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International Space Station Cathode Life Testing Status

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Dynacs Engineering Company, Inc.

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International Space Station Cathode Life Testing Status

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To demonstrate adequate lifetime and performance capabilities of a hollow cathode for use on the International Space Station (ISS) plasma contactor system, life tests of multiple hollow cathode assemblies (HCAs) were initiated at operating conditions simulating on-orbit operation. Three HCAs are presently being tested. These HCAs are operated with a continuous 6 sccm xenon flow rate and 3 A anode current. Emission current requirements are simulated with a square waveform consisting of 50 minutes at a 2.5 A emission current and 40 minutes with no emission current. As of July 1998, these HCAs have accumulated between 11,700 and 14,200 hours. While there have been changes in operating behavior, the three HCAs continue to operate stably within ISS specifications and are expected to demonstrate the required lifetime.

Introduction

A hollow cathode-based plasma contactor system has been baselined for use on the International Space Station to reduce spacecraft electrical charging.[1] The plasma contactor system provides a low impedance connection to space plasma with a hollow cathode assembly (HCA). The operational requirements of the HCA include an electron emission capability of up to 10 A and an operational lifetime of 18,000 hours. Other component-level tests, including a hollow cathode,[2] cathode heater[3] life tests, and an accelerated cyclic ignition test,[4] have been conducted as part of the effort to demonstrate compliance with mission requirements.

In order to demonstrate the lifetime capability, multiple high-fidelity development model HCAs are being life-tested to 27,000 hours at conditions simulating on-orbit operation. To date, three HCAs, designated HCA-003, -010, and -013, have accumulated 12,400, 11,700, and 14,200 hours, respectively. A fourth HCA had also been under test but this test was voluntarily terminated at 8,000 hours to conduct destructive analyses prior to the HCA critical design review. The HCA condition was excellent and has been reported elsewhere.[5] This report will update an earlier work[5] by discussing the operating performance of HCAs -003, -010, and -013 since hours 10,900, 7,800, and 10,200, respectively.

Apparatus

Hollow Cathode Assembly

A development model HCA design was used for mission profile life testing. While there are minor differences between the development model and spaceflight designs,[1,4] they are functionally identical and the test results are expected to be valid for the flight hardware. Briefly, the HCA consists of an orificed cathode tube with a low-work function electron emitter installed at the downstream end. A sheathed heater is mounted on the exterior of the cathode tube for conditioning and ignition. An integral anode shell is mounted around the cathode and electrically isolated from it.

Test Configuration

All of the HCAs are operated continuously with a fixed current of 3 A between the cathode and anode. For mission profile life testing, each HCA emits an additional current to an external anode plate mounted downstream. A bias voltage is applied to this plate to extract the simulated spacecraft charge control current. A photograph of an HCA/bias anode arrangement is shown in Figure 1. All HCA/bias anode configurations and their respective power supplies are electrically isolated from each other, and from vacuum facility ground.

Power Supplies

Commercial power supplies are used to operate the HCA heater and discharge and to extract the bias current. All power supplies are operated in current controlled mode. The heater and anode power supplies provide up to 8.5 A and 3.0 A, respectively. The bias power supply can provide up to 10 A, although a current of 2.5 A is used for life testing. An breadboard ignitor supply[6] provided a high-voltage pulse[4] to ignite the HCA discharges.

Laboratory Gas Feed Systems

One of the two gas feed systems used to deliver xenon to the HCAs is shown in Figure 2. The xenon flow rate is measured and controlled with a mass flow controller. A mass flow meter is located upstream of the flow controller to provide redundant flow measurement. Protocols developed for the plasma contactor program are used to mitigate xenon gas contamination throughout the course of this test. Further details on the feed systems have been discussed previously.[7]

Vacuum Facility

The mission profile life testing is being performed in a 1.0 m diameter x 1.5 m long stainless steel tank evacuated with a 0.89 m diameter cryo-pump. This cryo-pump has a pumping speed of approximately 1,300 L/s on xenon which maintains the facility at a base pressure of 3.0×10^{-6} Pa (2.3×10^{-8} Torr) and a pressure of 2.0×10^{-2} Pa (1.5×10^{-4} Torr) during HCA operation.

Data Acquisition and Control System

Life testing is controlled and monitored by computer. Heater, anode, and bias currents, xenon flow rate, and test sequencing are the control parameters for the life test. Test chamber pressure, heater, anode, and bias voltages, and cathode temperature data are automatically acquired and monitored to terminate life testing in case of an off-normal condition. Finally, AC components of anode and bias voltages and currents are measured manually with an oscilloscope.

Test Procedures and Operating Conditions

For all testing, cathode conditioning and ignition procedures used in these tests are the same as those for the spaceflight HCAs.[1] Whenever the HCA was exposed to air, cathode conditioning procedures were conducted to prepare the cathode electron emitter for operation.

The HCA discharge is ignited with the following procedure. A heater current of 8.5 A is applied. After a fixed period, xenon gas flow is initiated and following a short flow stabilization period, the anode open circuit voltage and ignition pulse are applied. Heater power is maintained until an anode current is detected. Immediately after ignition, the ignitor and heater power supplies are turned off and the discharge between cathode and anode is allowed to stabilize. The ignition procedure is described in further detail elsewhere.[4] A performance evaluation of the HCA is typically conducted at the start of each test segment during which anode voltages are measured as a function of xenon flow rate at a fixed anode current. Life testing is then initiated (or resumed).

The HCA operating conditions for all testing are listed in Table 1. Test conditions were defined by a previous study which found that the International Space Station will require on average an electron current during approximately 50 minutes of the 90 minute orbital period.[8] Although the HCA is designed to provide an electron emission current of up to 10 A, the maximum sustained electron emission current is anticipated to be approximately 2.5 A during this emission period.[8] During the remaining 40 minutes of the orbit, the idle period, no electron emission current is required and the discharge is maintained at an anode current of 3.0 A. This profile is repeated continuously.

Some deviations from these nominal test conditions are noted. HCA-010 was briefly operated in an on-off mode to support a plasma contactor system trade study examining xenon usage. During operation in this mode, the HCA discharge was ignited just prior to each emission period and extinguished at the start of each idle period. The on-off mode was initiated at hour 2,370 and was changed back to continuous-on mode after hour 6,445, after successfully completing 4,369 cycles, as indicated in Table 1.

Results and Discussion

To date, there have been 35 test interruptions. These interruptions occurred as a result of facility or test support equipment failures. None of the interruptions were due to the HCAs, and these shut-downs were performed in a manner which did not compromise the integrity of the HCAs. The behavior of the anode and bias voltages at the end of idle and emission periods is used as the main indicator of HCA health. The ignition times and performance evaluations are also used to assess the condition of each HCA during life testing. The results of the HCAs -003, -010, and -013 collected since hours 10,900, 7,800, and 10,200, respectively will be presented and discussed.

HCA Performance Evaluations

HCA performance was evaluated during the course of life testing by measuring the anode voltage over a range of xenon flow rates at a fixed current. Figure 3 shows the performance of HCA-003 at the start of the test segments. As can be seen, the anode voltage behavior has remained approximately the same, with some variation in voltage levels. The performance of HCAs -010 and -013 exhibited similar behavior, as shown in Figure 4. In this figure, the HCA anode voltages were averaged from all profiles measured to date. The voltages at 6 sccm have varied within a maximum bandwidth of 5.5 V over the course of the life tests. This bandwidth is similar to that observed in a 28,000 hour hollow cathode life test.[2] The small differences in anode voltage between the three HCAs can be attributed to slight variations in HCA geometry.[5]

Life Test Performance

As of July 1998, HCAs -003, -010, and -013, have accumulated 12,400, 11,700, and 14,200 hours of operation, respectively. Operation on all devices has remained within the specifications of the ISS HCA. These specifications include ignition within 30 minutes and operating anode voltages $\leq$ 40 VDC.[1] The anode voltage and ignition time behavior to date will be examined in this section.

As mentioned previously, anode and bias voltages are monitored to determine the condition of the HCAs. Figures 5-7 show the anode and bias voltages at the end of idle and emission periods for each HCA. To date, none of the devices have exhibited monotonic changes in anode or bias voltages over the course of life testing which would indicate life-limiting changes. There have been repeated instances of increases of several volts occurring over periods of several thousand hours. However, similar increases have occurred during these life tests as well as during a hollow cathode life test[2] after which the voltages eventually returned to lower values. HCA end-of-period voltages for all three devices have varied within a maximum bandwidth of 6.9 V, as shown in Table 2.

Another indicator of HCA condition is the time for ignition to occur, as measured from the start of the pre-heat. The ignition times for the three HCAs over the course of the life test are shown in Figure 8. The time required to ignite the HCAs has generally been less than 6 minutes for all HCAs, which is characteristic for this HCA design.[1] Ignition times greater than 6 minutes occurred during the initial series of ignitions following HCA fabrication, which is typical. Recently, two devices have required longer times to ignite.

HCA-003 has required between 11.8 and 23 minutes to ignite for ignitions 37, 38, and 42. Ignitions 39–41 and 43–45 all required 6.6 minutes or less. All of these ignitions occurred between hours 10,860 and 12,415. The increased ignition times all occurred following conditioning of the HCA whereas the shorter ignition times occurred when the device was restarted without conditioning (not required at these times). This behavior suggests that the electron emitter condition is responsible for the increased ignition times, however, anode and bias voltages and their dynamic behavior has been relatively stable over the period of these ignitions.

HCA-010 ignition times were less than 6 minutes up to ignition 31 of mission profile life testing. These include all of the 4,358 ignitions performed during the operation in on-off mode when the device typically ignited within 3.7-4.0 minutes. However, the ignition time exceed 6 minutes during ignitions 32, 33, and 37–39. The ignition time reached a maximum of 12 minutes during its last ignition. Unlike HCA-003, the increased ignition times did not only occur after conditioning, however the HCA had been conditioned prior to ignitions 32, 33, and 38.

The AC components of anode and bias voltages ('noise') are checked periodically to verify that spot mode operation is being maintained.[1] While low levels of noise are normal and have been present throughout life testing, increased anode voltage noise began to occur during idle periods after several thousand hours of operation. This noise was similar for all HCAs because it has been low-frequency (~1 Hz) and non-periodic. However, the magnitude and time of appearance of the noise differs between the three HCAs, with the noise ranging between 0.5 and 4.0 V peak-to-peak. Additionally, none of the devices has exhibited any monotonic increases in the noise to date. The observed characteristics indicate that the noise is not due to transition from spot to plume noise.

While the cause of the increased ignition times and anode voltage noise during the idle period is unknown, it is suspected that they are likely due to changes in the low work-function surface formation process in the electron emitter. These changes would be consistent with cathode aging,[2] in particular since they have begun to occur after several thousand hours of operation. Another factor that may contribute to these changes is the operating mode which results in the HCA operating at two different emission levels. While the causes listed above are speculated to be occurring, a comprehensive explanation for all of the changes will likely have to wait until post-test destructive analyses of the HCAs can be performed.

All of the HCAs continue to operate within ISS specifications and have not exhibited any rapid or monotonic changes which could indicate imminent failure.

Concluding Remarks

Mission profile life testing of development model HCAs is on-going. Three HCAs are presently being life tested under conditions simulating projected on-orbit conditions. As of July 1998, these devices have accumulated between 11,700 and 14,200 hours. They have demonstrated the longest lifetime of any xenon hollow cathode operated at multiple emission currents. HCA operation, as determined by anode and bias voltage behavior, has been relatively stable. While there have been changes in HCA performance, operation has remained within the ISS specification. At this time, none of the observed changes are anticipated to prevent the demonstration of the required lifetime.

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[1] Patterson, M.J., et al., "Space Station Cathode Design, Performance, and Operating Specifications," IEPC Paper 97-170, August 1997.

[2] Sarver-Verhey, T.R., "28,000 Hour Xenon Hollow Cathode Life Test Results," NASA/CR-97-206231, IEPC Paper 97-168, November 1997.

[3] Soulas, G.C., "Status of Hollow Cathode Heater Development for the Space Station Plasma Contactor," AIAA Paper 94-3309, July 1994.

[4] Zakany, J.E. and Pinero, L., "Space Station Cathode Ignition Test Status at 32,000 Cycles," IEPC Paper 97-167, August 1997.

[5] Soulas, G.C. and Sarver-Verhey, T.R., "International Space Station Cathode Life Testing," NASA/CR-97-206230, November, 1997.

[6] Hamley, J.A., et al., "Development of a Power Electronics Unit for the Space Station Plasma Contactor," IEPC Paper 93-052, September 1993.

[7] Soulas, G.C., "Multiple Hollow Cathode Wear Testing for the Space Station Plasma Contactor," AIAA Paper 94-3310, June 1994.

[8] Personal Communication, Katz, I., S-Cubed Division of Maxwell Labs, San Diego, CA, July 1994.

Table 1 Life Test Operating Conditions

HCA Designation	Life Test Hours	On-off Cycles[a]	Anode Current, A	Bias Current, A	Emission Period, min.	Idle Period, min.
HCA-003	0-12,415	n/a	3	2.5	50	40
HCA-010	0-2,370	n/a	3	2.5	50	40
	2,370-6,445	4,358	3	2.5	50	40
	6,445-11,667	n/a	3	2.5	50	40
HCA-013	0-14,158	n/a	3	2.5	50	40

[a] HCA discharge is extinguished during the idle periods.

Table 2 Life Test Voltage Bandwidths

HCA Designation	Accumulated Hours[a]	Voltage Bandwidths		
		Idle Period	Emission Period	
		Anode, V	Anode, V	Bias, V
HCA-003	12,415	5.3	2.5	4.9
HCA-010	11,667	6.9	4.8	5.1
HCA-013	14,158	5.1	3.5	3.9

[a] As of July 1998.

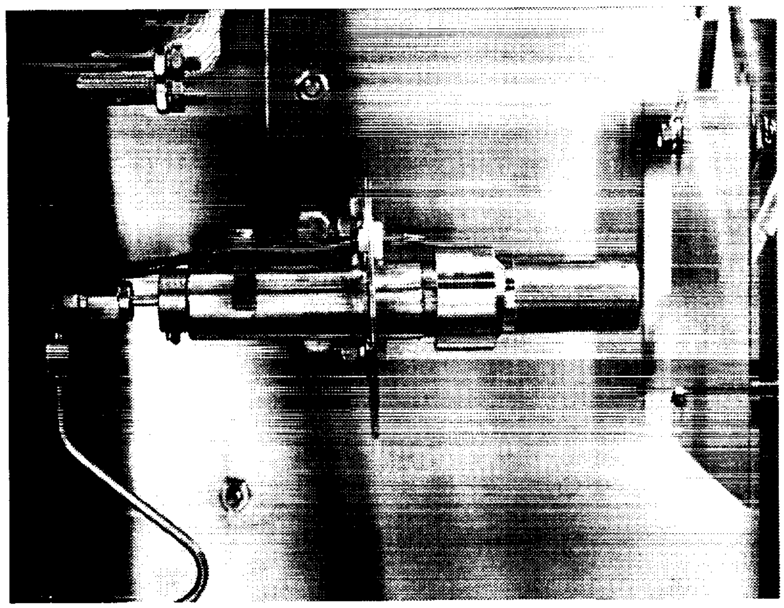

Figure 1. Photograph of development model HCA with an external bias anode used for mission profile life testing. The external bias anode is to the right in the photograph.

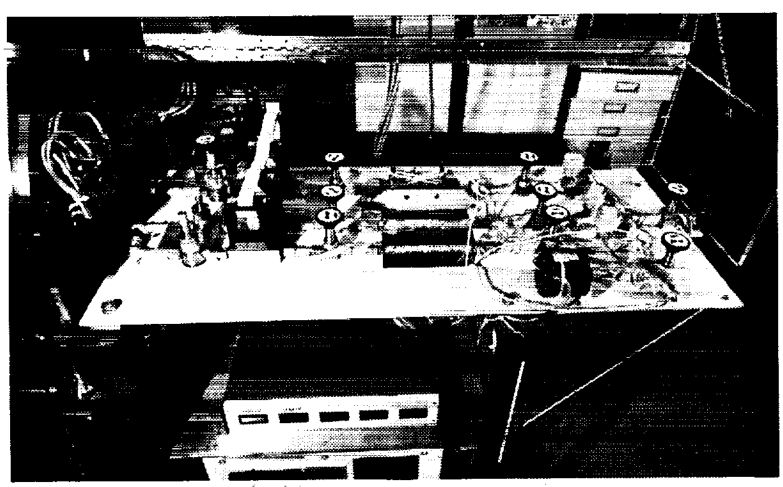

Figure 2. Xenon feed system used for mission profile and ignition testing.

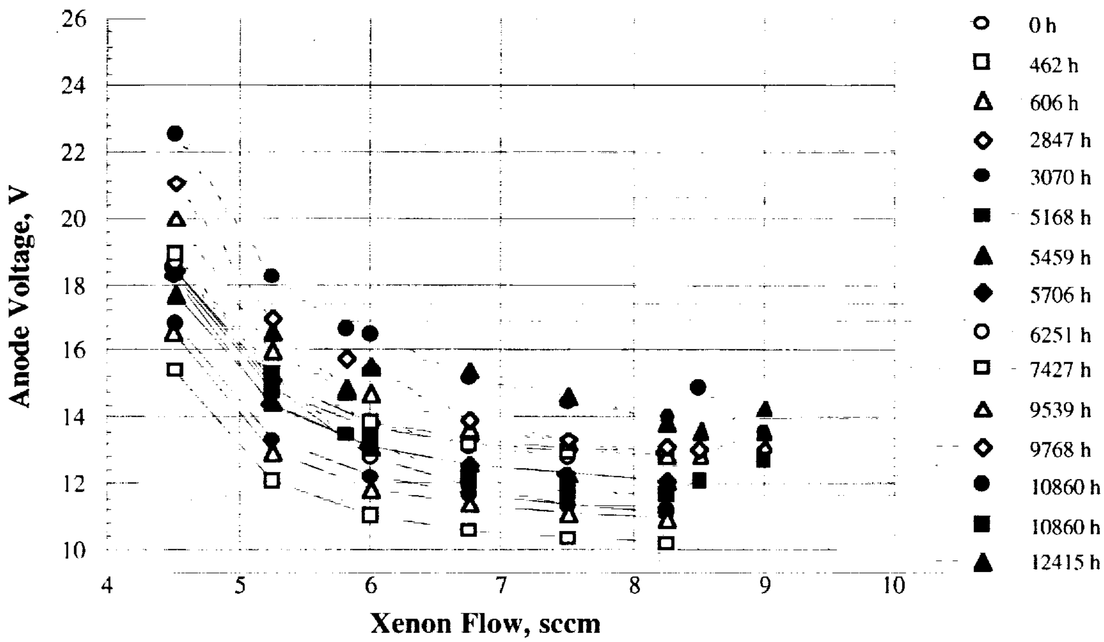

Figure 3. Performance evaluation profiles for HCA-003. Evaluations performed at beginning of test segments following the accumulation of the indicated times.

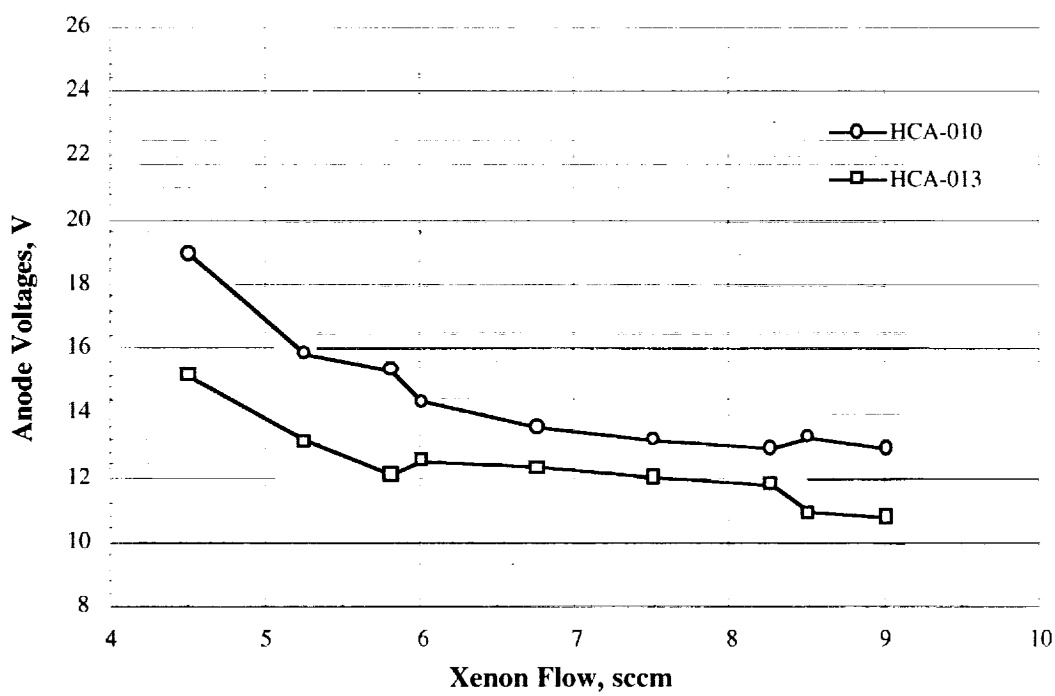

Figure 4. Performance evaluation for the HCAs -010 and -013. Each trace represents the average of all of the evaluation data sets for each device.

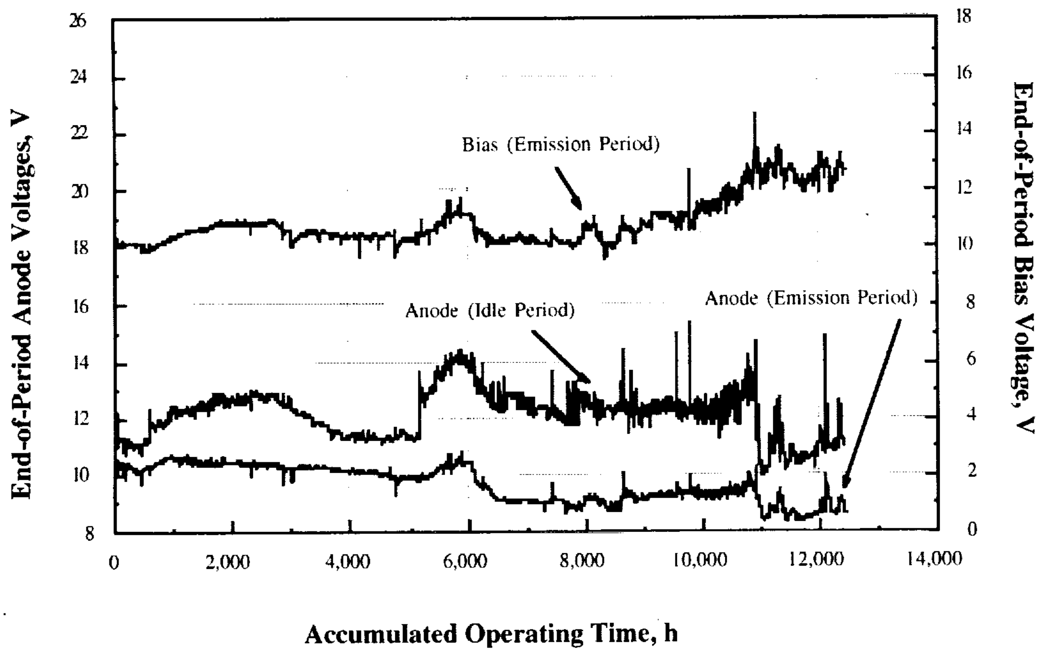

Figure 5. HCA-003 life test anode and bias voltages at the end of idle and emission periods.

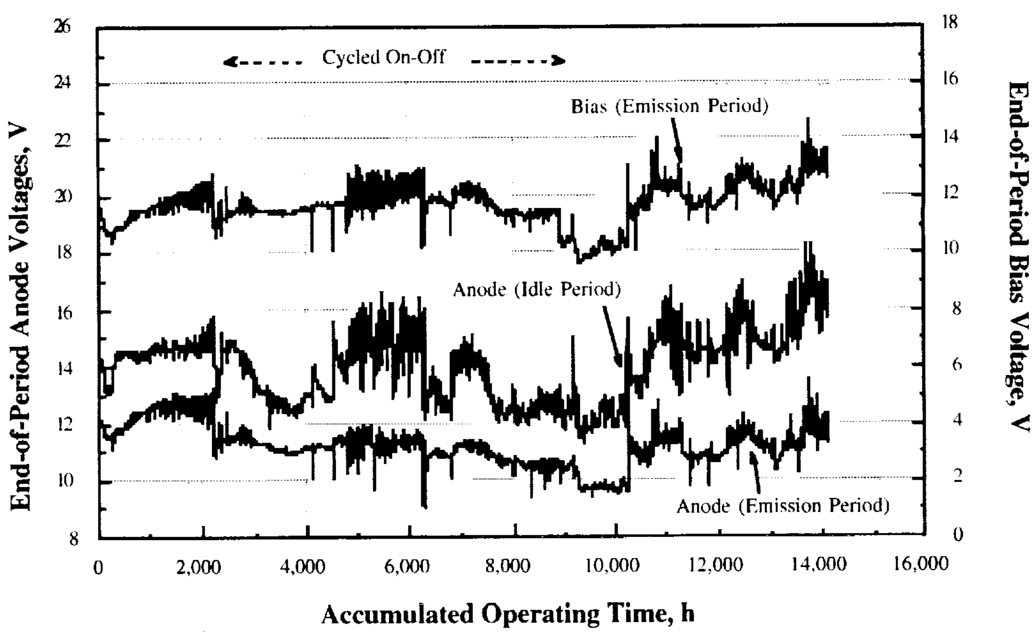

Figure 6. HCA-010 life test anode and bias voltages at the end of idle and emission periods. The indicated time is longer than the actual accumulated time because it includes the off periods when this HCA was cycled on-off.

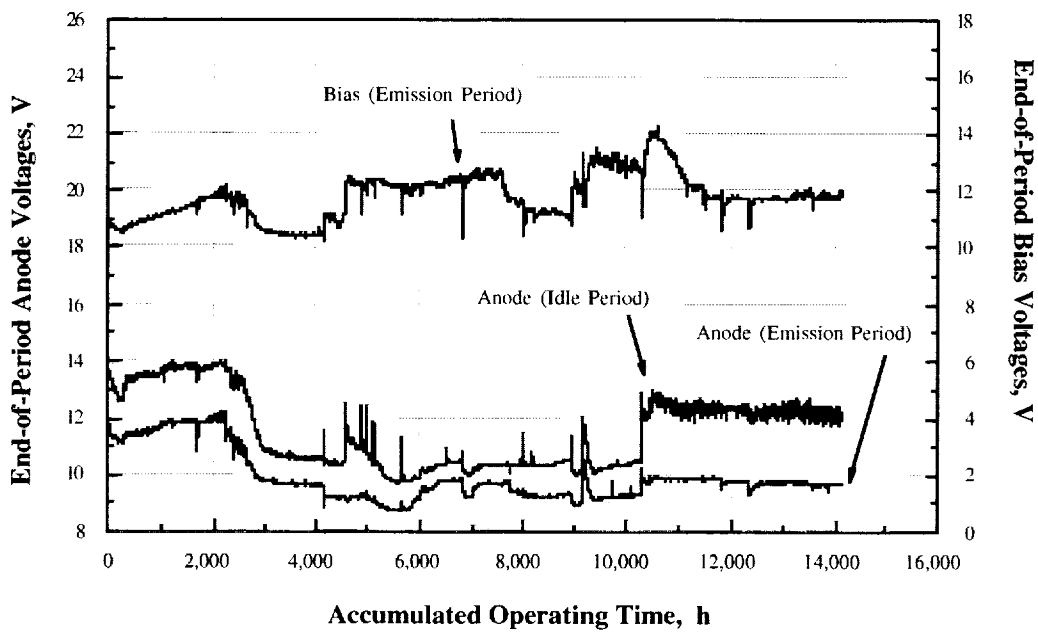

Figure 7. HCA-013 life test anode and bias voltages at the end of idle and emission periods.

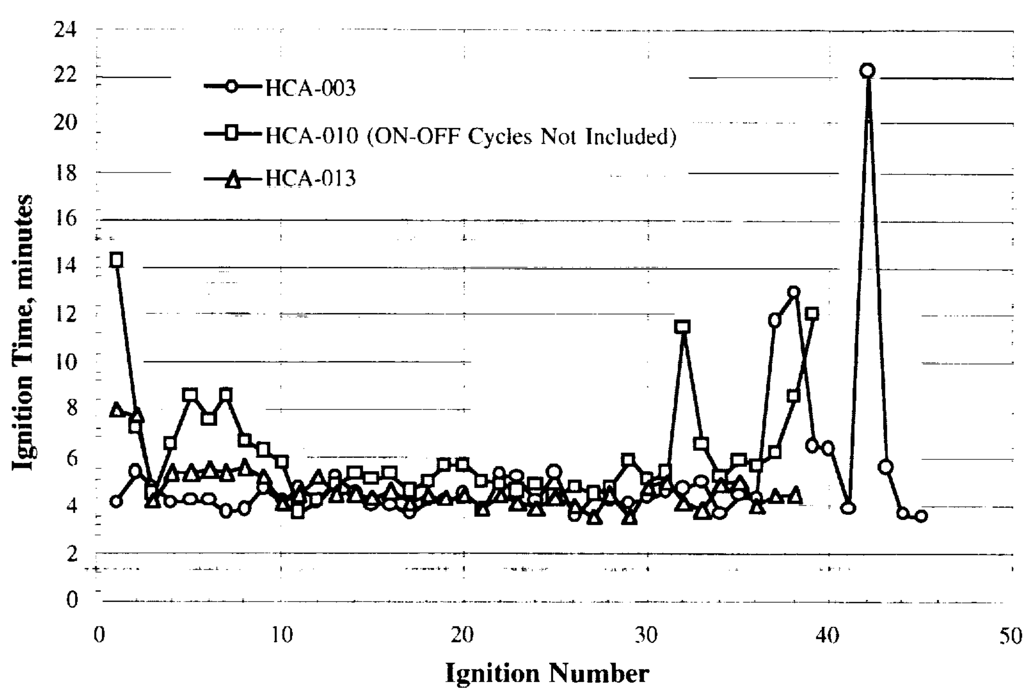

Figure 8. Ignition time as a function of ignition number.

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13. ABSTRACT *(Maximum 200 words)*

To demonstrate adequate lifetime and performance capabilities of a hollow cathode for use on the International Space Station (ISS) plasma contactor system, life tests of multiple hollow cathode assemblies (HCAs) were initiated at operating conditions simulating on-orbit operation. Three HCAs are presently being tested. These HCAs are operated with a continuous 6 sccm xenon flow rate and 3 A anode current. Emission current requirements are simulated with a square waveform consisting of 50 minutes at a 2.5 A emission current and 40 minutes with no emission current. As of July 1998, these HCAs have accumulated between 11,700 and 14,200 hours. While there have been changes in operating behavior, the three HCAs continue to operate stably within ISS specifications and are expected to demonstrate the required lifetime.

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