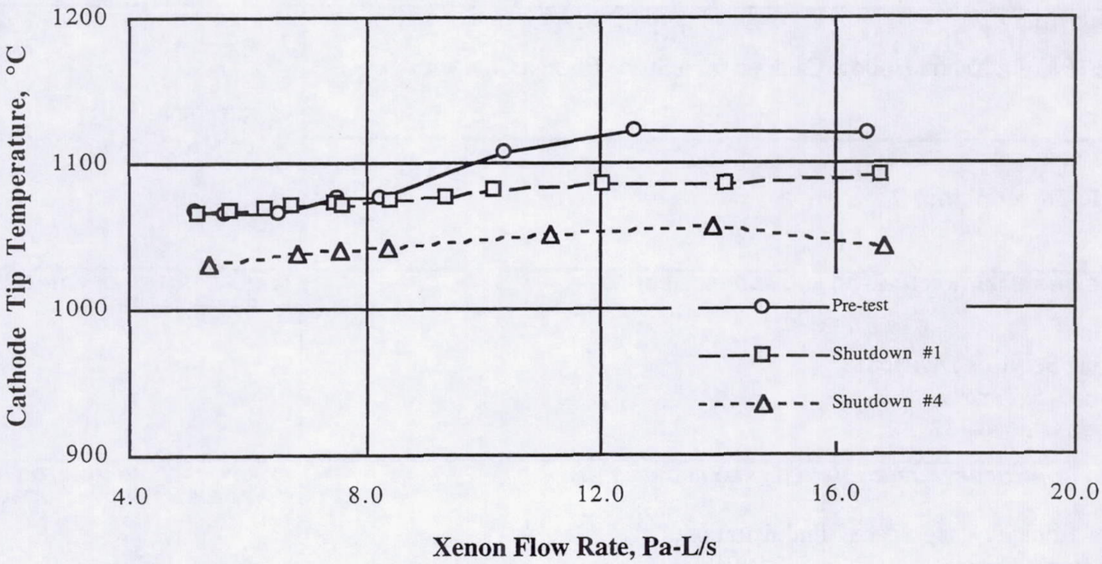
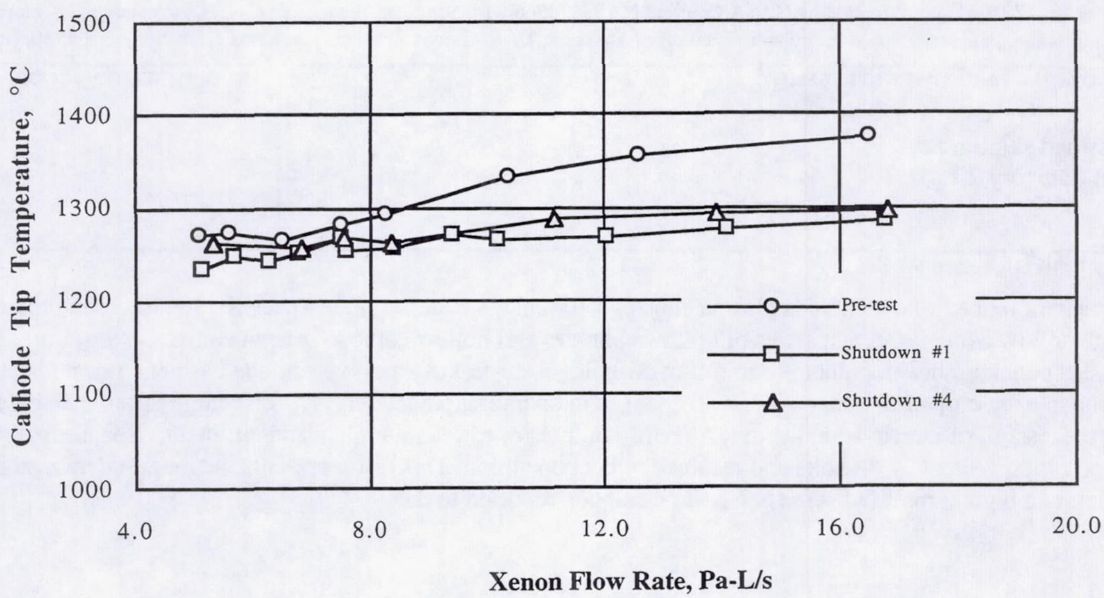


Figure 15 Discharge voltage versus xenon flow rate. All data taken at a fixed emission current of 12.0 A. Data sets repesent cathode performance after different restarts over the course of the test.



(a) Cathode temperatures measured with Type R thermocouple.



(b) Cathode temperatures measured with a disappearing filament pyrometer.

Figure 16 Cathode temperatures versus xenon flow rate. All data taken at a fixed emission current of 12.0 A. In part a), data shown is from a type R thermocouple spot-welded onto the cathode body tube near the cathode tip. In part b), the temperatures were measured with a disappearring filament pyrometer, which incorporated a surface emissivity value of 0.39.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1994	Final Contractor Report

4. TITLE AND SUBTITLE

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

5. FUNDING NUMBERS

WU–506–42–31
C–NAS3–25266

6. AUTHOR(S)

Timothy R. Sarver-Verhey

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NYMA, Inc.
Engineering Services Division
2001 Aerospace Parkway
Brook Park, Ohio 44142

8. PERFORMING ORGANIZATION REPORT NUMBER

E–9246

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR–195402

11. SUPPLEMENTARY NOTES

Prepared for the International Electric Propulsion Conference cosponsored by AIAA, AIDAA, DGLR, and JSASS, Seattle, Washington, September 13–17, 1993. Work funded by NASA Contract NAS3–25266 with Sverdrup Technology, Inc., Lewis Research Center Group. Project Manager, Michael Patterson, Space Propulsion Technology Division, NASA Lewis Research Center, organization code 5330, (216) 433–7481.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 20

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Implementation of a hollow cathode plasma contactor for charge control on the Space Station has required validation of long-life hollow cathodes. A test series of hollow cathodes and hollow cathode plasma contactors was initiated as part of the plasma contactor development program. An on-going wear-test of a hollow cathode has demonstrated cathode operation in excess of 4700 hours with small changes in operating parameters. The discharge experienced 4 shutdowns during the test, all of which were due to test facility failures or expellant replenishment. In all cases, the cathode was reignited at approximately 42 volts and resumed typical operation. This test represents the longest demonstrated stable operation of a high current (>1 A) xenon hollow cathode reported to date.

14. SUBJECT TERMS

Hollow cathode; Plasma contactor; Electron emitter; Ion propulsion; Thruster

15. NUMBER OF PAGES

21

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102