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Heater Validation for the NEXT-C Hollow Cathodes

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Heater Validation for the NEXT-C Hollow Cathodes

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Abstract

Swaged cathode heaters whose design was successfully demonstrated under a prior flight project are to be provided by the NASA Glenn Research Center for the NEXT-C ion thruster being fabricated by Aerojet Rocketdyne. Extensive requalification activities were performed to validate process controls that had to be reestablished or revised because systemic changes prevented reuse of the past approaches. A development batch of heaters was successfully fabricated based on the new process controls. Acceptance and cyclic life testing of multiple discharge and neutralizer sized heaters extracted from the development batch was initiated in August, 2016, with the last heater completing testing in April, 2017. Cyclic life testing results substantially exceeded the NEXT-C thruster requirement as well as all past experience for GRC-fabricated units. The heaters demonstrated ultimate cyclic life capability of 19050 to 33500 cycles. A qualification batch of heaters is now being fabricated using the finalized process controls. A set of six heaters will be acceptance and cyclic tested to verify conformance to the behavior observed with the development heaters. The heaters for flight use will be provided to the contractor from the remainder of the qualification batch. This paper summarizes the fabrication process control activities and the acceptance and life testing of the development heater units.

Nomenclature

ASTM	American Society of Testing and Materials
DCA	Discharge Cathode Assembly
GRC	Glenn Research Center
IPD	Internal Process Document
ISS	International Space Station
LDT	Long-Duration Test
NCA	Neutralizer Cathode Assembly
NEXT	NASA’s Evolutionary Xenon Thruster
NEXT-C	NASA’s Evolutionary Xenon Thruster—Commercial
NSTAR	NASA’s Solar Electric Propulsion Technology Application Readiness
PCU	Plasma Contactor Unit
PPU	Power Processing Unit

1.0 Introduction

The NASA Glenn Research Center is responsible for the development of NASA’s Evolutionary Xenon Thruster ion propulsion system (Ref. 1). The NEXT system is a next generation ion propulsion system to follow the successful NSTAR ion propulsion system that propelled NASA’s Deep Space 1 spacecraft and is presently propelling the Dawn spacecraft (Refs. 2 and 3). Propulsion system elements developed by the NEXT project include a high performance, 7 kW ion thruster; a high-efficiency 7 kW power processing unit; a highly flexible advanced xenon propellant management system; and a compact, light-weight thruster gimbal. In 2015, the NEXT project transitioned from development to providing spaceflight hardware under the new project name NASA’s Evolutionary Xenon Thruster-Commercial

(NEXT-C). The flight hardware for the NEXT-C project includes two thrusters and two power processor units and is being manufactured by Aerojet Rocketdyne, Inc. for use on NASA missions.

Two hollow cathodes are required for operation of the NEXT-C thrusters. First, the discharge cathode assembly that provides charged particles for the plasma within the discharge chamber that is then extracted for beam formation. Second, a neutralizer cathode assembly provides electrons to neutralize the generated beam. Each of these cathodes required a heater for critical operations. Swaged tantalum coaxial heaters were matured to flight readiness at NASA GRC in the 1990s of the International Space Station Plasma Contactor Units. These heaters were subsequently employed on the NSTAR and NEXT thrusters. Because of the reliability demonstrated with the prior GRC-manufactured heaters, the decision was made to utilize NASA GRC-fabricated heaters for the NEXT-C thrusters. It was necessary to fabricate new heaters because there was no existing stock of the appropriately sized swaged heaters. Another factor that had to be considered was that, prior to the NEXT-C project, the last heater fabrication effort which occurred between 2010 and 2012 resulted in hardware that failed to meet the required cyclic capability due to what was eventually determined to be a materials issue.

Starting in 2015, testing was undertaken to resolve the materials problem and to reverify heater reliability for the discharge and neutralizer cathode configurations. The testing objectives included: develop new acceptance processes to insure materials compliance; update and reestablish materials specification, fabrication processes, and inspection procedures; and cyclically test newly fabricated units to demonstrate reliability. This testing effort was performed through the fabrication of two batches of heaters. The first was a development fabrication run to define the required processes and validate cyclic lifetime capability. Fabrication and testing of a second batch of heaters with the new processes will serve to qualify the readiness of the process controls for flight hardware. A set of heaters from the qualification batch will be provided to the thruster fabricator as Government Furnished Equipment for the NEXT-C project. Additionally, a subset of the qualification batch shall be acceptance and cyclic testing at GRC for performance verification. The fabrication and life testing performance of the development batch of heaters is reported here. Additionally, a summary of the fabrication of the qualification batch that is currently underway and which will provide flight-qualified heaters to be installed in the NEXT-C thrusters will be provided.

2.0 Background

The hollow cathode utilized in the NEXT-C electrostatic ion thruster requires a heater for two operations. First, it is used to condition the electron emitting surfaces inside the cathode by raising the component temperature to remove any water vapor and oxygen-based contaminants that would have accumulated during the time the spacecraft was exposed to atmospheric conditions prior to launch. Second, it provides the heat necessary to prepare the emitter for plasma discharge ignition (Ref. 4).

Since the heater represents a single point failure for the thruster, reliable heater cycling capability is necessary. NASA GRC has an extensive history in the development and validation of hollow cathode heaters because of its use in different electric propulsion technologies. As previously mentioned, swaged coaxial heaters with significant cyclic life capability were developed and have been in use in orbit in the International Space Station Plasma Contactor Unit since 1999 (Ref. 4). While these heaters were subsequently used on flight missions of electrostatic ion thrusters, Heater configurations were evolved to support the larger discharge hollow cathode for NEXT ion thruster, where the cyclic capability was further demonstrated (Ref. 5). The testing history for the GRC-fabricated heaters are summarized as part of this paper.

2.1 Swaged Heater for Hollow Cathode Use

The swaged heater is comprised of a refractory metal sheath swaged over a ceramic insulator with a refractory wire centered in the insulator and sheath. This center conductor is welded to the outer sheath at one end of the heater. The assembled heater cable is formed into helical coils. The heater is then positioned

Figure 1.—Neutralizer heater schematic.

Figure 2.—Discharge heater schematic.

on the cathode tube over the region of the electron-emitting material. A radiation shield comprised of a refractory metal foil is wrapped around the helical coils of the heater several times and spot-welded into place. The bare swaged heater for both the neutralizer and discharge cathode assemblies are illustrated in Figure 1 and Figure 2, respectively.

The heater is operated by applying a DC current for a specified time that will result in the hollow cathode and the emitter contained within to be heated to a target temperature. To initiate hollow cathode and thus ion thruster operation, the heaters can be required to operate up to several thousand times, depending on the mission requirements. In addition, the conditioning and ignition operations are performed several times during the ground testing during thruster fabrication and qualification prior to installation on the spacecraft.

2.2 GRC Heater History

The use of swaged heaters in hollow cathodes had been identified as a better technical approach prior to the ISS PCU program (Ref. 6). Previously, ceramic-coated refractory filament heaters were typically installed on the cathodes. However, these heaters were found to be prone to cracking under extended cyclic operation. Mueller also identified many of the critical factors that needed to be controlled to produce high reliability heaters. However, despite being in common use by the end of the 1980s, the formalization of the processes and methods used for fabrication, assembly, and test were not undertaken until the ISS PCU project (Ref. 4). The use of ISU PCU heater design has continued through the evolution of NASA’s electrostatic thruster development. The chronology of the use of GRC swaged heaters is summarized in Table 6 in the Appendix which shows fabrication cycles, hardware use, and test experience.

3.0 Fabrication Processes and Methods

Simple replication of the heater fabrication processes with the originally defined materials to preserve the flight heritage established in the ISS PCU project was not possible because of systemic changes. Table 7 in the Appendix lists these changes and solutions that were developed to resolve each of them. Several activities had to be undertaken to recover the original heater capability. In order to undertake the development fabrication phase of this project, the following tasks were performed.

1. *Development and validation of fabrication procedures*—Capabilities that were part of the original fabrication processes, primarily those related to in-house diagnostic techniques, have been lost since the early 90s due to institutional changes and personnel loss. Specific examples include annealing furnace availability and specialized refractory material welding capability. Consequently, external vendors were located and validated for furnace operations; a new welding method was developed and extensively tested; and in-house technical personnel undertook extensive training to perform critical steps.
2. *Requalification of materials*—A significant effort was performed to reestablish material specifications because it had been found to address deficiencies identified during a previous manufacturing run. In particular, it was found that procuring materials based on the same ASTM standard used in the ISS PCU project resulted in the delivery of material that did not matched prior operating behavior. Heater testing with the material as delivered resulted in reduced heater reliability with respect to the metric established in the ISS PCU project. After an extensive investigation, it was determined that oxygen content of the delivered material significantly exceeded the ASTM standard. However, the standard had not been violated because compliance

was maintained with the bulk material prior to forming the final delivered product. Chemical analysis of the delivered form revealed the excessive oxygen content with respect to the ASTM standard and past batches of the material. In order to ensure compliance of the delivered material with past experience, chemical analysis of that material is performed when delivered to insure acceptability. The additional work that this detailed material characterization represents has been implemented only to address identified problems.

3. *Formalization of process documents*—The revised fabrication process documentation has been formalized with the participation of the NEXT-C team, quality assurance personnel, and a configuration manager. The current set of processes, listed in Table 1, are necessary for the NEXT-C flight thruster and are the first qualified replacement of the documentation since the ISS PCU project.

While the activities listed above were performed for this fabrication cycle, similar issues have arisen in previous manufacturing cycles. A summary of the lessons learned are provided in Table 2 as precautions for future heater fabrication.

The motivation for the initial development fabrication run and cyclic testing cycle was to prove out the revised fabrication processes, external vendors, and new in-house personnel qualifications. During this development work the process documentation was revised, tested, and formally qualified. With the successful completion of those activities, fabrication of a qualification batch of heaters was initiated. A subset of this batch will be cyclically tested to validate the fabrication processes. The heaters designated for flight will then be delivered to the thruster fabricator for integration into the hollow cathode assemblies.

TABLE 1.—NEXT-C HEATER PROCESS DOCUMENTATION

Internal process documents	Title
GRC-NEXTC-IPD-051	Swaged Heater Fabrication
GRC-NEXTC-DOC-047	Heater Materials Specification, Acceptance, and Verification Record
GRC-NEXTC-IPD-048	Cleaning of Metal Parts
GRC-NEXTC-IPD-049	Swaged Heater Compaction Test
GRC-NEXTC-IPD-050	Swaged Heater Thermal Imaging Test
GRC-NEXTC-IPD-052	Swaged Heater Termination Weld
GRC-NEXTC-IPD-053	Assembly of Swaged Heater Unit for Heater Testing
GRC-NEXTC-IPD-054	Swaged Heater Cyclic Testing for Life Assessment
GRC-NEXTC-IPD-055	Swaged Heater Confidence Testing
Drawings	Title
161101MRA101	Neutralizer Cathode Assembly Swaged Heater
161101MRA102	Discharge Cathode Assembly Swaged Heater
161101MRA200	Termination Weld Assembly
161101MRA202	Orbital Welding and Facing Collet

TABLE 2.—HEATER PROCESSES LESSONS LEARNED

Lesson learned	Risks
Fabrication processes have to be maintained, exercised	Personnel, organizational changes; technical advances
Revision of some processes are inevitable	Stockpiling materials, securing tooling/equipment, certifying specific personnel are proactive steps, but no guarantee of future capability. Material formation/development, new techniques, limits of standards documentation.
Heater fabrication cycles for EP programs not efficient/ effective at ensure capability through regular use	Fabrication should be performed with increased frequency to maintain personnel, tooling, and knowledge. Commercialization of processes have been attempted in past, but currently no qualified vendor that can meet NASA requirements. Low unit requirement inhibits profit potential for vendor.
Knowledge of the component materials going into the heaters are critical to meeting performance requirements	Reliance on vendor adherence to standards has not been guarantee against unacceptable performance. Testing of materials, particularly center conductor, is critical to materials determination.

4.0 Testing Approach

4.1 Heater Test Configuration

In order to expediently demonstrate heater cycling lifetime, an accelerated operating profile was developed during the ISS PCU project that has been employed for multiple heater validation activities (Ref. 6). While there have been changes to the hollow cathodes since that time, the temperature critical elements of the hollow cathode have remained the same along with the hollow cathode ignition procedure. These factors continue to drive the required heater operating time for each cathode ignition and serve as the basis for heater component testing. Consequently, the cyclic ON/OFF profile consisted of a 6-min powered stage and a 4-min unpowered stage. The ON time duration is based on the discharge ignition procedure and represents the nominal powered period for typical cathode start-up. The OFF time is the accelerated part of the cycle and captures a majority of the cool-down of the cathode and subsequently the majority of the temperature change that the cathode and heater will experience. While there have been other experiments that have investigated heater behavior over larger temperature ranges that better reflect on-orbit behavior, the accelerated cycle used here has not resulted in an erroneous assessment of heater performance on-orbit or other behavior that has necessitated an improved testing profile.

When the heater is ON, it is powered at a constant current of 8.5 ADC. Heater electrical performance is monitored during the powered stage. Type R thermocouples are attached to refractory metal tubes that serve as cathode tube analogs during this testing. The temperatures and test facility pressure are also logged during testing by the data acquisition system at a rate of 0.1 Hz. The computer-controlled data acquisition system also monitors operating limits on voltages, currents, temperatures, and facility pressure and will shut-down powered operation in the event of any limit violation.

The heater test configuration in the test facility is shown in Figure 3 where the set of development heaters, three discharge and three neutralizer units, are shown.

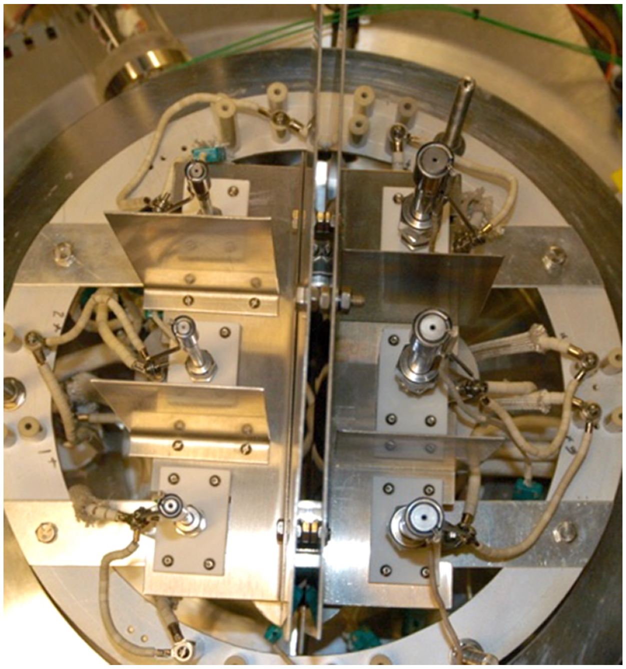

Figure 3.—Tested heater configuration in test stand.

Prior to life testing, the heaters were confidence tested to determine viability of each heater unit for life testing. The steps of the confidence testing process are summarized in Table 3.

The acceptance criterion used in this phase is the change in hot resistance at the end of the ON phase that occurs in each heater during the 150 cycles performed during the Burn-in step. The hot resistance as a function of cycle number is shown in Figure 4. The six heaters were all found to be within the acceptance range based on historical performance. While the changes in heater operating voltage during the first cycles were not unexpected, the heater performance in the discharge cathode heaters was found to typically exhibit behavior as shown in Figure 5 where the heater voltage peaks earlier in the powered ON phase and not at the end as it typical of the neutralizer heaters. This behavior was observed to diminish over the course of the cycle life test at differing rates for each of the discharge heaters. The exact cause of the higher voltages at early operation is currently not determined. The behavior has been observed in past discharge heater operation. However, it does not appear to occur with the neutralizer heaters. At this time, the behavior is suspected to be related to the electrical configuration, including the geometrical characteristics, of the larger discharge heaters.

Cyclic testing of the six heaters began in early August 2016. Testing continued until April 2017. The heater performance was monitored by tracking the heater power and hot resistance based on the heater voltage and current measured at the end of each powered cycle. The heater powers at end of the ON phase for all six heaters cyclically tested is shown in Figure 6. The corresponding heater hot resistance is shown in Figure 7.

TABLE 3.—HEATER CONFIDENCE TESTING STEPS

Step	Test procedure
Heater bake-out	Operate steady-state at 26 percent, 46 percent of full current for 24 hr
Burn-in	Perform 150 cycles at full current with nominal test profile
Heater current profile	Heater behavior under current ramping by (1) continuous current ramp to full current over 8.5 hr period, or (2) Step current up at 26, 46, 85, and 100 percent with 2 hr holds

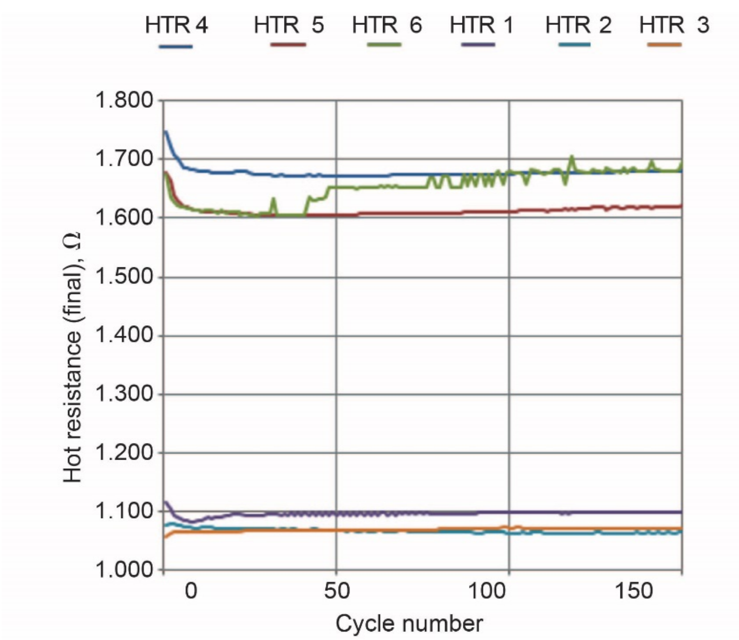

Figure 4.—Heater hot resistance behavior during confidence testing.

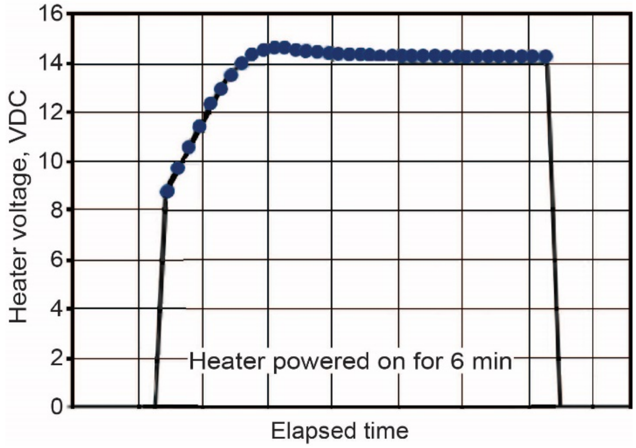

Figure 5.—Heater voltage behavior at early cycling.

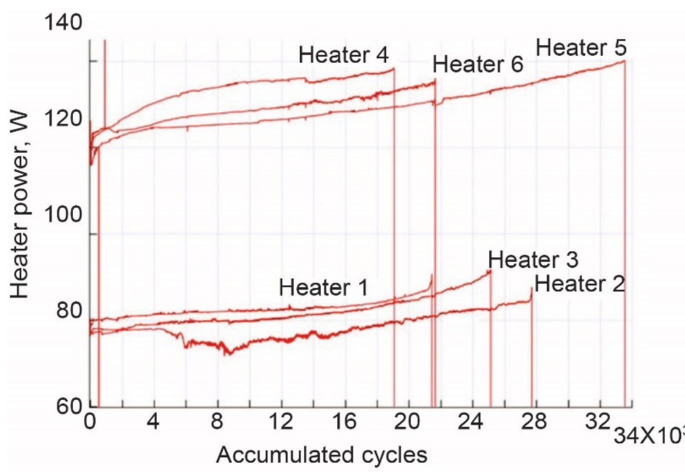

Figure 6.—Heater power vs. Cycle number.

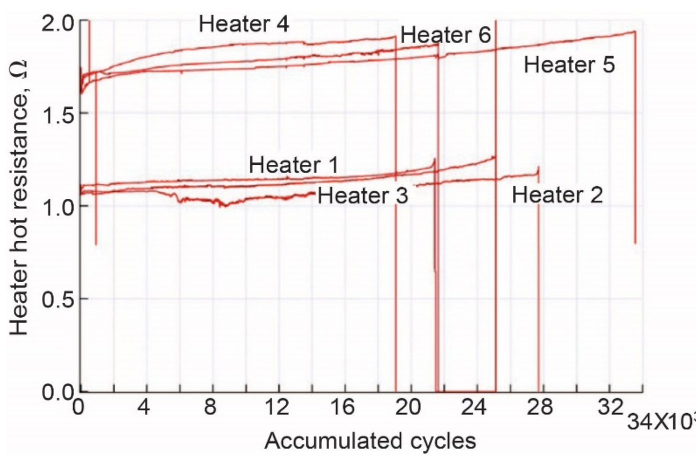

Figure 7.—Hot resistance vs. Cycle number.

TABLE 4.—HEATER FAILURE SUMMARY

Heater/position	Heater size, in.	Accumulated cycles	Failure mode
1	1/4	21,479	Shorted
2	1/4	25,117	Open
3	1/4	27,700	Shorted
4	1/2	19,059	Open
5	1/2	33,551	Shorted
6	1/2	21,626	Open

The development heaters demonstrated the largest ultimate cycle life achieved with a GRC-fabricated heater operated under the accelerated cycle operating conditions. The results exceeded the NEXT-C target of 3650 cycles (Ref. 7) by factors between 5.2 and 9.2. While these results indicate that the heater cyclic capability is fully recovered to the level of the ISS PCU flight hardware, we do not have a clear explanation for the larger ultimate life of these heaters with respect to past units.

The total number of accumulated cycles and failure behavior is summarized in Table 4. Failures occurred either with the heater going open-circuit suggesting a physical break in the heater element, or the heater "shorted" at some point along the electrical path which resulted in the heater voltage decreasing by approximately a factor of 2. The failure behaviors were expected based on past heater testing; micro-analyses of the failed test articles are underway to identify the location of and conditions at the failure site to verify similarity to prior heaters.

The cyclic testing of heaters selected from the qualification batch will be performed using the same procedures as reported here. The testing will validate the compliance of the newly fabricated heaters with the development heater performance and will demonstrate sufficient cyclic performance to meet the NEXT-C thruster requirements. The remainder of the heaters will be designated as flight-qualified with a designated number of discharge and neutralizer heaters delivered to Aerojet Rocketdyne for integration into cathode assemblies.

5.0 Life Time Assessment

Cyclic testing of GRC-fabricated swaged cathode heaters to validate life capability has always been restricted by resource constraints to a small set of units that are operated to failure. Multiple heaters are tested in cathode-like configurations typically in a small vacuum facility to understand unit-to-unit variations and maximize the collection of cyclic life performance data. The heater cyclic life capability is based on the test performance presented here. That data is also used to assess heater reliability using Weibull Analysis. This analytical approach, which was first used for GRC-fabricated heaters during the ISS PCU project, is used in other technical fields to determine unit-to-unit reliability with small data sets.

A Weibull analysis of the failed heaters was performed using a rank regression to determine the critical values for the two-parameter Weibull distribution, as defined in Equation (1).

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{1}$$

where $F(t)$ is the fraction of the population failing; t is cycles to failure; β is the shape factor that describes the type of failures experience; and η is the scale factor that provides the characteristic life estimate for a majority of the population. The Weibull distribution is used to calculate the survival probability, with 90 percent confidence interval, for this batch of heaters. The resulting factors for the Weibull distribution for the NEXT-C heaters are compiled in Table 5 for the total set of tested heaters as well as break-down for the two heater configurations. Hence, the B10 value for reliability, also included in Table 5, which has been used for life predictions of GRC swaged heaters, represents the expected life for 90 percent of the batch. Heater reliability, represented by the B10 value, has been used in past systems assessments to analyze the risk of heater failure on the larger propulsion system.

TABLE 5.—WEIBULL RESULTS FOR CURRENT AND HISTORICAL CYCLE TESTS

Heater sets	Beta shape factor	Nu scale factor	B10 estimate
All NEXT-C heaters	4.9	26,932	10,731
1/4 in.	7.52	26,181	12,237
1/2 in.	3.01	27,958	4,175
ISS PCU heaters	9.21	12,444	6,687
2008 NEXT 1/2 in. heaters	51.19	14,105	12,615
2012 NEXT 1/2 in. heaters	2.49	13,995	1,784

The Weibull analysis employed assumes there is a single failure mechanism responsible for the end of life. For the swaged heaters, this failure mechanism is believed to be the breaking of the center conductor that results in the heater losing electrical conductivity, or through an undetermined transport mechanism, where the fractured center conductor makes electrical contact with the sheath material, resulting in the step reduction in heater voltage. Since the heaters experience the same changes in operation at failure for both heater sizes, the analysis results for all six heaters are considered to be valid. Future work may determine factors that require the different heater sizes to be considered as distinct sets with their own reliability behavior. The cause of center conductor failure has been attributed to grain growth due to high temperature operation that will lead to “necking” at the grain boundaries and subsequent hot spot formations at this location (Ref. 8) but definitive determination of the failure mechanism has yet to be made.

The swaged heater cyclic performance was a substantial improvement over past GRC-fabricated heaters, with the shortest-lived device in the development batch out-performing the longest lived of all previous heaters. The whole-batch B10 of 10,731 exceeded the B10 metric of 6,700 cycles established in the ISS PCU project. The large variation in lifetime did yield a B10 for the discharge heaters of 4,100 cycles. The cause of the variation is not known at this time.

6.0 Summary

The cyclic life performance of the swaged heaters designed for the NEXT-C hollow cathodes was determined to range between 19,000 to 33,500 cycles in accelerated testing, significantly exceeding the cycle capability of all past GRC-fabricated heaters. Following an extensive effort to revise and reestablished prior capabilities required for fabrication of this heater design, development heaters were fabricated and tested to their ultimate life. The performance exceeded the NEXT-C thruster cycle life specification by factors of 5.2 to 9.2, and yielded a B10 estimate of heater reliability of 10,700 cycles. Fabrication of a qualification batch of heaters has begun and, after verifying compliance on a subset of this batch, the flight units for the NEXT-C thruster fabrication will be delivered to Aerojet Rocketdyne.

Appendix—GRC Swaged Heater History

TABLE 6.—GRC HEATER FABRICATION HISTORY

Date	Program	Fabrication status	Testing configuration	Heater size (Cathode size), in.	Testing results	Notes
1991 to 1994	ISS PCU	Development	Free heater on tube, with termination	1/4	17000?	Process and configuration development; formal docs
1993 to 1995	ISS PCU	Flight hardware	Free heater on tube, with termination	1/4	10500 to 12900	---------------------
1995 to 1997	NSTAR-DS-1/ DAWN	Development and Flight hardware	Heaters in Cathode assemblies with termination	1/4	In space operation of >200/>400 cycles	---------------------
2002	NEXT	Development	Heaters in Cathode assembly with termination	1/2	13800 to 14200 cyclic	First fabrication of 1/2 in. heaters for DCAs; cyclic testing on cathode assem-blies only
2003 to 2005	NSTAR/ NEXT	Development	Heaters in Cathode assembly with termination	1/4 and 1/2	10,000 cycles without failure	Heater testing suspended-performed only on DCAs; 1/4 in. heaters of this batch not tested
2010 to 2012	NEXT	Development	Free heaters on tube	1/4 and 1/2	6200 to 17000	Flight hardware fabrication required for NEXT thruster exposed material issue resulting in reduced heater life capability
2015 to 2016	NEXT-C	Development	Free heaters on tube	1/4 and 1/2	19000 to 33500	New heater fabrication task to resolve problems of previous cycle; revalidate heater cyclic capability; update process documentation for flight hardware fabrication
2017	NEXT-C	Flight hardware	Free heaters on tube	1/4 and 1/2	TBP	Fabricate heaters required for NEXT-C thruster builds

TABLE 7.—FABRICATION CAPABILITY EVOLUTION

Process issue	Change	Adaptation
Fabrication frequency	Past success of heater fabrication not transportable for new fabrication cycle; Fabrication cycles too infrequent to maintain capability	Revalidated all processes to ensure successful heater capability
Reliance on specific personnel	Personnel no longer available (retirement, changed position)	Qualification of new personnel; Develop and validate new processes; Including qualification methods
Reliance on specific capability	Services, equipment no longer available	Validate external providers; Revise processes to allow; Recreate and validate unique capability
Material certification	Loss or changes to traditional vendors; Past approaches for material certification insufficient to maintain heater performance capability; Material sourcing restrictions	Validate material specifications with quantitative analysis of delivered materials; Investigated variety of physical characteristics to improve material acceptance
Reliance on fabrication process documentation	Documentation needed to reflect changes in heater configuration; Past processes no longer relevant, some processes poorly defined for new technical personnel; Institutional changes required updating to document content	Revised documentation to captured heater configuration changes; Updated process to reflect new methods, equipment, capabilities; Fully qualified documentation for flight hardware production

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