A Review of Testing of Hollow Cathodes for The International Space Station Plasma Contactor[*][†]

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Since October 2000, two plasma contactors have been providing charge control on the International Space Station (ISS). At the heart of each of the two plasma contactors is a hollow cathode assembly (HCA) that produces the contacting xenon plasma. The HCA is the result of 9 years of design and testing at the NASA Glenn Research Center. This paper summarizes HCA testing that has been performed to date. As of this time, one cathode has demonstrated approximately 28,000 hours of lifetime during constant, high current use. Another cathode, HCA.014, has demonstrated 42,000 ignitions before cathode heater failure. In addition to these cathodes, four cathodes, HCA.006, HCA.003, HCA.010, and HCA.013 have undergone cyclic testing to simulate the variable current demand expected on the ISS. HCA.006 accumulated 8,000 hours of life test operation prior to being voluntarily stopped for analysis before the flight units were fabricated. HCA.010 has accumulated 15,876 hours of life testing, and 4,424 ignitions during ignition testing. HCA.003 and HCA.013 have accumulated 12,415 and 18,823 hours of life testing respectively.

Introduction

The high voltage solar arrays of the International Space Station (ISS) power system are designed to operate at output voltages of typically 140-160 volts. The negative tap of the ISS solar arrays is electrically tied to the habitat modules, structure, and radiators. As a consequence of both the electrical configuration and plasma collection by the station, the ISS habitat modules, structure and radiators are predicted to float as much as 120 V negative with respect to the ambient space plasma potential, depending on ISS orientation and orbital position [1]. If uncompensated, this large negative potential could lead to arcing through insulating surfaces on the ISS, ion bombardment resulting in sputter erosion of surfaces, as well as an unsafe condition for astronauts during EVA maneuvers. To mitigate the effect of these large negative voltages, a plasma contactor system has been baselined to actively control space station charging [1].

The ISS has placed upon a plasma contactor system requirements on control of spacecraft charging as well as plasma contactor operability. An ISS plasma contactor system is required to control station charging to within +/- 40 V of ambient space plasma potential. The effect of **v** x **B** charging as the ISS moves through the earth's magnetic field tightens the requirement to within +/- 20 V of ambient space plasma potential. The charge control device should also be capable of

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self-regulated emission under variable demand. Additionally, practical requirements include long life, reliable ignition, and operability after environmental exposure during manufacture and integration. A hollow cathode plasma source is well suited for the application, and was therefore selected as the design approach for the station plasma contactor system [1].

This report is a comprehensive review of the experimental development and continuing engineering support of hollow cathode assemblies for the International Space Station plasma contactor. This work has been performed at the NASA Glenn Research Center in the On-board Propulsion Branch. This paper discusses the early development tests of the ISS hollow cathode assemblies (HCA), extended duration life tests and repetitive ignition tests. Also included are data from the acceptance testing of the flight cathode assemblies, development of low flow cathodes and acceptance testing of the flight plasma contactor units (PCU).

Hollow Cathode Design

The HCA design was chosen for its long life and effective, self-regulated operation under variable demand. The HCA has a long heritage traceable to the neutalizer on ion engines [2]. A drawing of the ISS HCA is shown in Figure 1. An enclosed keeper cathode was chosen since only electron current emission was required and this configuration has been proven to efficiently provide a low voltage coupling to the ambient plasma. A small diameter orifice was employed on the downstream end of the cathode tube to increase internal cathode pressures for cathode operation, thereby reducing the expellant requirements for the PCU. A low work function, impregnated tungsten thermionic emitter insert was placed in the cathode tube at the downstream end to reduce cathode operating temperatures and voltages, to facilitate starting, and to produce the dense plasma in the cathode interior from which the HCA electron current is extracted. A cathode heater was included in the design to provide for fast, reliable HCA ignition and to evolve contaminants on the emitter surface after atmospheric exposure. Refractory metals and alloys were chosen for fabrication of a rugged, durable cathode assembly. Each of these components works together to yield a reliable and efficient electron source for the ISS PCU.

Hollow Cathode Assembly Development Testing

To demonstrate the requirements of a charge control system on the ISS a comprehensive cathode test program was initiated at the NASA Glenn Research Center in 1992. A summary listing of the base requirements for operation of the ISS HCA are given in Table 1. Following are summaries of the hollow cathode tests which either established the requirements detailed in Table 1, or verified that the flight HCAs developed at the NASA Glenn Research Center met those requirements.

Cathode operation

The longest test of cathode operation run to date was a 27,800 hour life test run from December 30, 1992 to May 2, 1997, reported by Sarver-Verhey [3]. This test helped define the operational requirements in Table 1 and provided a benchmark for cathode life. The cathode for this test had a 50% larger orifice diameter compared to ISS hollow cathodes. Like the ISS HCAs, the test cathode had a barium calcium aluminate impregnated porous tungsten emitter insert, and a sheathed cathode heater. The cathode was operated without a keeper, with a continuous 12 A emission current delivered to a refractory metal anode downstream of the cathode orifice plate. Xenon flow rate through the cathode was held constant at 4.2 sccm until hour 16,700. After that time, the flow rate was gradually increased to a maximum value of 4.7 sccm, in order to reduce the DC and AC components of the anode voltage to acceptable values. Characterization of the cathode before the start of life testing revealed a sharp increase in the anode voltage for flow rates below 3.6 sccm. By the end of the life test, the onset of this rapidly rising anode voltage had increased to 4.8 sccm. The increasing flow rate requirements and flow rate lower limit for low anode voltage operation were attributed to a 14% increase in orifice diameter by the end of testing. Increases in cathode work function may have also played a role in increasing the required cathode flow rate. Cathode temperatures were observed to fall through the life test until hour 23,000, at which time the cathode temperature rose rapidly by ~100 °C. This temperature rise was attributed to degradation of the insert resulting in an increase in emitter work function. Prior to hour 23,776, the cathode ignition voltage had increased modestly from 42 to 54 V. After being restarted at hour 23,776, an ignition voltage of 725 V was required. The ignition voltage continued to increase to 950 V at hour 27,795, 1046 V at hour 27,800 and failed to ignite thereafter.

The 27,800 hour life test cathode was destructively analyzed to identify potential life limiting mechanisms [4]. Optical and electron microscopy as well as x-ray diffraction were employed to examine changes in the cathode physical dimensions, metallurgy, and chemistry. The orifice plate was found to have signs of modest erosion, with a <6% change in orifice thickness. The orifice diameter was found to have increased by 14 %, which may have caused the anode voltage to become more sensitive to flow variations. Metallic tungsten depositions were identified on the upstream side of the orifice plate and on the downstream end of the emitter insert. On the upstream end of the insert, thick layers of $BaWO_4$ and Ba_2CaWO_6 were found. These layers were increasing in thickness from 5 μm to 90 μm from 7.6 mm upstream of the orifice to the upstream end of the insert. These layers were likely the result of enhanced chemistry due to high local pressures of Ba and BaO in the insert region. It is hypothesized that the effects of insert chemistry were the cause of cathode failure.

Initial space station hollow cathode tests also included a four cathode wear test conducted by Soulas [5]. This test helped to verify the cathode operational requirements in Table 1, as well as cathode operating procedures. The four cathodes were quite different from the finalized ISS HCA design; they had orifice diameters twice the size of space station cathodes and were operated without keepers. The cathodes did include sheathed heaters at the downstream end and barium calcium aluminate impregnated porous tungsten emitter inserts. The cathodes were operated during the wear test at 10 A discharge current collected by and anode downstream from the cathode. Xenon flow rate through each cathode was 8.4 sccm. Three of the four cathodes reached 2,015 hours of operation before voluntary termination of the test, while the remaining cathode reached 2,005 hours before voluntary termination. Discharge voltage, cathode tip temperature, and ignition voltage were monitored for each cathode through the duration of the wear test. Discharge and ignition voltages were largely stable and unchanging during the duration of the test. Cathode temperatures measured at the orifice plate were also relatively stable, with deviations when the cathode was restarted after a test shutdown. The average value of these parameters as well as ranges for the parameters are given in Table 2.

Heaters

A heater is required on the ISS PCU hollow cathode to raise the downstream end of the cathode tube to about 1100 °C. This high temperature is necessary to drive off potentially life-shortening contamination from the hollow cathode thermionic emitter insert and to establish thermionic emission temperatures in the insert for ignition. For reasons related to reliability and ease of manufacture, sheathed heaters were chosen early in the design process for the ISS PCU hollow cathode. The sheathed heater is a coaxial design, with a refractory metal center conductor, surrounding oxide insulator and conducting refractory metal outer sheath. The heater is terminated at one end so that the sheath acts as the return path for center conductor current. The heater is coiled around the outside of the cathode tube at the downstream end. The heater is shielded from radiating excessively by a metal foil wrapped around the outside of the coil. A diagram of the heater is shown in Figure 2.

Soulas reported the results of heater testing, which helped finalize the heater design requirements in Table 1 [6]. Testing included measuring the cathode temperature as a function of heater input power as the power is ramped up from zero. The heater was observed to generate a maximum cathode tube temperature of about 1100 °C at currents > 7 A. Unit-to-unit variation in temperature and power also increased with increasing current. In addition, it was observed that the entire cathode power and temperature characteristics with respect to current increased after the cathodes were cycled. Heaters were repeatedly cycled to ignition temperatures for either 6,000 cycles or 700 cycles. A cycle consisted of 10 minutes at high current followed by 10 minutes of zero current. Two main changes in heater operation were noted during cyclic testing of the heaters. First, the heater power was observed to increase rapidly during the first 150 cycles. This initially rapid rise was thereafter referred to as heater “burn-in”. After burn-in, the heater power was observed to increase from 4.8 to 17% by the end of the testing, due to increases in heater resistance. One heater failed during cyclic testing by abruptly going to open circuit. The heater center conductor was observed to have necked down during operation and it eventually fractured at that point. The necking was attributed to conductor microstructure and center conductor oxidation due to insulator impurities.

Other heater materials and fabrication methods were also tested, resulting in a finalized heater design for the PCU. Heaters manufactured as in [6] where found to have inadequate life when the heater operating current requirements were increased from 7.5 A to 8.5 A. A new standard material was developed and was eventually adopted for the ISS PCU HCA. Six heaters with this standard center conductor were cycled from 10,500 to nearly 13,000 cycles, exceeding the 6,000 cycle requirement in Table 1. When grain growth was discovered after operation of the standard heater center conductor, grain stabilized center conductors were tested. No improvement in heater life was found for these heaters. Additionally, four heaters with refractory alloy center conductors were tested, and failed after an average of 1,524 cycles. Table 3 summarizes all of the heater tests performed at NASA Glenn Research Center in support of the ISS PCU project and their results.

HCA Mission Profile

The life test of hollow cathodes in a mission profile cyclic current condition has been on-going at NASA Glenn Research Center since 1994. This life test has been reported in several papers, most recently by Sarver-Verhey [7]. As an addition to the 28,000 hour life test, this test will further demonstrate that the HCA capability exceeds the lifetime requirements in Table 1. Details of the test systems are given in the paper and will not be discussed here. Since the ISS is expected to demand as much as 2.5 A of emission current for only 50 minutes of its 90 minute orbital period, the test conditions were cyclically varied. A 2.5 A current was collected by an external bias anode positioned downstream of the cathode for only 50 minutes of the 90 minute cycle. For the remaining 40 minutes of the cycle, zero current was collected by the external bias anode. A constant current of 3.0 A was collected at the anode for the entire 90 minute cycle. This profile was repeated continuously for test articles HCA.003 and HCA.013. For its first 1,672 hours, HCA.006 emitted current to the bias anode for only 30 minutes, and emitted zero current to the bias anode for 60 minutes at an anode current of 2 A. From hour 1,672 to hour 2,863 the HCA.006 cathode was run on the same modified cycle with 3 A collected at the anode. The nominal test conditions were employed from hour 2,863 on. HCA.010 also deviated slightly from the nominal conditions. It was operated in an on/off mode such that the cathode was extinguished for 40 minutes of the 90 minute cycle, and re-ignited for the 50 minute emission of 2.5 A. This on/off mode was tested as an option to extend PCU life by eliminating Xe flow when no emission current was required. This on/off mode was started at hour 2,370 and the nominal test condition was returned to at hour 6,445. During the on/off period 4,369 ignitions were successfully completed.

The results of life testing of HCA.006 were reported by Soulas and Sarver-Verhey in 1997 [8]. HCA.006 accumulated 8,030 hours of life test operation before being voluntarily terminated for destructive analysis. Anode and bias voltages were time independent over the duration of the life test. Destructive analysis of the cathode revealed little change in the dimensions of the cathode and anode orifices and channel lengths. The orifice plate was slightly textured from ion bombardment. No heater erosion was noted. Analysis of the insert found tungsten crystal deposition at the downstream end of the insert. Barium tungstate formations were found upstream from that, and impregnate was identified upstream from the tungstate. These results were consistent with those reported for the 28,000 hour life test article. Based on these results, cathode life was estimated to be 18,000 hours [8].

HCA.003 has accumulated 12,415 hours of life testing and 45 ignitions to date. Anode and bias anode voltages are shown in Figure 3, and ignition times are shown in Figure 4. The anode voltage ranged from 10 V to 14 V during periods of zero emission, and from about 8 V to less than 11 V during emission periods. The bias anode voltage ranged from 18 V to 22 V. No substantial trends with time are noted for the anode voltage for this cathode, though an upward trend of the bias voltage for the last 4,000 hours of cathode operation was noted. Ignition times stayed between 3 and 6 minutes until ignition numbers 37, 38, and 42, when the ignition times were between 11.8 and 23 minutes. Sarver-Verhey attributed these long ignition times and an observed increase in the AC component of the anode voltage to changes in the work function of the cathode insert [7].

After, 12,415 hours of testing, HCA.003 failed to ignite. HCA.003 was disassembled and the insert was removed. The old insert was placed in a test cathode to verify its operability. The test cathode failed to ignite, indicating that the insert condition had caused the ignition problem of HCA.003. With a new insert installed, HCA.003 was performance tested. Ignition occurred within 3.58 minutes. The insert of HCA.003 was known to have cracked during vibration testing of the cathode. The cracked insert is hypothesized to have resulted in an early failure of the cathode. At the time of the vibration test, an inadequate mounting scheme was employed to keep the insert in place. During the vibration test, the insert broke free, and cracked upon striking the cathode tube walls. As a consequence, this mounting scheme was abandoned for a more rugged mounting in the flight cathodes.

HCA.010 has accumulated 15,876 hours under power, 18,082 total hours of life testing, and 4,424 ignitions. Anode and bias voltages are shown in Figure 5. Ignition times for test restarts are shown in Figure 6; the cyclic ignition testing ignitions are not included. The anode voltage ranged from about 11 V to less than 23 V during periods of zero emission, and from 9 V to less than 14 V during emission periods. The cathode bias voltage ranged from 9.5 V to 15 V. The anode voltage during zero emission mode and the bias voltage appear to be undergoing a protracted increase which began just before hour 10,000.

As can be seen in Figure 6, HCA.010 ignition times, excluding those during cyclic ignition testing, began increasing at approximately the thirtieth cathode ignition. The ignition time increased from about 4.5 minutes at ignition 30 (hour 6,445) to as high as 61 minutes at ignition 45 (hour 11,667). Then, at ignition 58 (hour 15,022), the cathode failed to ignite. The cause of the failure was postulated to be cool operation of the HCA during ignition. Ignition was subsequently accomplished with slightly increased gas flow. Subsequent ignition times range from 6.6 minutes to 20.57 minutes.

HCA.013 has accumulated 18,823 hours of life testing and 62 ignitions. Anode and bias voltages are shown in Figure 7, and ignition times are shown in Figure 8. The anode voltage ranged from about 9.5 V to 15 V during periods of zero emission, and from 9.5 V to 12 V during emission periods. The cathode bias voltage ranged from 10.5 V to 14 V. The anode and bias voltages show monotonic trends. Cathode ignition time has increased slightly from about 4.5 minutes before ignition 42 to about 6 minutes after ignition 42. The first two cathode ignition times are an exception at 8 min. Typically, the ignition time is longer during the first few ignitions.

Cyclic-ignition

In order to demonstrate the ignition reliability of the ISS PCU hollow cathodes called out in Table 1, a repetitive ignition test was run. The HCA tested was a development unit labeled HCA.014. This cathode was essentially identical to the ISS PCU flight cathodes. The details of the test setup have been reported previously and will not be repeated here [9].

The HCA was operated in two distinct profiles. The first was an accelerated profile, in which the cathode was ignited, then run for 1 minute and then shut off for 20 minutes. The second profile was a mission-like profile, in which the cathode was ignited and run for 50 minutes followed by a 40 minute off period. At the time the test was devised, it was anticipated that the HCAs on orbit would be ignited for the portion of the orbital cycle when emission current would be required, and extinguished when emission was not required. Subsequent to this test, it was decided to leave the cathode ignited for the entire orbital period. In both cases, ignition is defined as >2.5 A collected at the anode, and the xenon flow rate was 6.0 sccm. The accelerated profile was run for 3,000 cycles followed by 50 cycles of the 90 minute profile.

HCA.014 accumulated 42,014 ignitions before the cathode heater eventually failed due to a short. During ignition testing, the anode voltage of HCA.014, measured at the end of each ignition cycle, ranged from 11.6 V to 17.4 V. Most ignitions occurred within 7 minutes. A Weibull analysis performed on the ignition data for HCA.014 found that 99%, 95%, and 90% of all ignitions occurred within 5.8, 5.0, and 4.9 minutes, respectively [1]. A strong dependence between heater power and ignition time was noted during this test.

Environmental exposure

In order to assess the effect of exposure of the cathode to atmosphere during installation and transportation, several environmental exposure tests were performed. These tests involved exposing the cathode to various thermal conditions at varying levels of relative humidity and then performance and wear testing the cathodes. The results of these tests established the acceptable environmental exposure conditions in Table 1.

HCA.008 was performance acceptance tested, and then placed in a 25 °C, 50 % relative humidity environmental chamber for 1,250 hours. Subsequently the cathode was performance acceptance tested again and then wear tested for 1,065 hours. The cathode was performance acceptance tested intermittently through the wear test. Results of the performance acceptance tests before and after exposure are shown in Figure 9. A very slight difference in anode voltage before and after testing is apparent in the measurement at 6 sccm, where large sample sizes improved the resolution of differences. The magnitude of the difference is quite small, however, and is considered inconsequential.

HCA.009 was also performance acceptance tested, then placed in a 25 °C, 50% relative humidity environmental chamber for 1,250 hours. The cathode was then installed in a 27 °C, 52% relative humidity environmental chamber for an additional 1,250 hours. Subsequently the cathode was again performance characterized. The performance characterizations are summarized in Figure 10. The anode voltages for HCA.009 were indistinguishable from each other, indicating that environmental exposure had no impact on the performance of the cathode.

Flight HCA Acceptance Testing

All flight HCAs are acceptance tested prior to delivery and installation into the ISS PCU. The flight HCAs manufactured to date are shown in Figure 11. Acceptance testing includes a heater confidence test. The cathode heater is cycled through a 150 cycle burn-in to verify heater function and test workmanship. Also included in acceptance testing is a test of the cathodes in idle mode (no emission current). Figure 12 shows the anode voltage versus clamping current characteristics for the flight HCA's during acceptance testing, at 6 sccm. The high unit-to-unit repeatability during this initial testing is evident in Figure 12. Finally, acceptance testing included clamp testing to verify 10 A emission current operation at less than 20 V.

Continuing NASA GRC Engineering Support

The engineering effort to support the ISS plasma contactor program is on-going at NASA Glenn Research Center. Hollow cathode life testing is continuing until the life test articles have reached 1.5 times their rated life. Integration of the HCA into the Boeing developed PCU is also supported by GRC engineers and technicians. Final flight model PCU acceptance testing is performed at GRC in its world class vacuum facilities. Reduced expellant flow HCAs have also been developed at GRC to extend the operating life of on-orbit PCU's.

PCU Acceptance Testing

Before a PCU is ready for launch, it is acceptance tested with an integrated HCA. Figure 13 shows the HCA integrated into the PCU. Acceptance testing is performed in a 4.6 m diameter, 19.2 m long cryo-pumped vacuum facility with 3.5 million L/s N_2 pumping speed. This testing includes functional checks on the operation of the PCU, an extended duration test in idle mode, and a clamping voltage verification. To date, four PCU's have successfully completed acceptance testing, including QUAL as well as the flight units FM.01, FM.02, and FM.03. FM.01 and FM.02 are the units currently in use on the ISS. FM.03 is a backup and replacement for FM.01 and FM.02.

Low-flow HCA Development

To increase the on-orbit lifetime of the plasma contactor, and hence reduce ISS logistics requirements for PCU reflight, an activity was initiated to develop a reduced-flow rate HCA. A reduction in the required flow rate of xenon through the HCA would delay exhaustion of the on-orbit propellant load of xenon gas in the PCU beyond the nominal 2-year life. The operational requirements for the HCA (emission current, dynamic range, clamp voltage) remain as specified, but modifications to the HCA design accommodate a reduction in flow rate (below the minimum of 5.8 sccm xenon).

To this end, a number of prototype HCAs that accommodate rapid changes to the critical design features controlling the required flow rate were designed and fabricated. To satisfy the electron current demand at the limiting potential required of the HCA, a minimum ion production is necessary. Hence, design features which control the cathode ionization efficiency and ion transparency were investigated. These features included the shape, size, and aspect ratio of the orifice of the enclosed keeper anode, as well as the cathode-anode electrode spacing, among others.

Five different HCA configurations were investigated, including the baseline ISS HCA design. From these tests, the most promising configuration was selected for more detailed characterizations. From these characterizations in both diode and triode (emission currents up to 10 Amperes) mode operation, a flow rate reduction of approximately a factor of two (to about 3.0 sccm xenon) appeared feasible. Two engineering model versions of this low-flow HCA configuration were subsequently manufactured at NASA GRC. These units are prepared to undergo detailed performance characterizations, with one unit to subsequently undergo mission-profile life testing to qualify the design for flight.

Summary

Extensive testing has been performed at NASA GRC to establish requirements for the hollow cathode in a plasma contactor system and to verify that manufactured HCAs are capable of meeting those requirements. The ISS program requires a plasma contactor system capable of controlling spacecraft charging to within ±20 V of ambient space plasma potential. In addition, the plasma contactor system must be capable of reliable and predictable operation over an extended life. Testing at GRC has provided a hollow cathode assembly that conforms to these requirements.

The operational requirements of hollow cathode assemblies have been defined and refined in a number of tests. The 28,000 hour cathode life test by Sarver-Verhey [3] helped initially define hollow cathode operating parameters. The 2000 hour cathode wear test performed by Soulas [5] and the mission profile life testing that is on-going [7] have further refined the parameters of cathode operation.

Cathode lifetime has been the subject of two tests. The longest test to date is a 28,000 hour test of a single cathode at constant emission current [3]. This test was conducted until cathode failure, which was attributed to chemical changes within the cathode insert. A long duration of 4 cathodes in a cyclic emission current, mission-like profile has also been run. One cathode was stopped after 8000 hours of operation, the remaining three have accumulated between 12,000 and 18,000 hours of operation. These two tests have established an expected cathode lifetime of 18,000 hours.

A number of other tests have further refined the cathode design. The heater design employed by the ISS plasma contactor hollow cathode assemblies has been qualified [6]. Environmental testing was performed to establish the effect of atmospheric exposure of the cathode during installation. Ignition testing verified that the hollow cathode assemblies developed by GRC would surpass the ignition reliability requirements [9].

A reliable hollow cathode assembly for the International Space Station plasma contactor has been designed and tested by the NASA Glenn Research Center. Issues of cathode operation, life, and reliability have been addressed. The hollow cathode assembly developed at NASA GRC has been shown to meet or exceed all requirements for the ISS PCU.

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Table 1. International Space Station hollow cathode assembly requirements summary.

Type	**Description**
Operation	10 V ≤ anode voltage ≤ 18 V when: 3.0 A anode current, 0.0 A emission current, 5.8 sccm ≤ xenon flow rate ≤ 7.50 sccm, Discharge has stabilized.
Operation	Emission current > 10 A when: Cathode biased –20 V relative to an external anode, Anode is > 2 meters removed from cathode, Discharge has stabilized.
Operation	Capable of self regulated emission of current.
Lifetime	Electron emission lifetime > 18,000 hours.
Ignition	Capable of > 6000 ignitions at > 99% reliability.
Ignition	HCA initially demonstrates a minimum of 10 ignitions in which a 3.0 A anode current is established in < 6.0 minutes.
Ignition	During initial ignition, transition from a gas breakdown (estabishment of a non-zero anode current) to a fully-on ignition state (3.0 A anode current) < 10 seconds.
Heater	Heater is capable of > 6000 cycles at > 99% reliability without failing
Heater	Initial heater cold resistance is 0.245 Ω ± 0.025 Ω.
Heater	During initial testing, heater hot resistance changes < 0.060 Ω.
Exposure	Meets performance requirements following exposure to a storage environment with temperature from –20 °C to 65 °C with a dewpoint ≤ -30 °C.
Exposure	Meets performance requirements following 1250 hours exposure to temperatures ≤ 35 °C with a dewpoint of ≤ 15 °C where the ambient temperature is > 2 °C above the dewpoint.

Table 2. Four cathode wear test results. Cathodes were operated at 10 A emission current to a downstream anode. The xenon flow rate was 8.4 sccm. Cathodes 1A, 1B, and 2A all accumulated 2015 hours of operation; cathode 2B accumulated on 2005 hours of operation. [5]

Parameter	Mean Values				Data Ranges			
	1A	1B	2A	2B	1A	1B	2A	2B
Discharge Voltage, V	8.54	8.39	8.31	8.27	1.32	1.11	1.47	1.44
Ignition Voltage, V	17.4	16.5	17.5	16.6	7.0	3.5	4.1	5.0
Thermocouple Temp., °C	1109	1083	1049	1112	64	77	77	52

Table 3. Summary of swaged heater life testing conducted at the NASA Glenn Research Center.

Htr No.	Center Conductor	Burn-in (Amp, min. ON/ OFF, No. Cycles)	Cycle profile (Amp, min. ON/ OFF)	Cycles at Condition	Total No. of Cycles	Completed/failed (c/f)?	Destructive Analyses? (Results)
001	Alternate processing	n/a	7.5 A, 10 - 10	5986	5986	F	Yes (Large grain size, esp. at fracture region)
002				6300	6300	C	Yes (Large grain size, esp. at fracture region)
003				6300	6300	C	No
005		7.5, 10/10, 100	7.5 A, 10 - 10 7.5 A, 5 – 5	8291 1139	9430	F	No
006			7.5 A, 10 - 10	700	700	C	No
007				700	700	C	No
008		7.5, 10/10, 150	7.5 A, 10 - 10 7.5 A, 5 - 5 8.5 A, 6 - 4	6525 9822 733	17080	F	No
009			7.5 A, 10 - 10 7.5 A, 5 - 5	6525 3902	10427	F	No
022	Standard	7.5, 10/10, 150	7.5 A, 5 - 5 7.5 A, 6 - 4	9822 1415	11387	C	Yes (Very large grain sizes)
023				9822 1415	11387	C	Yes (Very large grain sizes over entire heater length)
024				9822 1415	11387	C	Yes (Very large grain sizes)
038			8.5, 6 – 4 Power-limited		12972	F	No
039					12100	F	No
040					10568	F	No
100	Alternate processing	7.5, 10/10, 150	8.5 A, 6 - 4	3828	3978	F	No
101				2754	2904	F	No
103				1894	2044	F	No
112	Grain-stabilized	7.5, 10/10, 150	7.5 A, 10 - 10 8.5 A, 6 - 4	7405	7555	F	No
113				5176	5326	F	No
114			7.5 A, 10 - 10 8.5 A, 6 - 4 8.5 A, 6 - 4 Power-limited	7088 4757	11995	F	No
115		8.5, 6/4, 150	8.5 A, 6 - 4 Power-limited	4548	4548	F	No
122	Refractory alloy	8.5, 6/4, 150	8.5 A, 6 - 4	1361	1361	F	No
123				1734	1734	F	No
128				1497	1497	F	No
124				1505	1505	F	No

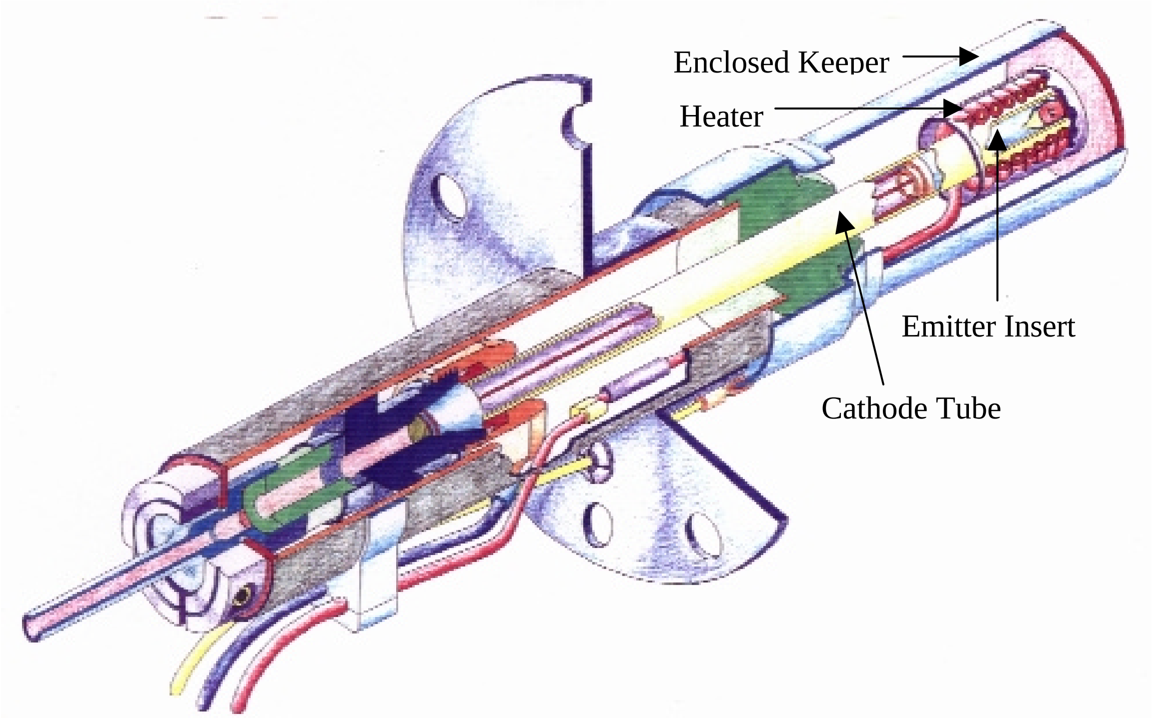

Figure 1. Drawing of a flight HCA (drawing not to scale).

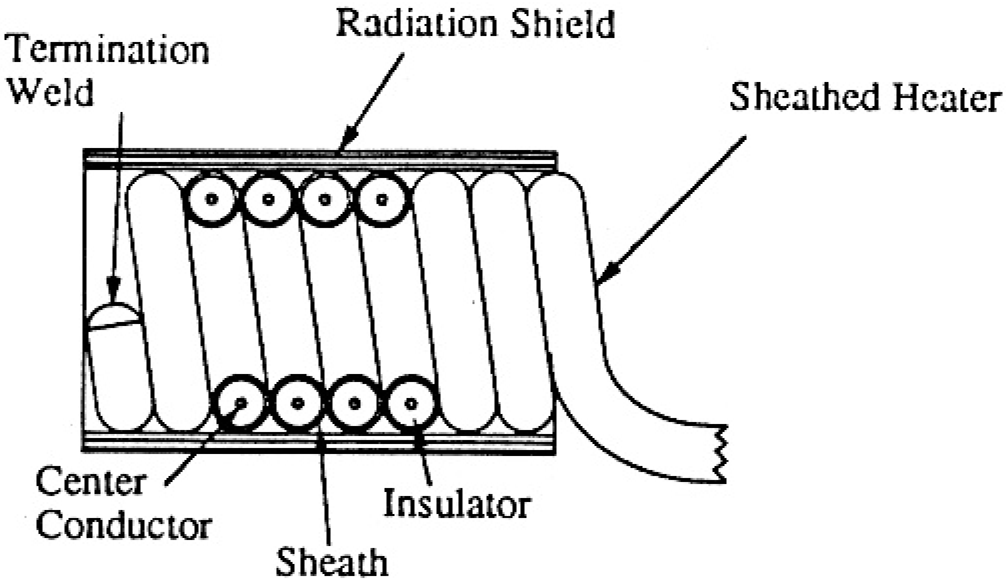

Figure 2. Diagram of the heater assembly designed for the International Space Station hollow cathode assembly (drawing not to scale).

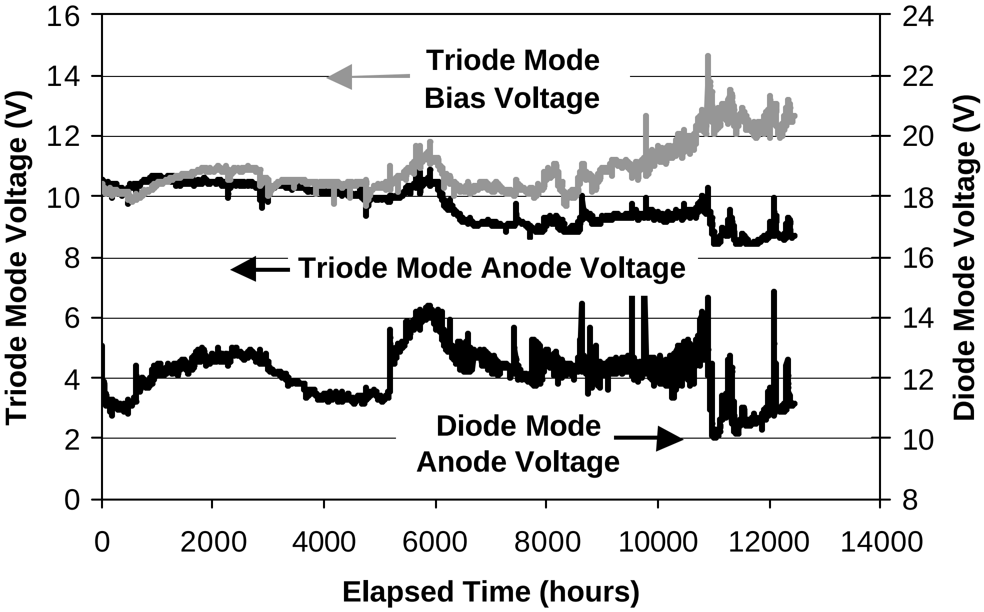

Figure 3. HCA.003 bias and anode voltages plotted as a function of elapsed time. Anode and bias voltages at the end of triode mode operation are plotted and should be referred to the left axis. Anode voltage at the end of diode mode is plotted and should be referred to the right axis.

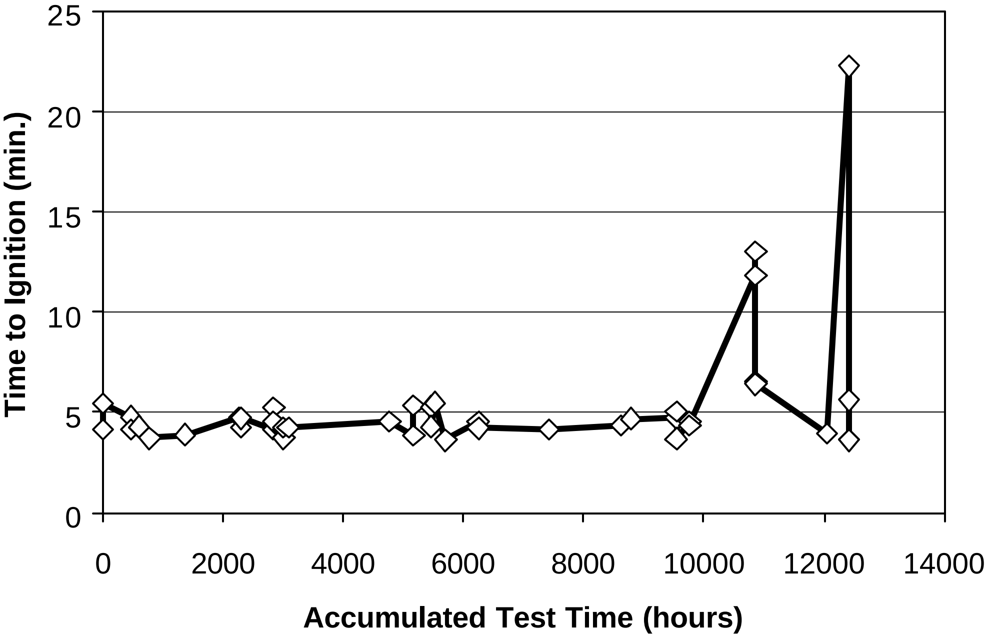

Figure 4. Time to ignition for HCA.003 plotted versus number of accumulated hours of life testing. Time to ignition is defined as the time from application of heater power to the anode current surpassing 2.5 A.

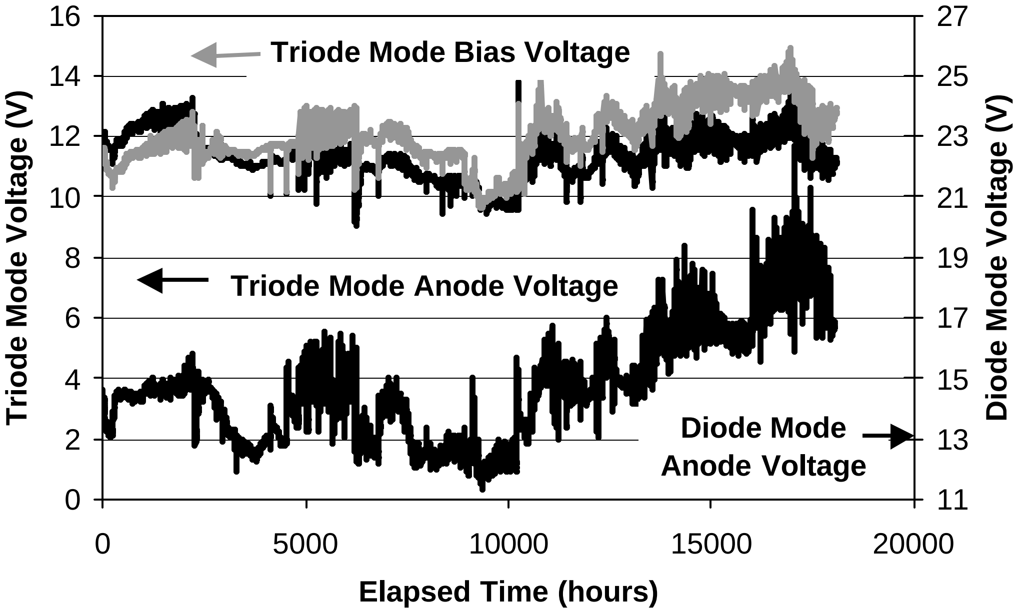

Figure 5. HCA.010 bias and anode voltages plotted as a function of elapsed time. Anode and bias voltages at the end of triode mode operation are plotted and should be referred to the left axis. Anode voltage at the end of diode mode is plotted and should be referred to the right axis.

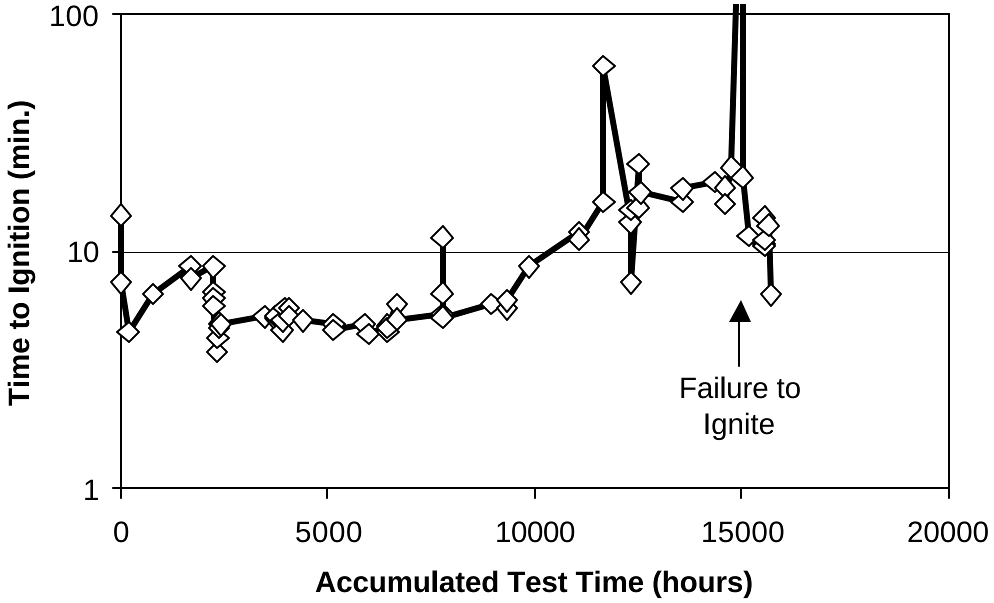

Figure 6. Time to ignition for HCA.010 plotted versus number of accumulated hours of life testing. Time to ignition is defined as the time from application of heater power to the anode current surpassing 2.5 A. Ignition times from ON/OFF cycling of HCA.010 are not included. Lines leaving the upper plot boundary indicate the ignition failure at hour 15,022.

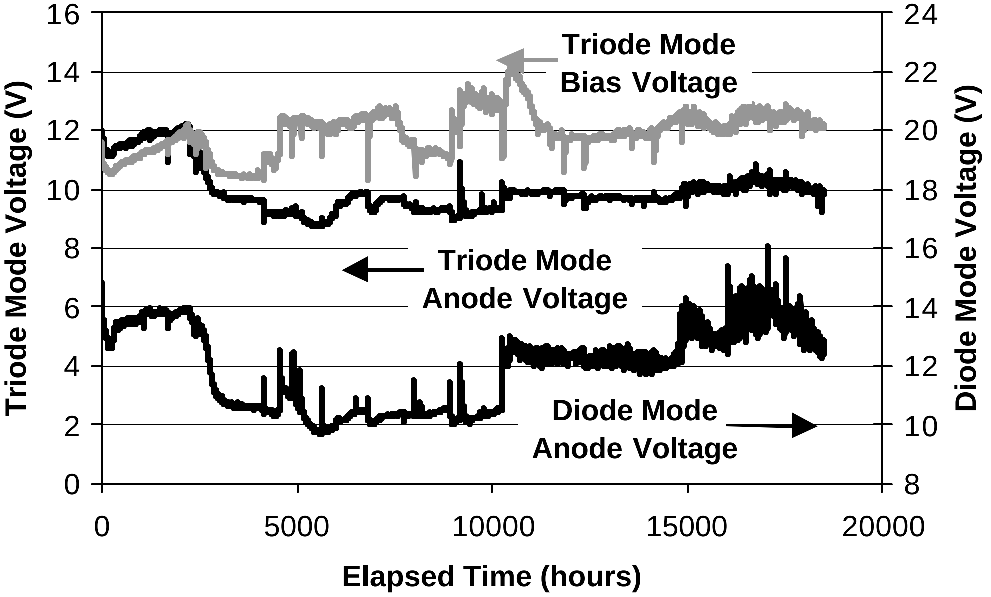

Figure 7. HCA.013 bias and anode voltages plotted as a function of elapsed time. Anode and bias voltages at the end of triode mode operation are plotted and should be referred to the left axis. Anode voltage at the end of diode mode is plotted and should be referred to the right axis.

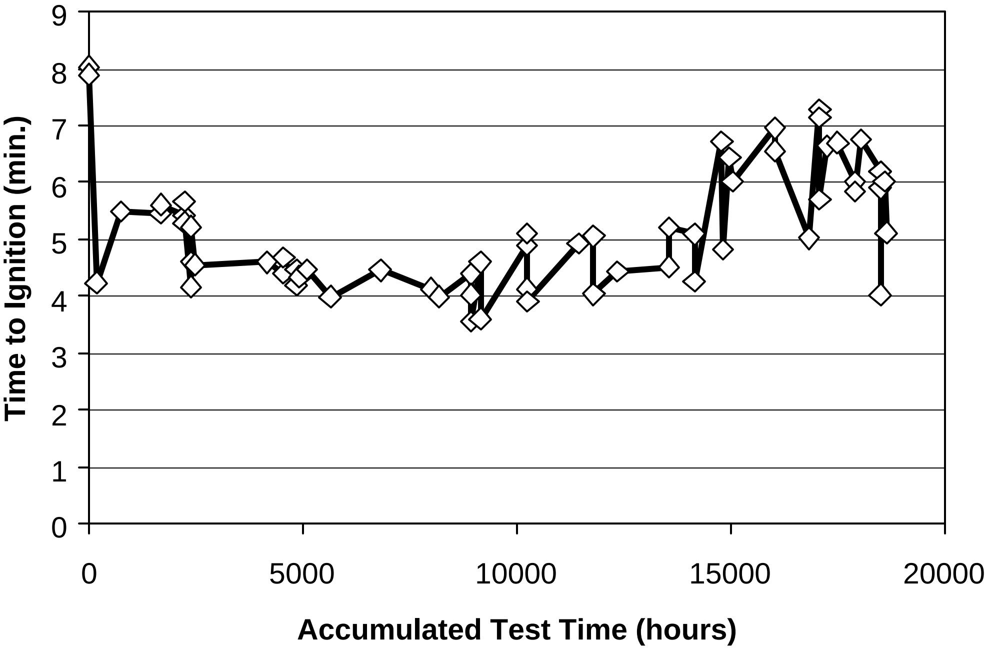

Figure 8. Time to ignition for HCA.013 plotted versus number of accumulated hours of life testing. Time to ignition is defined as the time from application of heater power to the anode current surpassing 2.5 A.

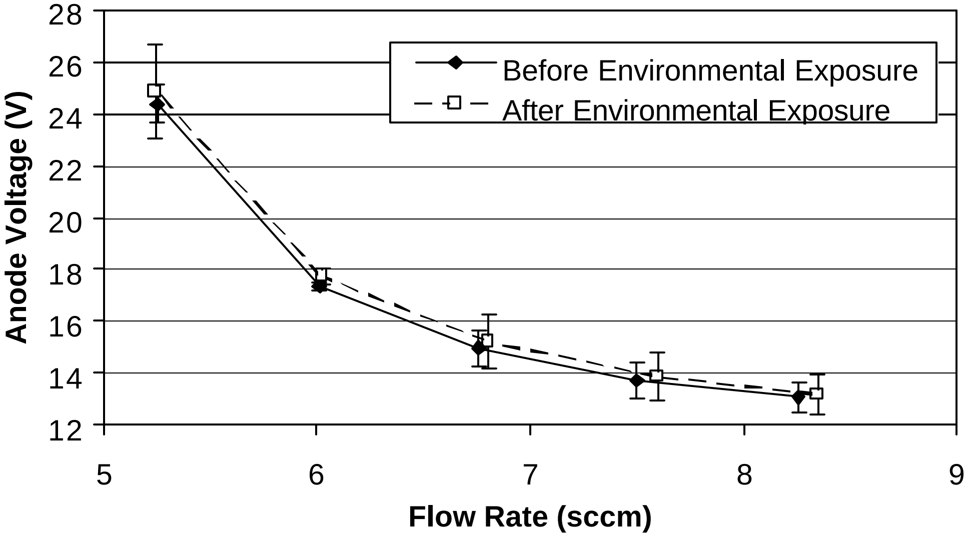

Figure 9. Comparison of the anode voltage of HCA.008 before and after environmental exposure. The anode voltage is presented at several flow rates. Each anode voltage is an average of 3 replicated values with the exception of the anode voltage at 6 sccm, which is an average of 9 replicated values. The error bars signify the 95% confidence intervals of the measurements; the 95% confidence intervals are contracted around the anode voltage at 6 sccm due to the larger sample size.

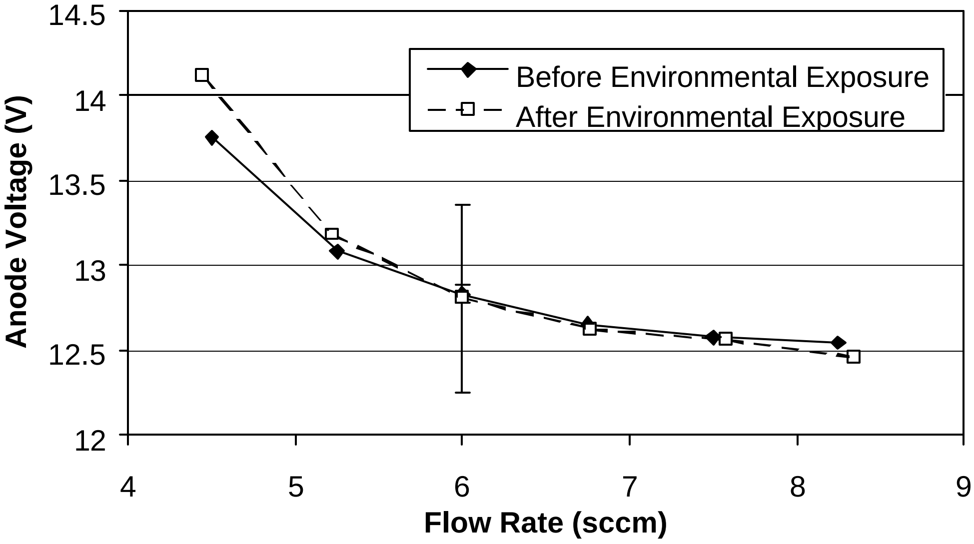

Figure 10. Comparison of the anode voltage of HCA.009 before and after environmental exposure. The anode voltage is presented at several flow rates. Each anode voltage is an average of 2 replicated values with the exception of the anode voltage at 6 sccm, which is an average of 6 replicated values. The error bars signify the 95% confidence intervals of the measurement at 6 sccm. The error bars at other flow rates are very large due to the extremely small sample sizes and therefore have been omitted.

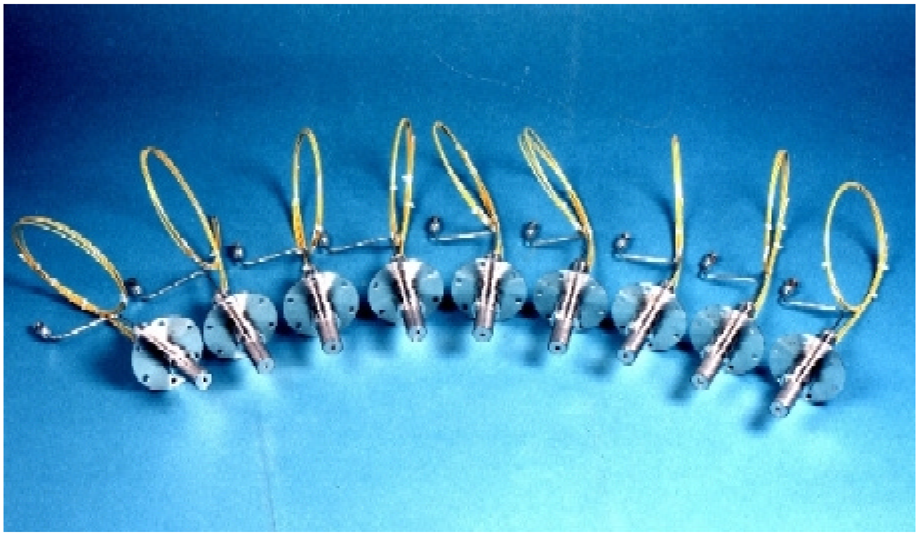

Figure 11. Photograph of 9 out of 12 flight HCA's designed and manufactured by NASA Glenn Research Center in support of the International Space Station plasma contactor program.

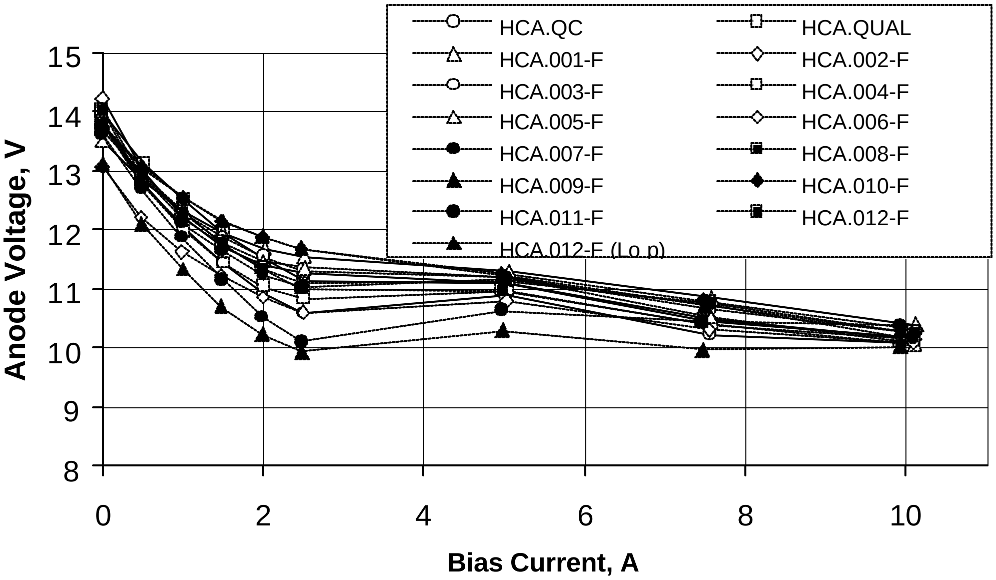

Figure 12. Anode voltage plotted versus current collected at the vacuum chamber wall during acceptance testing of the flight hollow cathode assemblies. The anode voltage data is collected during triode mode emission to the vacuum chamber wall. Xenon flow was held at 6.0 sccm, and the anode current was held at 3.0 A for the test.

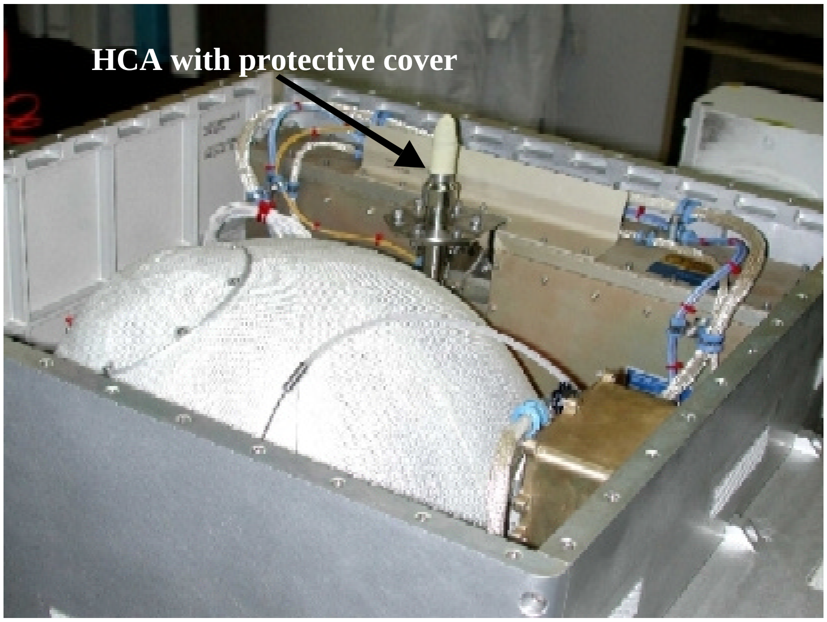

Figure 13. Photograph of flight HCA.004-F being integrated into the ISS PCU box. Image shows the PCU with its top cover removed. The large white sphere is the xenon storage tank. The HCA is pointed out in the picture.