

Qualification of the Flight Heaters for the NEXT-C Hollow Cathodes

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After successful validation of the design, swaged cathode heaters have been delivered by the NASA Glenn Research Center to Aerojet Rocketdyne for the fabrication of the NEXT-C ion thruster . NASA Glenn Research Center re-established and validated process controls as well as completed cyclic life testing of development heaters. Following an extensive requalification program, fabrication of a flight batch of heaters was executed using the qualified process controls. Of the 28 heaters fabricated in this flight batch, a set of six heaters were acceptance and cyclic tested to verify conformance with operational requirements. Upon completion of 200% of the NEXT-C cyclic requirement, the heater batch was certified by NASA for use in the flight hollow cathodes. Nine heaters from the batch of 28 were provided to Aerojet Rocketdyne in early 2018 for cathode fabrication. This paper summarizes the acceptance and cyclic life testing of the flight heaters and preliminary findings of post-test analyses.

I. Introduction

NASA's state of the art ion thrusters require two hollow cathodes for operation. The discharge cathode, which provides high energy electrons for xenon ionization within the discharge chamber, and the neutralizer cathode, which provides electrons to the beam to prevent spacecraft charging and allow sustained beam extraction. Each cathode requires an associated coaxial heater in order to increase the cathode temperature to generate sufficient thermionic emission for ignition. NASA GRC has an extensive history, beginning in the 1970s, in the development and validation of hollow cathode heaters because of their use in a variety of electric propulsion technologies. Coaxial heaters with significant cyclic life capability were developed and have been in use on orbit for the International Space Station Plasma Contactor (ISS PCU) unit since 1999 [1]. These heaters were subsequently deployed on the NSTAR thrusters used on NASA's Deep Space 1 and Dawn missions [2?].

Following the successful deployment of NSTAR, NASA GRC began development of NASA's Evolutionary Xenon Thruster (NEXT) in 2001 and fabricated several engineering and laboratory models by 2002 [3]. After 15 years of in-house research and development, the technology has been transferred to commercial partner Aerojet Rocketdyne (AR) under the NASA Evolutionary Xenon Thruster – Commercial (NEXT-C) contract [4, 5]. The NEXT-C contract will produce two NEXT-C ion thrusters, two power processing units (PPU), and spare cathode assemblies. The first flight thruster and PPU will be completed in 2019 and delivered to the DART mission for launch in late 2020 or early 2021 [6]. The NEXT-C contract targeted a cathode heater lifetime requirement of 3,650 cycles, which was based on a hypothetical orbiter mission which would require one ignition per day for 10 years [7]. Cathode heaters represent a single point of failure for the NEXT-C thruster and therefore reliable cyclic capability is necessary.

II. Background

At the start of the NEXT-C contract, the cathode heaters were identified as a potential manufacturing risk for several reasons: 1) they are a single point of failure, 2) heaters built to NEXT specifications had not been produced in 10+ years, and 3) previous attempts to transfer the manufacturing process from NASA GRC to other partners produced unsatisfactory results. For these reasons, the decision was made to have NASA GRC produce the flight heaters. The

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history of GRC fabricated swaged heaters is shown in the appendix. In 2015, a development batch was produced by GRC to re-verify all materials properties, manufacturing procedures and controls, heater reliability, and cathode configurations. The results of the development heater testing is described in a paper by Verhey [8]. Following the development heater testing, a batch of heaters to be used on the flight thrusters was fabricated by GRC and provided to AR as government furnished equipment. A subset of six heaters from this batch was selected for life testing to qualify the batch. This paper describes the results of the qualification testing of the six flight qualified heaters.

The cathode heaters serve two functions for the NEXT-C thruster. The first is to condition the cathodes, removing contaminants that may be present on the cathode emitter from exposure to atmospheric conditions prior to spacecraft launch. The conditioning process involves slowly heating up the cathode tube and internal electron emitter in order to bake off any water vapor or oxygen containing compounds that have accumulated within the cathode. The second heater function is to sufficiently heat the cathode's electron emitter such that electron emission is adequate to ignite the plasma discharge. Once the discharge is ignited, the plasma is hot enough to maintain electron emission and the cathode becomes self-heating.

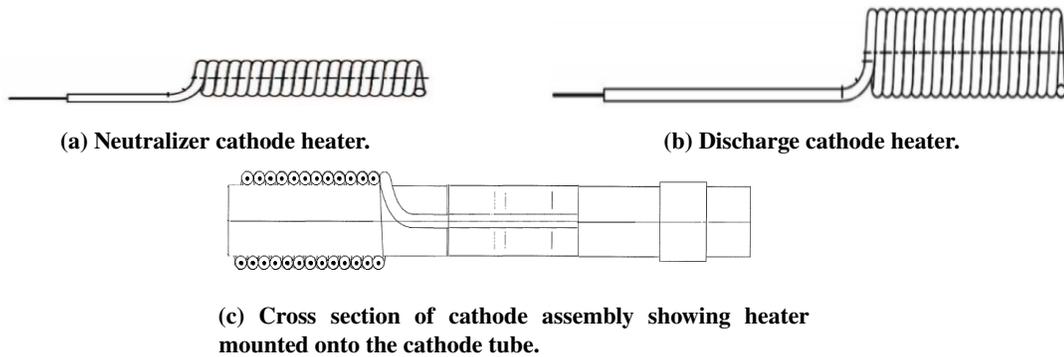


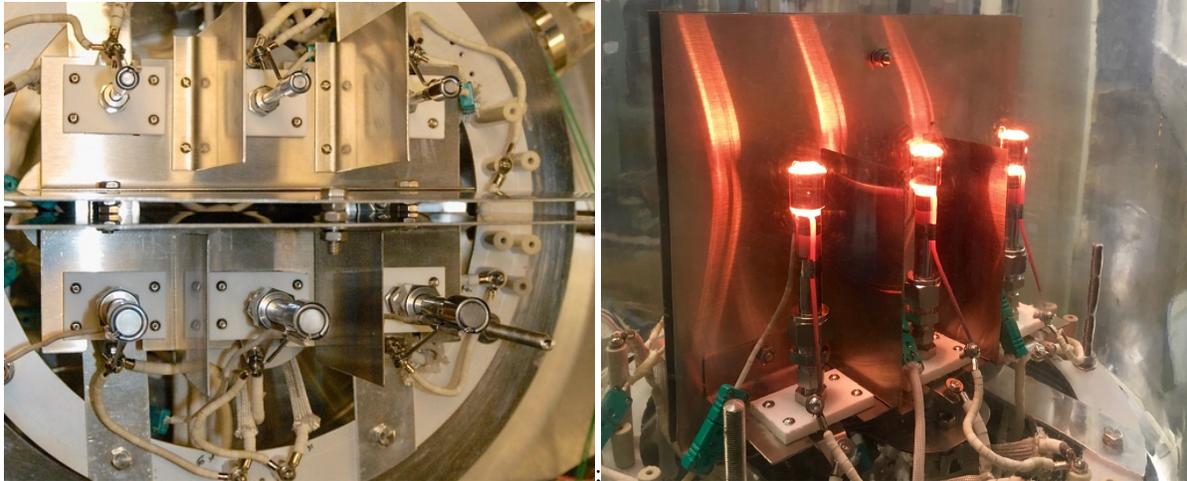
Fig. 1 Schematics of the neutralizer and discharge heaters and cathode assembly. Not to scale.

A. Heater Design

NASA GRC hollow cathodes utilize a swaged heater design. A refractory metal sheath is swaged around a ceramic insulator that contains a refractory metal wire at the center. This center conducting wire is welded to the outer metal sheath at one end of the heater. Then the heater is coiled such that it can be positioned onto the cathode tube. Schematics of a heater at both the component level and mounted onto a cathode tube are shown in Fig. 1. The discharge cathode is larger (0.5" diameter), and emits the full discharge current, which can be on the order of 20 A. The neutralizer cathode is smaller (0.25" diameter), and usually supports less than 10 A. Heaters are operated with a DC power supply to ohmically heat the cathodes. Current passes through the center heater wire into the outer metal sheath at the welded termination, and then returns through the cathode tube. Depending on the mission throttling profile, the cathode heaters may be operated only a handful of times or possibly up to many thousands of times. For this reason, GRC cyclically tests a subset of a manufacturing batch to verify lifetime capability.

III. Test Setup

To reduce the time required to perform cyclic lifetime testing, a test setup was utilized that enabled simultaneous operation of six heaters and an operating profile that was developed during the ISS PCU project and previously used for multiple heater validation tests [9]. While cathode design has slightly changed over the years, the ignition procedure has not changed, and the ignition procedure serves as the basis for the lifetime requirement of the heaters. Each on/off cycle consists of a 6 min on time and 4 min off time. The on/off cycle is illustrated in Fig. 3. The current is either on at 8.5 ADC or off at 0 ADC, and the temperature increases to around 1200 °C by the end of the on cycle and cools off to about 500 °C by the end of the off cycle. The temperature is measured using a type R thermocouple attached to the cathode tube at the orifice plate (or equivalent) weld. The 6 min on time represents a cathode ignition. The 4 min off time is abbreviated to capture the majority of the temperature decrease that the cathode will experience. Other experiments have investigated heater operation over larger temperature ranges, but the temperature range here has successfully reflected the on-orbit performance of heaters in prior flight programs (ISS PCU and NSTAR) [10]. A data



(a) Top down view showing all six heaters within the vacuum chamber.

(b) Three heaters during the on cycle.

Fig. 2 Photographs of test setup and heaters operating.

acquisition system measures the current, voltage, and temperature of each heater as well as the facility pressure and logs data at 0.1 Hz. The DAQ also monitors for limits on each parameter and will shut off power to the heaters if a limit is encountered. Heaters 1-3 are 0.25" for the neutralizer cathode and heaters 4-6 are 0.5" for the discharge cathode.

IV. Test Results

The testing is broken into two sections: confidence testing and life testing. Confidence testing includes a bakeout processes, current ramping, and the first 150 on/off cycles. This confidence testing confirms the viability of each heater for life testing. Following confidence testing the heaters are life tested, where each heater is turned on and off until failure.

A. Confidence Testing

Table 1 lays out the confidence testing procedure. After installation in the vacuum chamber, the heaters are baked out for two days prior to cyclic testing in order to remove any water or oxygen based contaminants. Following conditioning,

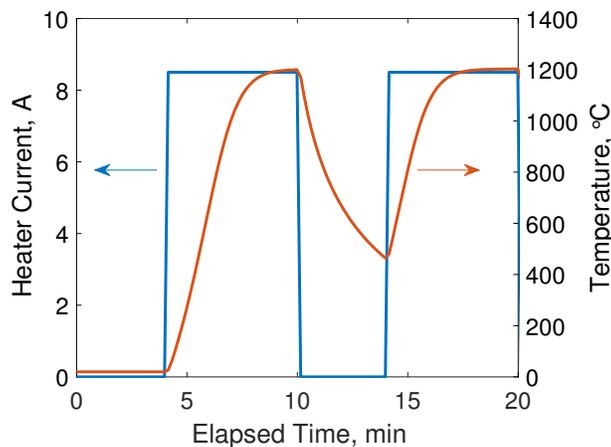


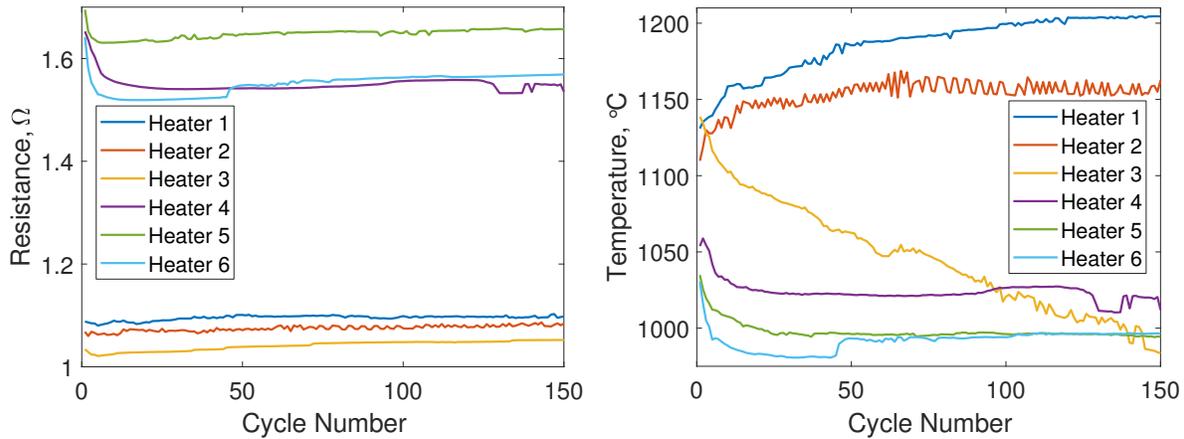
Fig. 3 Example on/off cycles, showing the heater current and temperature over the course of a cycle.

Table 1 Confidence testing procedure.

Test	Description	Duration
Low current bakeout	Operate steady-state at 26% of full current	24 h
High current bakeout	Operate steady-state at 46% of full current	24 h
Burn-in	150 on/off cycles	25 h
Continuous Current Profile	One heater of each size is slowly ramped from 0 to 8.5 A	8.5 h
Step Current Profile	Remaining two heaters of each size are stepped from 0 to 26%, 46%, 85%, and 100% of full current with 2 h holds at each current	8 h

every heater is cycled 150 times. The resistance and temperature at the end of each cycle is shown in figure 4. The acceptance criterion of the confidence testing is the change in hot resistance of the heaters over the course of 150 cycles. As can be seen in figure 4a, the larger heaters have a higher hot resistance as expected, and the hot resistance is relatively constant across the first 150 cycles for all heaters. The discharge heaters show a drop in resistance within the first ~10 cycles of the burn-in. All heaters passed the change in resistance requirement for proceeding with life testing.

Figure 4b shows the temperature changes over the course of confidence testing. The neutralizer heaters run slightly hotter because all heaters use the same current and the discharge cathodes have more thermal mass. The temperature behavior of heater 3 is due to the fact that the thermocouples are spot welded to the cathode tube, and repeated thermal cycling causes the weld to break and the thermocouple separates from the tube. Throughout testing all the thermocouples eventually detached.



(a) Resistance of heaters during confidence testing.

(b) Temperature of heaters during confidence testing.

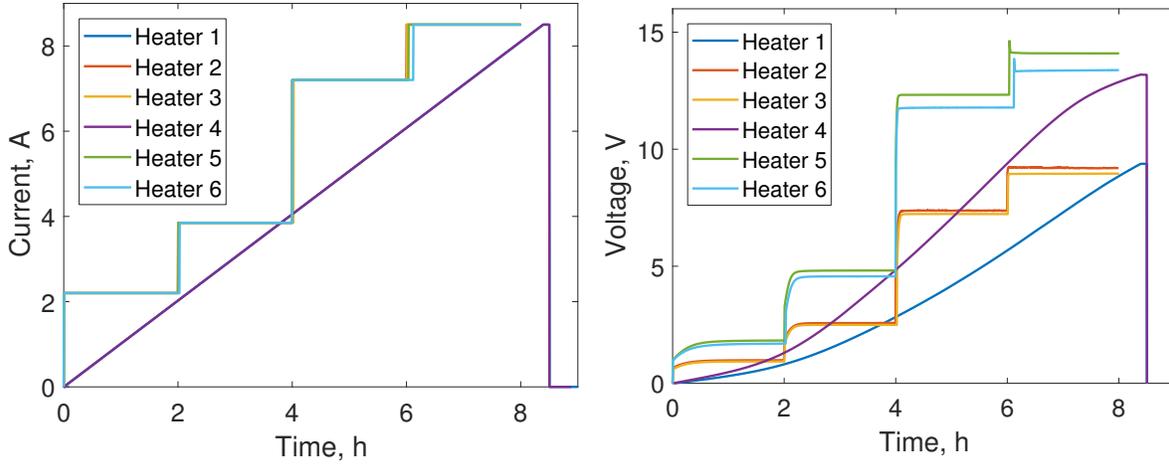
Fig. 4 Confidence testing cycling results.

Following cyclic testing, confidence testing concludes by continuously current ramping two heaters (one of each size) and current stepping the remaining heaters. Figure 5 shows the current and voltages during this process. All current steps were held for 2 h and the current ramp rate was 1 A/h.

B. Life Testing

The life testing of all heaters continued until every heater failed. Two heaters failed by shorting and the other four failed open circuit. The cyclic testing was completed in three segments, where the two breaks were due to facility maintenance and the US government shutdown. Pressure remained ≤ 5 Torr during vacuum breaks.

Figure 6 shows the hot resistance values as a function of cycle number over the course of the test. As expected, the resistance generally increases as the number of cycles increases. Heaters 3 and 6 show steep drops in resistance due to a



(a) Current of heaters during steps and ramps.

(b) Voltage of heaters during steps and ramps.

Fig. 5 Confidence testing current stepping and ramping.

short developing, most likely within the coils of the heater. After shorting, the heaters go open circuit within a few cycles.

Table 2 shows number of cycles each heater achieved, and compares the total cycles to the development heater batch. The first heater failed at 10,578 cycles and the final heater failed at 29,003 cycles. While the number of cycles demonstrated with the flight heaters was less than the number demonstrated with the development heaters, every flight heater exceeded the NEXT-C requirement of 3,650 cycles. The first development heater failure occurred at 19,059 cycles, by which point four of the flight heaters had already failed.

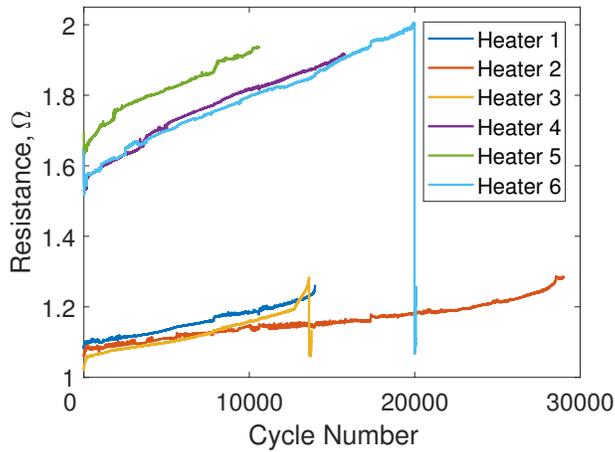


Fig. 6 Heater hot resistance at the end of each cycle throughout the life test.

V. Life Assessment

Cyclic testing of GRC-fabricated swaged cathode heaters to validate lifetime capability has always been restricted by resource constraints to a small set of units that are operated to failure. The small vacuum facility has capacity for six heaters, and each life test takes approximately a year to complete. Only a small number of heaters are fabricated in each batch, and an even smaller number is tested to failure, therefore our lifetime assessment is inherently limited by a small data set. We determine cyclic life capability 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

Table 2 Life testing results.

Heater Position	Heater Size	Development Heaters		Flight Heaters	
		Total Cycles	Failure Mode	Total Cycles	Failure Mode
1	0.25"	21,479	Shorted	13,976	Open
2	0.25"	25,117	Open	29,003	Open
3	0.25"	27,700	Shorted	13,613	Shorted
4	0.5"	19,059	Open	15,758	Open
5	0.5"	33,551	Shorted	10,578	Open
6	0.5"	21,626	Open	19,988	Shorted

with small data sets.

Weibull analysis of the failed heaters was performed using a rank regression to determine the critical values for the two-parameter Weibull distribution:

$$F(t) = 1 - e^{-(t/\eta)^\beta} \quad (1)$$

where $F(t)$ is the fraction of the population failing, t is the cycles to failure, β is the shape factor that describes the type of failures experienced, 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 for each batch of heaters, with a 90% confidence interval. The B10 lifetime represents the expected cyclic life capability of 90% of the production batch. Heater reliability, represented by B10 lifetime, has been used in past systems assessments to analyze the risk of heater failure within the larger ion propulsion system. Figure 7a shows the inputs to the Weibull analysis as well as the Weibull fits for both the development and flight batches. Figure 7b shows the estimated survival rate according to the Weibull analysis.

Table 3 shows the B10 lifetime estimates for the flight heaters, as well as B10 lifetime estimates for past GRC fabricated swaged heaters. The B10 lifetime estimate for the flight heater is 3,940 cycles, which, while much lower than the first observed failure at 10,578 cycles, is greater than the NEXT-C requirement of 3,650 cycles. Dividing the set of six tested heaters, into two groups of three—the larger 0.5" heaters and 0.25" heaters—diminishes the B10 lifetime estimate to 2,584 and 1,089 cycles respectively. Unsurprisingly, halving the already small sample size in the Weibull analysis can produce higher variability B10 lifetime estimates. The B10 lifetime from the Weibull analysis is highly

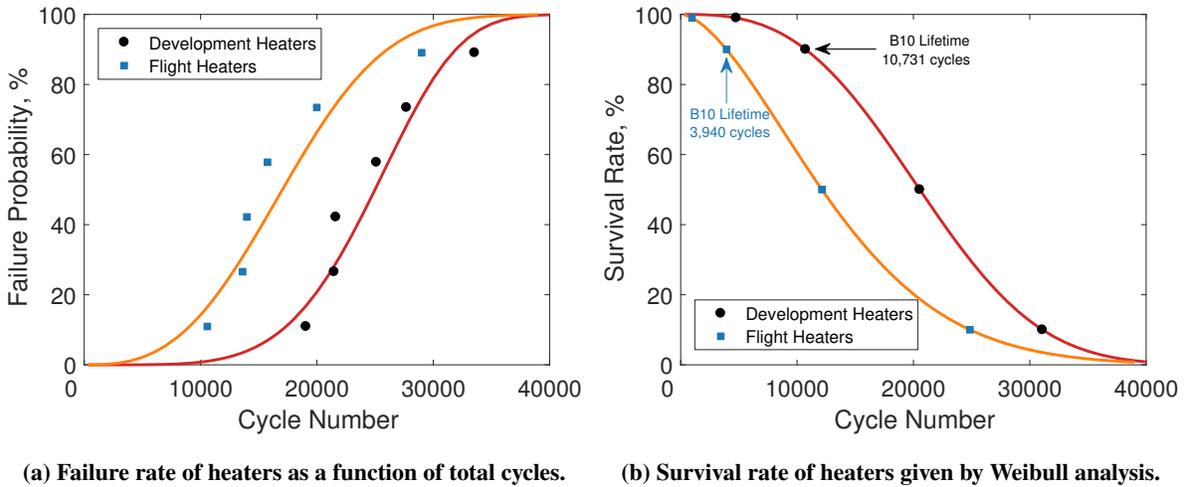


Fig. 7 Weibull analysis of both development and flight heater batches, showing the B10 lifetimes of each.

sensitive to the range between heater failures. The ISS PCU pathfinder and flight heaters lasted between 6,102 and 17,807 cycles and 10,568 and 12,977 cycles respectively. The NEXT 2002 heaters lasted between 13,789 cycles and

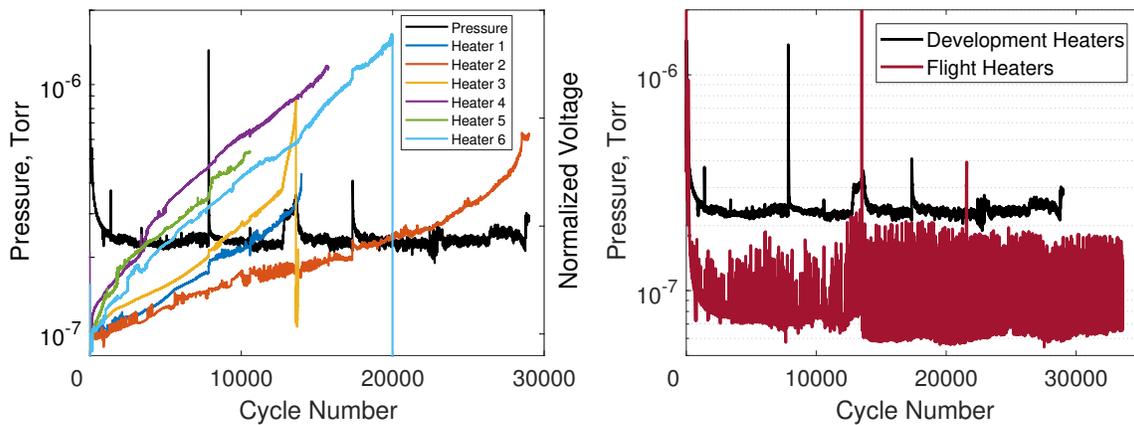
Table 3 B10 lifetime estimate for the flight heaters compared to past GRC fabricated swaged heaters.

Heater Set	B10 Estimate
2019 NEXT-C Flight Heaters	3,940
0.25" Only	1,089
0.5" Only	2,584
2017 NEXT-C Development Heaters	10,731
0.25" Only	12,237
0.5" Only	4,175
2012 NEXT 0.5" Heaters	1,784
2002 NEXT 0.5" Heaters	12,615
1995 ISS PCU Flight 0.25" Heaters	6,687
1991 ISS PCU Pathfinder 0.25" Heaters	2,519

14,257 cycles. The NEXT 2012 heaters lasted between 7,205 and 17,807 cycles. From Table 2, the development heaters lasted between 19,059 and 33,551 cycles and the flight heaters lasted between 10,578 and 29,003 cycles. So while on average, the actual tested cyclic life of the flight heaters was greater than the ISS PCU or 2008 NEXT heaters, the flight heaters have a lower B10 lifetime estimate because the spread of failures for ISS PCU and NEXT 2008 heaters was within 2,500 and 500 cycles respectively.

Both the development and flight heaters had extremely large spreads, 14,500 and 18,500 cycles respectively. However, the development heaters had a slightly smaller spread and had more cycles for the first and last failure, leading a B10 estimate that is $\sim 2.7\times$ greater for the development heaters. The cause of the high variability in the flight batch is not known at this time.

Originally, it was thought that the flight and development heaters would exhibit very similar lifetimes, given that they were fabricated in short succession with the same processes and materials. Figure 8a shows the pressure during flight



(a) Pressure during life testing plotted with normalized heater voltage. (b) Pressure during development and flight testing.

Fig. 8 Recorded pressure during flight testing shows that an increase in pressure can lead to an increase in heater operating voltage.

heater testing alongside heater voltage, which has been normalized to the beginning of the test for visual clarity. The figure shows that a steep pressure increase, or spike, can lead to a step change in the operating voltage (increased hot resistance). Notice particularly heaters 1, 3, and 5 around 8,000 cycles where the pressure spikes to over 10^{-6} Torr, and

heaters 2 and 6 around 17,000 cycles where the pressure spikes from 2×10^{-7} to 4×10^{-7} Torr. Figure 8b compares the pressure during the flight and development testing. The average pressure during development testing was 8.4×10^{-8} Torr and the average pressure during flight testing was 2.4×10^{-7} Torr. The pressure during development testing was much noisier, but also generally lower than the pressure during flight testing. The air contains contaminants that can adversely affect lifetime by oxidizing the refractory metals within the heater. This may explain why the development heaters achieved greater cyclic life on average than the flight heaters.

The Weibull analysis 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. The cause of center conductor failure has been attributed to grain growth due to high temperature operation that leads to ‘necking’ at the grain boundaries and subsequent hot spot formations at this location, but definitive determination of the failure mechanism has yet to be made [11]. A secondary behavior sometimes takes place, where the fractured center conductor physically moves through the ceramic insulator and makes electrical contact with the outer sheath, resulting in a steep decrease in hot resistance. There appears to be no way to determine which failure mechanism will occur first or which heaters will undergo which failure.

Since the heaters experience the same changes in operation at failure for both heater sizes, the Weibull analysis results for all six heaters as a group is considered to be valid. Also, there is no definitive trend to distinguish between heater sizes; it is not as if all 0.5” heaters last longer than 0.25” heaters or vice versa. The cyclic life of a given heater is not correlated to heater size.

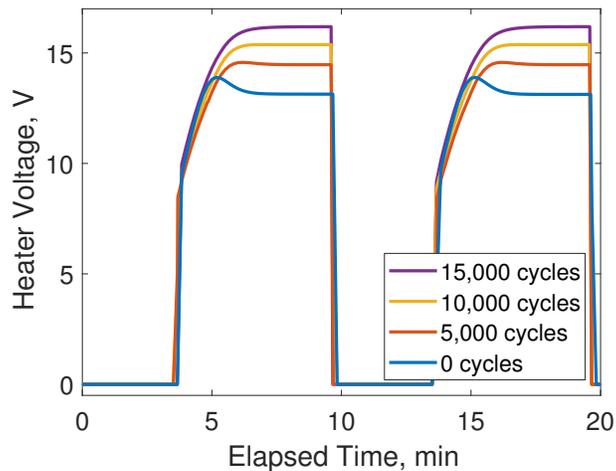


Fig. 9 Example heater voltage profile during on/off cycles at various points throughout the test.

Note that for the larger discharge heaters, early in the test, the voltage peaks near the start of the on cycle and then levels off. This behavior slowly diminishes until there is no peak in the voltage during the on cycle. Figure 9 shows this behavior. At the beginning of the test, the peak is prominent, but by the time the heater has undergone 10,000 cycles, the voltage peak disappears. The exact cause of this behavior is not determined, but it is observed when operating the NEXT thruster. The behavior is not observed in the smaller neutralizer heaters, therefore it is suspected to be related to the geometrical characteristics of the larger heater and possibly the electrical configuration.

VI. Conclusion

After fabrication of the flight batch of heaters for both hollow cathodes for the NEXT-C thruster, a subset was cyclically life tested to failure to verify the lifetime requirement. All heaters met the verification requirement by demonstrating $2\times$ the specified life of 3,650 cycles. Heater behavior during confidence and cyclic testing was consistent with prior heater experience at GRC, including failures. Heaters failed between 10,578 and 29,003 cycles during accelerated life testing. On average, only the development heaters lasted longer than the flight heaters out of all the previous swaged heaters fabricated by GRC. The estimated B10 lifetime of the flight heaters is 3,940 cycles. The flight heaters were delivered to Aerojet Rocketdyne for inclusion into the NEXT-C thrusters.

Appendix
History of GRC Fabricated Swaged Heaters

Year	Program	Fabrication Type	Testing Configuration	Heater Size	Testing Results	Notes
1991 to 1994	ISS PCU	Development	Free heaters on tube	0.25"	6,102 to 17,807	Process, procedure, and configuration development
1993 to 1995	ISS PCU	Flight Hardware	Free heater on tube	0.25"	10,568 to 12,977	In operation aboard ISS since October 2000
1995 to 1997	NSTAR-DS1/Dawn	Flight Hardware	Heaters in cathode assemblies	0.25"	In-space operation of >200/>400 cycles	Operated in space from 1998-2001/2007-2018
2002	NEXT	Development	Heaters in cathode assemblies	0.5"	13,789 to 14,257	First fabrication of 0.5" heaters
2003 to 2005	NSTAR/NEXT	Development	Heaters in cathode assemblies	0.25" and 0.5"	10,000 cycles without failure	Heater testing voluntarily suspended
2010 to 2012	NEXT	Development	Free heaters on tube	0.25" and 0.5"	7,205 to 17,807	Testing exposed material issue resulting in reduced cyclic capability
2015 to 2017	NEXT-C	Development	Free heaters on tubes	0.25" and 0.5"	19,059 to 33,551	Development cycle to resolve problems of previous fabrication batch, re-validate cyclic capability, and update process documents for flight hardware
2017 to 2019	NEXT-C	Flight Hardware	Free heaters on tube	0.25" and 0.5"	10,578 to 29,003	Heaters required for NEXT-C flight thrusters delivered to DART mission

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