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NASA Contractor Report 191131

Hollow Cathode Heater Development for the Space Station Plasma Contactor

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October 1993

Prepared for
Lewis Research Center
Under Contract NAS3-25266

NASA

National Aeronautics and
Space Administration

HOLLOW CATHODE HEATER DEVELOPMENT FOR THE SPACE STATION PLASMA CONTACTOR

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Abstract

A hollow cathode-based plasma contactor has been selected for use on the Space Station. During the operation of the plasma contactor, the hollow cathode heater will endure approximately 12000 thermal cycles. Since a hollow cathode heater failure would result in a plasma contactor failure, a hollow cathode heater development program was established to produce a reliable heater design. The development program includes the heater design, process documents for both heater fabrication and assembly, and heater testing. The heater design was a modification of a sheathed ion thruster cathode heater. Three heaters have been tested to date using direct current power supplies. Performance testing was conducted to determine input current and power requirements for achieving activation and ignition temperatures, single unit operational repeatability, and unit-to-unit operational repeatability. Comparisons of performance testing data at the ignition input current level for the three heaters show the unit-to-unit repeatability of input power and tube temperature near the cathode tip to be within 3.5 W and 44 °C, respectively. Cyclic testing was then conducted to evaluate reliability under thermal cycling. The first heater, although damaged during assembly, completed 5985 ignition cycles before failing. Two additional heaters were subsequently fabricated and have completed 3178 cycles to date in an on-going test.

Introduction

A hollow cathode-based plasma contactor has been baselined for use on Space Station to reduce station charging.[1] The hollow cathode utilized by the plasma contactor requires a heater to provide heat to 1) remove contaminants from the cathode electron emitting insert surface during activation and 2) ignite the discharge.[1] Although it is not anticipated that the plasma contactor will be cycled on and off, the contactor emission current to the space plasma will vary throughout the course of an orbit[1] which will impart a cyclic thermal load onto the heater. It is anticipated that the heater will endure approximately 12000 thermal cycles, most of which will occur to an unpowered heater. Without a reliable heater that can withstand these thermal cycles, the plasma contactor may fail.

Ion thrusters also utilize these heaters for the discharge and neutralizer hollow cathodes. The 30-cm derated xenon ion thruster[2] tested at the NASA Lewis Research Center (LeRC) utilizes the same heater as that of the plasma contactor. Near term applications for ion thruster technology include north-south station-keeping and on-orbit repositioning missions.[3-7] For these missions, it is anticipated that the thruster cathodes will be operated for 3000-4000 on-off cycles on large communication satellites to achieve lifetimes in excess of ten years.[3-7] A reliable heater will be essential to meet these life time requirements.

Potted heaters, alumina flame/plasma sprayed heaters, and sheathed heaters have been developed for plasma contactors and ion thrusters. Although all heater types have been successfully tested,[8-10] only alumina flame/plasma sprayed and sheathed hollow cathode heaters were investigated in this program since there was a considerable amount of experience with these types at LeRC. While alumina flame/plasma sprayed hollow cathode heaters were successfully flight tested on the SERT II spacecraft,[9] a later program, using larger diameter cathodes, revealed that the alumina insulation was prone to cracking after fewer than 1000 thermal cycles, and that this cracking typically resulted in a heater failure.[10] Furthermore, fabrication procedures for alumina flame/plasma sprayed heaters involved high levels of skill and attention to detail that exceeded those required for sheathed heaters.[11] To avoid these problems, sheathed heaters were utilized. Sheathed heaters were shown to operate reliably for thousands of on-off cycles for both ion thrusters[10] and resisto-

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jets,[12] and were baselined for use on the J-series 30-cm mercury ion thruster, an engineering model thruster for a solar electric propulsion system ground demonstration program.[13] The J-series hollow cathode heater design, however, suffered from a high failure rate during acceptance testing and a termination design that was complex, fragile, and difficult to fabricate.[13]

For the plasma contactor hollow cathode heater, the J-series hollow cathode heater design was modified to increase heater reliability. A test program was developed to verify reliability under thousands of cyclic thermal loads. Heater design, fabrication, and inspection procedures were developed. A heater test facility that included a computer data acquisition and control system was designed and assembled. Heater testing, which includes performance testing to determine power requirements and operational repeatability and cyclic testing to evaluate reliability, is underway for several heaters.

This paper presents the status of the heater development program for the Space Station plasma contactor. The heater development program is initially discussed. Aspects of the experimental program, including the test facility, the heater design, and the heater test procedures, are then presented. Finally, results from heater testing are presented and discussed.

Heater Development Program

A flow chart describing the hollow cathode heater development program is shown in Fig. 1. The heater development program was designed to be an iterative process between the heater design and process documents, the heater assembly, and heater testing. The heater design and process documents were based on heater requirements for the plasma contactor cathode. Following heater assembly, the heaters were tested, and results from these tests were used to modify the heater design and process documents. The hollow cathode heater design is validated upon successful completion of all heater testing.

The heater design was sheathed concept and is shown in Fig. 2. The basic elements of the heater are the center conductor, the insulator, the sheath, the terminations, and the radiation shield. The center conductor is the heat source, the sheath encloses the heating element and closes the electrical circuit, and the insulator provides electrical isolation for and thermal conduction between the center conductor and sheath. The terminations couple the center conductor to the circuit, and the radiation shield reduces radiated power losses. The detailed heater design will be discussed in a later section.

The fabrication procedures were written with sufficient detail to ensure repeatability of the assembly process. They include specifications for all cleaning, swaging, annealing, welding, and brazing processes, as well as the assembly procedures. Inspection procedures were included to ensure successful heater fabrication. These procedures include visual, radiographic, and thermographic inspections, an insulation compaction measurement, and cold resistance measurements. The heater assembly process includes a record of all material data to ensure traceability of heater material, as well as the implementation of fabrication and inspection procedures. As a final test of heater unit reliability, an acceptance testing procedure is conducted. This test includes a cold heater resistance measurement before and after completing a series of on-off cycles.

Heater tests for design validation include cyclic testing of the plasma contactor and hollow cathode, vibrational testing of plasma contactor, and testing of the heater unit alone. This paper will focus on the latter. Testing of the heater unit alone includes performance testing and cyclic testing. Performance testing is used to determine input current and power requirements for achieving activation and ignition temperatures, single unit operational repeatability, and unit-to-unit operational repeatability. Performance tests are conducted before and after cyclic testing. Cyclic testing is used to evaluate heater reliability under a cyclic thermal load by subjecting the heater to an ion thruster qualification test for a ten year, north-south station-keeping mission on a large communication satellite. Using the industry qualification standard of 1.5 times the maximum number of cycles,[4,6] such a test would require a successful completion of around 6000 on-off cycles.

Test Apparatus

Heater Test Facility and Apparatus

All testing was conducted within a 0.31 m inner diameter, 0.36 m long stainless steel port that was mounted onto Vacuum Facility 5 at LeRC. The test facility is shown in Fig. 3. The port was isolated from Vacuum Facility 5 and was pumped by a turbomolecular pump that was backed by a mechanical pump. Base port pressures were on the order of 1.3×10^{-4} Pa (1×10^{-6} torr) as measured by an ionization gauge. A low background pressure was necessary to preclude excessive oxidation of heater and cathode components which could result in inaccurate performance data and/or failure. Since past tests of sheathed heaters were successfully conducted within this pressure range,[10] this range was adequate.

The heaters were mounted onto hollow cathodes with electron emitting inserts installed to simulate the cathode thermal mass. The cathodes were secured to ceramic isolators that were mounted on a steel platform with stainless steel sheet metal for radiation shields, as shown in Fig. 4. This arrangement was designed to accommodate the testing of three heaters simultaneously. No attempt was made to initiate a discharge.

A schematic of the computerized data acquisition and control (DAC) system utilized for heater testing is shown in Fig. 5. A computer and a digital-to-analog converter were used with a General Purpose Interface Bus (GPIB) to control three 16 V, 10 A DC heater power supplies. Use of direct current for the hollow cathode heater allows for reduced conducted and radiated electromagnetic interference during plasma contactor activation and ignition. With the heater as a load, the current regulation and ripple of the power supplies were < 0.8% and < 0.81%, respectively. The computer-GPIB configuration was further used to control two 16 channel multiplexers and an analog-to-digital converter for data acquisition. The multiplexers, which contained signal conditioners to electrically isolate the DAC system and to condition incoming signals, were commanded to send their analog signals to an analog-to-digital converter which then was commanded to send the converted digitized signals to the computer via the GPIB. The computer saved these data on an external disk drive and printed a hard copy. Monitored parameters included heater currents and voltages, tube temperatures near the cathode tip, and port pressure. Currents were measured with current transducers, voltages with volt meters, temperatures with platinum/platinum-13% rhodium thermocouples, and port pressures with an ionization gauge. A strip chart recorder was installed to continuously monitor the heater currents, voltages, and the port pressure.

Heater Design

The modified heater design is shown in Fig. 2. It is a modified version of the J-series ion thruster heater design. It consists of a sheathed heater with 8 helical coils used to heat the hollow cathode. The amount of swaging was reduced to avoid damaging the center conductor and the insulation thickness was increased to preclude the center conductor from making contact with the sheath during the swaging process. The reduced swaging resulted in a larger center conductor diameter than the J-series cathode heater. The heater impedance at ignition temperature was 1.1 Ω. Although this low impedance imposes a loss in power processor efficiency due to the low operating voltages, heater reliability is increased due to the decreased probability of damaging the center conductor during the swaging process. For the heater termination, the center conductor of the sheathed heater was welded to a larger diameter wire. A sleeve was brazed to the sheathed heater and filled with a high temperature ceramic cement. This assembly removes stress from the center conductor and reduces resistive power losses. The wire was terminated with a stake-on. The radiation shield was a metal foil shield that was wrapped around the heater coils and was retained by spot-welds.

Heater Test Procedures

Heater testing consisted of performance and cyclic testing. Performance testing involved ramping the heater input current to a fixed current level in order to measure the tube temperature near the cathode tip as a function of input power. This test was conducted before and after cyclic testing. The heater produced a maximum tube temperature of ~ 1100° C. Cyclic testing involved cycling the heater to ignition temperatures for 6000 cycles. Each cycle consisted of 10 minutes at high heat input power to simulate ignition and 10 minutes at power off for cooling. A typical temperature characteristic is shown in Fig. 6. The ignition time simulation was a maximum value chosen pending testing to determine an actual ignition time. The cooling time was chosen to impose a significant thermal stress on the heater while minimizing cycle time. The rate of heater cooling was found to decrease substantially within the first 10 minutes of heater power shut-down.

Results and Discussion

To date, three heaters have been tested. The first heater, labeled PCU-H-001, was cycled to failure. The following two heaters, labeled PCU-H-002 and PCU-H-003, have been performance tested and are currently under cyclic testing. The following sections will present and discuss the test results of each heater.

Heater PCU-H-001

The first heater tested, labeled PCU-H-001, was assembled without any inspection of the hardware during fabrication. Furthermore, acceptance testing was not conducted. The testing objectives of this heater were to verify that the heater termination design was satisfactory and to obtain an initial estimate on the cyclic lifetime capability of the design. During the installation of the heater onto the hollow cathode, the heater sheath surface and shape were damaged. However, since no heater insulation was exposed and the heater cold resistance did not change, testing was initiated. To ensure that the temperature at the sheath/sleeve interface did not exceed the brazing temperature, a platinum/platinum-13% rhodium thermocouple was spot-welded onto the sheath at this interface to monitor the temperature.

The performance of the heater before cyclic testing, as characterized by the tube temperature near the cathode tip as a function of input power, is shown in Fig. 7. The heater termination design was found to be satisfactory, and so cyclic testing of the heater was initiated. Peak heater input powers, cathode tube temperatures, and heater sheath/sleeve interface temperatures for various cycles are plotted in Fig. 8, 9, and 10, respectively. The heater input power increased by 1.8% of the starting value within the first 233 cycles, indicating that a "burn-in" of the heater had occurred. By cycle 4359, the input power had risen linearly by 3.0%. By cycle 5933, the input power had risen by 5.6% at an increased linear rate. The heater input power then increased sharply by 6.7% during cycle 5985, after which the heater failed. The cathode tube temperature increased by 17 °C within the first 577 cycles after which the temperature decreased by 63 °C by cycle 3859. The heater sheath-sleeve interface temperature also decreased by 42 °C of the starting value by cycle 5933.

The heater was inspected after failure to determine the cause of the failure and to identify any other problems. A radiographic examination of the heater revealed nothing conclusive. A destructive examination of the heater revealed a break in the center conductor at the fourth coil from the weld of the center conductor to the sheath. The cause of this discontinuity is unknown, however it is anticipated that it is due, in part, to prior mishandling during assembly. The cathode tube thermocouple immediately separated from the cathode tube upon removal of the heater from the vacuum facility. The decrease in the cathode tube temperature shown in Fig. 9 may have been due to a poor thermocouple attachment. A visual examination of the heater sleeve revealed discoloration resulting from oxidation. The decrease in the heater sheath-sleeve interface temperature was probably the result of the cooling effect caused by the increased emissivity at this location. Finally, a visual examination of the ceramic cement revealed that it was very brittle. The brittleness was found to be caused, in part, by an improper mixing of the compound that resulted in a weakened ceramic.

Heaters PCU-H-002 & -003

The following two heaters, labeled PCU-H-002 and -003, were fabricated and inspected according to the process documents. The installation procedure of the heater onto the cathode was modified to prevent damaging the test article. Acceptance testing was successfully conducted for both heaters. Pre-test cold resistance measurements of the thermocouple attachments to the cathode tubes were made in order to monitor any changes in this junction. Cold resistance measurements indicated that the fabrication of these heaters duplicated that of PCU-H-001.

The performance of all heaters is compared in Fig. 7. At the ignition input current, tube temperature near the cathode tip and input power repeatability were within 44 °C and 3.5 W, respectively. The disparity in the cathode tube temperatures were partly due the difficulty in maintaining an exact thermocouple location from heater to heater. As a result, this disparity was considered acceptable. The repeatability of input power was equivalent to that of past ion thruster heater testing.[10]

The heaters are currently being cycled and have completed 3178 cycles to date. The peak input powers and cathode tube temperatures for various cycles are shown in Fig. 11 and 12, respectively. The heater input powers of heaters PCU-H-002 and -003 increased by 2.1% and 2.8%, respectively, within the first 300 cycles indicating that a "burn-in" of the heaters had occurred, similar to that of heater PCU-H-001. By cycle 3178, the heater input powers increased linearly by ~ 10% of the starting values, 4 times greater than that of heater PCU-H-001. The cause of this change is unknown. Power levels between heaters PCU-H-002 and -003 differed by less than 1.8%. The cathode tube thermocouples for heaters PCU-H-002 and -003 failed to operate properly after cycles 802 and 1104, respectively, for unknown reasons. The cathode tube temperatures for heaters PCU-H-002 and -003 increased by 13 °C and 27 °C, respectively, within the first 135 cycles, and then started to decrease. This trend was also observed with heater PCU-H-001. Temperature differences between heaters PCU-H-002 and -003 were as high as 48 °C at the beginning of the test, but were less than 9 °C by cycle 802.

Conclusion

A heater development program was established to produce a reliable hollow cathode heater design for the Space Station plasma contactor. A heater design was determined and fabrication and inspection procedures were developed to ensure a repeatable design. A heater test facility that utilized a computerized data acquisition and control system was assembled. Heater testing was conducted to determine power requirements for cathode activation and discharge ignition, single unit operational repeatability, unit-to-unit operational repeatability, and overall heater reliability. Three heaters have been fabricated to date. The first, although damaged during assembly, completed 5985 cycles before failing. The peak input power increased by 6.7% of the starting value and failed due to a break in the center conductor. Testing for two heaters is ongoing and 3178 cycles have been completed to date. The heater-to-heater repeatability of tube temperatures near the cathode tip and input powers at the ignition input current level were found to be within 44 °C and 3.5 W, respectively.

Additional heaters will be fabricated and tested. Results from cathode discharge and plasma contactor life testing will be essential to determine if sputtering of heater components will be a problem. Furthermore, heater design validation will require passing vibrational testing of the plasma contactor.

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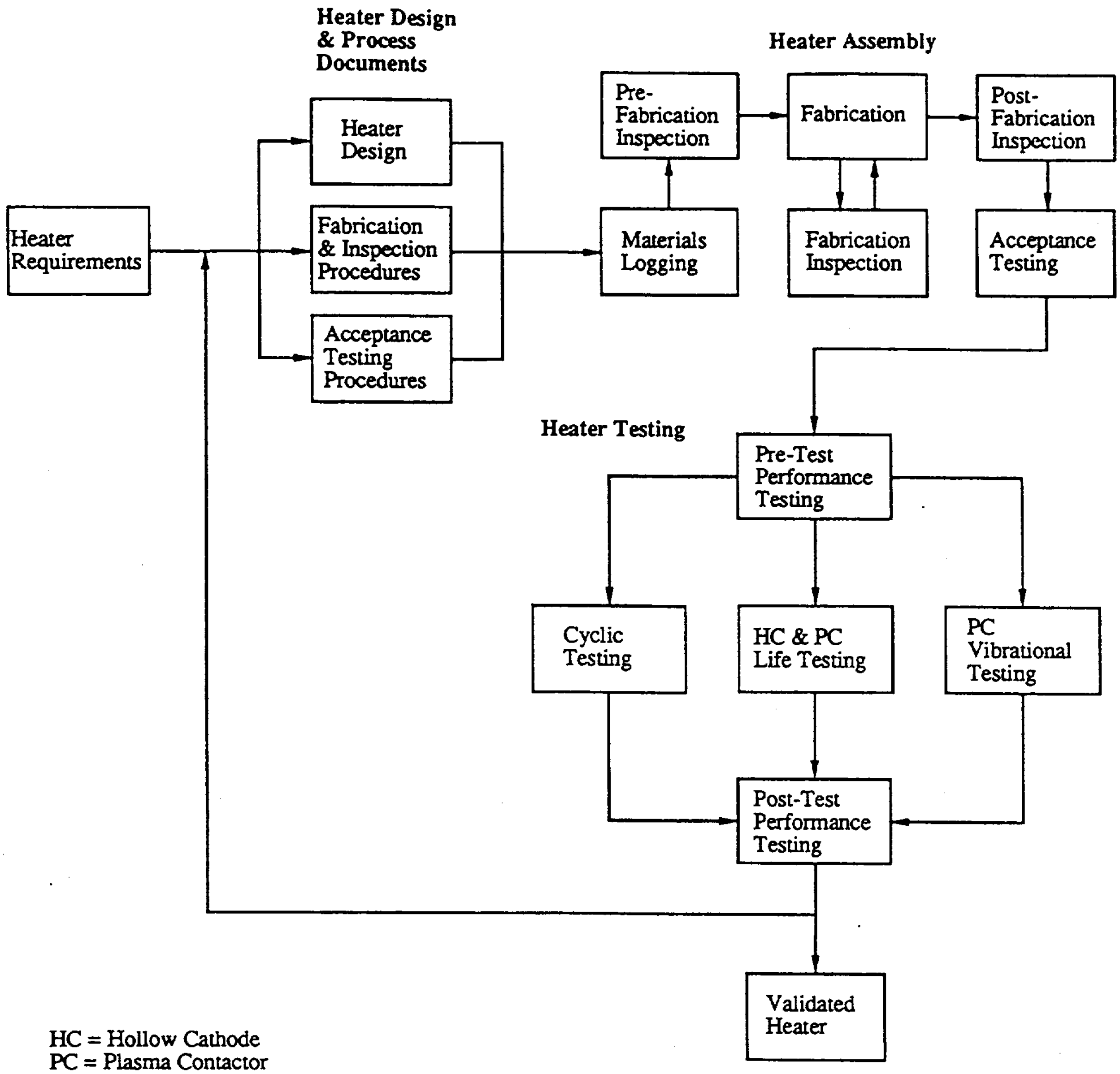

Fig. 1. Hollow Cathode Heater Development Flow Chart.

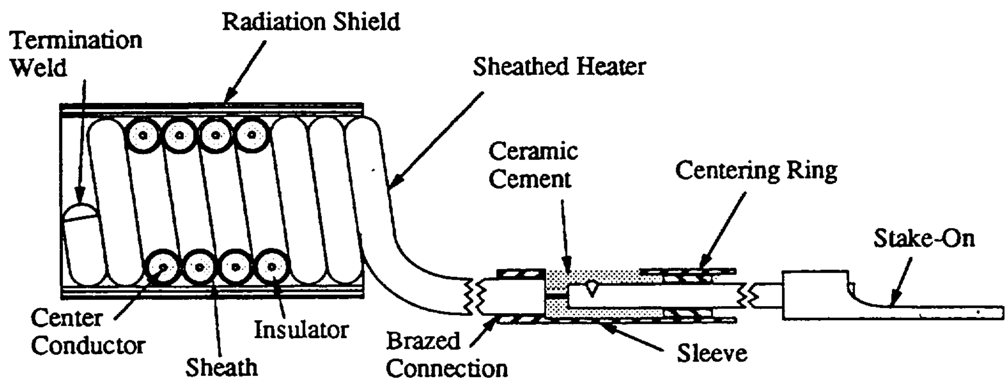

Fig. 2. Modified Heater Design.

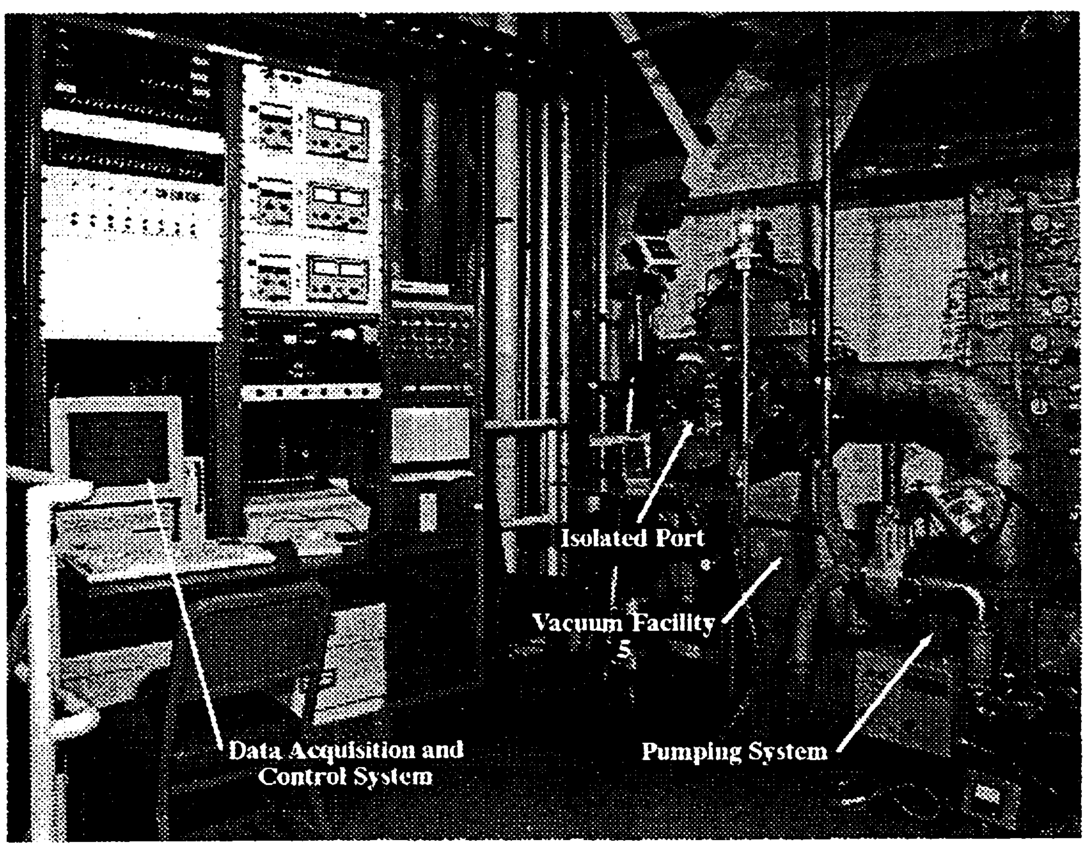

Fig. 3. Heater Test Facility.

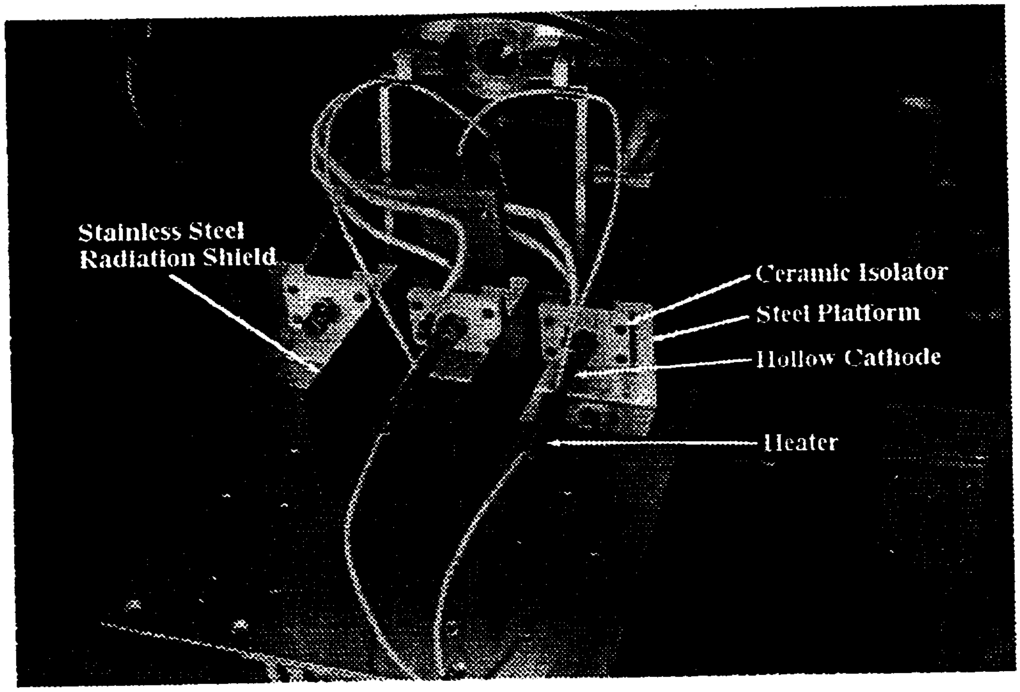

Fig. 4. Heater Test Platform With Radiation Shields.

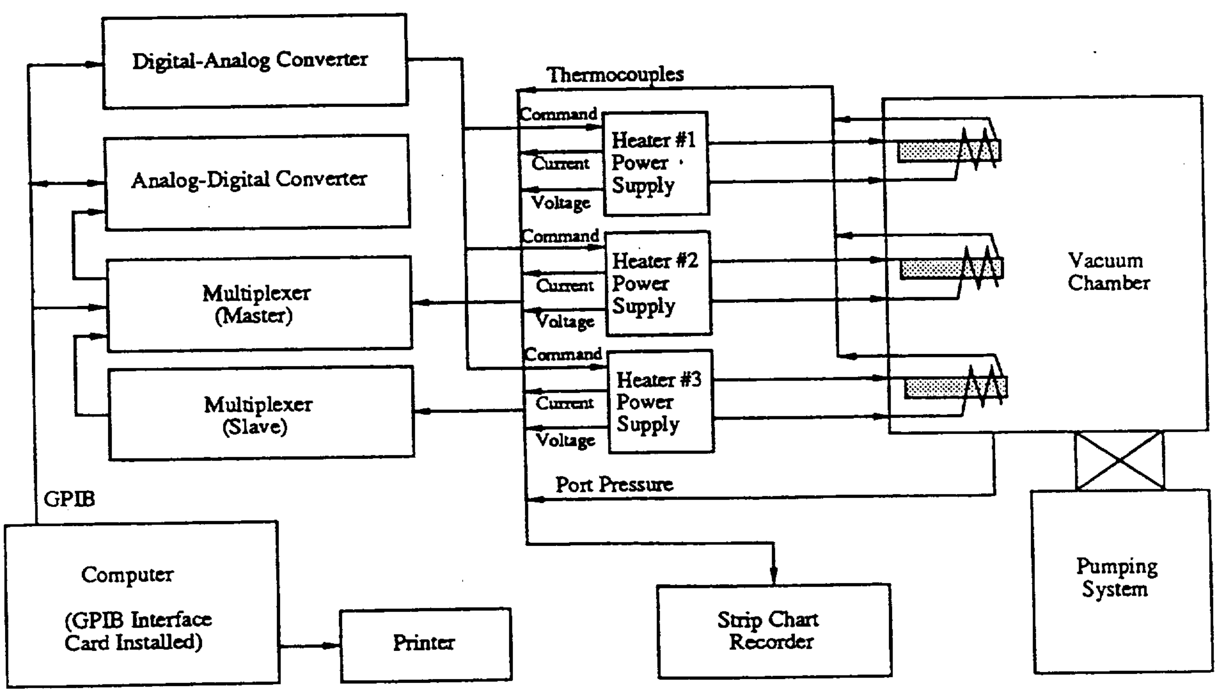

Fig. 5. Data Acquisition and Control System Schematic.

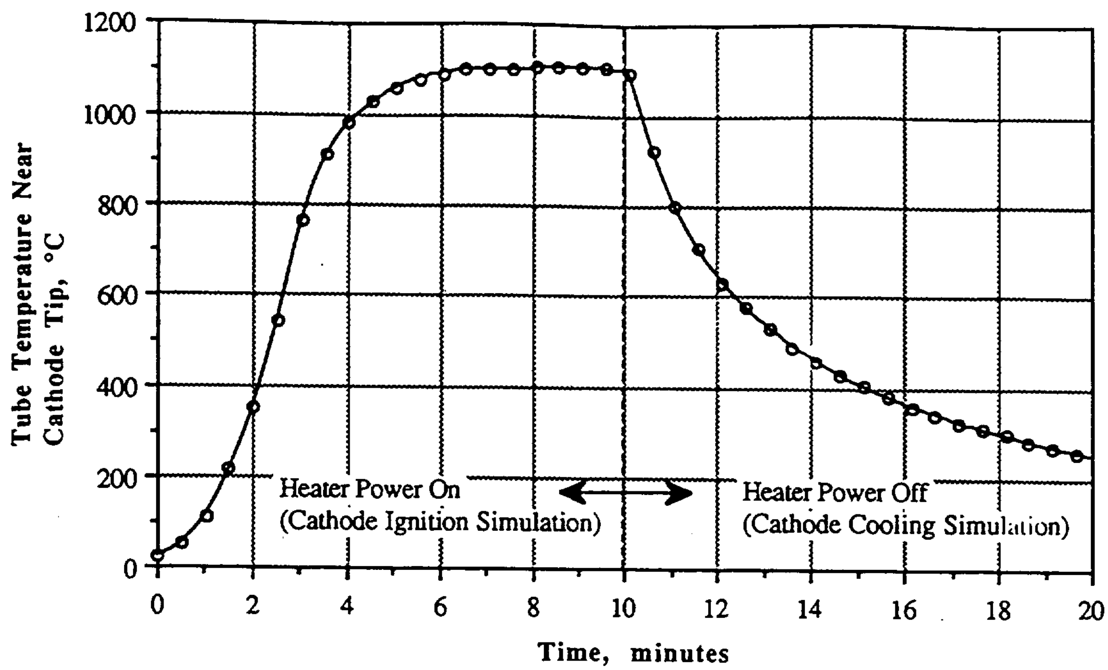

Fig. 6. Typical Temperature Profile for One Cycle.

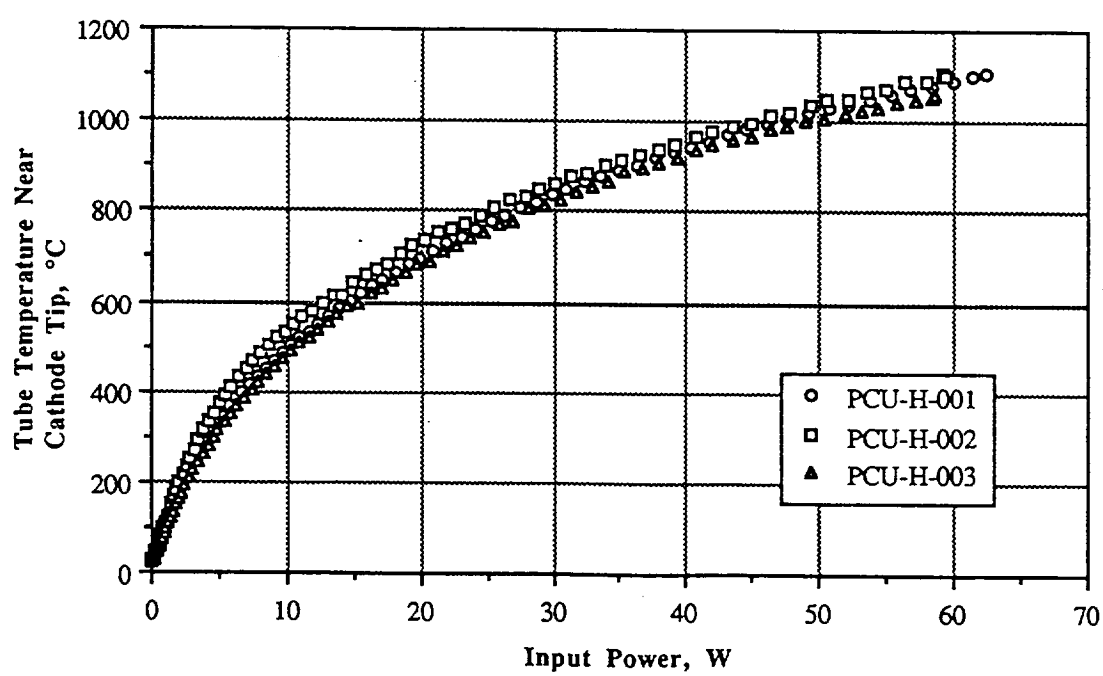

Fig. 7. Tube Temperature Near the Cathode Tip as a Function of Input Power for Heaters PCU-H-001, -002, and -003 (Pre-Cyclic Testing).

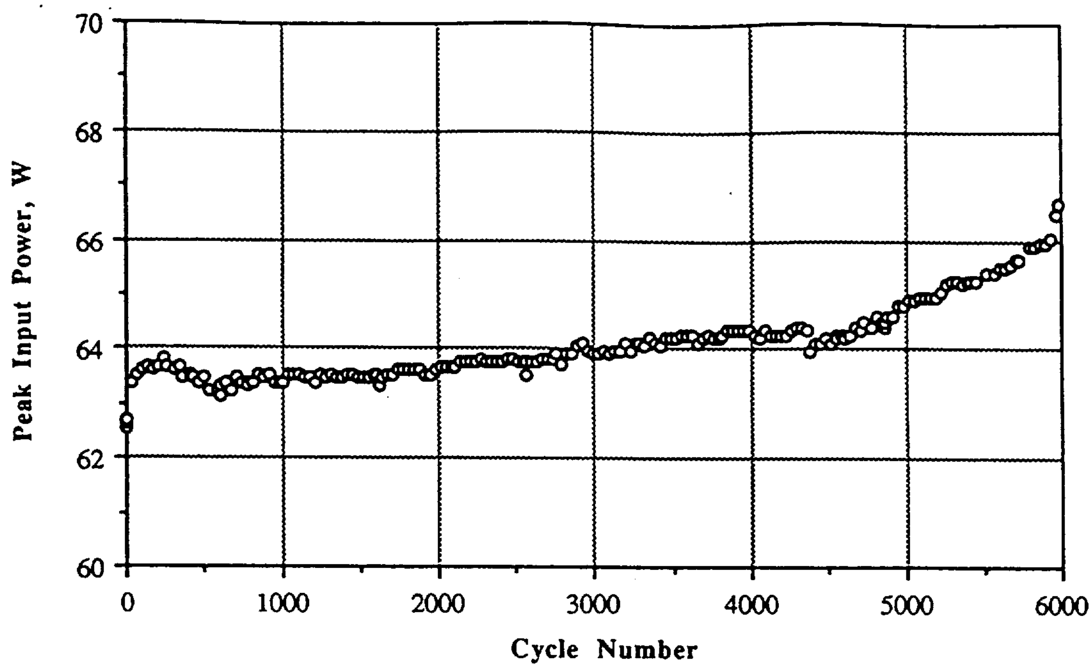

Fig. 8. Peak Heater Input Powers at Various Cycles for Heater PCU-H-001.

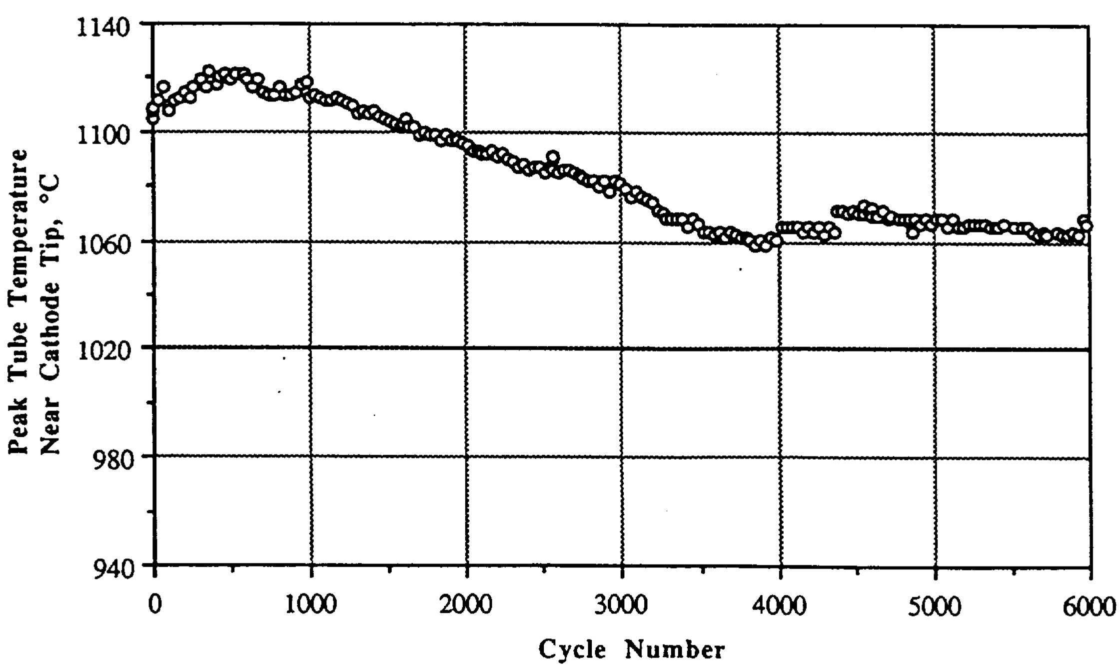

Fig. 9. Peak Tube Temperatures Near the Cathode Tip at Various Cycles for Heater PCU-H-001.

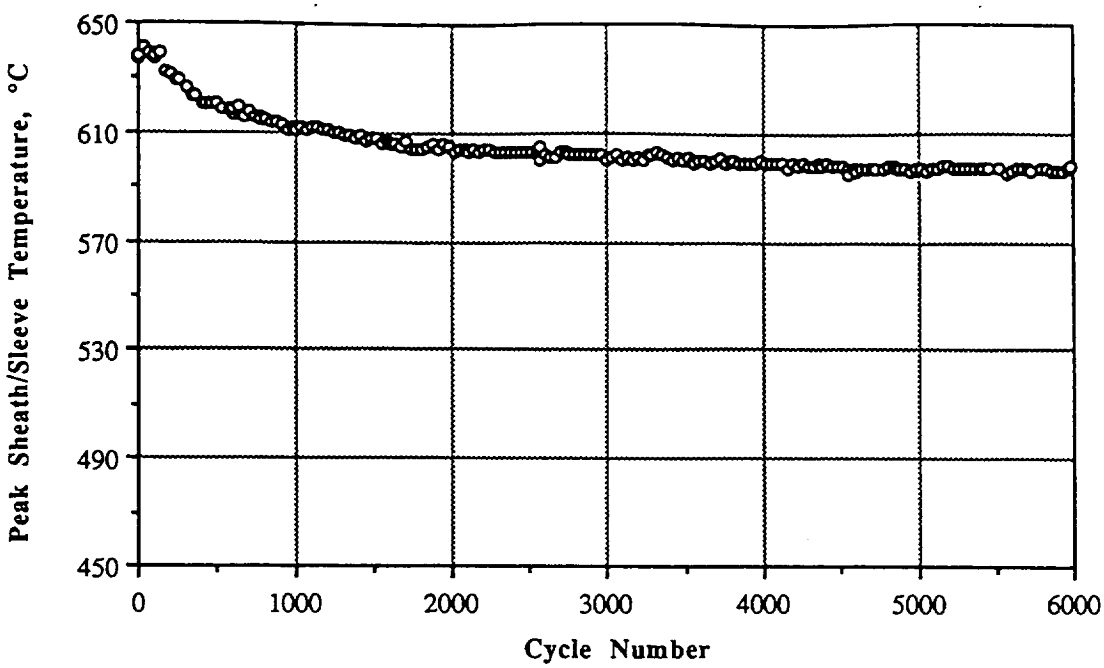

Fig. 10. Peak Heater Sheath/Sleeve Interface Temperatures at Various Cycles for Heater PCU-H-001.

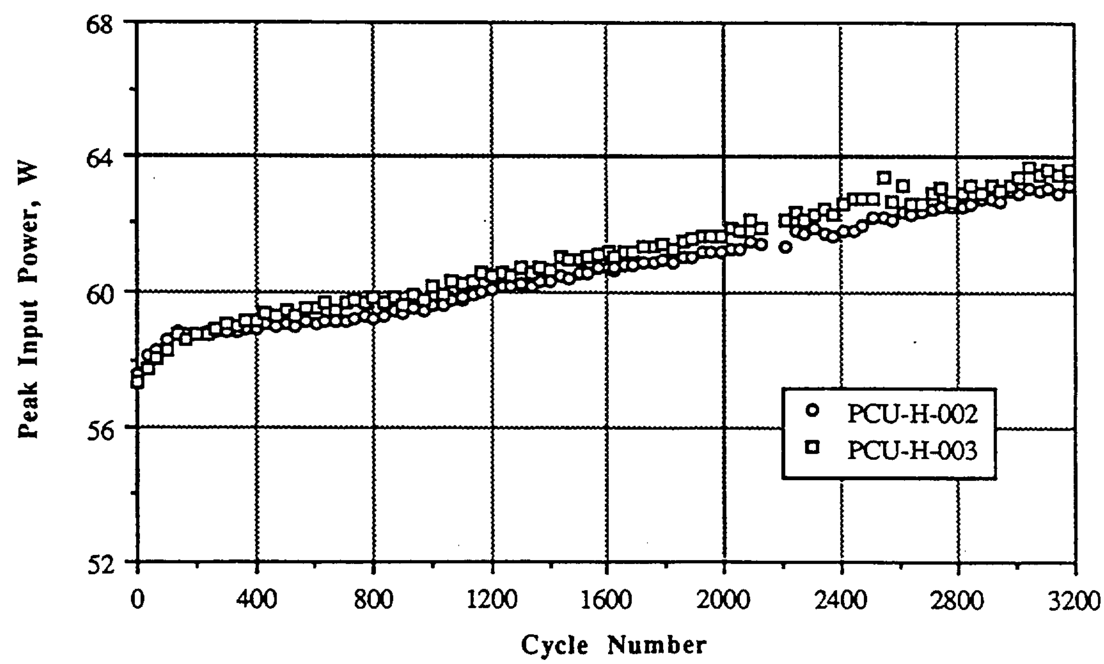

Fig. 11. Peak Heater Input Powers at Various Cycles for Heaters PCU-H-002 and -003.

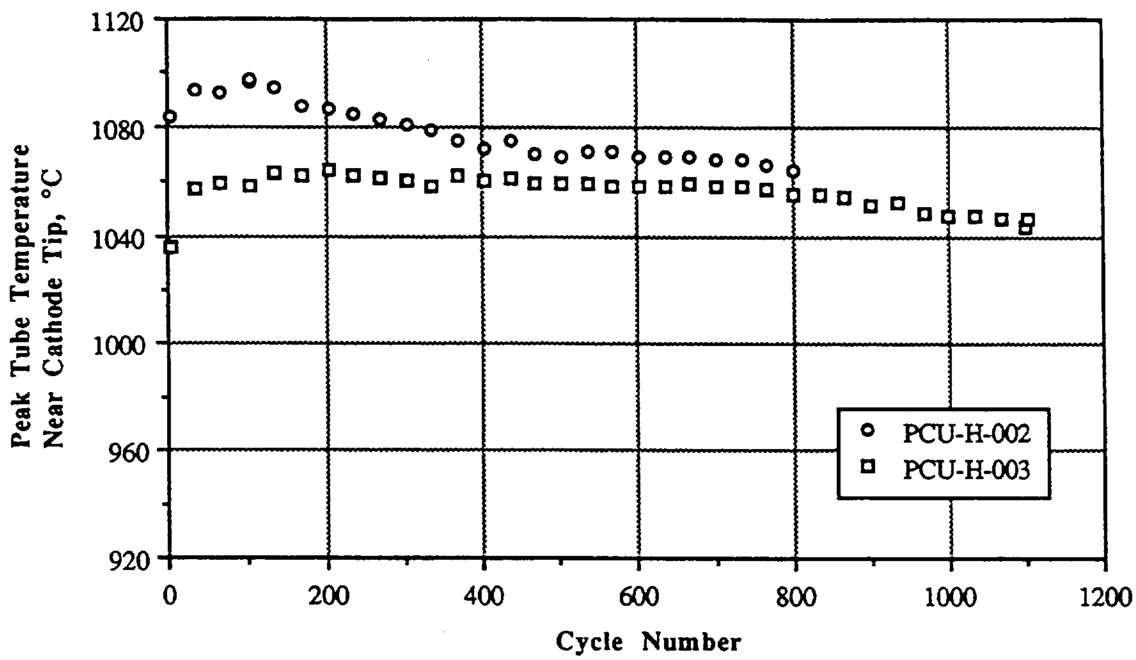

Fig. 12. Peak Tube Temperatures Near the Cathode Tip at Various Cycles for Heater PCU-H-002 and -003.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1993	Final Contractor Report

4. TITLE AND SUBTITLE

Hollow Cathode Heater Development for the Space Station Plasma Contactor

5. FUNDING NUMBERS

WU–474–46–10
C–NAS3–25266

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

E–7846

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR–191131

11. SUPPLEMENTARY NOTES

Prepared for the 23rd International Electric Propulsion Conference cosponsored by AIAA, DGLR, and JSASS, Seattle, Washington, September 13–16, 1993. Project Manager, Michael J. Patterson, Space Propulsion Technology Division, NASA Lewis Research Center, (216) 433–7481.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 20

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS

Heater; Hollow cathode; Plasma contactor

15. NUMBER OF PAGES

14

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	