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Comparison of On-Orbit and Ground Based Hollow Cathode Operation

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COMPARISON OF ON-ORBIT AND GROUND BASED HOLLOW CATHODE OPERATION

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ABSTRACT

The Plasma Contactor Unit (PCU) was developed by the Rocketdyne division of Boeing to control charging of the International Space Station (ISS). Each PCU contains a Hollow Cathode Assembly (HCA), which emits the charge control electrons. The HCAs were designed and fabricated at NASA's Glenn Research Center (GRC). GRC's HCA development program included manufacture of engineering, qualification, and flight model HCAs as well as wear tests and qualification tests. GRC is currently tracking the on-orbit data for the flight HCAs. This data will be discussed with comparison to operating parameters verified by ground based HCA tests. The flight HCAs continue to operate flawlessly. The first unit has accumulated more than 3650 hours of on-orbit operation and the second unit has accumulated over 5550 hours.

INTRODUCTION

The International Space Station (ISS) high voltage solar arrays deliver output voltages of 140 V to 160 V. The electrical configuration of the ISS and the plasma current balance could cause the station to float at voltages predicted to be as much as 120 V below the ambient space plasma if no charge control device is used. If large negative floating potentials are present, the ISS could interact with ambient space plasma. These interactions could include arcing and sputter erosion.[1]

The development of a plasma contactor for charge control aboard a space station began in 1992 with the United States' Space Station Freedom plasma contactor project at the NASA Glenn Research Center (GRC). The information and research from this program was carried over into the design of the International Space Station (ISS) plasma contactors in 1994. Hollow cathodes were chosen for this application due to their efficient, variable, and rapid emission of high electron currents.[1]

The plasma contactor units (PCUs), developed by the Rocketdyne division of Boeing, and shown in Figure 1, use a hollow cathode assembly (HCA), shown in Figure 2, to generate electrons used for ISS charge control. GRC was tasked with the development and delivery of the flight HCAs. The mechanical design of the HCA is described in Reference 2. GRC's HCA development program included manufacture of engineering, qualification, and flight model HCAs as well as wear tests and qualification tests. During the development program, two main long duration cathode tests were conducted. During one of these tests a single cathode reached 28,000 hours of operation before an ignition failure.[3] In the second test four units were tested simultaneously with one cathode reaching 19,000 hours without failure, before the test was voluntarily shut down for cathode analysis.[4,5] Table I lists the final status of each of these life test HCAs. The ignition reliability of the HCAs were also tested. In one test, an HCA reached over 32,000 ignitions without failure.[6]

The first two plasma contactor units (PCUs), which were acceptance tested at GRC, were delivered aboard the shuttle Discovery in October of 2000 by the crew of STS-92. Two PCUs are used to ensure full redundancy, and they are co-located on the Z1 truss, shown in Figure 3, of the ISS in the area marked on Figure 4. The first ignition of a PCU aboard the ISS occurred on October 16, 2000.

OPERATIONAL REQUIREMENTS

The single primary design requirement for the PCUs was to control the ISS structure floating potential at all points on the station to ±40 V of the local space plasma potential. The effect of v x B charging as the ISS moves through the Earth's magnetic tightens this requirement to ±20 V.[1,6] The PCU carries enough xenon to operate continuously for 18,000 hours, enabling it to perform this function for more than 2 years.

Numerous requirements were instituted for the design of the HCAs. One requirement of the HCAs is to emit current up to 10 A in a self-regulating manner under dynamic conditions at clamping voltages ≤20 V between HCA common and the local space plasma potential. Another requirement is that the HCA be capable of operating for a minimum of 18,000 hours, which is based on the expellant available in the PCU. Ignition requirements were also instituted including the requirement that the HCA be capable of 6000 ignitions with no less than 99% reliability.[2]

ON-ORBIT OPERATION STATUS

The first two flight HCAs (identified as HCA.001-F in PCU1 and HCA.003-F in PCU2) are currently still in operation aboard the space station. Though originally designed for continuous operation, the HCAs currently operate only during extra-vehicular activities (EVAs), shuttle docking, or as deemed necessary. The operation of the HCAs was changed in order to extend the life of the PCU by operating the HCA for vehicle potential control during mission critical events, which necessitate single-fault tolerant capability.[7] The HCAs are normally operated simultaneously for the purpose of redundancy. The HCAs maintain a continuous flow of 6 sccm of xenon gas for the duration of their operation. The HCAs operate by emitting three amperes of current to the anode and are allowed to emit current as necessary to the space plasma. The current is emitted to the space plasma is termed "clamping current". Table II shows the status of each flight cathode as of June 16, 2003. As of that date, HCA.001-F had accumulated approximately 3655 hours of on-orbit operation, with 36 ignitions and HCA.003-F had accumulated 5551.4324 hours with 35 ignitions.

COMPARISON OF ON-ORBIT TO GROUND BASED OPERATION

Many parameters are available from on-orbit data, which can be directly compared to the ground based development testing. Parameters such as ignition time and anode voltage serve as a good measure of cathode health. As cathodes begin to degrade with operation time, ignition times and anode voltages have been seen to increase in ground based development testing. Several long duration wear tests have shown that anode voltages begin to rise with operation time after 500 to 1000 hours of operation.[3,8,9] Several mechanisms have been speculated as the cause of these changes such as: geometric changes in the cathode (due to deposition, erosion, or sputtering), pressure changes, and thermochemistry.[9,10] To verify that no geometric changes are affecting the anode voltages of the ground based life test, the life test HCAs from Reference 4, were inspected to verify their dimensions. The inspection consisted of using a pin gauge to manually inspect each cathode. Although the life test cathodes had accumulated thousands of hours of operation, no change was seen to the cathode orifice or keeper orifice as has been reported in similar tests.[3]

Barium depletion, and contamination, as well as other factors, can all cause increases in ignition time. Figure 5 shows ignition time versus ignition number for all ignitions accumulated by the flight HCAs. For this study, the ignition duration is determined to be the time from the start of the cathode warm-up procedure to the measurement of a voltage that indicates plasma has formed between the cathode and anode electrode. The graph shows that the ignition times tend to oscillate, but remain below six minutes. There is no apparent pattern in the ignition times and they do not show any trends of significantly increasing over time. Table III shows the maximum and average ignition times for the HCAs in this study.

As of this study, the last time the flight HCAs were operated simultaneously was April 8, 2003. Table IV shows the total operation time, ignition number and ignition duration for this operation segment. Figures 6 and 7 plot anode voltage and clamping currents for the flight HCAs during operation on this date. The graphs show that the anode voltages and clamping currents have similar magnitudes and trends. The anode voltage decreases from ignition to a "steady state" operating voltage in about 1.5 to 2 hours. Steady state anode voltages remain below about 17 V for all on-orbit HCA data. Anode voltages range from 12.8 V to 14.7 V for HCA.001-F and 12.2 V to 13.8 V for HCA.003-F. Clamping currents range from 0.003 A to 0.052 A for HCA.001-F and 0.003 to 0.035 A for HCA.003-F. The clamping currents show that, at most, only 0.052 A of current is required to control the charge on the ISS. As more structure and solar arrays are added, more current may be required from the HCAs.

On May 16, 2003 HCA.003-F was commanded to operate for a performance test. This was ignition number 35 for HCA.003-F and the unit ignited in 290 seconds. HCA.003-F was operated for approximately 479 hours during this segment, allowing it to reach a total accumulated time of approximately 5551 hours. Figure 8 shows anode voltages for HCA.003-F in the 24-hour span leading up to a total of 5551 hours of operation. The trace shows the cyclic operation of the HCA. HCA.003-F exhibits anode voltages in the range of 13.0 to 13.7 volts. Figure 9 plots HCA.003-F's clamping current versus accumulated operating time. As seen in Figure 6, the clamping current produced by HCA.003-F has a minimum of approximately 0.003 A, and a maximum of approximately 0.05 A.

CONCLUSIONS

While the currents required for charge control on board the ISS are below the predicted values, the HCAs are functioning within the operational requirements. Ignition times remain no longer than 6 minutes. Steady state anode voltages remain below about 17 V for all on-orbit HCA data. There have been no HCA failures on-orbit. All data indicate that the HCAs are operating properly.

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1. Patterson, M.J., et al., “Plasma Contactor for Space Station Freedom,” AIAA Paper No. 93-2228, June 1993.
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Table I.—Status of Life Test Cathodes

Unit	Accumulated Hours	Accumulated Ignitions
HCA-003	12415	38
HCA-006	8030	Data not Available
HCA-010	15876	4424
HCA-013	18873	59

Table II.—Status of Flight Cathodes as of June 16, 2003

Unit	Approximate Accumulated Operation Time, hrs	Accumulated Ignitions
HCA.001-F	3655	36
HCA.003-F	5551	35

Table III.—Maximum and Average Ignition Times

Unit	Maximum Ignition Time, sec	Average Ignition Time, sec
HCA.001-F	335	257
HCA.003-F	353	252

Table IV.—Operation on April 8, 2003

Unit	Approximate Accumulated Operation Time, hrs	Ignition Number	Ignition Time, sec
HCA.001-F	15	36	290
HCA.003-F	15	34	220

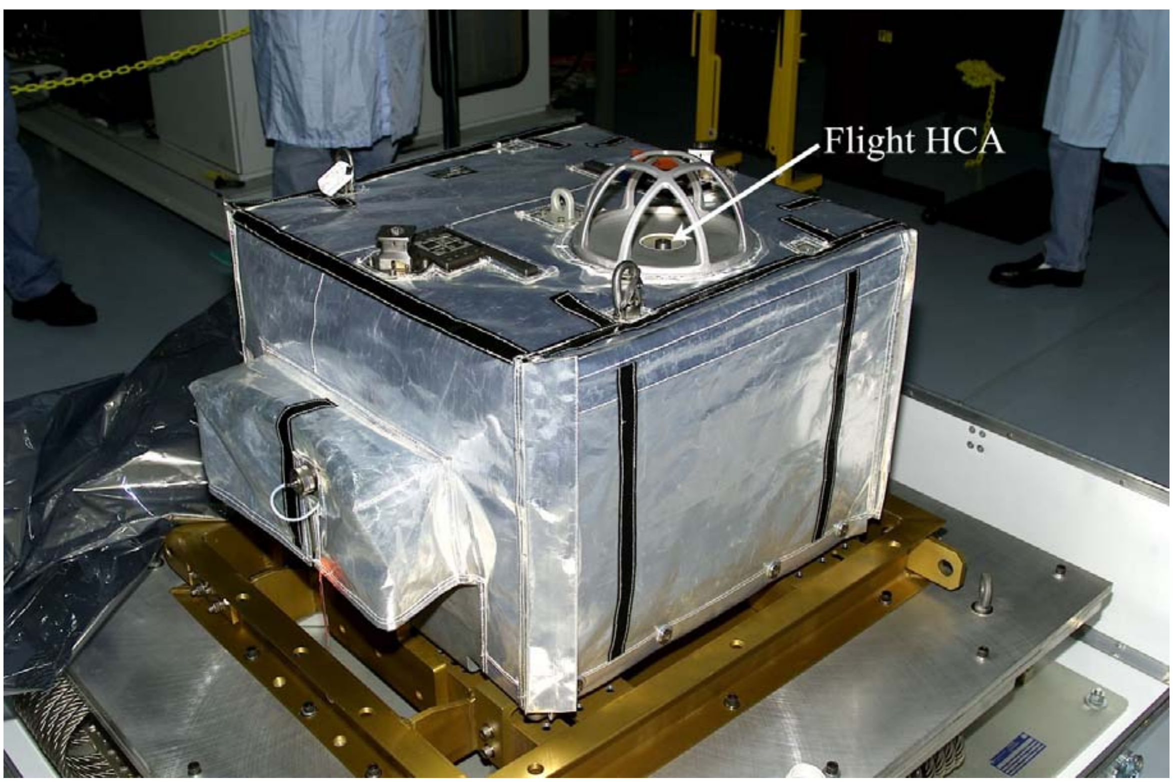

Figure 1.—Plasma Contactor Unit

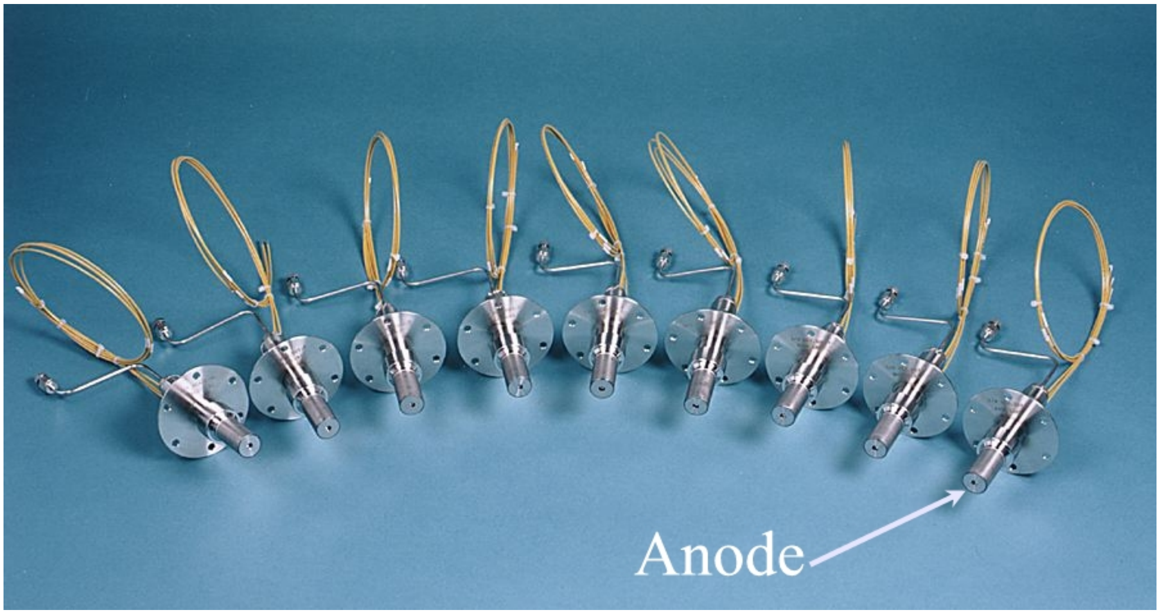

Figure 2.—Flight Hollow Cathode Assemblies

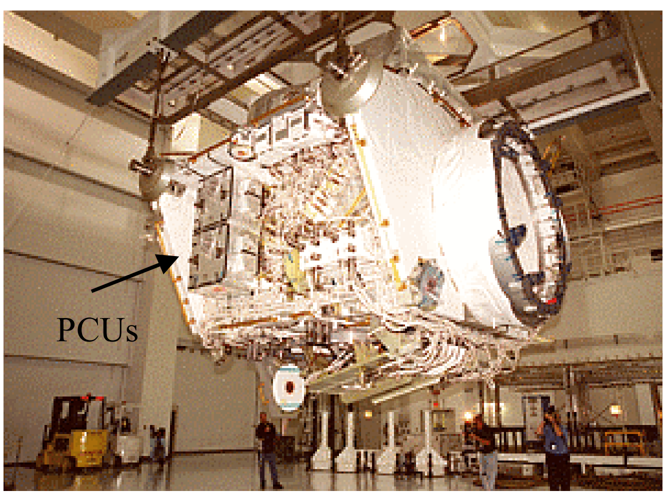

Figure 3.—Plasma Contactors on the Z1 Truss

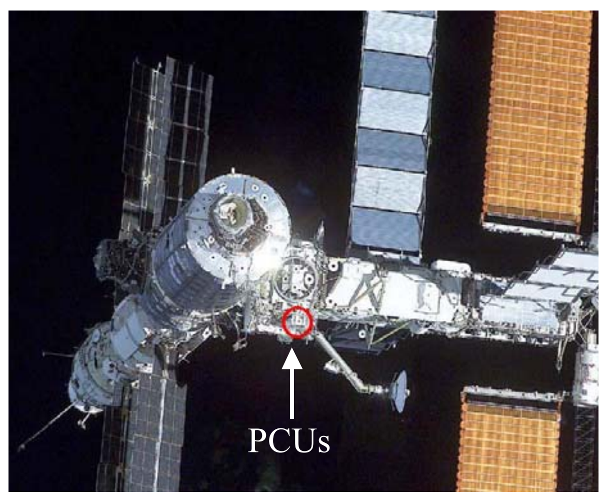

Figure 4.—Plasma Contactor Location on the ISS

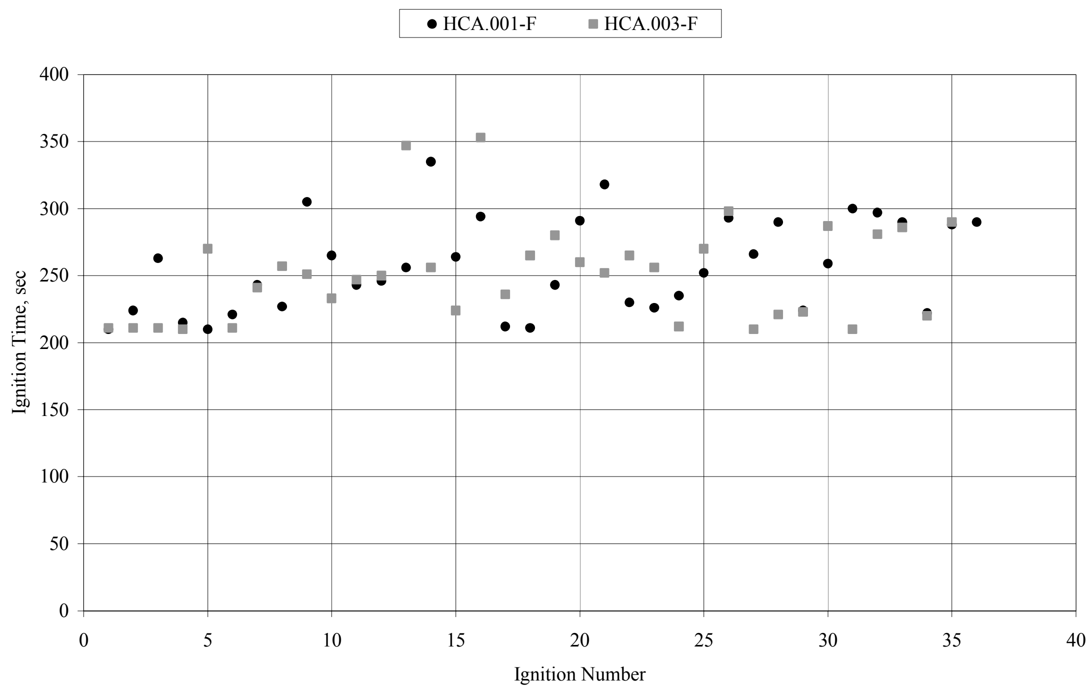

Figure 5.—On-Orbit Ignition Time vs. Ignition Number

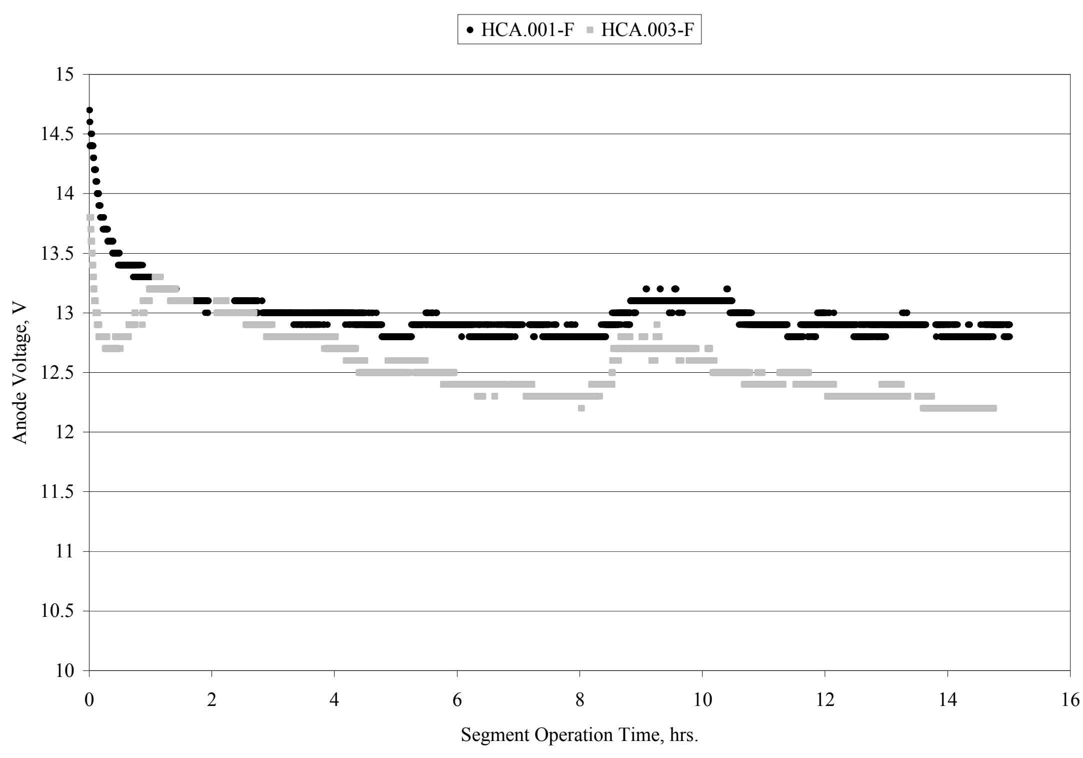

Figure 6.—Anode Voltage vs. Segment Operating Time for Operation on April 8, 2003

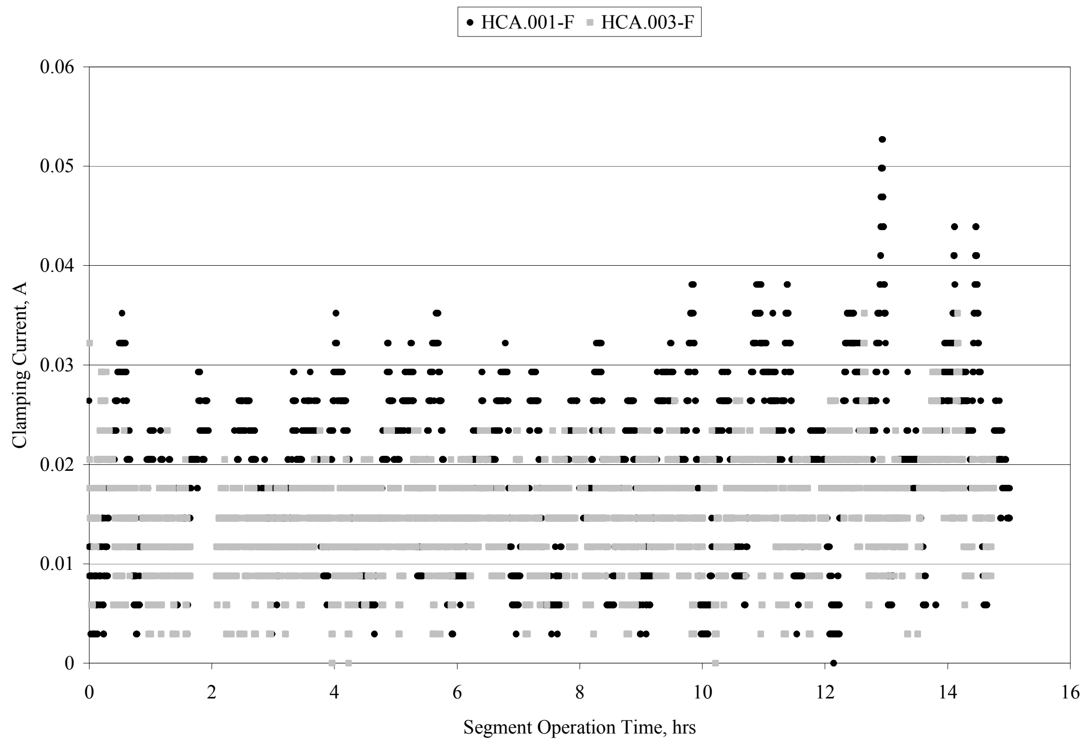

Figure 7.—Clamping Current vs. Segment Operating Time for Operation on April 8, 2003

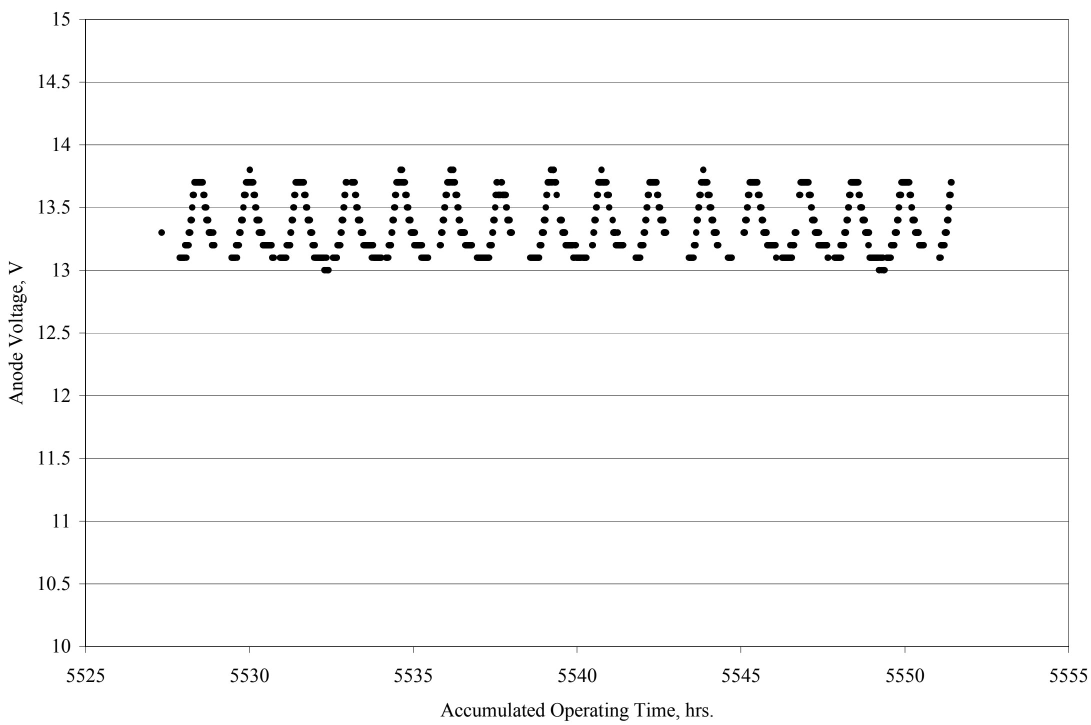

Figure 8.—HCA.003-F Anode Voltage vs. Total Accumulated Operating Time to 5551 hours

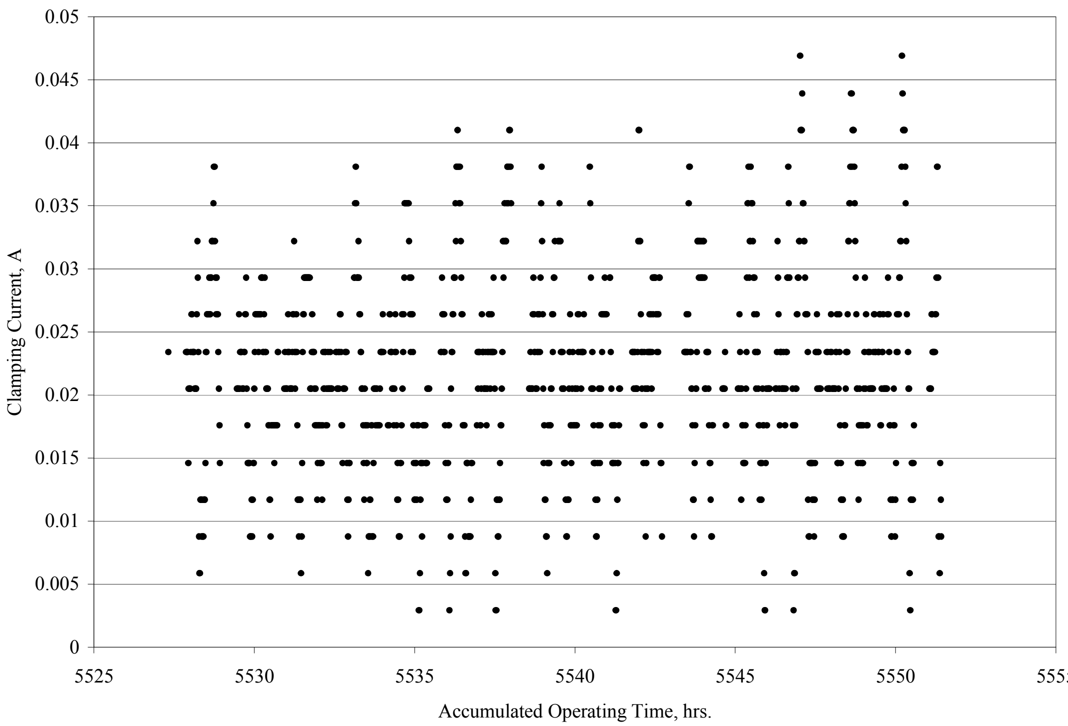

Figure 9.—HCA.003-F Clamping Current vs. Total Accumulated Time for Operation to 5551 hours

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