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28,000 Hour Xenon Hollow Cathode Life Test Results

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28,000 hour Xenon Hollow Cathode Life Test Results

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The International Space Station Plasma Contactor System requires a hollow cathode assembly (HCA) with a lifetime of at least 18,000 hours. Critical components of the HCA include the hollow cathode and electron emitter. A series of hollow cathode wear tests was performed which included a life test operated at the maximum current of the HCA. This test sought to verify the hollow cathode design and contamination control protocols. The life test accumulated 27,800 hours of operation before failing to ignite. The hollow cathode exhibited relatively small changes in operating parameters over the course of the test. This life test is the longest duration test of a high current xenon hollow cathode reported to date.

Introduction

A plasma contactor with a xenon hollow cathode assembly (HCA) has been baselined for the International Space Station (ISS).[1] The plasma contactor will provide a connection from station structure to the surrounding space plasma and alleviate the build-up of electrical charge on the ISS.[2] Operational requirements for the HCA are to provide an electron emission current of up to 10 A and a life of 18,000 hours.[3] In order to meet these HCA requirements, a reliable, long-life hollow cathode and electron emitter are needed.

While there is substantial experience using hollow cathodes with mercury,[4,5] the number of life tests performed with xenon is small, particularly with regards to operation at high currents (>1 A).[6,7,8,9,10,11,12] In addition, there have been several instances of performance degradation and cathode failure,[6,7,8,13,14,15] and none has met the requirements for the ISS HCA.

A hollow cathode test program was initiated at the NASA Lewis Research Center to resolve life-limiting problems. The primary cause believed to be responsible for performance and physical degradation was oxygen contamination of the electron emitter surfaces. To address the contamination, control protocols were implemented and gas feed system fidelity was improved.[9] These changes resulted in improved hollow cathode performance and reduced degradation of the emitter surfaces, as demonstrated by the successful completion of multiple hollow cathode wear tests[9,10] and the ongoing life tests of several development model HCAs.[11]

A life test of a xenon hollow cathode was performed with two objectives: 1) to demonstrate control of contamination via incorporation of all protocols previously developed, 2) to demonstrate that a hollow cathode can meet the 18,000 hour ISS lifetime requirement with margin. The hollow cathode was successfully operated for 27,800 hours at an emission current of 12 A before the test was terminated due to changes in operating characteristics. The demonstrated life time was well beyond the life test goal.

Apparatus and Procedures

Hollow Cathode

The hollow cathode, shown in Fig. 1, is similar to the flight HCA cathode.[3] Like the HCA cathode, it consisted of a refractory metal tube with a plate welded to one end. The plate has a small orifice with a chamfer on the downstream surface. The electron emitter consists of a porous sintered tungsten cylinder impregnated with barium-containing compound placed in the downstream end of the tube. Electrical leads, attached to the rear of the electron emitter, were welded to the interior of the upstream end of the hollow cathode tube. These leads provided electrical contact and maintained the position of the emitter in the tube.

A sheathed heater, used for conditioning and ignition, was fitted on the outside of the cathode tube over the region occupied by the electron emitter. Several layers of metal foil were wrapped around the heater to reduce radiated power losses.

While this hollow cathode was functionally and materially similar to that used in the development and flight model HCAs,[3] there were mechanical differences that included the orifice diameter and heater geometry. These differences are minor and do not involve critical components so that the data obtained in this test should be directly applicable to the HCA. In part, the differences were due to the fact that this life test was initiated more than one year before the flight-type HCA design was completed.

Test Configuration

The life test was performed in a diode configuration with a planar anode mounted approximately 6 cm downstream of the hollow cathode (see Fig. 2). Information pertaining to test configuration, feed system design, power supplies, and instrumentation was provided in an earlier report.[16]

During the test, cathode temperature measurements were made with three thermocouples attached to different locations on the cathode body (see Fig. 1) and with two pyrometers sighted onto different locations on the cathode. The pyrometers used were a disappearing filament (DF) pyrometer and an infrared (IR) thermometer.

Several changes in the test configuration and instrumentation were required during the life test. The first change occurred when the tip thermocouple, used as the primary temperature measurement, detached after 6,949 hours. As a result, the DF pyrometer measurement was used as the tip temperature measurement for the remainder of the life test. This measurement was used for characterization under flow rate variation, conditioning, and ignition. Additionally, it provided qualitative indications of the cathode condition. The DF pyrometer readings were found to be approximately 100 °C higher than the tip thermocouple readings. The difference in measured temperature using the two techniques was attributed to several factors, including surface contact resistance and surface emissivity. The data shown in this paper are the DF pyrometer measurements corrected only for surface emissivity.

A second change was the removal of a gas purifier from the gas feed system. Over the course of the life test, the feed system was disassembled several times, primarily to replace xenon bottles. After each instance, strict cleaning procedures were followed and feed system integrity was verified before restarting the life test. During a feed system disassembly at hour 21,269, the purifier was believed to have been exhausted by direct atmospheric exposure due to an in-line valve failure. The purifier is rendered inert once the purification medium has been saturated. It was, therefore, removed during the shut-down at hour 23,776. Removal of the purifier was believed to be inconsequential because other cathodes had been operated successfully for periods in excess of 10,000 hours using similar gas feed systems, but without a gas purifier.[10] The purifier was included in this feed system because the life test was initiated prior to those findings.

Third, the calibration of the xenon mass flow meter changed slightly over the test. The flow meter was calibrated with a volumetric calibrator three times; before the test, after 23,776 hours (the hollow cathode remained under vacuum), and after 27,800 hours. The calibrations indicated that the flow rate increased by approximately 3.8% between test start and 23,776 hours and by approximately 3.1% over the duration of the life test. The calibration results were incorporated into the flow rates reported here.

Finally, all ignitions prior to hour 23,776 were accomplished with an open-circuit voltage ^{2} 55 V. Subsequent ignitions required higher voltages, which were provided by a DC ignitor power supply.

Test Procedures

Procedures relating to feed system preparation and instrument calibration used in the life test were discussed in detail in an earlier report.[16] Two critical procedures were used in this life test. First, a cathode conditioning procedure was used whenever atmospheric exposure was suspected.[9]

Second, a fixed cathode ignition procedure was used. In this sequence, the cathode was first heated to high temperature for a fixed period after which an increasing DC voltage was applied between the hollow cathode and the planar anode until discharge breakdown occurred. The required breakdown voltage was used as an indicator of cathode condition.

The conditioning and ignition procedures used for this hollow cathode differ significantly from those used for the development model and flight HCAs.[3] This is because this life test was initiated before refined procedures were established for the HCA. The refinements simplified the procedures by eliminating unnecessary steps and implementing a different ignition approach. The procedural differences were not expected to invalidate the comparison between this hollow cathode and the flight HCAs.

Test Condition

The life test was conducted at an emission current of 12 A and a xenon flow rate of approximately 4.2 sccm. The current was selected because it was estimated at that time to be the maximum required emission current for the HCA hollow cathode and thus represented a very conservative operating point. The xenon flow rate was selected based on the pre-test characterization of the hollow cathode. Measurement of the anode voltage with varying flow rate indicated that 4.2 sccm was a stable operating condition.

Results and Discussions

Test Chronology

The life test was initiated on December 30, 1992, and terminated on May 2, 1997. During the life test, the cathode accumulated 27,800 hours (3.2 years) of operation, greatly exceeding its target of 18,000 hours. The behavior of the operating parameters is compiled in Table 1. These include the initial, mean, maximum, minimum, and final values of each parameter. Table 2 contains the chronology of the life test shut-downs and also chronicles the ignition voltages.

The xenon flow rate had to be increased starting at hour 16,700 in order to maintain the anode voltage at relatively low peak-to-peak noise levels. The required flow rate by the end of the life test was 4.7 sccm. The cause of increased flow rate has been attributed to changes in the hollow cathode, which will be discussed in a later section.

Two anomalies occurred during the life test. First, at approximately hour 1,467, the gate valve separating the hollow cathode and vacuum pump closed. The cathode continued to operate for approximately eight hours before shut-down, during which time the tip temperature rose to approximately 1170 °C (Tip thermocouple reading). Second, at approximately hour 13,854, the xenon flow rate decayed to approximately 2.6 sccm due to decaying xenon bottle pressure. This resulted in the hollow cathode operating at approximately 40 V for three hours before shut-down. Cathode operation was normal after both occurrences so neither was deemed to have caused irreversible changes.

Hollow Cathode Characterization

The hollow cathode was characterized repeatedly during the test by measuring the anode voltage and cathode temperatures under variation of xenon flow rate. The voltage and temperatures are the dependent operating parameters of the cathode and reflect changes in condition. Figure 3 shows the pre- and post-test behavior of the anode voltage as a function of the xenon flow rate at a fixed emission current of 12 A. At the start of the life test, the anode voltage increased rapidly at flow rates below approximately 3.6 sccm. By the end of the test, the anode voltage increased rapidly at flow rates below about 4.8 sccm. In addition, the anode voltages were higher at all flow rates. Characterizations performed during the test agreed with the trend shown in Fig. 3.

The nominal anode voltage at the life test flow rate increased by approximately 16% during the test. While this increase is indicative of changing cathode condition, it was within the bandwidth observed during previous HCA cathode life tests.[11] Additionally, the anode voltage during this life test was always significantly lower than the maximum allowable anode voltage of 40 V for the HCA.[3] Consequently, voltage increases similar to that observed during this life test should have negligible impact on HCA operation.

The effect of flow rate on cathode tip temperature over the course of the test is shown in Figure 4. The pre-test data and the data obtained at hour 27,795 exhibited comparable operating temperatures over much of the flow range. However, at the life test flow rate, the tip temperature increased by approximately 50 °C over the course of the test. This increase resulted in the hollow cathode operating near the cut-off temperature of 1,350 °C (DF pyrometer reading), which is discussed below.

Measurements taken during the life test up to the 23,776 hour mark were consistently and substantially lower than the pre-test and final temperature measurements over the entire flow range. This is illustrated in Fig. 4 by the data taken at hour 17,592. This data set was selected at random as a typical example of this behavior. After 23,776 hours, the tip temperatures below 4.6 sccm exceeded the pre-test values.

The cathode temperature exhibited the greatest sensitivity to xenon flow rate at the beginning of the life test. By the end of the life test, the cathode could not be operated below 4.2 sccm without the DC and AC components of the anode voltage rising significantly. The HCA flow rates were selected to ensure that the cathode does not operate near this region with significant DC and AC anode voltage components.[3] Therefore, this effect is expected to be inconsequential for the ISS program.

Life Test Performance

Hollow cathode performance during the life test was determined by monitoring the anode voltage and cathode temperatures. Figure 5 shows the behavior of the anode voltage as a function of test time. Two types of voltage variations were observed. First, the anode voltage varied over a period of several thousand hours with a mean value of 12.9 V. The range of this voltage variation is listed in Table 1.

Second, nominal daily voltage variations of approximately ± 0.3 V resulted from changes in xenon flow rate caused by ambient laboratory temperature changes. This variation appears as the noise on the anode voltage measurement in Fig. 5. The corresponding flow rate changes were typically ± 0.2 sccm.

Cathode temperatures, measured with two thermocouples and two pyrometers, are shown in Figure 6 as a function of test time. The temperatures exhibited two variations during the life test. The first variation was that the temperatures all decayed continually until approximately hour 23,000, at which time the temperatures started to rise rapidly.

For the test, a shut-down criterion of 1,350 °C (DF pyrometer reading) maximum cathode tip temperature was established in order to ensure that the condition of the hollow cathode and electron emitter were preserved against rapid changes due to operation at increased temperature. The cathode tip temperature rose until this value was reached at hour 23,776 and the life test was stopped for evaluation.

After flow meter recalibration and a feed system integrity check failed to identify any test support equipment problems that may have accounted for the cathode tip temperature increase, the life test was resumed. The cathode tip temperature subsequently stabilized approximately 1,315 °C and remained there for approximately 4,000 hours. The tip temperature then exceeded the 1,350 °C limit at approximately hour 27,795.

The second observed temperature variation, shown in Fig. 6, was the result of the daily variations in xenon flow rate due to laboratory ambient temperature changes. Because of the flow rate variations, the tip temperature measurements using the DF pyrometer varied by approximately 30 °C.

Three temperature 'spikes' occurred during the life test. The first occurred during the anomaly at hour 1,467. The second and third spikes occurred when the cathode tip temperature met or exceeded the cut-off temperatures at hour 23,776 and 27,800.

Dynamic behavior of the anode voltage and emission current signals were monitored with an oscilloscope. The peak-to-peak noise levels for emission current and anode voltage were ^{2} 1% and ^{2} 5%, respectively, during the test.

Ignition Characteristics

Prior to the restart at 23,776 hours, the discharge ignition voltage increased from approximately 42 to 54 V. Because increased ignition voltages have been associated with deteriorating cathode condition in previous extended tests,[6,7,8] the relatively small ignition voltage increase was taken as a good indicator that the cathode was not deteriorating. However, as noted in the previous section, the cathode temperature started to rise at approximately 23,000 hours until it reached the cut-off temperature at 23,776 hours. The ignition voltage required after that time was approximately 725 V, significantly greater than that required for previous ignitions. The ignition voltage continued to increase over the remainder of the life test, as shown in Table 2, while the cathode tip temperature stabilized at a higher temperature for the next 4,000 hours. During the last test segment starting at hour 27,795, the cathode tip temperature exceeded the cut-off temperature. At this time, the ignition voltage had risen to a level above that available from the power supplies and the test was terminated. This event was attributed to deterioration of the electron emitter condition.

Post-test Assessment

The hollow cathode ignition failure at 27,800 hours resulted in the termination of the life test. The ignition failure and the elevated cathode tip temperatures during the last test segment appear to be due to deterioration of the electron emitter condition. Specifically, it is suspected that the emitter work function increased because barium could not be readily provided to the emitter surface. Reduction in the barium production rate may be due simple depletion due to extended testing and/or reactive chemistry on the electron emitter due to contamination. These explanations are consistent with the observations of increased ignition difficulty and increased cathode temperatures necessary to compensate for the reduced barium production rate. Determination of the hollow cathode failure mechanism(s) will require the destructive examination of the hollow cathode and its electron emitter and this is in progress at this point. However, at this time, the failure is not believed to be due to contamination of the xenon gas.

Operating an electron emitter in excess of 1,350 °C (DF pyrometer reading) would result in increased rates of destructive chemistry in the emitter that may eventually result in complete emitter failure.[17] In order to preserve the hollow cathode and electron emitter conditions, the cathode was not operated for extended periods above this cut-off temperature. It is noteworthy that the anode voltage remained relatively stable throughout the cathode temperature increases, indicating that voltage was less sensitive than temperature to changes in emitter condition.

Destructive Analysis

The physical conditions of the hollow cathode and electron emitter are presently being evaluated. The pre- and post-test conditions of the hollow cathode are shown in Figure 7. Preliminary results indicate that the cathode orifice was generally in good shape and increased in diameter by approximately 14%. This change is believed to be sufficient to cause the shift in cathode operation shown in Fig. 3.

In addition, the orifice plate and cathode exterior surfaces were textured by ion bombardment, though the erosion was not sufficient to remove surface features (i.e orifice plate weld structure, orifice chamfer, sheathed heater surface).

Finally, the sheathed heater radiation shielding was found to be severely eroded, with the exposed surfaces exhibiting degradation. This erosion is attributed to ion bombardment due to operating the cathode with a planar anode that resulted in significant exposure of the heater radiation foil to the discharge plasma. This degradation is significant for this life test because it is suspected to have degraded heater capability. However, the HCA cathode does not experience similar degradation due to its configuration.[11] Destructive examination of the life test cathode is on-going.

Conclusion

A xenon hollow cathode life test was operated for approximately 27,800 hours in a diode configuration at a fixed emission current of 12 A. The hollow cathode operated at a nominal anode voltage of 12.9 V. The test was initiated at a xenon flow rate of 4.2 sccm that increased to 4.7 sccm by the end. While the required ignition voltage was approximately 50 V for the first 23,776 hours, subsequent ignitions required increasing breakdown voltages until the cathode failed to ignite at an applied voltage of 1,050 V. This failure terminated the life test. Additionally, the cathode tip temperature had exceeded a cut-off limit during the last test segment. The cause of the cathode ignition failure and increased tip temperature is attributed to electron emitter deterioration which is being actively investigated.

The life test of this xenon hollow cathode exceeded the 18,000 hour lifetime requirement of the ISS HCA cathode with margin. It is the longest reported test of a xenon hollow cathode operated at high emission currents to date.

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Table 1. Life test Parameters

Parameter	Value					Continuously Monitored?
	Initial	Mean	Min.	Max.	Final	
Anode Voltage, V	11.0	12.9	11.0	16.2	13.5	Yes
Emission Current, A	12.0	12.0	12.0	12.0	12.0	Yes
Xenon Flow Rate, sccm	4.22	4.33	3.77	5.22	4.70	Yes[†]
Cathode Tip Temperature, °C - t/c*	1,096	1,022	960	1,111	961	Yes
Cathode Tip Temperature, °C - DF pyro	1,350	1,260	1,179	1,368	1,358	No
Cathode Tip Temperature, °C - IR pyro	1,087	1,189	1,058	1,310	1,265	Yes
Cathode Body Temperature, °C - t/c	845	777	736	855	794	Yes

* Data obtained until thermocouple detached from cathode at hr. 6,949.

[†] Data signal added to computer data acquisition system after 13,861 hours.

Table 2. Life Test Chronology

Test Event	Ignition Voltage, V	Elapsed Time, hr.		Average Value		Cause of Interruption
		Segment	Total	Anode Voltage, V	Temp., °C (DF pyro)	
1	44	1,467	1,467	13.0	1,286	Accidental Gate Valve Closure
2	45	622	2,089	12.4	1,264	Power Failure
3	40	550	2,639	12.6	1,269	Accidental Gate Valve Closure
4	40	480	3,119	12.8	1,261	Xenon Bottle Change-out
5	44	1,653	4,772	13.4	1,248	Xenon Bottle Change-out
6	43	642	5,413	12.7	1,242	Power Failure
7	42	1,536	6,949	12.6	1,237	Power Failure
8	39	358	7,307	12.0	1,240	Xenon Bottle Change-out
9	39	2,700	10,007	13.1	1,247	Power Failure
10	42	180	10,187	11.7	1,249	Power Failure
11	42	304	10,490	12.0	1,248	Xenon Bottle Change-out
12	43	3,371	13,861	12.9	1,241	Off-normal Operation. Xenon Bottle Change-out
13	42	1,316	15,177	12.5	1,239	Parameter Limit Violation
14	45	616	15,793	12.5	1,233	Parameter Limit Violation
15	44	2,327	18,120	12.8	1,226	Power Failure
16	52	1,620	19,740	12.5	1,218	Government Shut-down
17	52	1,529	21,269	12.6	1,216	Power Failure. Xenon Bottle Change-out
18	54	541	21,810	12.4	1,217	Power Failure
19	62	1,966	23,776	12.6	1,261	Cut-off temperature exceeded
20	725 ± 25	2,851	26,627	12.9	1,312 ± 20	Cryo-pump regeneration & evaluation
21	950 ± 50	1,168	27,795	13.5	1,316 ± 20	Parameter Limit Violation
22	1046	5	27,800	13.7	1,358 ± 10	Cut-off temperature exceeded
23	n/a	n/a	27,800	n/a	n/a	Cathode failed to ignite

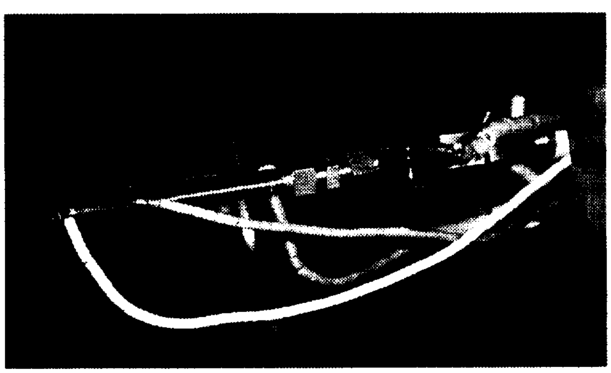


Figure 1. Life test hollow cathode.

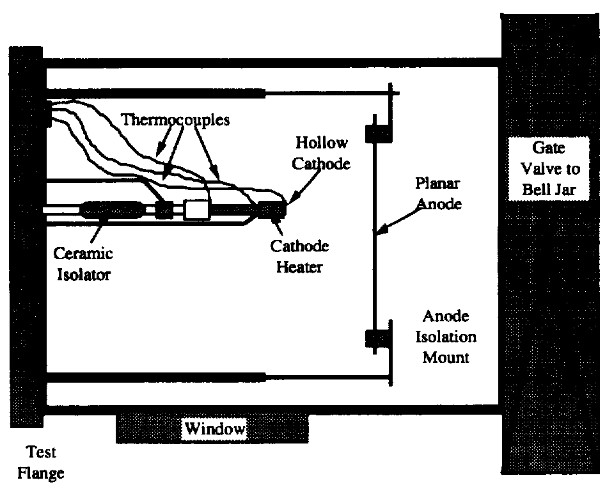


Figure 2. Schematic of life test configuration.

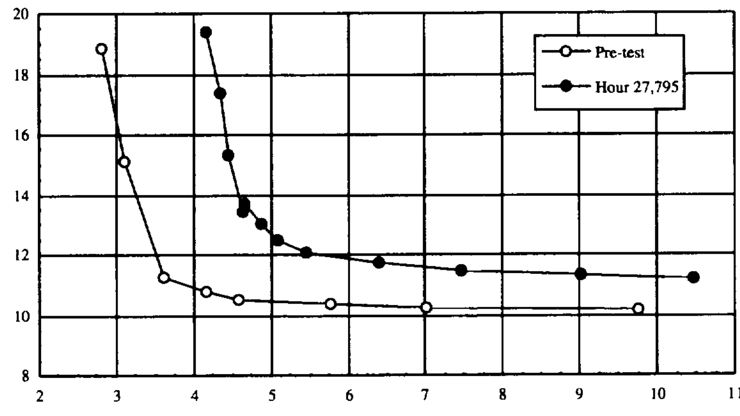


Figure 3. Anode voltage vs. xenon flow rate before and after life test.

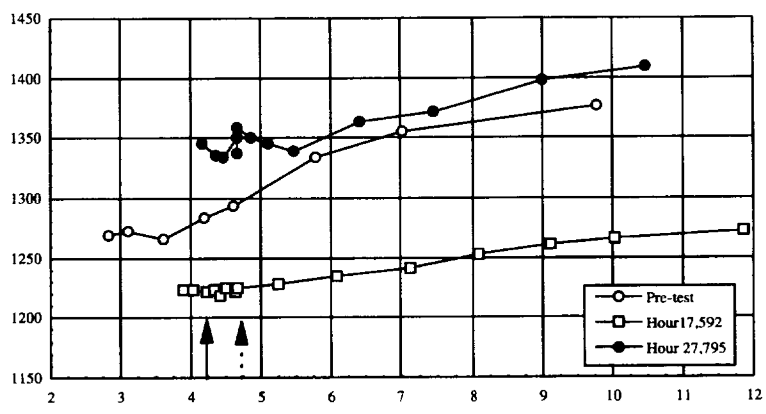


Figure 4. Hollow cathode operating temperature vs. xenon flow rate. All data taken with a disappearing filament pyrometer at a fixed emission current of 12 A. The arrows indicate the life test flow rate set point (solid line - pre-test; dotted line - Hour 27,795).

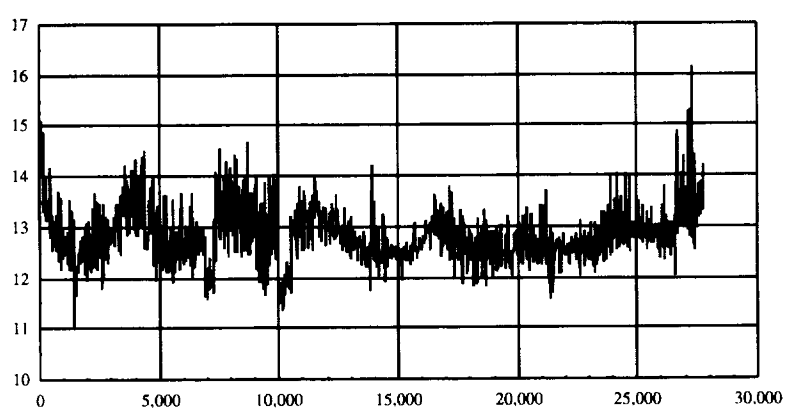


Figure 5. Anode voltage vs. test time.

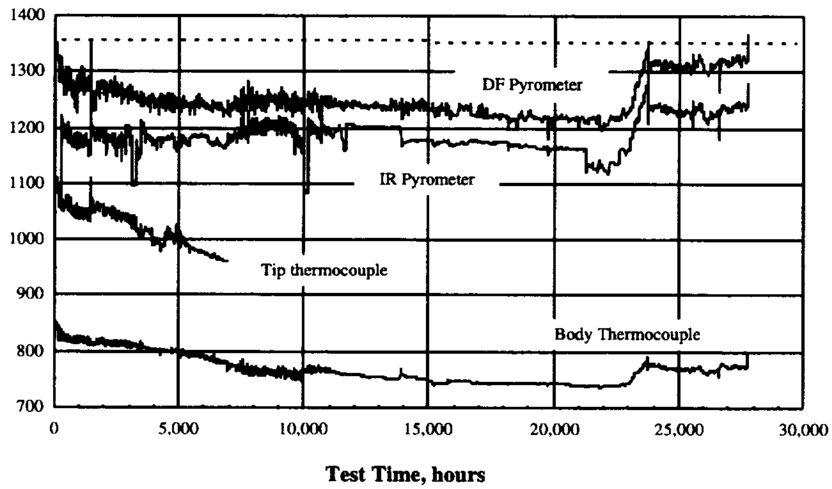
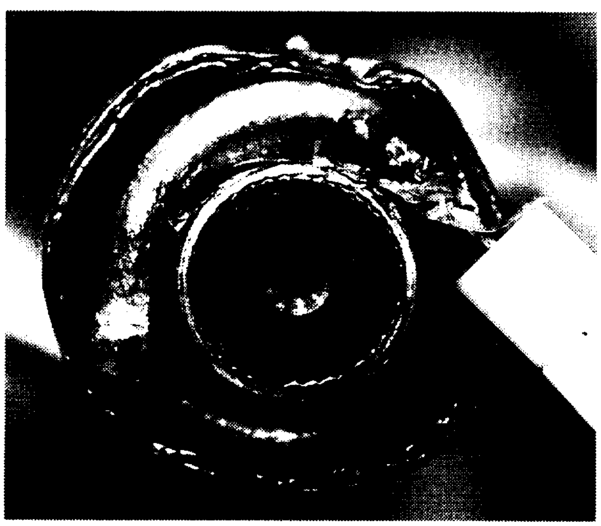
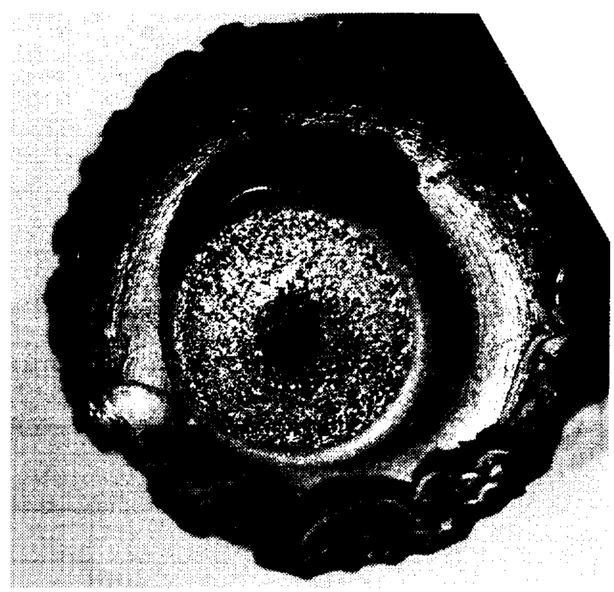


Figure 6. Cathode temperatures vs. test time. Temperatures measured with two thermocouples and two pyrometers. The dashed line indicates the life test cut-off temperature.



(a)



(b)

Figure 7. End view of the life test hollow cathode. (a) Pre-test. (b) Post-test.

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