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

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Outline

• Introduction
• Flight Heater Fabrication
• Confidence Testing
• Cyclic Life Testing
• Lifetime Assessment
• Conclusion
Introduction

• NEXT uses 2 hollow cathodes, each with an associated heater
• Discharge cathode is ½” and emits the discharge current ~ 20 A
• Neutralizer cathode is ¼” and supports < 10 A
• The cathode heaters serve 2 functions:
  – Condition the cathodes, removing contaminants, following exposure to atmospheric conditions
  – Sufficiently heat the cathode’s electron emitter such that emission is adequate to ignite the plasma discharge
NASA GRC Hollow Cathode Fabrication

- GRC has a long history of fabricating flight cathode heaters
- PCU heaters in operation aboard ISS since Oct 2000
- DS1 heaters operated in space for >200 cycles from 1998 to 2001
- Dawn heaters operated in space for >400 cycles from 2007 to 2018
- 2010 development heaters exposed a material issue that led to reduced cyclic capability
- 2015 was a second development cycle to re-validate processes

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

- GRC uses a swaged heater design
- A refractory metal sheath is swaged around a ceramic insulator
- The insulator contains a refractory metal wire at the center
- The central wire is welded to the outer metal sheath at one end
- The heater is coiled into shape
- Heaters are operated with a DC power supply to provide Ohmic heating
Test Setup

- 6 heaters are tested simultaneously
- Each heater is mounted on a cathode tube
- Radiation shields limit heating between adjacent heaters
- Type R thermocouples are welded to the orifice plate
- A DAQ records current, voltage, temperature, and pressure at 0.1 Hz
Test Procedure

• Each cycle consists of a 6 min on time and 4 min off time
  – 6 min on time represents a cathode ignition
  – 4 min off time is abbreviated to capture the majority of the ΔT
  – This duty cycle has successfully reflected performance of ISS PCU and NSTAR heaters
• Current is either on at 8.5 ADC or off at 0 ADC
• The temperature increases to >1000°C during an on cycle and falls by a factor of 2 during the off cycle
Confidence Testing

• Testing is broken into 2 parts:
  – Confidence Testing: Bakeout, current ramping, and the first 150 cycles
  – Life Testing: Heaters cycled until failure
• Confidence testing starts with 2 days of bakeout to remove any water or oxygen based contaminants

Confidence Testing Procedure

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low current bakeout</td>
<td>Operate steady-state at 26% of full current</td>
<td>24 h</td>
</tr>
<tr>
<td>High current bakeout</td>
<td>Operate steady-state at 46% of full current</td>
<td>24 h</td>
</tr>
<tr>
<td>Burn-in</td>
<td>150 on/off cycles</td>
<td>25 h</td>
</tr>
<tr>
<td>Continuous Current Profile</td>
<td>One heater of each size is slowly ramped from 0 to 8.5 A</td>
<td>8.5 h</td>
</tr>
<tr>
<td>Step Current Profile</td>
<td>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</td>
<td>8 h</td>
</tr>
</tbody>
</table>
Confidence Testing: Burn-In

- Each heater undergoes a 150 cycle burn in
- Values are recorded at the end of each cycle
- \( \frac{1}{2}'' \) heaters show a drop in hot resistance within the first \(~10\) cycles
- \( \frac{1}{4}'' \) heaters run hotter than \( \frac{1}{2}'' \) heaters
- Burn in acceptance criteria is range on the change in hot resistance
Confidence Testing: Ramps and Steps

- 1 heater of each size is continuously ramped at a rate of 1 A/h
- 2 remaining heaters of each size are stepped from 0 to 26%, 46%, 85%, and 100% of full current with 2 hour holds at each current
Cyclic Life Testing

• Each heater was tested till failure
• Heaters 3 and 6 shorted
• Other heaters failed open
• Testing was completed in 3 segments with two vacuum breaks
  – 1st due to facility pump maintenance
  – 2nd due to US government shutdown
  – Pressure remained ≤ 5 Torr
• Resistance generally increases as a function of cycle
• First failure of heater 5 at 10,578 cycles
• Last failure of heater 2 at 29,003 cycles
• Cyclic lifetime is not correlated to heater size
Lifetime Assessment

- NEXT-C requirement was 3,650 cycles
  - Verified by testing to 2x requirement
- Cyclic testing has always been restricted by resource constraints to small sample sizes
  - Small number of heaters are produced in each batch ~30
  - Vacuum facility has space for 6 heaters
  - Each cyclic life test takes > 1 year to complete
- Batch cyclic lifetime capability is determined using Weibull analysis
  - This approach is used in many fields to determine unit-to-unit reliability with small data sets
- Two parameter Weibull distribution—Fraction of Population Failing
  \[ F(t) = 1 - e^{-(t/\eta)^\beta} \]
Lifetime Assessment: Weibull Analysis

- B10 lifetime – 90% survival rate (90% confidence interval)
- B10 lifetime estimate is 3,940 cycles
- Comparison to development heaters in Verhey, et al., IEPC-2017-397
**Lifetime Assessment: Weibull Analysis**

- The flight heaters had a B10 lifetime estimate that met the NEXT-C requirement of 3,650 cycles
- The Weibull analysis is highly sensitive to the range between failures
  - The 2002 NEXT heaters lasted between 13,789 and 14,257 cycles (500 cycles)
- Reducing subset to 3 heaters leads to greater variance in B10 estimates
- Because all heaters are subject to the same failure mechanisms, grouping all 6 is considered valid

<table>
<thead>
<tr>
<th>Heater Set</th>
<th>B10 Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019 NEXT-C Flight Heaters</td>
<td>3,940</td>
</tr>
<tr>
<td>0.25” Only</td>
<td>1,089</td>
</tr>
<tr>
<td>0.5” Only</td>
<td>2,584</td>
</tr>
<tr>
<td>2017 NEXT-C Development Heaters</td>
<td>10,731</td>
</tr>
<tr>
<td>0.25” Only</td>
<td>12,237</td>
</tr>
<tr>
<td>0.5” Only</td>
<td>4,175</td>
</tr>
<tr>
<td>2012 NEXT 0.5” Heaters</td>
<td>1,784</td>
</tr>
<tr>
<td>2002 NEXT 0.5” Heaters</td>
<td>12,615</td>
</tr>
<tr>
<td>1995 ISS PCU Flight 0.25” Heaters</td>
<td>6,687</td>
</tr>
<tr>
<td>1991 ISS PCU Pathfinder 0.25” Heaters</td>
<td>2,519</td>
</tr>
</tbody>
</table>
Lifetime Assessment: Development and Flight Heaters

• Development heaters failed between 19,059 and 33,551 cycles (14,500 cycle spread)
  – By 19,059 cycles, 4 flight heaters had already failed
• Flight heaters failed between 10,578 and 29,003 cycles (18,500 cycle spread)
• B10 lifetime of development heaters was 2.7x that of flight heaters
• It was predicted that development and flight heaters would behave very similarly
Lifetime Assessment: Development and Flight Heaters

- Pressure increases can cause step changes in operating voltage (increased hot resistance)
- Average pressure during development testing: $8.4 \times 10^{-8}$ Torr
- Average pressure during flight testing: $2.4 \times 10^{-7}$ Torr
Lifetime Assessment: Failure Mechanisms

• Two heaters shorted and four heaters went open circuit
• Open circuit failure—Center conductor fails due to grain growth caused by high temperature operation that leads to ‘necking’ at the grain boundaries and subsequent hot spot formations at this location
• Short circuit failure—A fractured center conductor migrates through the ceramic insulator and makes electrical contact with the outer sheath, resulting in a steep decrease in hot resistance
• These are theorized, and a definitive determination has yet to be made
• There appears to be no way to predict which failure mechanism will affect which heater
Conclusion

• A subset of 6 heaters from the NEXT-C flight batch were cyclically life test to failure
• All heaters demonstrated 2x the life time requirement of 3,650 cycles
  – Heaters failed between 10,578 and 29,003 cycles
• The B10 lifetime is 3,940
• The development heaters lasted the longest of any GRC fabricated heaters
  – Differences in development and flight heaters may be due to the facility pressure
• Following fabrication, the flight heaters were delivered to Aerojet Rocketdyne for inclusion into the NEXT-C flight thruster which will be delivered to the DART mission in 2020
This work was completed as part of the NEXT-C project, which is supported by the Planetary Science Division of the Science Mission Directorate, NASA Headquarters and awarded to Aerojet Rocketdyne and ZIN Technologies.
Backup Slides
End of Cycle Temperature

- All thermocouples eventually fall off due to the weld breaking under thermal cycling
Heater Behavior: ½” Heaters

- For the ½” heaters early in the test, the voltage peaks near the start of the cycle then levels off.
- After 10,000 cycles this peaked disappears.
- The exact cause of this behavior has not been determined:
  - This behavior is observed during NEXT operation.
- This behavior is not observed with ¼” heaters.
- Suspected to be related to the geometrical characteristics, thermal mass, and possibly electrical configuration of the larger heater.
Heater 6 Failure

- Heater 6 shorted after cycle 19,988
  - Voltage dropped from over 17 V to below 10 V
  - Voltage became more noisy than typical

<table>
<thead>
<tr>
<th>Resistance, Ω</th>
<th>Installed</th>
<th>150 Cycles</th>
<th>10578 Cycles</th>
<th>20076 Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4365</td>
<td>0.4305</td>
<td>0.472</td>
<td>0.3998</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing voltage over cycle number](image1)

![Graph showing voltage over time](image2)
Heater 6 Failure

• As heater temperature increases, the top of the heater remains cold

4 min 21 s  4 min 40 s  5 min 32 s  5 min 42 s  5 min 50 s  6 min 1 s
Heater Temperatures: Radiation Shielding Effectiveness

- Heater 6 and 4 are running with temperatures 950-1050 C
- Heater 5 is around 90 C
Heater Voltage Behavior: Development and Flight Batch Compare

- Development heaters plotted alongside flight heaters