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ABSTRACT

The Plasma Contactor Units (PCUs) were developed at NASA Glenn Research Center (GRC) and Boeing for charge control on board the International Space Station (ISS). Since the first ignition of a PCU on 10/16/2000 over 3,900 hours of operation have been demonstrated on a single unit. In order to guarantee that the PCUs' hollow cathode assemblies (HCAs), which emit the electrons used for charge control, would satisfy the life requirement of 18,000 hours, a ground based hollow cathode life test program was initiated at GRC. The life test program aimed at 27,000 hours of operation on a single unit to demonstrate the industry standard 1.5 times operational life requirement. As of this printing, over 18,000 hours of operation have been accumulated on a single hollow cathode. By comparing the data received from the on-orbit HCAs to the data obtained for the life test cathodes, a comparison may be drawn to determine if the on-orbit HCAs are operating normally, with a final goal of predicting lifetime. Based on the data taken thus far, it can be concluded that the on-orbit HCAs are operating within their design specifications.

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 may 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 react with ambient space plasma. These reactions could include arcing and sputter erosion.^{1,2}

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), shown in Figure 1, aboard the ISS use a hollow cathode assembly (HCA), shown in Figure 2, to generate electrons used for ISS charge control. To verify that the HCAs are capable of completing their designated mission, a life test was started at NASA Glenn Research Center (GRC) in 1994.³ The goal of the test is to demonstrate 27,000 hrs of operation on a single HCA, which is 1.5 times the life requirement of the on-orbit HCAs. In addition to the life requirement, testing has been performed on the

effects of ignition on hollow cathode performance. The data taken from this test should provide insight into the operation of the on-orbit HCAs and aid in problem diagnosis as well as life estimation.

The first two plasma contactor units (PCUs) 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.

PLASMA CONTACTOR REQUIREMENTS

Three main requirements were instituted for the design of the ISS PCUs. First, each PCU must control the ISS structure floating potential at all points on the station to ± 40 V of the space plasma potential. The effect of $v \times B$ charging as the ISS moves through the Earth's magnetic field tightens this requirement to ± 20 V.^{4,5} Next each HCA is restricted to emit a maximum electron current of 10 A at no more than 20 V. Finally, the PCU must be able to operate for no less than 18,000 hours, which is based on the amount of propellant in the PCU.

In order to extend the operational life of the PCU an additional mode of operation was suggested, in which the PCU operates only during periods of active ISS charging. In order to ensure operation in this mode, the PCU was also required to be capable of 6000 ignitions with no less than 99% reliability.⁴

GROUND BASED TEST OPERATION

The ground based testing of flight type HCAs included testing four hollow cathodes. These cathodes are herein called life test cathodes and labeled HCA003, HCA006, HCA010, and HCA013. The cathodes were tested in a configuration designed to simulate the conditions predicted to exist on the ISS.³ The test began July 7, 1994 with HCA006. HCA006 was removed in 1996 for destructive analysis after 8000 hours of operation.⁶ Since the beginning of the ground based life test, 18,873 hours have been demonstrated on HCA013. HCA010 has operated for 15,876 hours and has demonstrated 4,424 ignitions. There have been no failures of the cathodes under test. HCA013 has successfully exceeded the lifetime requirement, and will be tested until the qualification requirement of 27,000 hours is reached. The current status of the life test cathodes can be seen in Table I. The life test cathodes operate with 40 minutes of 3.0 A electron current to the anode. This mode of operation is herein called "Diode Mode". This operation is followed by 50 minutes of 2.5 A electron current to a close proximity bias electrode. This mode of operation is herein called "Triode Mode". The cyclic operation is designed to mimic the 90-minute orbit of the ISS, which consists of 40 minutes of shade, at which time the arrays are not collecting current (simulated by diode mode), followed by 50 minutes of sunlight, during which time the solar arrays are collecting current (simulated by triode mode).

ON-ORBIT OPERATION

The first two PCUs (herein called flight cathodes and labeled PCU1 and PCU2) are currently still in operation aboard the space station. Table II shows the current status of each flight cathode. Though originally designed for continuous operation, these units operate only during extra-vehicular activities (EVAs), shuttle docking, or as deemed necessary. Typical discharge currents and anode voltages for these units are shown in Figures 5 and 6. Discharge current, which is the return current from the space plasma, ranges from 0.02 A to 0.05 A with voltages ranging from 12.5 V to 15 V. Figure 5 shows that the discharge currents on orbit are substantially lower than the life test triode mode emission current of 2.5 A, this is due to the fact that all of the ISS solar arrays have not all been installed, and therefore the ISS is not collecting as much current as previously predicted.

DATA ANALYSIS METHOD

Due to the large amount of data taken during the life test and the ISS, a program was needed that could

handle formatting, searching, and plotting millions of data points. A database program was chosen as the analysis platform, as databases can handle large amounts of records and can be integrated with other programs.

Life test data are taken in increments of one to five minutes, which allows the entire test to be analyzed simultaneously. Currently the test data are split, based on the year of testing, but plans exist to create a database containing all life test data. Data are imported and formatted from comma-separated files generated by the test, after which the files are easily analyzed. Plots from this test are created by generating tables from the data by selecting records at regular intervals to create plots that do not exceed a maximum of 10,000 data points.

ISS data are taken in one-second increments. Thus, when downloaded from the ISS archive, the files are substantially larger than those of the life test. A typical ISS flight can create over 2 million data points. Due to the file size, the only practical way to analyze large amounts of ISS data is on a per flight basis. Data from each ISS flight are imported into a database from fixed width files. The imported table is then formatted into dates, times, or numbers. After formatting, data holes are filled by inserting the previous value of a parameter into the hole, creating a complete data set. This method was chosen because the ISS appears to create entries only when values change and complete data sets yield fewer errors when analyzed by the computer. Plots of this data are generated in the same method as life test plots. Cathode operating time is estimated by the database by testing for the "PCU on" condition and subtracting start from end times of this condition.

COMPARISON OF ON-ORBIT TO GROUND BASED OPERATION

Ignition times and anode voltages have been shown to be a good indicator of cathode health. In order to diagnose the health of the flight cathodes, their performance was compared to the performance of life test cathodes.

Ignition times for both life test and flight cathodes are shown in Table III. The listed ignition times begin with application of heater power. Ignition is completed when the anode voltage is less than the open circuit voltage. Life test cathode ignition times, plotted in Figure 7, show a span from 211 seconds to 400 seconds for the majority of the ignitions. HCA010 has long ignition times during the first few ignitions, but this may be related experimentation with ignition procedures. Geometric changes, barium depletion, and

contamination, as well as other factors, can all cause increases in ignition time. Evolution of barium tungstate from long duration operation appears to be the main cause of ignition time increases.⁸ For life test cathodes, there does appear to be a trend of increasing ignition time with the number of ignitions.

The flight cathode ignition times span 210 seconds to 353 seconds. There is a slight rising trend, seen in Figure 8, which is consistent with the life test plot in Figure 7. After ignition 10, both life test and flight cathode ignition times fall in the 210 s to 350 s range, and there were no incidents of abnormally long ignition times.

As shown in Table II, flight cathode PCU1 has operated for 2742 hours. Based on this, a comparison between initial operation and operation at 3,000 hours was initiated. In order to make legible plots, only data for HCA006 and PCU2 are shown. Several long duration wear tests have shown that anode voltages begin to rise with operation time and oscillate after 500 to 1000 hours of operation.⁷⁻¹¹ Several mechanisms have been speculated as the cause of these changes such as: geometric changes in the cathode⁹ (due to deposition, erosion, or sputtering), pressure changes, and thermochemistry^{8,12}. To verify that no geometric changes are affecting the anode voltages of this test, the life test cathodes were inspected to verify their dimensions. The inspection consisted of using a pin gauge to manually inspect each cathode. Although the life test cathodes have accumulated thousands of hours of operation, no change was seen to the cathode orifice or keeper orifice as has been reported in similar tests.¹¹

As shown in Figure 9 and 10, data from the first operation of life test and flight cathodes show a distribution in anode voltage between 11.5 V and 17 V for life test cathodes and 12.2 V to 16.2 V for the flight cathodes. The peaks shown in Figure 9 correspond to cathode operation in diode mode, which simulates the ISS shade condition, while the valleys correspond to operation in triode mode, which simulates the sunlight condition. Peaks and valleys for the flight cathode anode voltages correspond to the position of the ISS. The data from first operation verify that the anode voltages of the flight cathodes are on the same order as the life test cathodes during the beginning of cathode life.

Figure 11 and 12 show anode voltage plots for life test HCA006 and flight cathode PCU2 operating at approximately 3,000 hours. Anode voltages range from 11.5 V to 14 V for the life test cathode and 12.8 V to 13.5 V for the flight cathode. Like the beginning of life data, the flight cathodes do not show peaks and valleys

as seen in the life test data. The data from 3,000 hours show that, while the patterns appear different, the anode voltage ranges are similar. Since both of the flight cathodes and the life test cathodes are operating with similar maximum and minimum voltages, it should be possible to use data taken from the ground based life test to simulate operation of flight cathodes.

CONCLUSIONS

After comparing the ignition times and anode voltages of the ISS HCAs to the HCAs used in the ground based life test at GRC, it can be concluded that all cathodes are operating within design specifications and demonstrate similar anode voltages and ignition times. Anode voltages are in the same range at the beginning of life and after 3,000 hours. Ground tests of HCAs operating for periods of 18,000 hours are continuing to operate without incident. These results indicate that the ISS HCAs should continue to exhibit stable operation and ignite reliably.

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Table I – Status of Life Test Cathodes

Unit	Accumulated Hours	Accumulated Ignitions	Status
HCA003	12414.6	38	Under Test
HCA006	8029.8		Disassembled for Analysis
HCA010	15876.1	4424	Under Test
HCA013	18873.2	59	Under Test

Table II – Status of Flight Cathodes

Unit	Accumulated Hours (Estimated)	Accumulated Ignitions
PCU1	2742	29
PCU2	3956	25

Table III – Ignition Times

Ignition Number	Ignition Times, sec				
	PCU1	PCU2	HCA003	HCA010	HCA013
1	210	211		855	
2	224	211		422	340
3	263	211	421	275	317
4	215	210	421	398	250
5	210	270	245	520	276
6	220	211	260	460	313
7	243	241	421	517	273
8	227	257	223	406	276
9	305	251	256	354	264
10	265	233	255	225	280
11	242	247	274	258	273
12	246	250	230	299	252
13	256	347	303	290	268
14	335	256	320	300	260
15	264	224	316	320	268
16	294	353	258	312	253
17	212	236	329	320	239
18	211	265	217	277	267
19	243	280	277	306	227
20	291	260	270	348	211
21	318	252	253	348	240
22	230	265	249	306	239
23	226	256	246	295	263
24	234	212	260	279	241
25	252	270	281	295	276
26	293		283	269	216
27	266		302	292	293
28	290		270	274	306
29	224		261	358	248
30			709	311	234

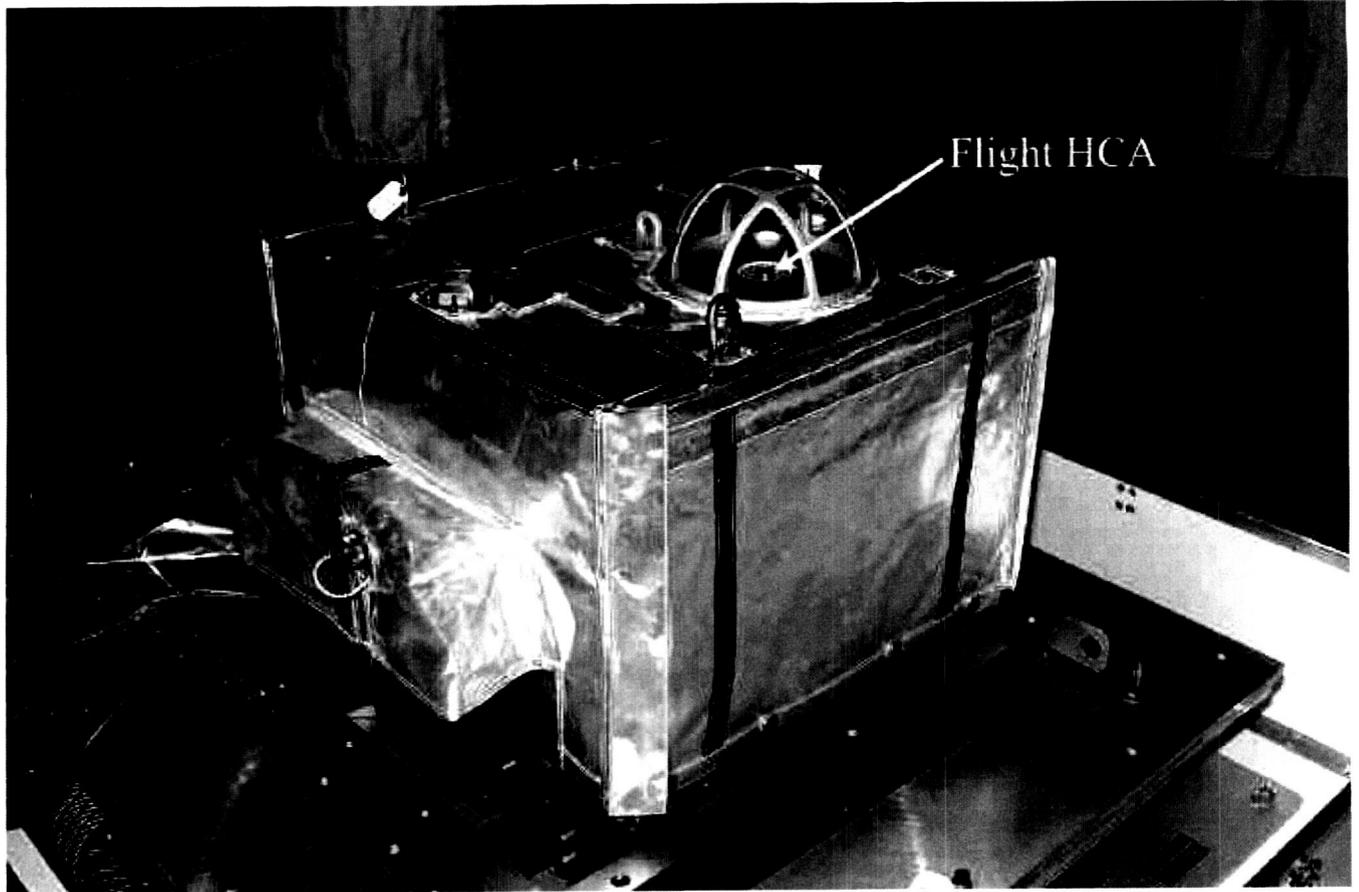


Figure 1 – Plasma Contactor Unit

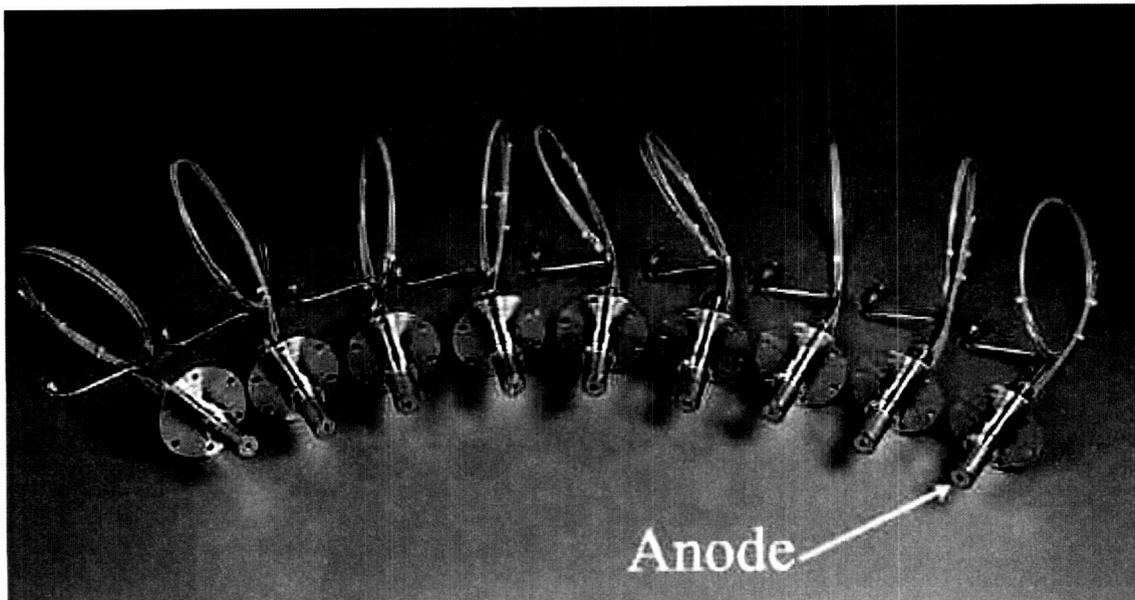


Figure 2 – Flight Hollow Cathode Assemblies

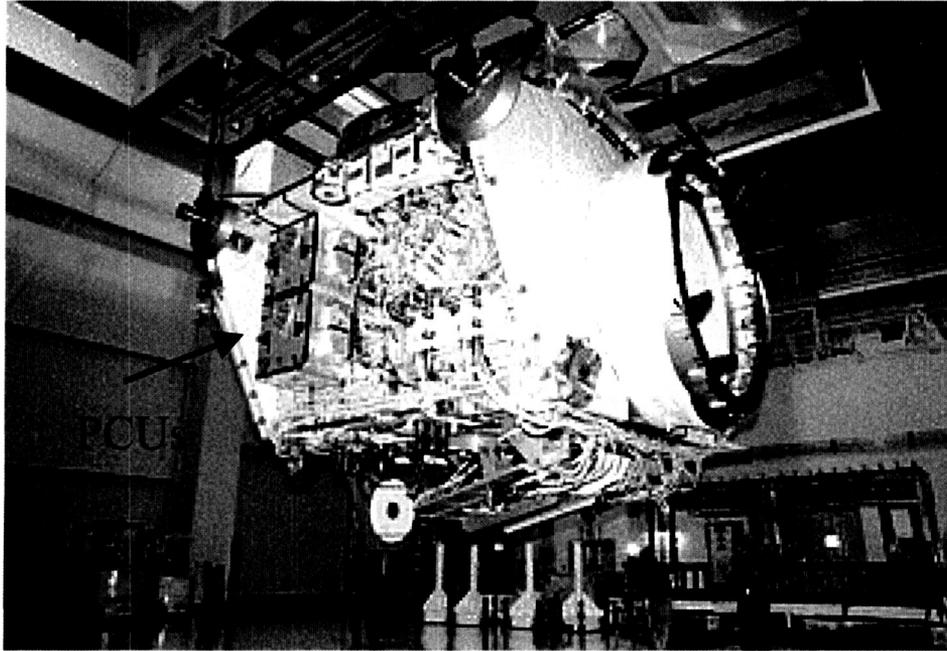


Figure 3 – Plasma Contactors on the Z1 Truss

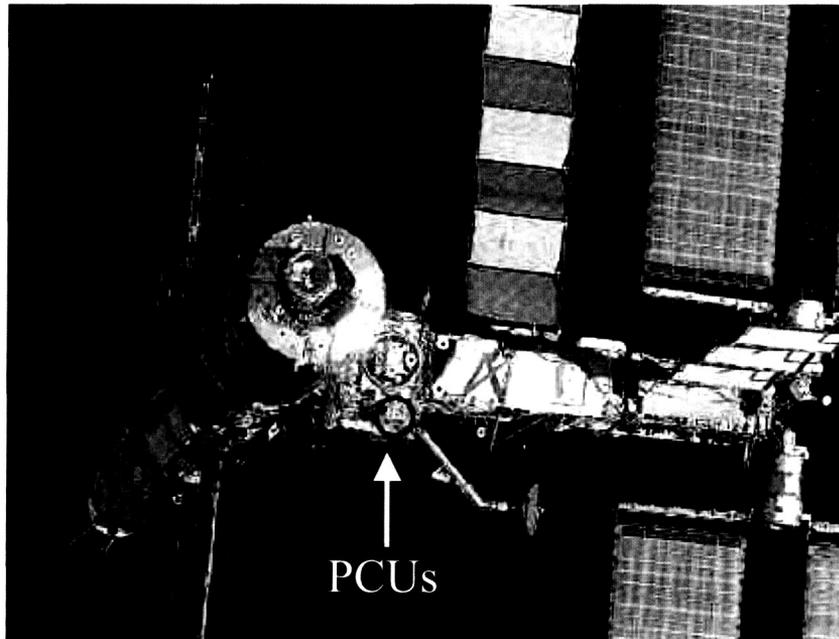


Figure 4 – Plasma Contactor Location on the ISS

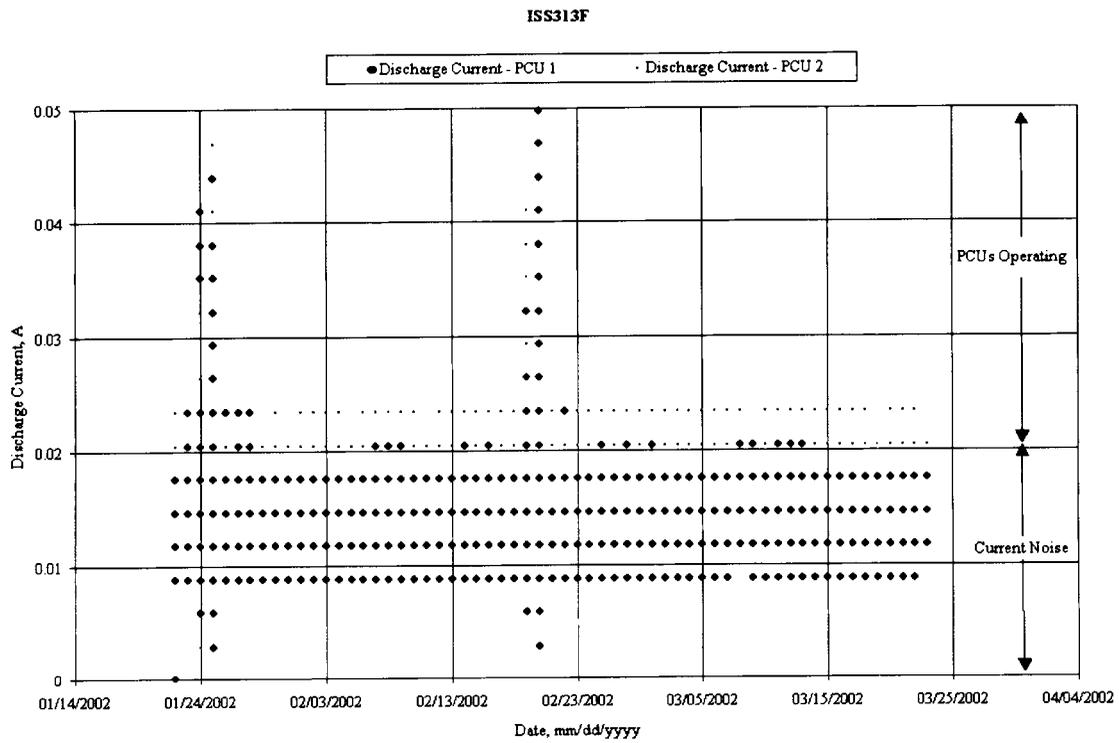


Figure 5 – PCU Discharge Current vs. Day for ISS Flight 313F

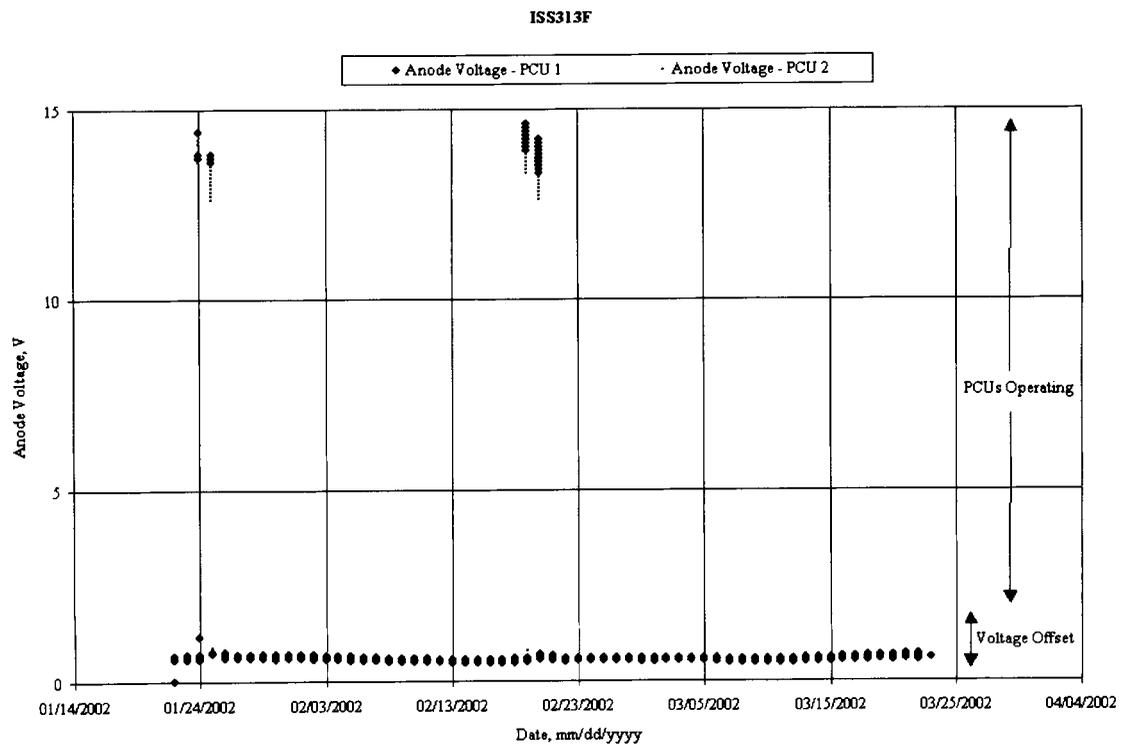


Figure 6 - PCU Anode Voltage vs. Day for ISS Flight 313F

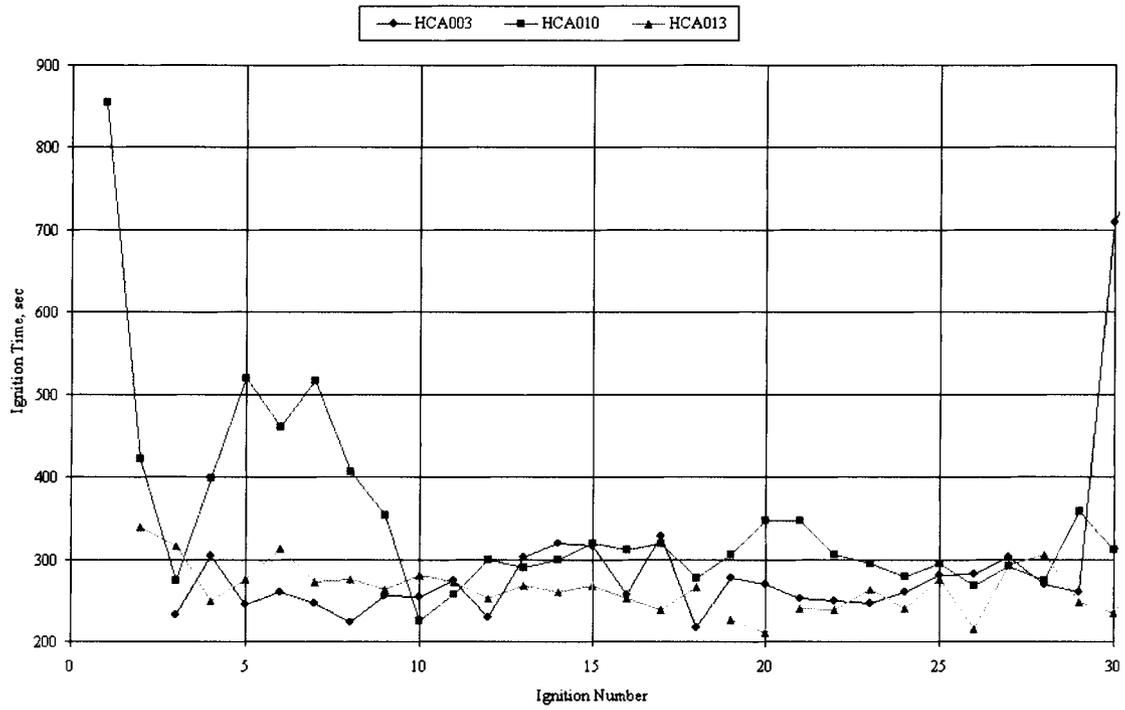


Figure 7 – Life Test Hollow Cathode Assembly Ignition Times

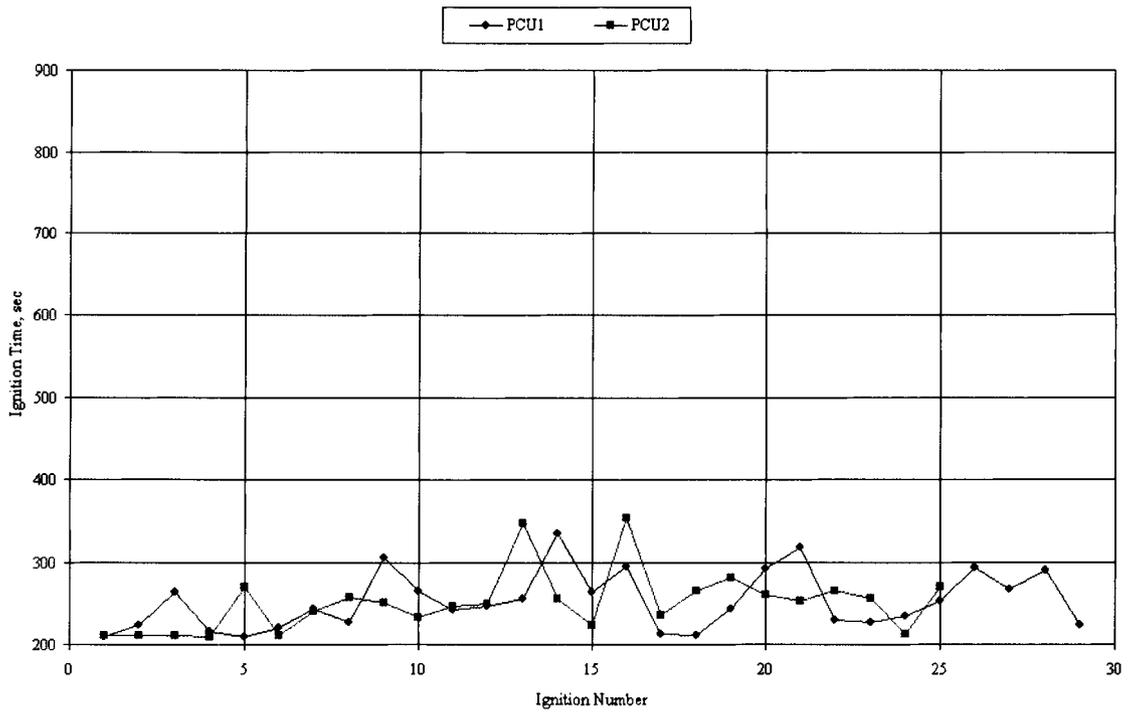


Figure 8 – Flight Hollow Cathode Assembly Ignition Times

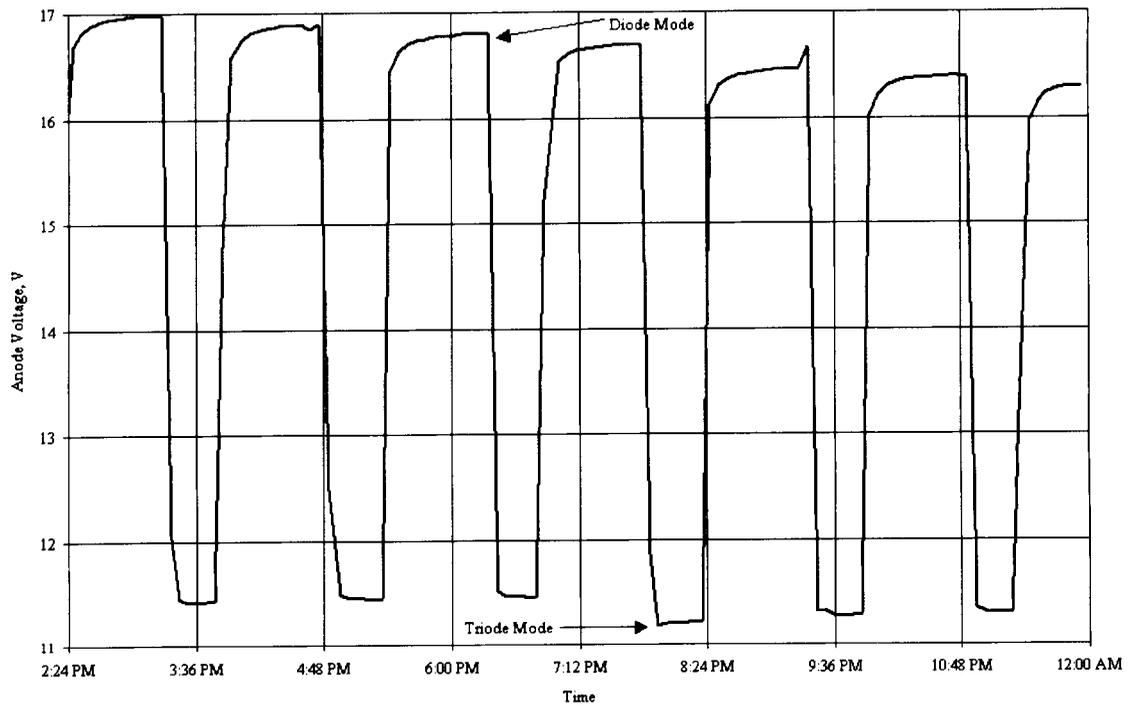


Figure 9 – HCA006 Anode Voltage During Initial Operation on 07/08/1994

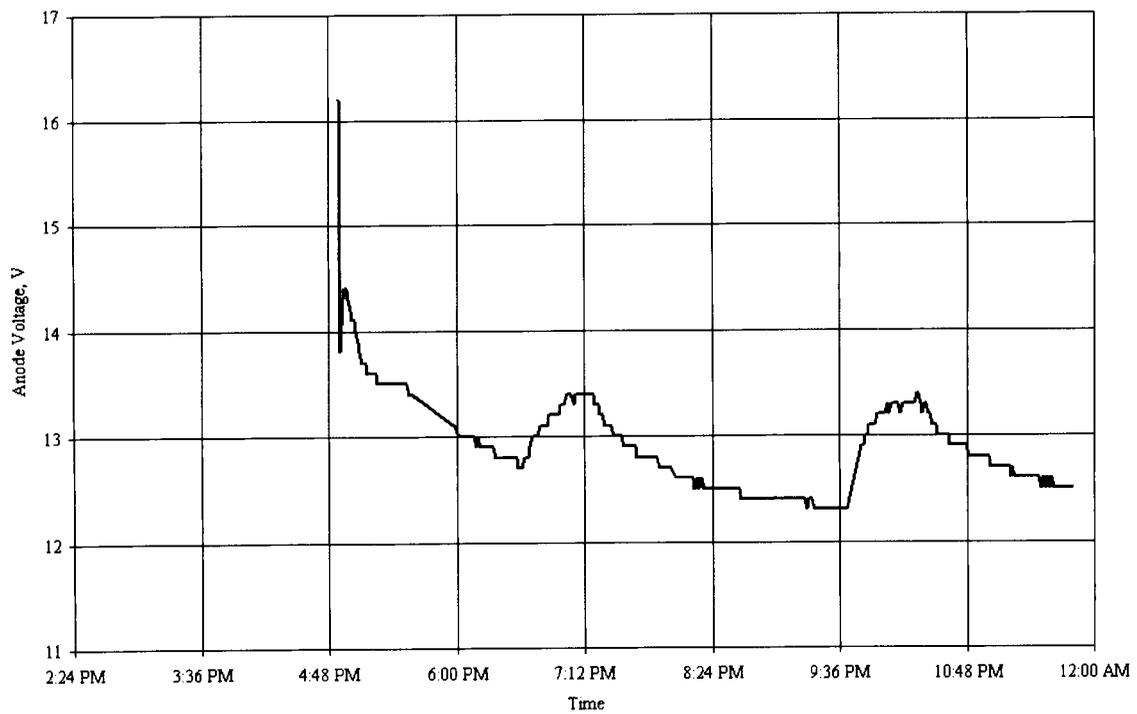


Figure 10 – PCU2 Anode Voltage During Initial Operation on 11/17/2000

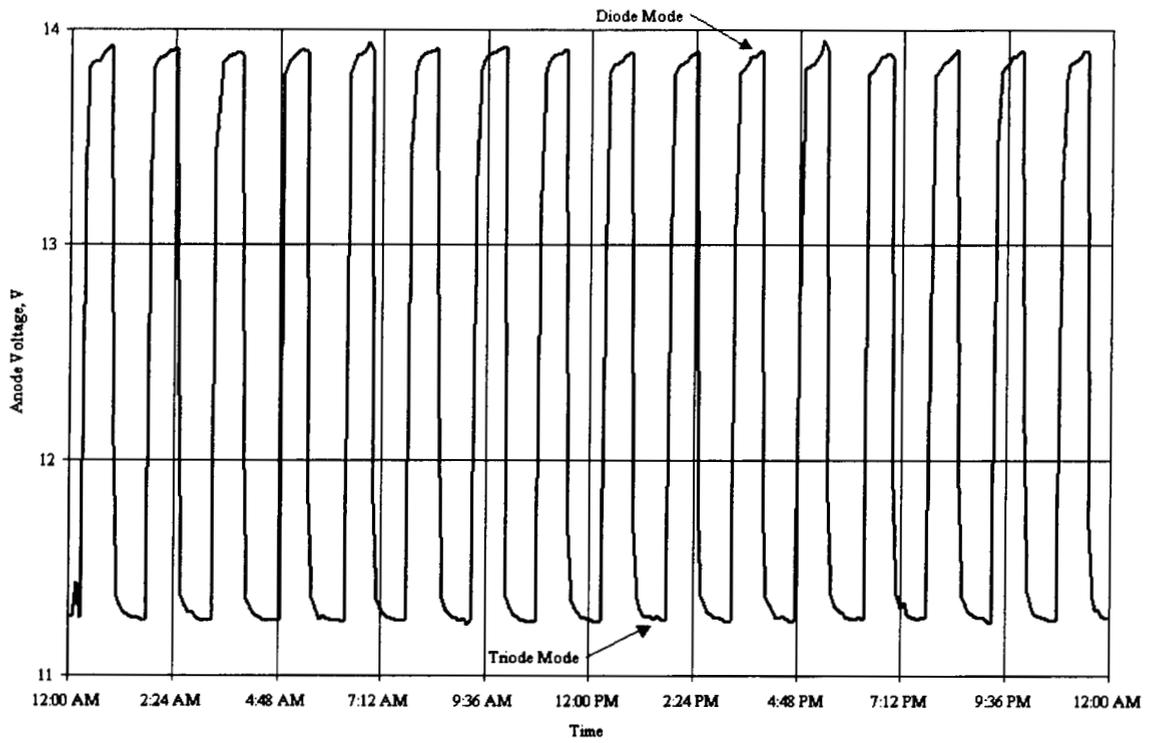


Figure 11 – HCA006 Anode Voltage After Approximately 3,000 Hours of Operation

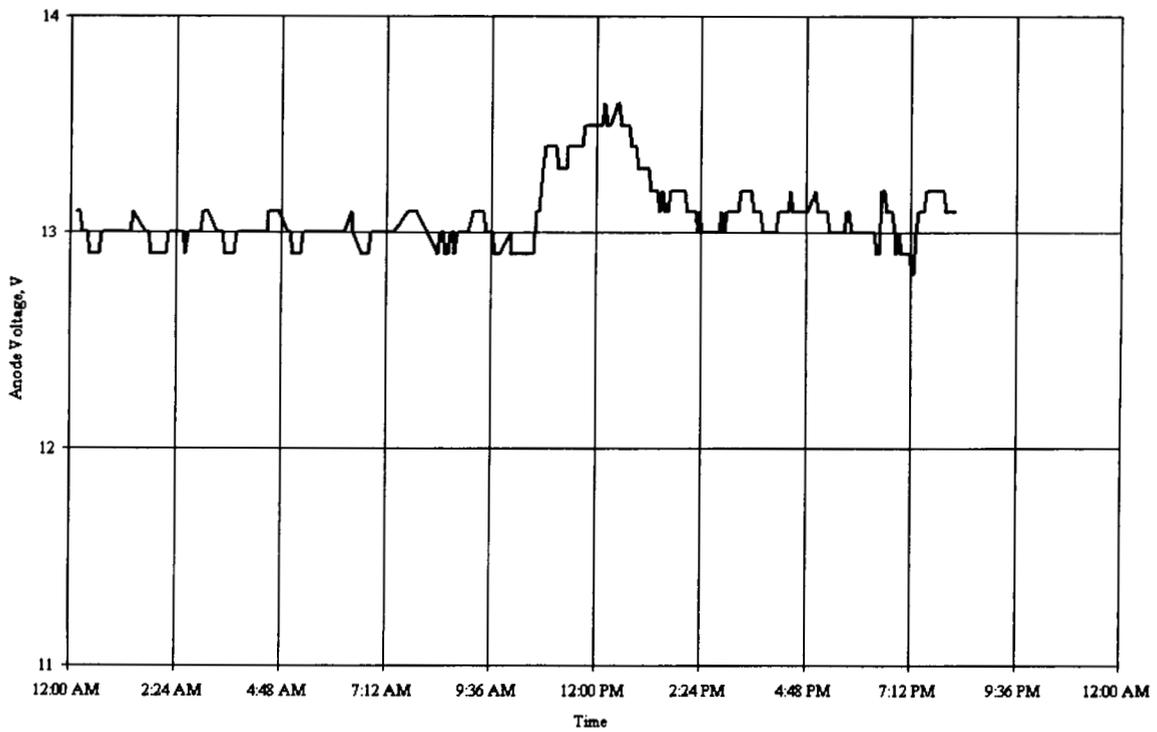


Figure 12 – PCU2 Anode Voltage After Approximately 3,000 Hours of Operation

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