National Aeronautics and Space Administration

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

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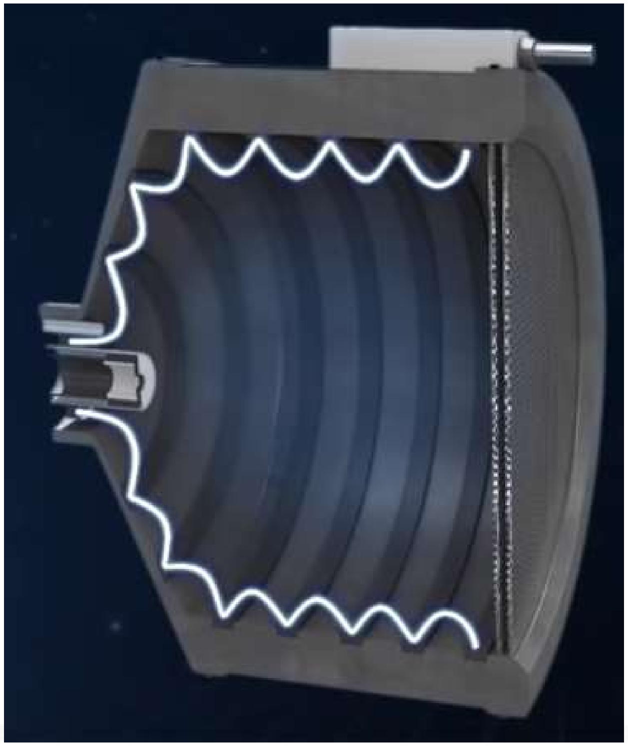
NASA'S EVOLUTIONARY XENON THRUSTER–COMMERCIAL

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



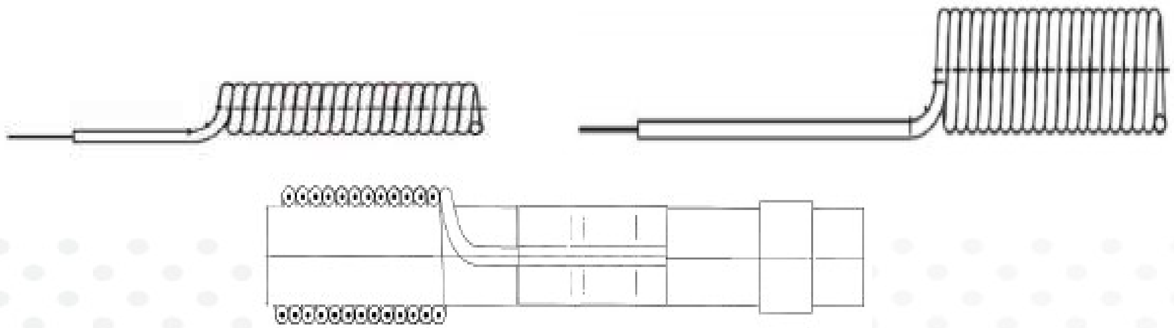
NASA GRC Hollow Cathode Fabrication

- 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

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

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

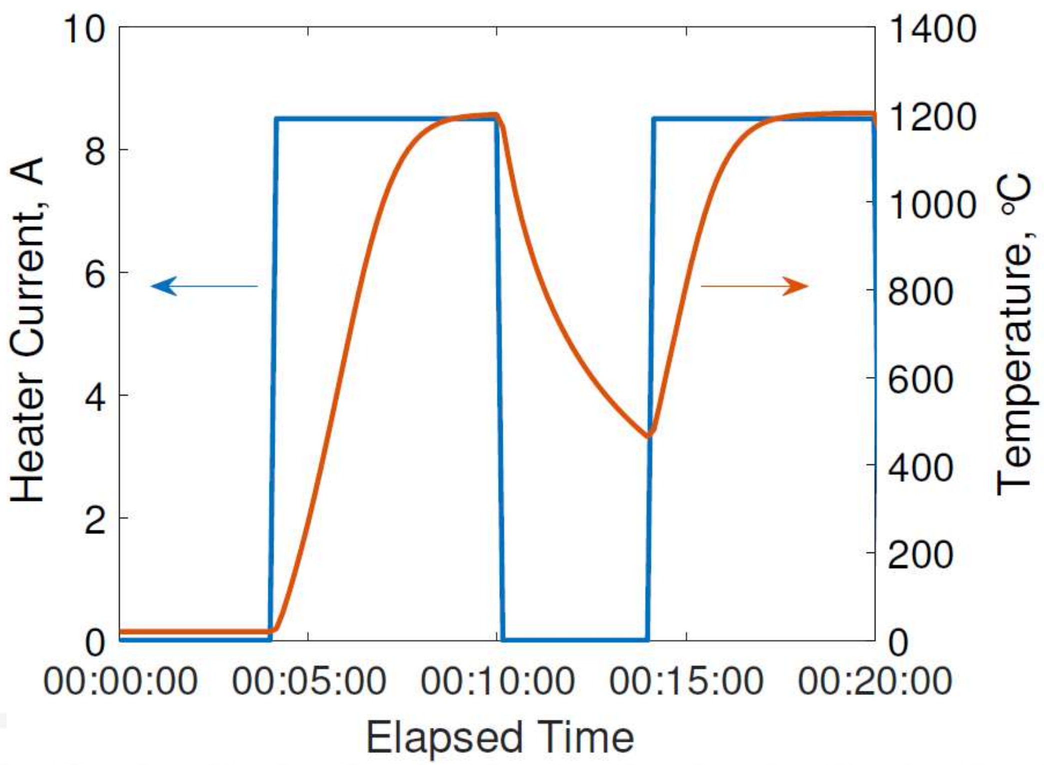


Test Setup

- 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

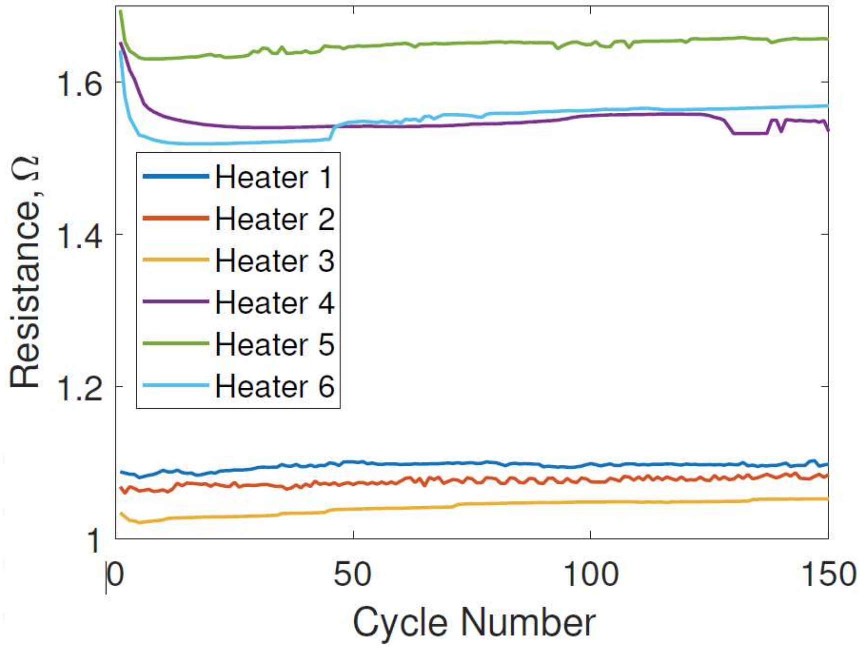
- Testing is broken into 2 parts:
  - Confidence Testing: Bakeout, current ramping, and the first 150 cycles
  - Life Testing: Heaters cycled until failure
- Confidence testing starts with 2 days of bakeout to remove any water or oxygen based contaminants

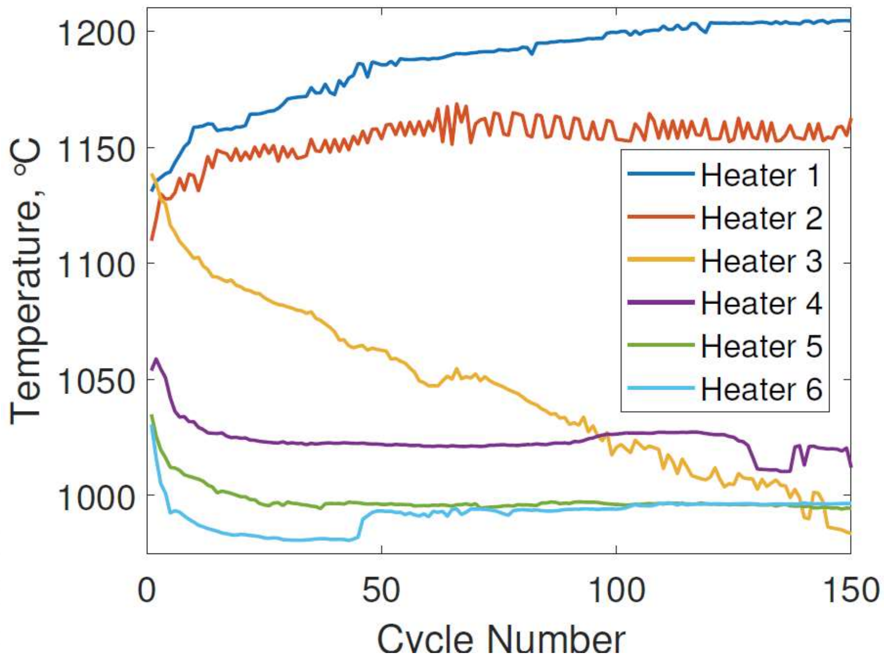
Confidence Testing Procedure

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

Confidence Testing: Burn-In

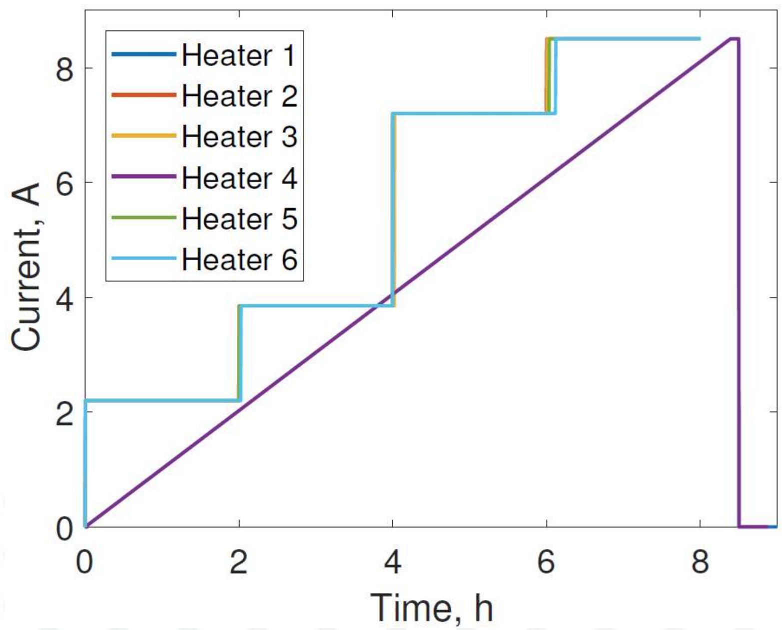
- Each heater undergoes a 150 cycle burn in
- Values are recorded at the end of each cycle
- ½'' heaters show a drop in hot resistance within the first ~10 cycles
- ¼'' heaters run hotter than ½'' heaters
- Burn in acceptance criteria is range on the change in hot resistance

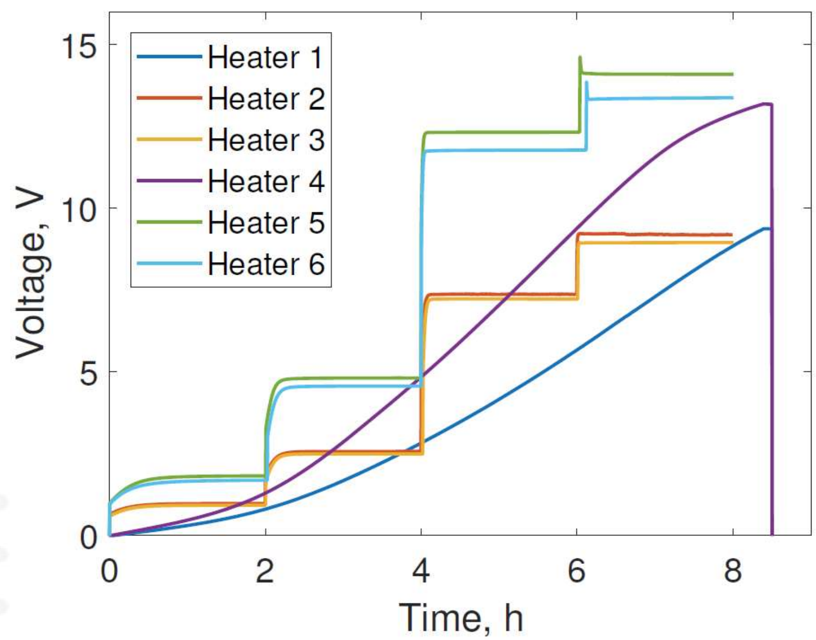




Confidence Testing: Ramps and Steps

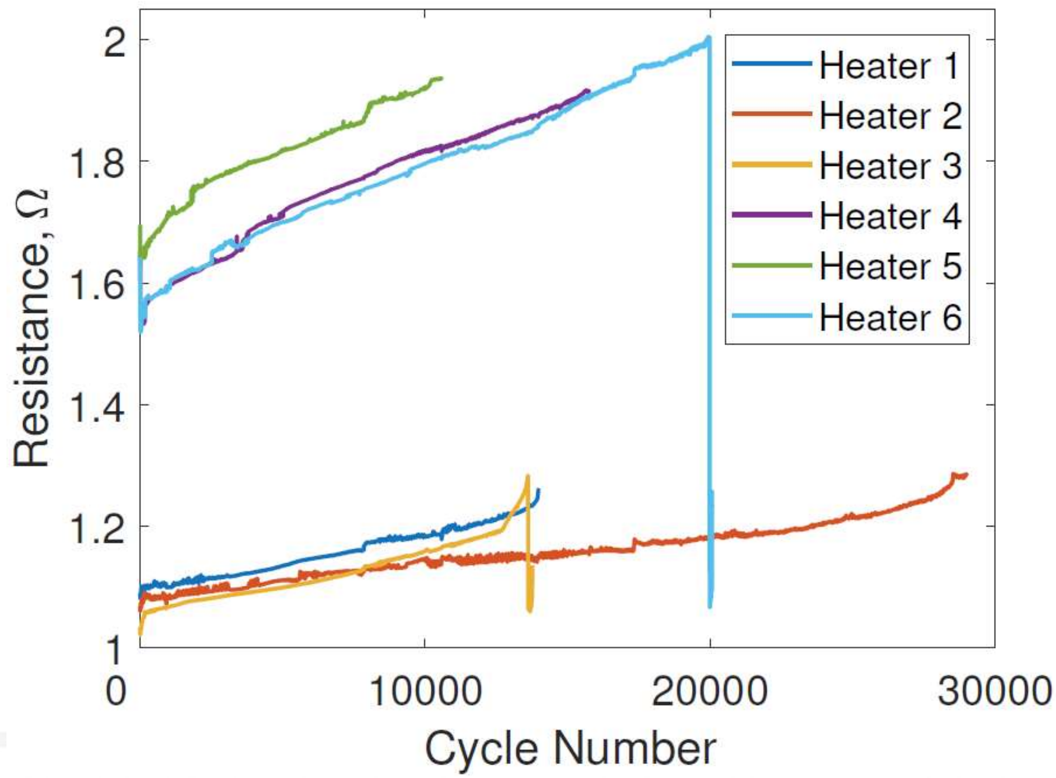
- 1 heater of each size is continuously ramped at a rate of 1 A/h
- 2 remaining heaters of each size are stepped from 0 to 26%, 46%, 85%, and 100% of full current with 2 hour holds at each current





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



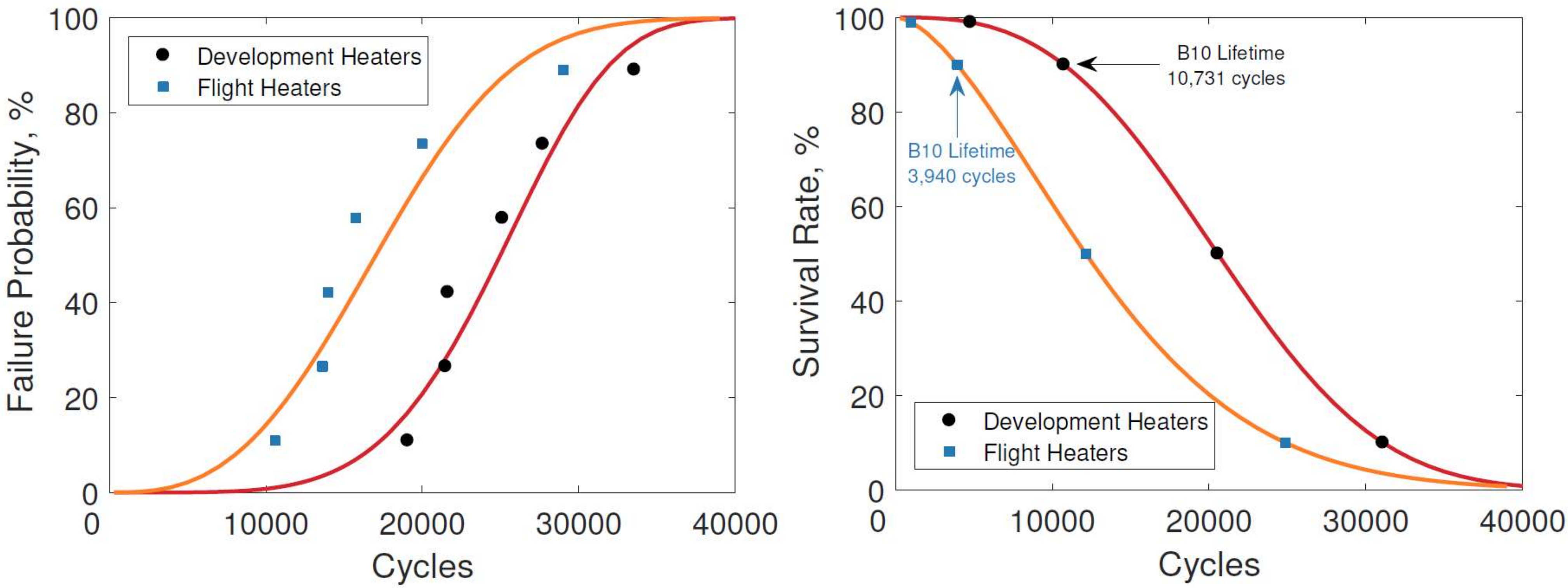
Lifetime Assessment

- 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

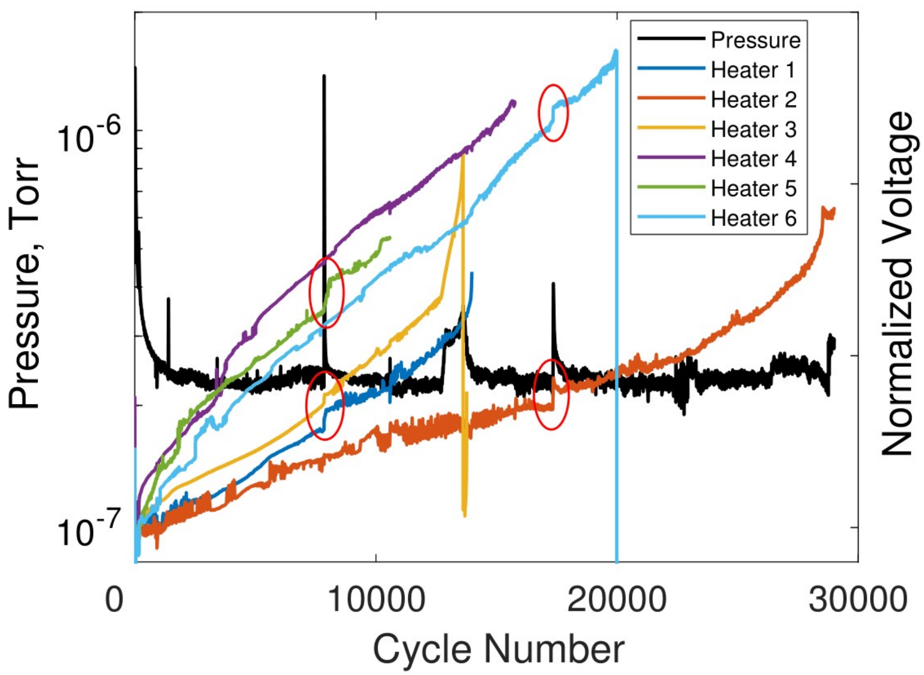
Heater Set	B10 Estimate
2019 NEXT-C Flight Heaters	3,940
0.25" Only	1,089
0.5" Only	2,584
2017 NEXT-C Development Heaters	10,731
0.25" Only	12,237
0.5" Only	4,175
2012 NEXT 0.5" Heaters	1,784
2002 NEXT 0.5" Heaters	12,615
1995 ISS PCU Flight 0.25" Heaters	6,687
1991 ISS PCU Pathfinder 0.25" Heaters	2,519

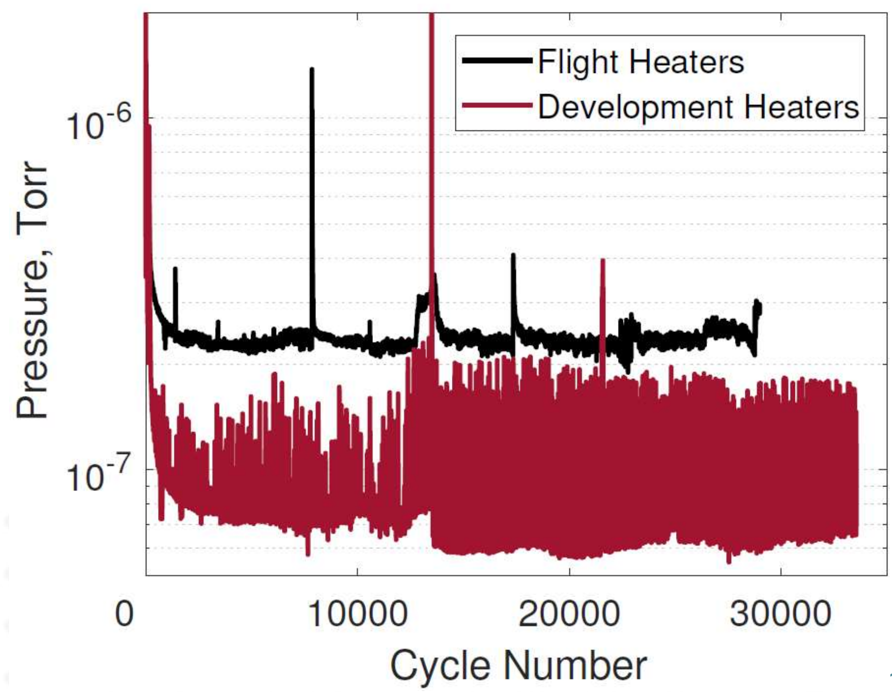
Lifetime Assessment: Development and Flight Heaters

- 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 texting: 8.4×10^{-8} Torr
- Average pressure during flight testing: 2.4×10^{-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

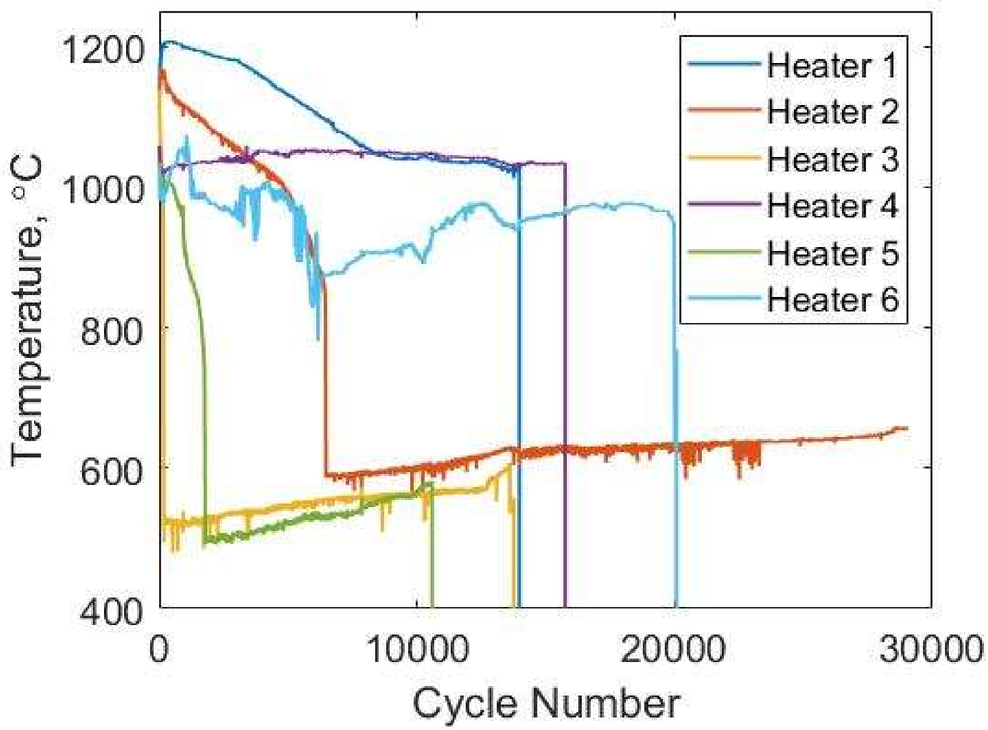
- A subset of 6 heaters from the NEXT-C flight batch were cyclically life test to failure
- All heaters demonstrated 2x the life time requirement of 3,650 cycles
  - Heaters failed between 10,578 and 29,003 cycles
- The B10 lifetime is 3,940
- The development heaters lasted the longest of any GRC fabricated 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

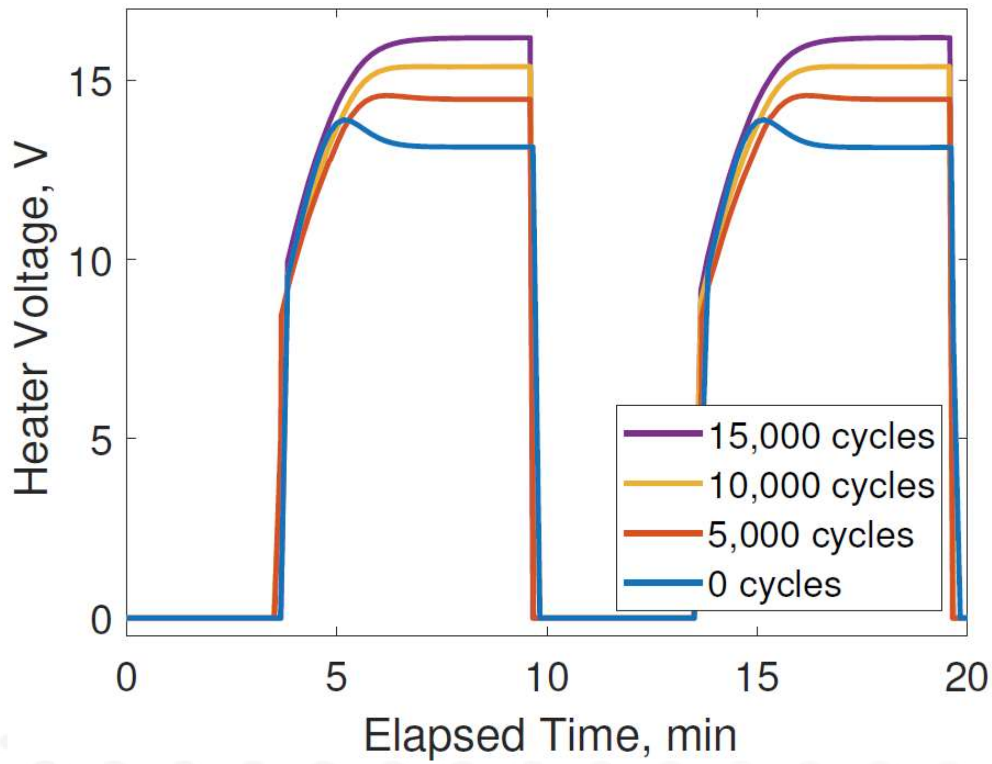
End of Cycle Temperature

- 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

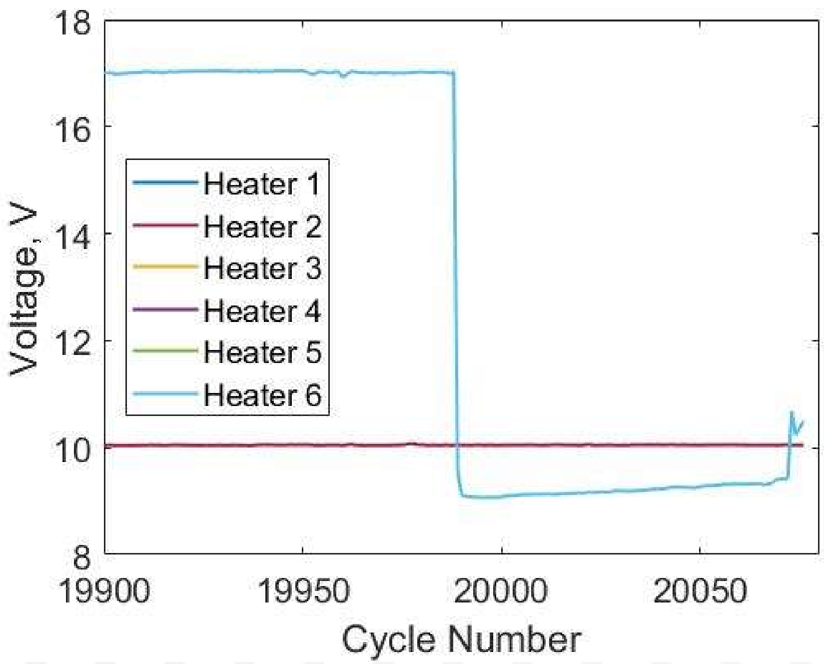


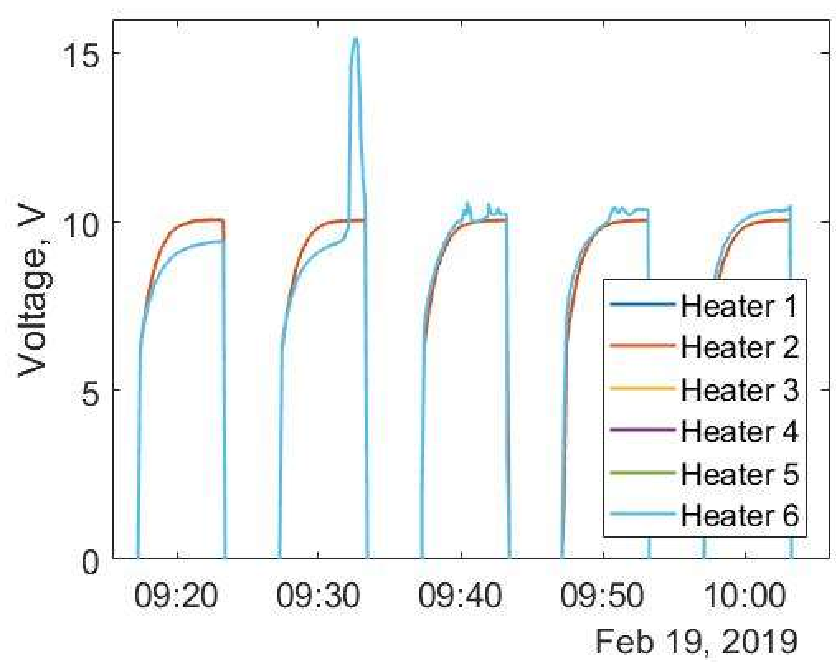
Heater 6 Failure

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

Heater 6 Cold Resistances (At Flange)

	Installed	150 Cycles	10578 Cycles	20076 Cycles
Resistance, Ω	0.4365	0.4305	0.472	0.3998





Heater 6 Failure

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

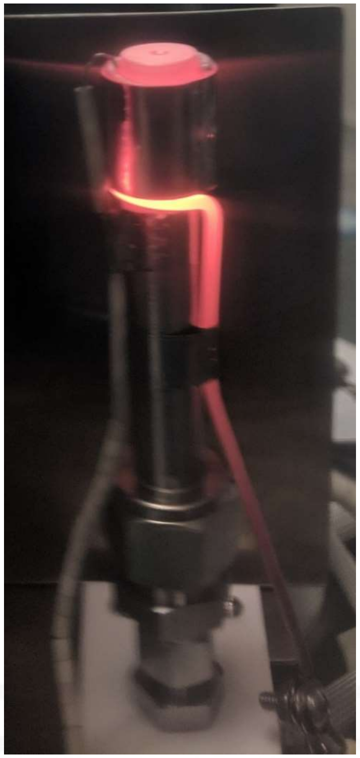
4 min 21 s

4 min 40 s

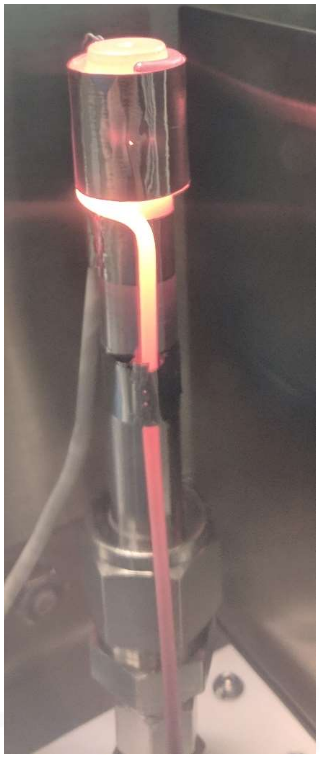
5 min 32 s

5 min 42 s

5 min 50 s



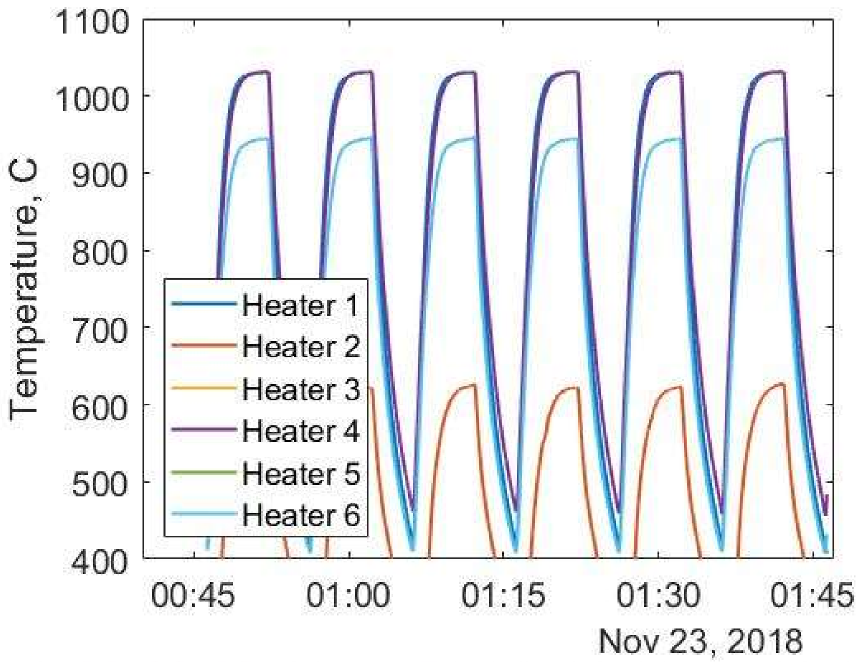
6 min 1 s

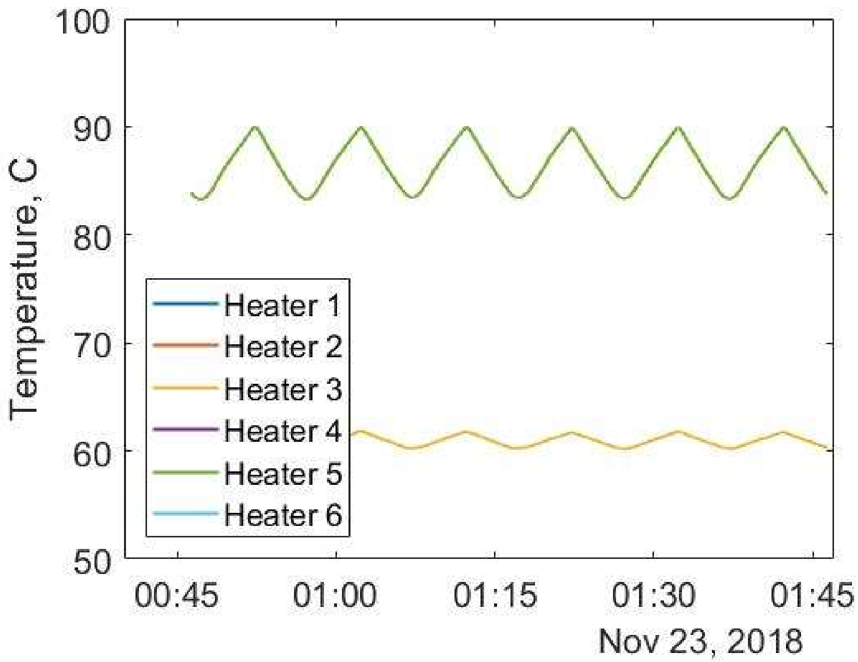


On Cycle Time

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