Alkali Metal Heat Pipes for Kilopower

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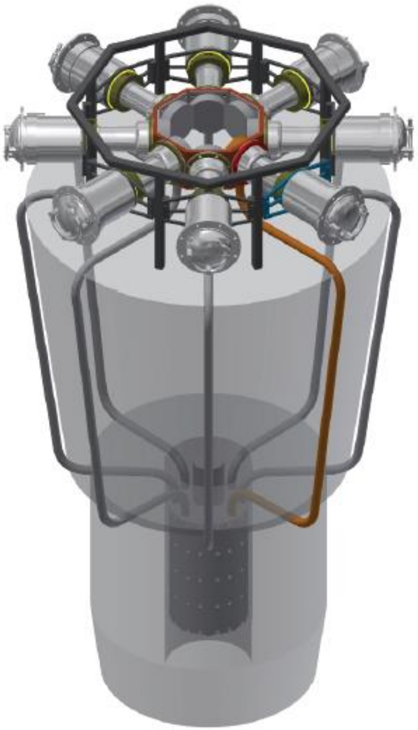
Outline

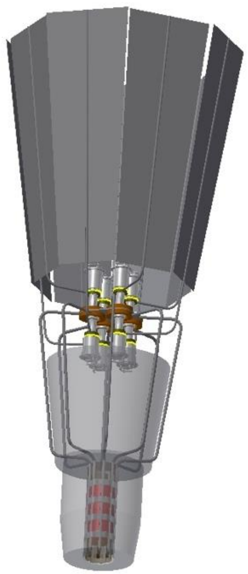
- Motivation
- Background
- Objectives
- Initial Thermosyphons for Kilopower
  - Fabrication
  - Performance Testing
  - Startup improvement
- Improved Heat Pipes and Thermosyphons for Kilopower
  - Improved Condenser Plate
  - Reduced Pool Height
- Future Work
- Acknowledgements

Space Nuclear Power

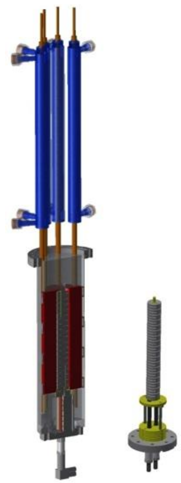
- The Fission Surface Power System (FSPS) is designed to operate from 10 to 100 kWe
- Current Radioisotope Power Systems (RPSs) operate below 500 We.
  - Limited supply of plutonium
- NASA Glenn currently developing the Kilopower system to address the power gap between current RPS and FSPS, with power generation from 1 to 10 kWe.
  - Space science missions and Martian surface power applications
  - 1 kWe to 10 kWe Stirling systems
- Alkali metal heat pipes would be used to transfer heat from the reactor to the Stirling
- Water heat pipes would be used to transfer the waste heat from the Stirling engines to a radiator panel



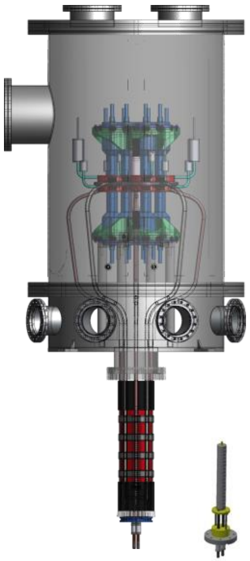
Kilowatt Reactor Using Stirling Technology (KRUSTy)



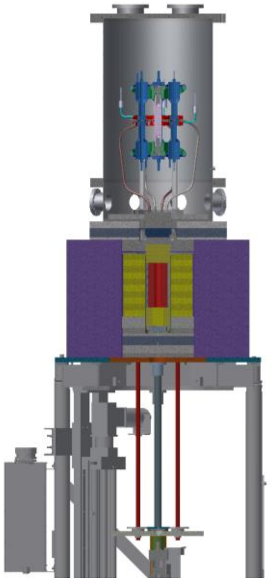
Notional Flight System Concept



Thermal Prototype & Materials Testing (Year 1)



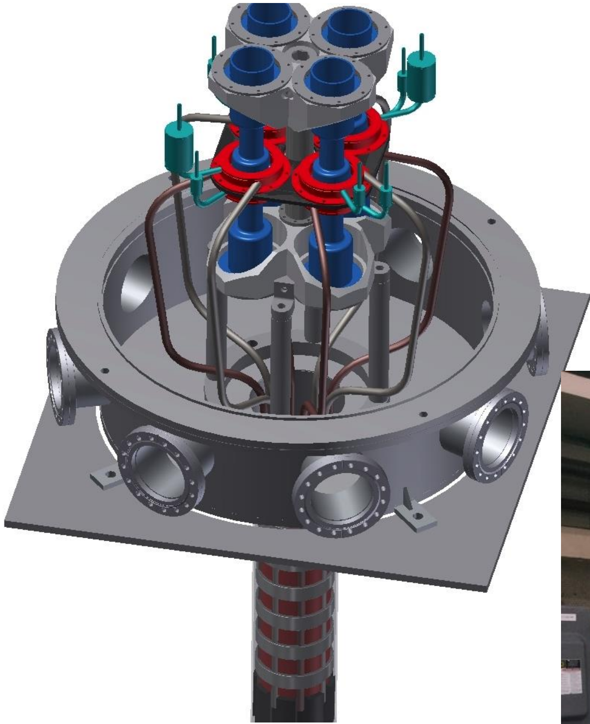
Thermal-Vac System Test with Depleted Uranium Core at GRC (Year 2)

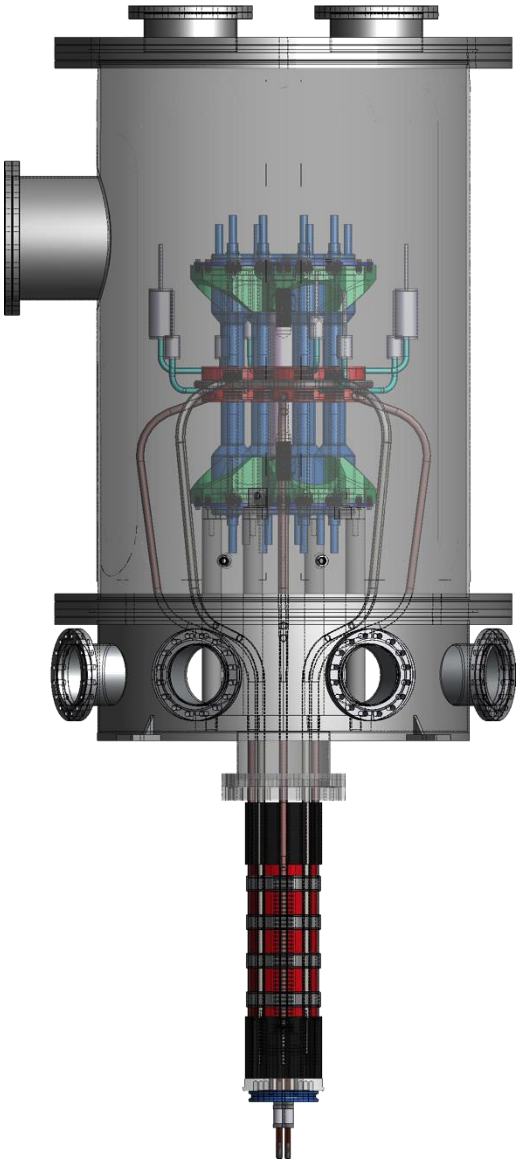


Reactor Prototype Test with Highly-Enriched Uranium Core at NNSS (Year 3)

- Verify system-level performance of flight-like U-Mo reactor core, sodium heat pipes, and Stirling power conversion at prototypic operating conditions (temperature, heat flux, power) in vacuum
- Establish technical foundation for 1 to 10 kWe-class fission power systems

Latest Configuration of 1 kW$_e$ Krusty Nuclear Demonstration





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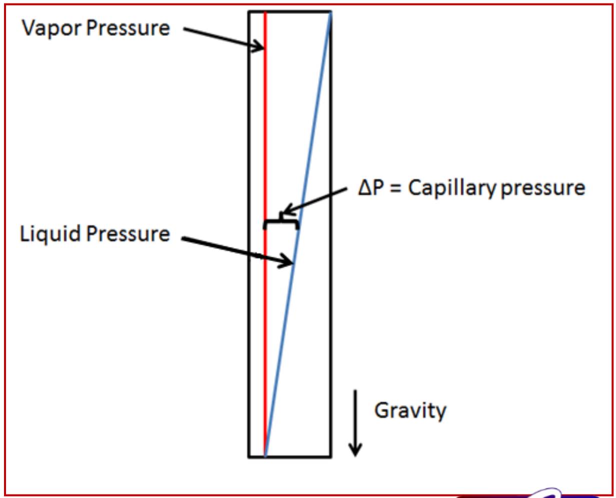
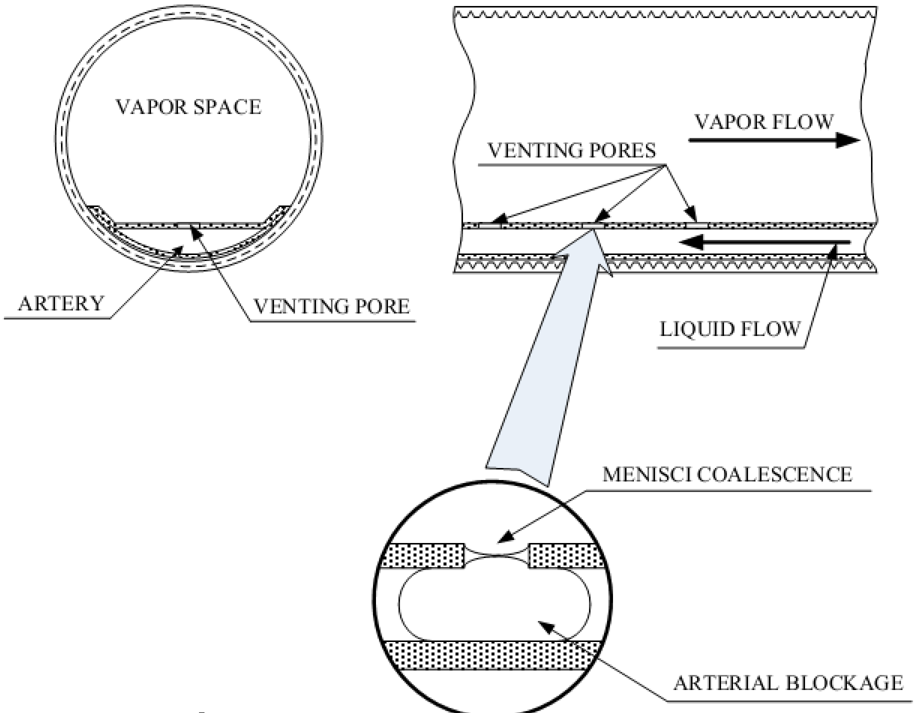
Motivation

- Arterial heat pipes are the current default design for spacecraft nuclear reactors, however, de-priming of the artery during ground testing is a problem
- Hybrid screen-grooved and self-venting arterial heat pipes offer potential benefits over standard arterial heat pipes
  - The grooves will reprime automatically
  - The self-venting arterial pipes also automatically reprime
- The vapor pressure and liquid pressure at the bottom of the heat pipe are identical.
- As the height increases, the liquid pressure drop decreases, due to the hydrostatic head.
- At higher elevations, vapor will be sucked into the artery, depriming it



Concept of Self-Venting Arterial CCHP



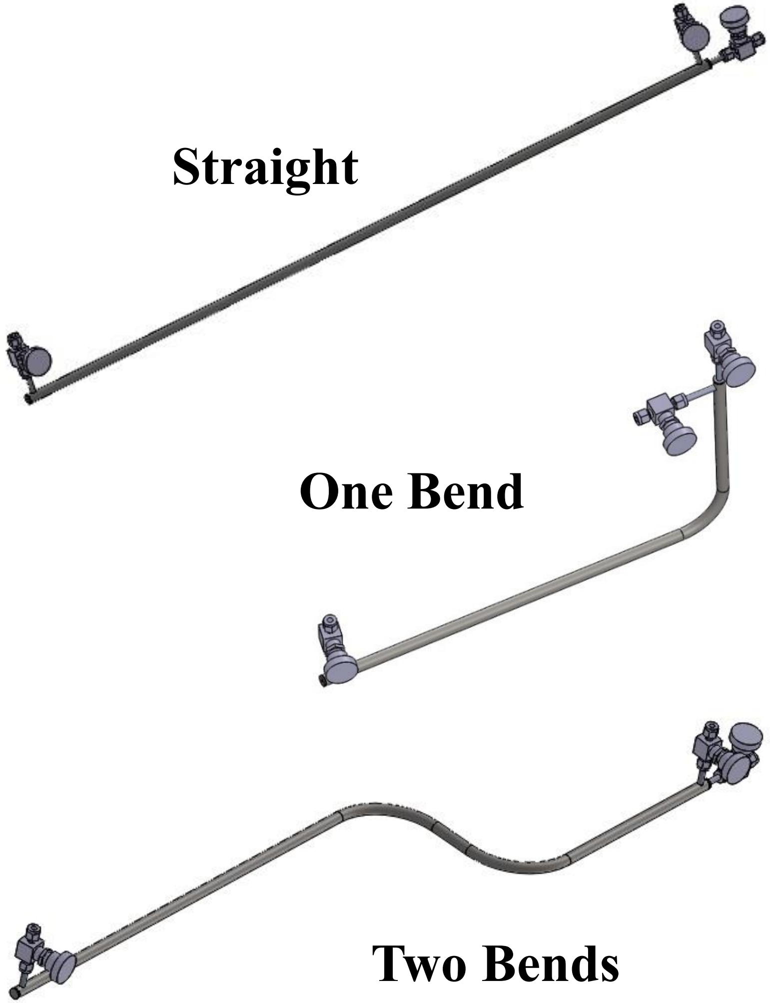
Kaya et. al, 2011

- Difference from a conventional arterial pipe is that small venting pores are located in the evaporator section of the CCHP
- The venting pores provide an escape route for any trapped vapor or NCG in the artery
- The design eliminates the single point failure nature of previous arterial CCHPs
- The self-priming heat pipe design has been validated with ammonia in numerous Russian spacecraft (TRL 9)

Technical Objectives

- Overall Objective: Develop low-mass alkali metal heat pipes for space fission reactors using both thermosyphons and self-venting arterial heat pipe wicks
- Fabricate and test full length versions of the self-venting arterial wick heat pipes and thermosyphons for the Stirling energy conversion systems.
  - Thermosyphons of interest for initial testing, and for use on Mar and the Moon
- 9 pipes – 3 fully wicked and the rest of them wicked only in the evaporator
- Investigate the suitability of using self-venting arterial wick structure in gravity aided orientation

- **Bend development**
  - To evaluate if artery heat pipes can be manufactured in bent configurations
  - 39.37 inch overall length, 3.0” radius 90° bends
  - 6 inch evaporator section, 6 inch condenser section
  - Bend 1 is 12” overall length from condenser end
  - Bend 2 is 2” (end of first bend to start of second bend) toward the evaporator. This simulates the two closest bends in the deliverable heat pipes.
  - .094” square artery. 030” venting pores diameter and 0.80” spacing in the evaporator artery
  - Radius bend heat pipe to be manufactured and performance tested straight, then bent. Will have venting pores
    - 0.50 inch OD x .035 inch wall stainless steel 316 shell
    - 250/inch mesh x .0016 wire diameter stainless steel 316 screen wick
  - All testing in vacuum chamber

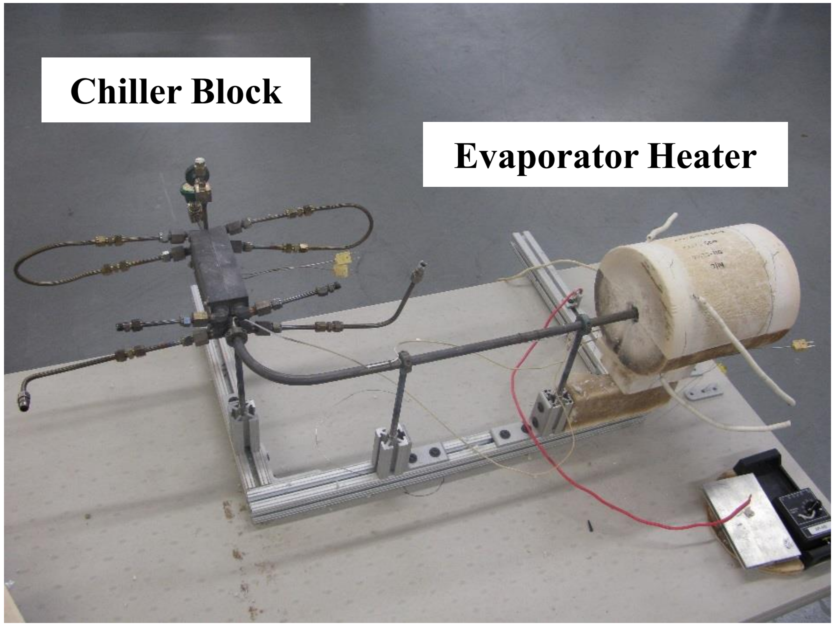


High Temperature Radius Bend Artery Heat Pipe

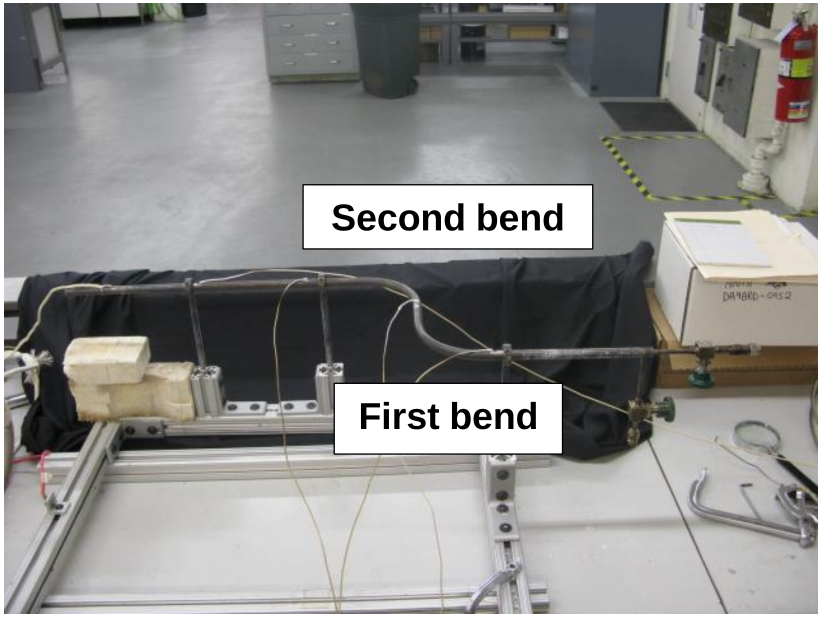
Radius Bend Heat Pipe Fabrication

Straight

One Bend



Two Bends



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High Temperature Radius Bend Artery Heat Pipe

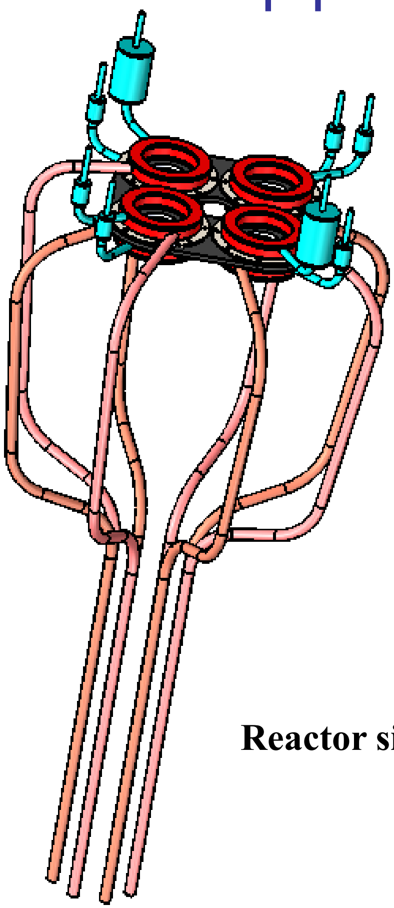
Summary

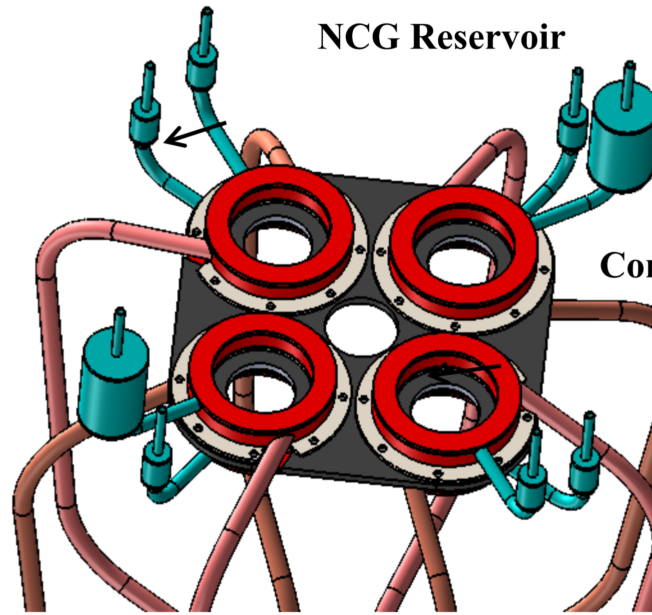
- Table summarizes power transport capacity for radius bend heat pipes.
- All configurations indicate artery flow.
- One bend power transport is almost the same as straight.
- Two bend power capacity is lower, but input power steps in testing was 50 watts, within test accuracy. It is possible that the multiple bends can begin to infringe on vapor flow, reducing power capacity. More data is required, will compile from thermosyphon testing.
- Heat pipe restarted (self-primed) after each dryout.

		Power (W)	
Configuration	Adverse Elevation	Theoretical	Measured
Straight	Horizontal (0.3”)	706	520
	1”	472	340
One Bend	Horizontal		520
Two Bends	Horizontal		443

Details in 2015 STCW presentation

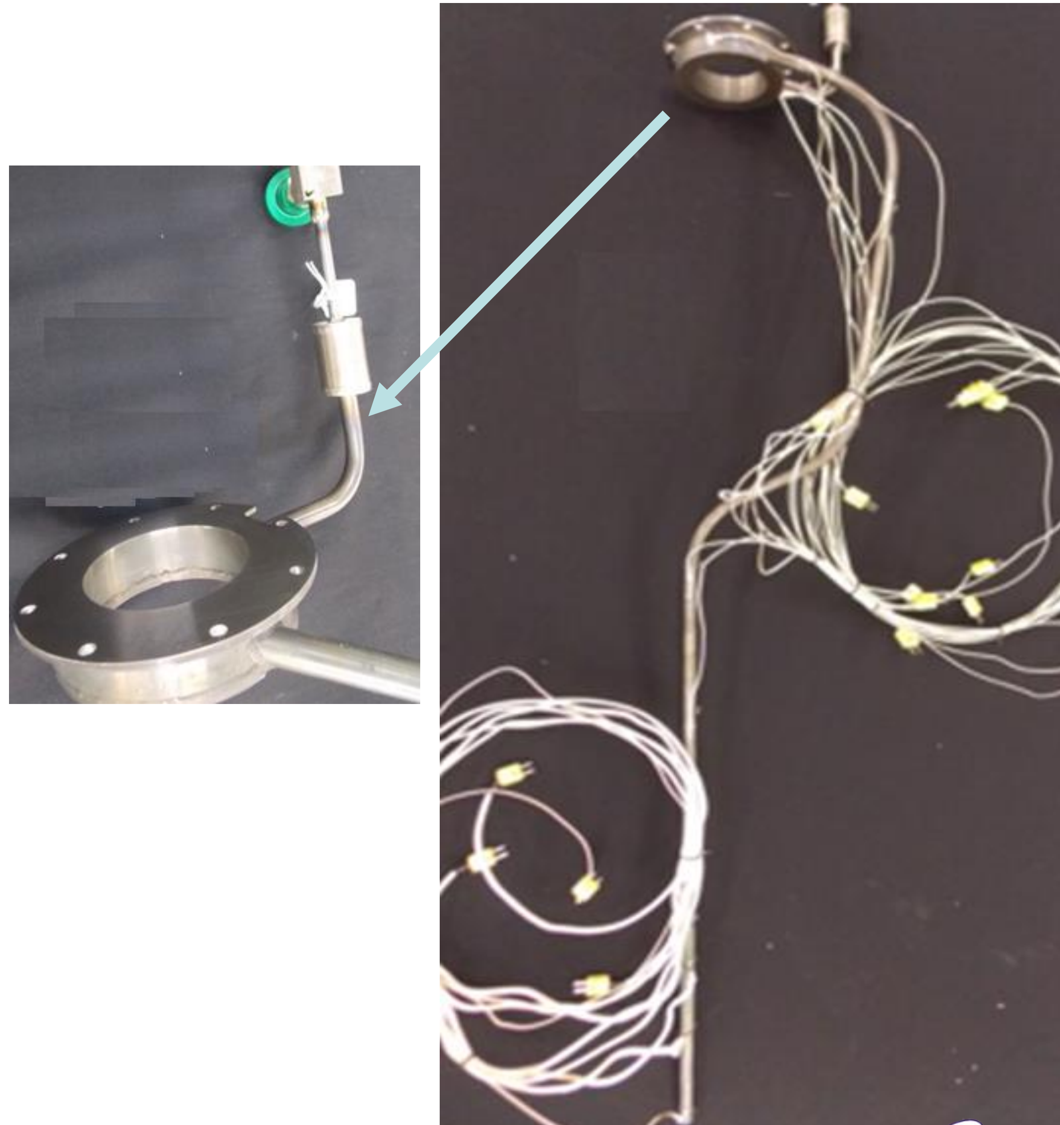
- The current design of the system determines the shape of the pipes



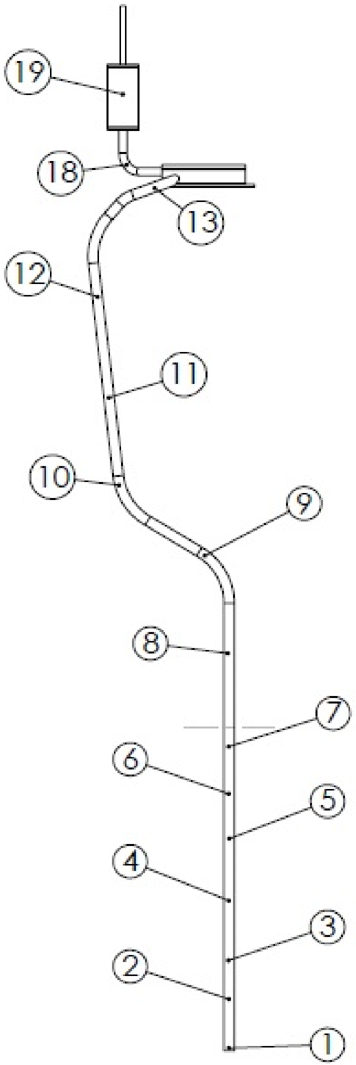


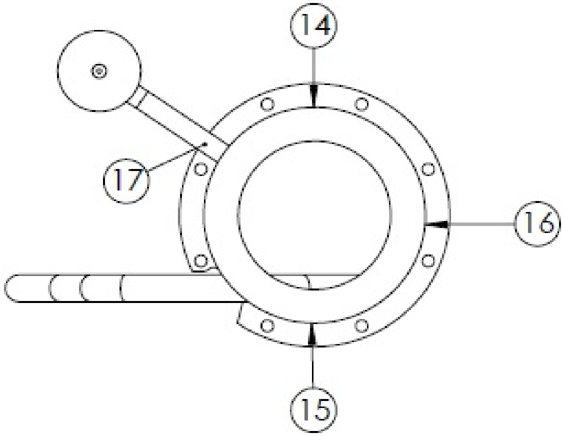
Full Scale – Self Venting Arterial Heat Pipe Testing

- Two Full Scale Arterial Heat Pipes were fabricated and tested in vacuum
  - Before Bending:
    - Intensive vacuum testing was carried for the straight pipes.
    - At 0.4” against gravity orientation:
      - Pipe 1: 405W
      - Pipe 2: 370W
  - After Bending
    - At 0.4” against gravity orientation:
      - Pipe 1: 290W
      - Pipe 2: 210W
- Vapor Temperature was ~ 710° C
- **<u>The pipes underperform</u>**
  - Alternative wick configuration is being developed:
  - Hybrid wick – grooves/screen



Alkali Metal Heat Pipe - Thermocouples Map





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Deliverable Thermosyphons

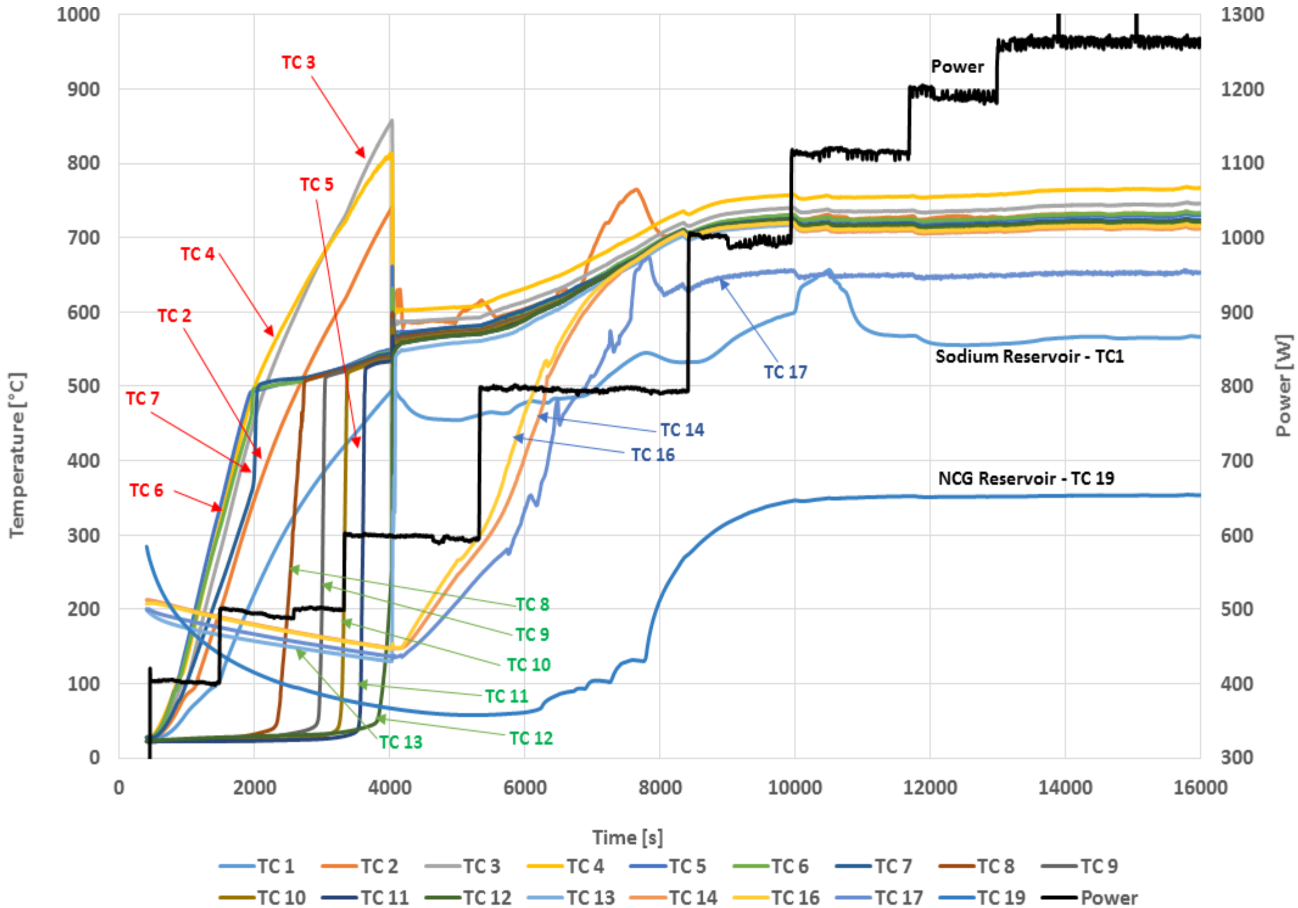
- 9 Kilopower (full scale) thermosyphons were designed, fabricated, tested and delivered to NASA GRC.
  - 7 heat pipes were gas charged
  - 2 heat pipes were VCHPs – for heat pipe failure simulation
    - Heat reservoir to shut down the thermosyphon
- They were tested at ACT in ambient only since the actual configuration would not allow vacuum testing at ACT
  - Heat Leaks ~570W
  - No pipe reached dry out
- Initial Problems:
  - Temperature spikes during startup
  - Slow startup
  - Condenser orientation

Pipe No	Electric Power	Net Power	Dry Out
1	1250	680	No
2	1250	680	No
3	1200	630	No
4	1050	480	No
5	1150	580	No
6	1250	680	No
7	1200	630	No
8	1250	680	No
9	1200	630	No

Reservoir temperature during shut down of the heat pipe

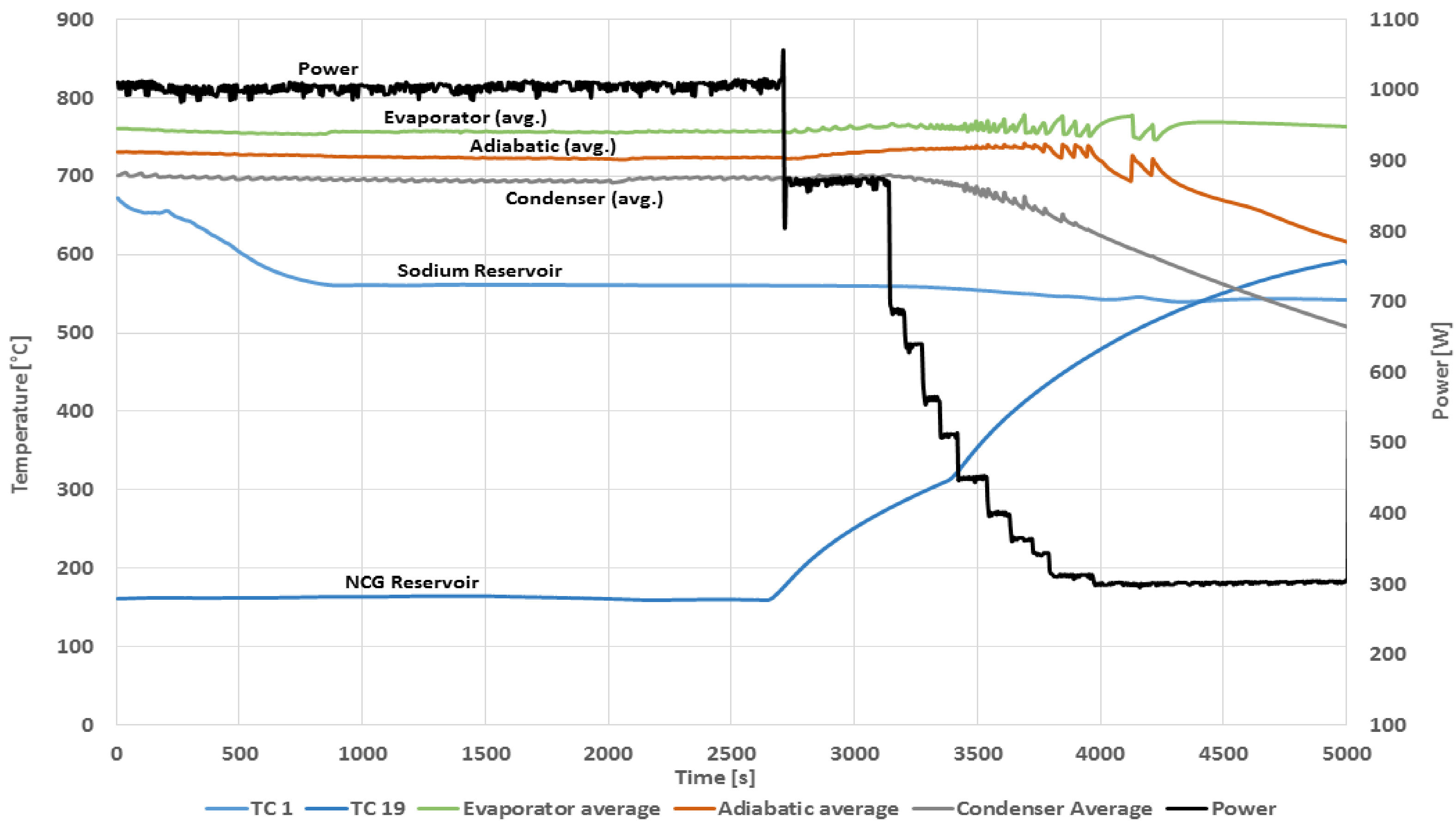
Deliverable Thermosyphons

- Heat Pipe No 3 - VCHP
  - Significant temperature spike in the evaporator



Deliverable Thermosyphons

- **VCHP Test of Heat Pipe 3 (ambient)**
  - **The test was stopped when LN cooling stopped.**
  - **Only average temperatures are shown**



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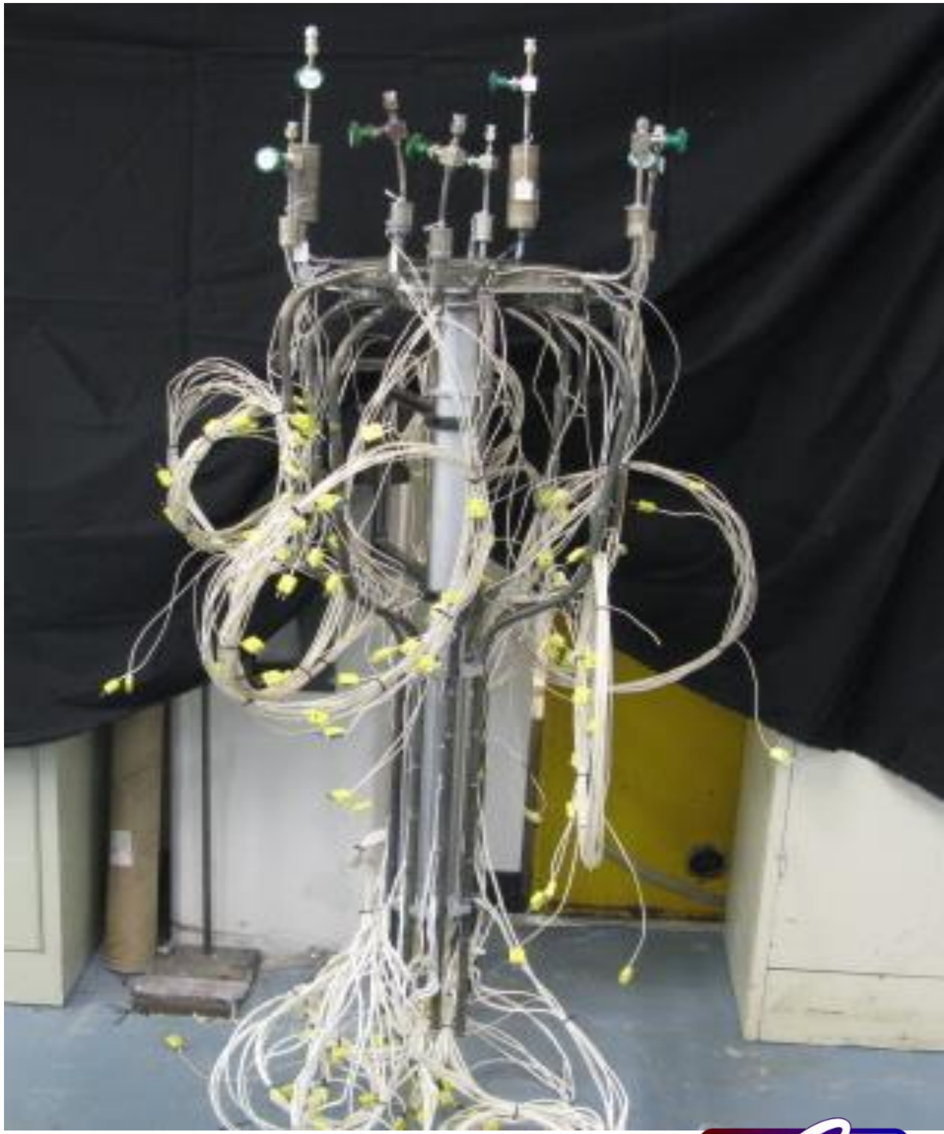
Deliverable Thermosyphons

- Set of thermosyphons delivered for Kilopower test with an electrically heated stainless steel core
  - Complete system from core to Stirling Convertors

- Thermosyphons successfully tested in the NASA Glenn Electrically Heated Test Rig in April – June time interval

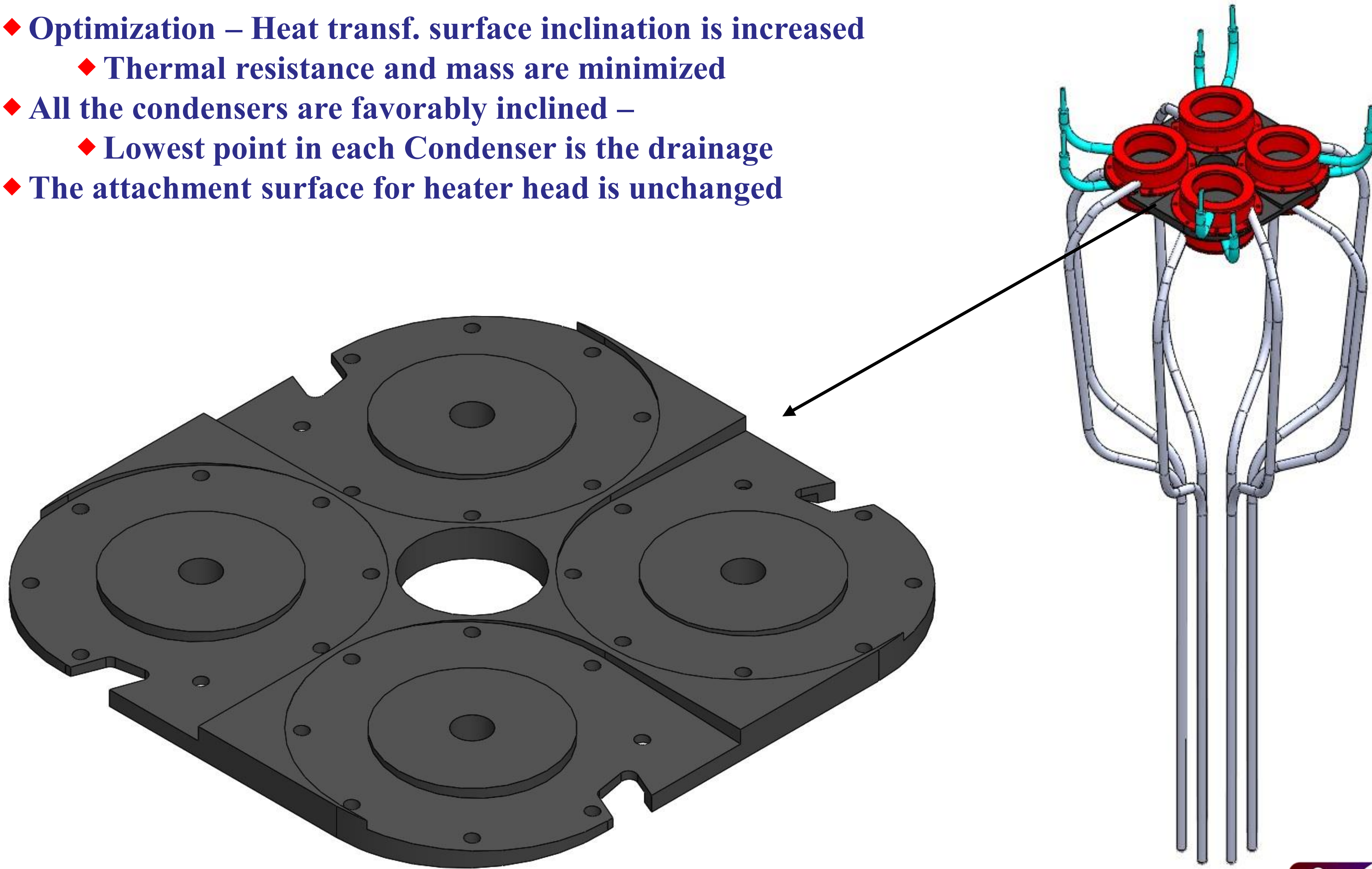


Thermosyphon Improvements

- Another set of 10 heat pipes/thermosyphons will be delivered in August - September 2016
- Two sets of changes were made to improve performance
  - The heat collector plate was redesigned to improve drainage, minimizing the sodium charge
  - The evaporator wick was modified to minimize the sodium pool
- A new prototype with cylindrical condenser was tested to validate the startup with the new evaporator wick
- Startup improved significantly
  - Significantly smaller temperature spikes
  - Shorter duration

- Heat Collecting Nickel Plate -

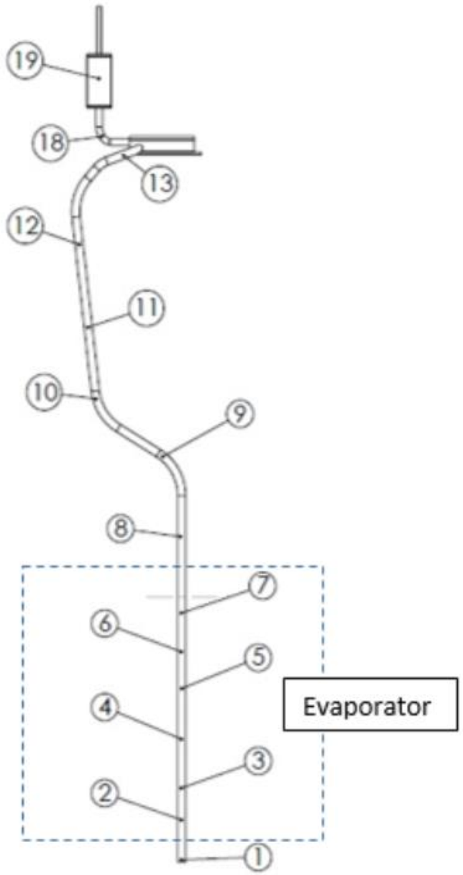
- **Optimization – Heat transf. surface inclination is increased**
  - **Thermal resistance and mass are minimized**
- **All the condensers are favorably inclined –**
  - **Lowest point in each Condenser is the drainage**
- **The attachment surface for heater head is unchanged**

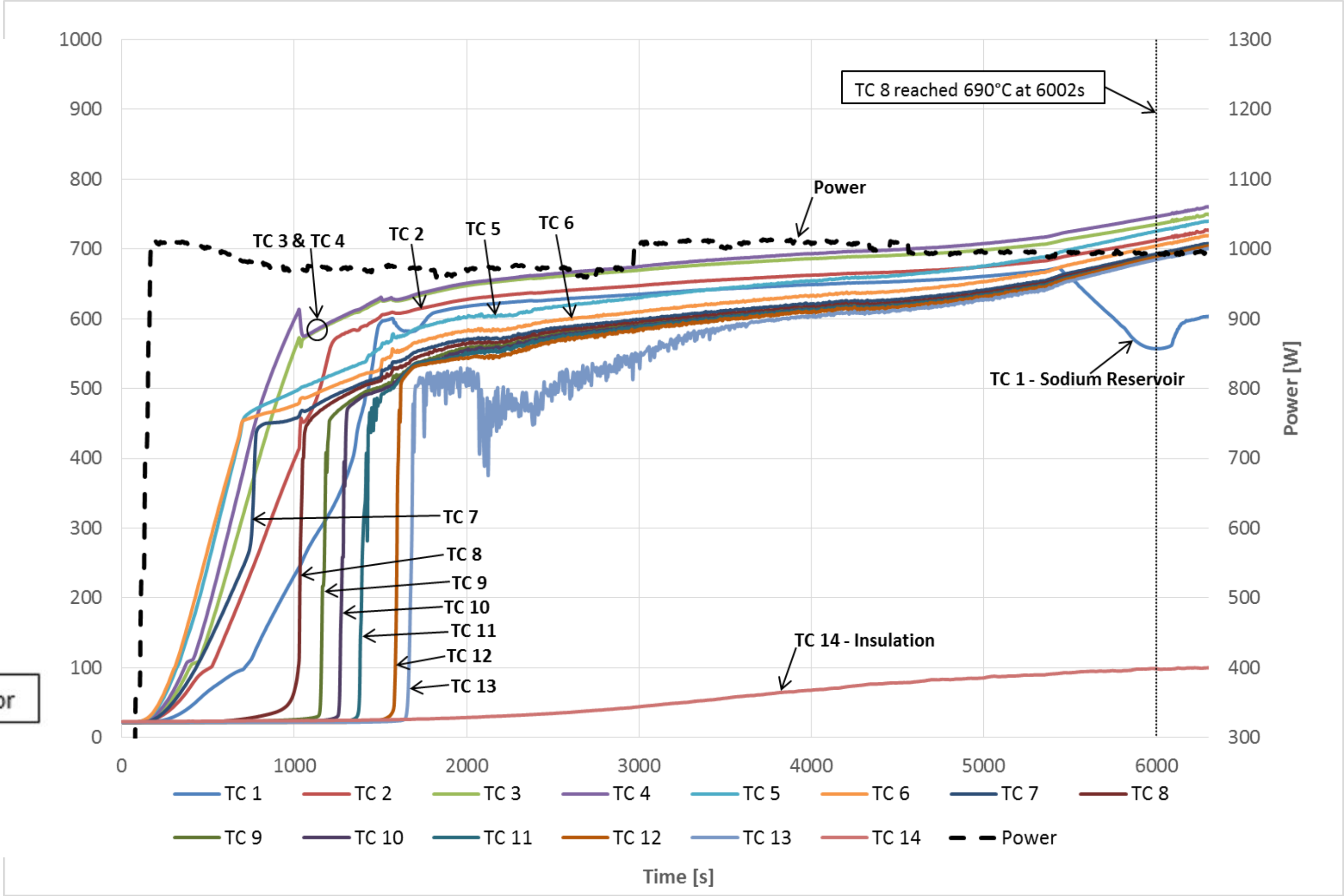


Alkali Metal Pool Boiling

- During operation on Earth, most of the sodium in the wick will drain out of the adiabatic section
  - Limited storage space below the reactor, due to shielding, etc.
  - Large portion of the evaporator is filled with a sodium pool
- Alkali metal pool boilers typically require very large superheats to initiate boiling – can be 100's of degrees
  - Boiling requires nucleation sites with trapped gas or vapor
  - Alkali metal working fluid removes the oxides from the nucleation sites, allowing the fluid to quench most nucleation sites
  - Porous media on the surface helps to reduce the required superheat, but still can require 200° C
- Wick thickness increased in evaporator to hold more of the sodium and reduce the pool height

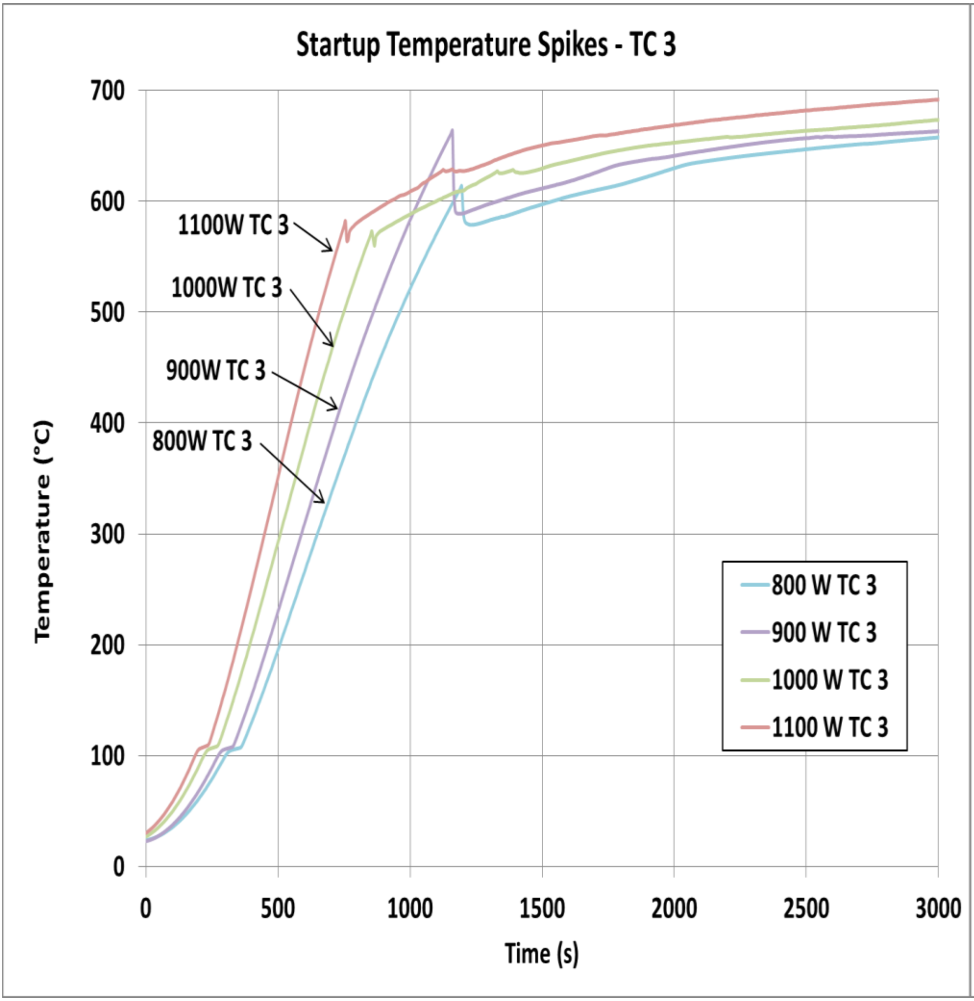
◆ Testing with 1000W startup power

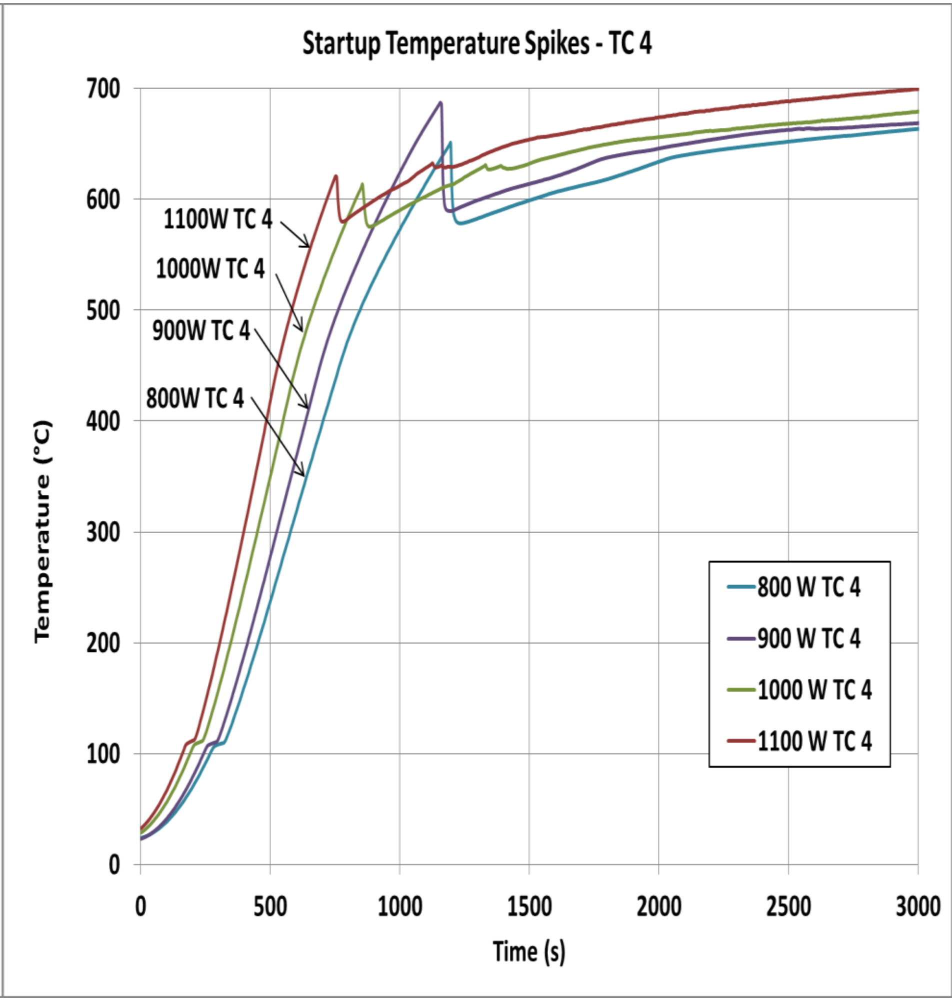




Second Generation Thermosyphons - Startup improvement

- **Smaller temperature spikes.**





Future Work

- The new set of alkali metal pipes is 65% done.
- 6 pipes tested and show good performance:
  - Power
  - Smooth and relatively fast Start up
  - Low thermal resistance in the condenser
    - NCG charge is significantly decreased. It helps only the startup.
    - Condenser is NCG free at nominal temperature (~770C)
- The rest of 4 thermosiphons are instrumented and ready to be charged
- Intended delivery to NASA – end of August 2016

- The fully wicked pipe is under construction
  - Wick changed to hybrid structure grooves and screen

Acknowledgements

- This research was sponsored by NASA Glenn Research Center under Contract No. NNX12CE07P
  - Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration
- Mr. Marc Gibson was the NASA GRC contract technical monitor
- Don Palac allowed ACT to use relevant/updated information/slides about the system
- Tim Wagner, Larry Waltman and Corey Wagner were the laboratory technicians responsible for the development of the self-venting arterial heat pipe

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