Water-Titanium Heat Pipes for Spacecraft Fission Power

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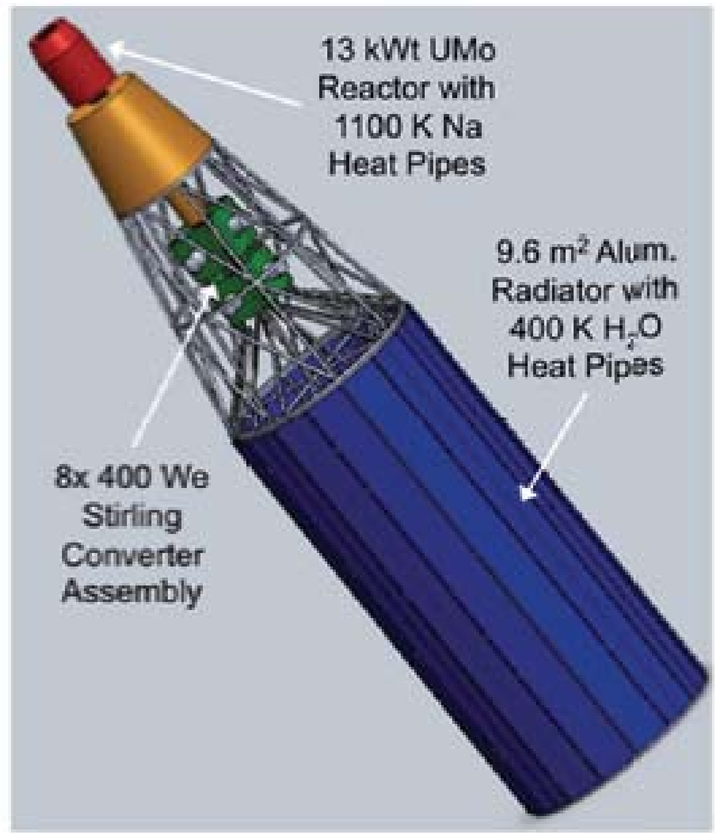
Motivation

- NASA Glenn is examining small fission reactors for future space transportation and surface power applications
  - These Kilopower reactors would have an 8 to 15 year design life that could be available for a 2020 launch to support future NASA science missions
  - Both 1 kWe thermoelectric and 3 kWe Stirling systems have been examined
- Titanium-Water heat pipes have been proposed to transport the waste heat from the Stirling converters to the system radiator.



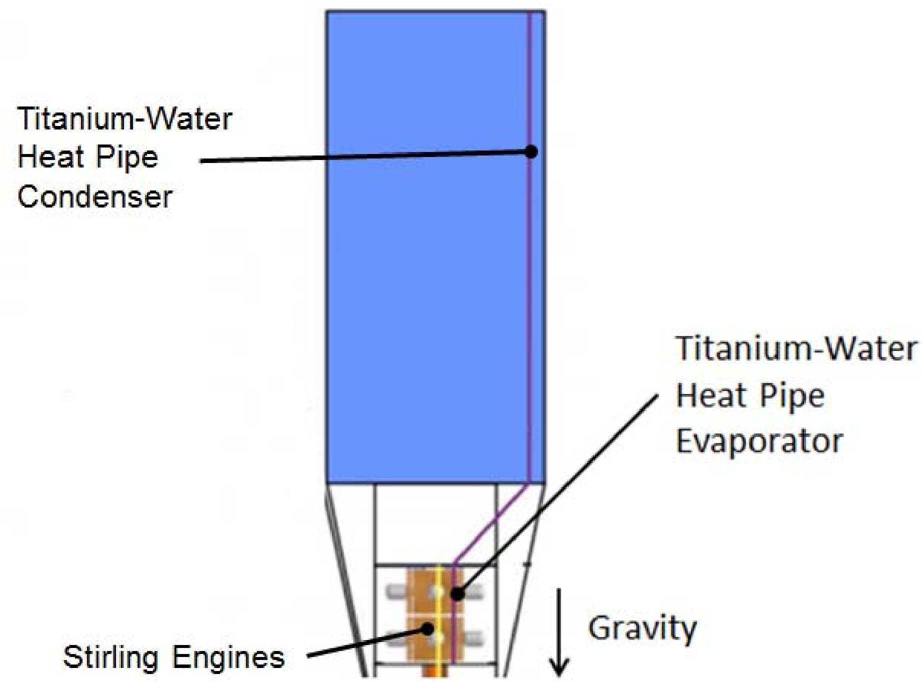
Mason, Gibson, and Poston, 2013

Wicks for Long Spacecraft Heat Pipes

- Previous spacecraft heat pipe designs have neglected ground testability, and assumed a grooved wick
- The Kilopower heat pipes must accommodate four different operating conditions:
  - Operation in space, with zero gravity. Liquid is returned from the condenser to the evaporator by capillary forces in the wick.
  - Operation on earth, with a slight adverse orientation, to estimate performance in space. The heat pipe is operated with the evaporator slightly oriented above the condenser. The adverse orientations are typically 0.1, 0.2, and 0.3 inches.
  - Ground testing, with the heat pipes gravity aided. The heat pipes will deprime in this orientation. Liquid is returned to the evaporator by gravity
  - Launch, with the evaporator elevated above the condenser. The heat pipes will deprime in this condition

Heat Pipe Operation

- During ground testing the heat pipes will operate as thermosyphons, with the evaporator (by the Stirling engines) below the condenser (radiator).
  - During these tests, the grooves and self-venting arteries will deprime
  - A wick in the evaporator is required during start-up, to supply liquid to the evaporator before liquid drips back down from the condenser.



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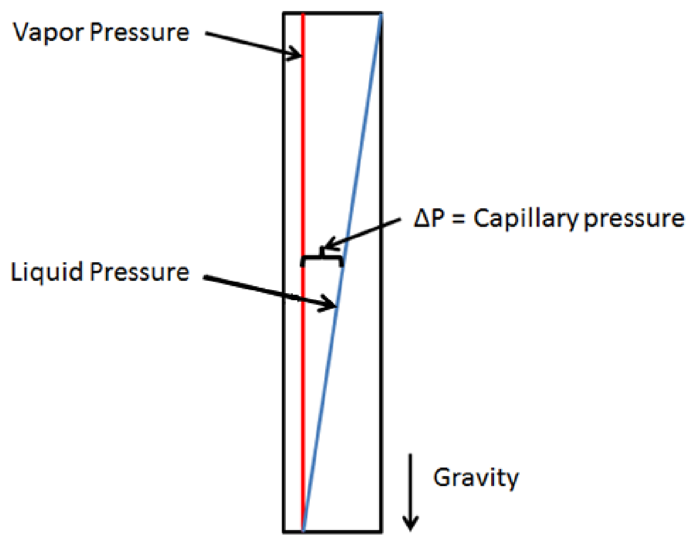
Heat Pipe Operation

- During ground testing the Kilopower system will be oriented so that the wick in the self-venting pipe to deprime due to the variation in liquid pressure along the length of the heat pipe due to gravity
  - In this case, 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



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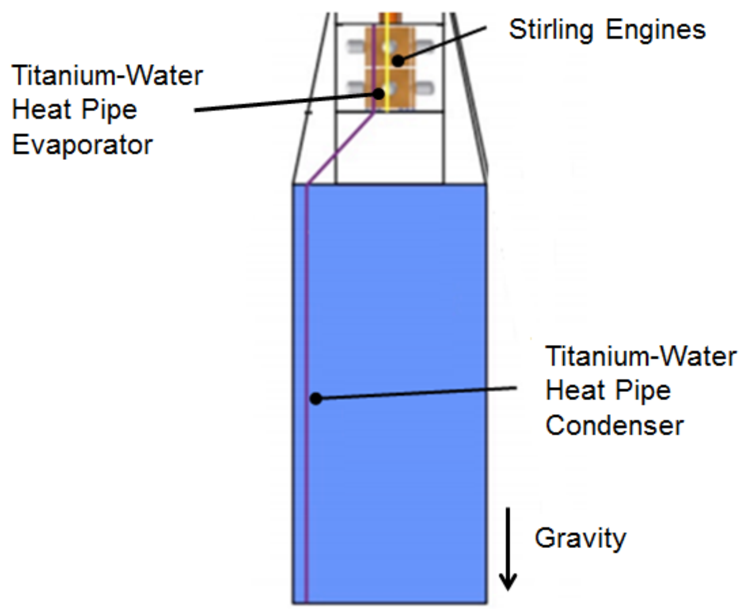
Heat Pipe Operation

- When the Kilopower system is prepared for launch, the system will be oriented such that the evaporator will be above the condenser
  - This orientation will cause the pipe to deprime
  - Once in space the pipe will need to reprime and begin working.
    - The hybrid-wick heat pipe is known to reprime spontaneously.
    - Testing will show that the self-venting arterial pipe will also reprime and start operating



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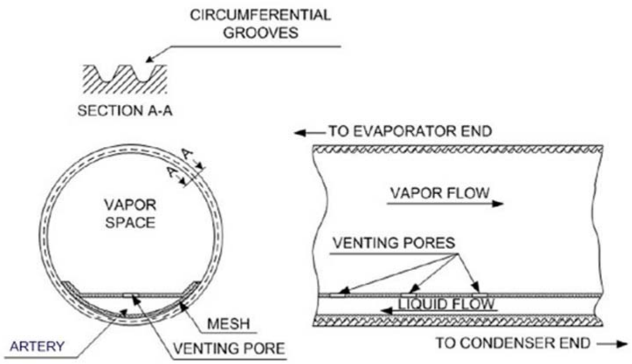
Wicks for Long Spacecraft Heat Pipes

- Four wick designs are suitable for carrying significant power over long distances in space
  - Arterial heat pipes with sintered powder (or screen) wicks
  - Grooved heat pipe wicks
  - Hybrid Grooved Screen wicks
  - Russian self-venting arterial heat pipes.
- Only grooved and self-venting arterial are suitable for this application

d) Grooved Wick



e) Self-Venting Arterial Wick

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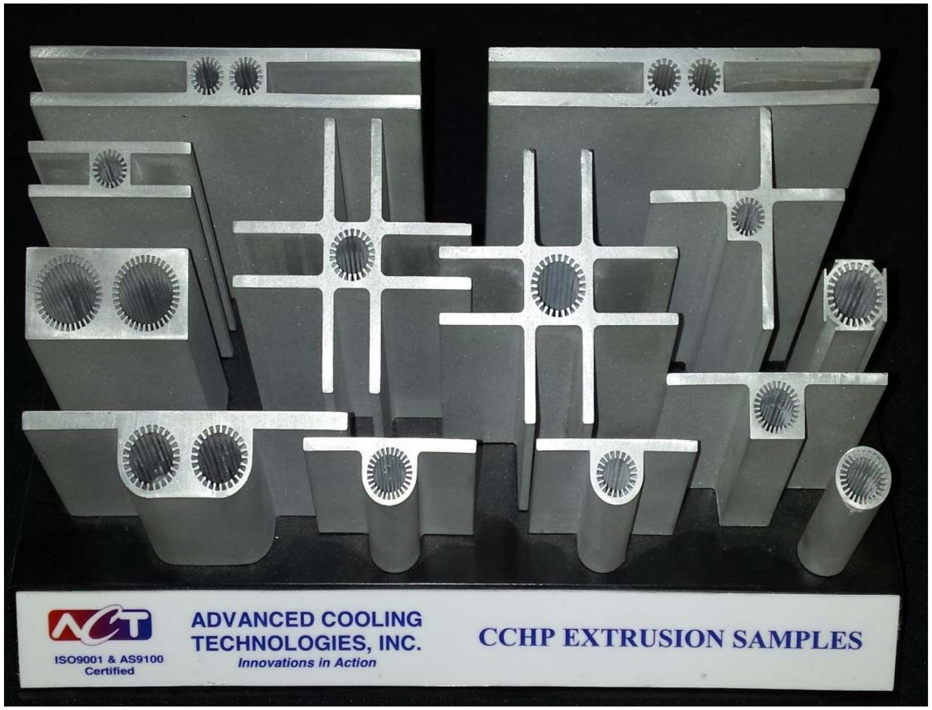
Grooved Constant Conductance Heat Pipes (CCHPs)

- Standard wick used in spacecraft CCHPs, diodes, and Variable Conductance Heat Pipes (VCHPs)
- Benefit of the grooved wick is that it cannot be de-primed by vapor bubbles since the bubbles can vent into the vapor space
- Grooves have a very high permeability, allowing very long heat pipes for operation in zero-g
- Only flaw is that they are suitable only for space or for gravity aided sections of a heat pipe
  - Same large pore size responsible for the high permeability results in low pumping capability
  - Operate 2.5 mm against gravity



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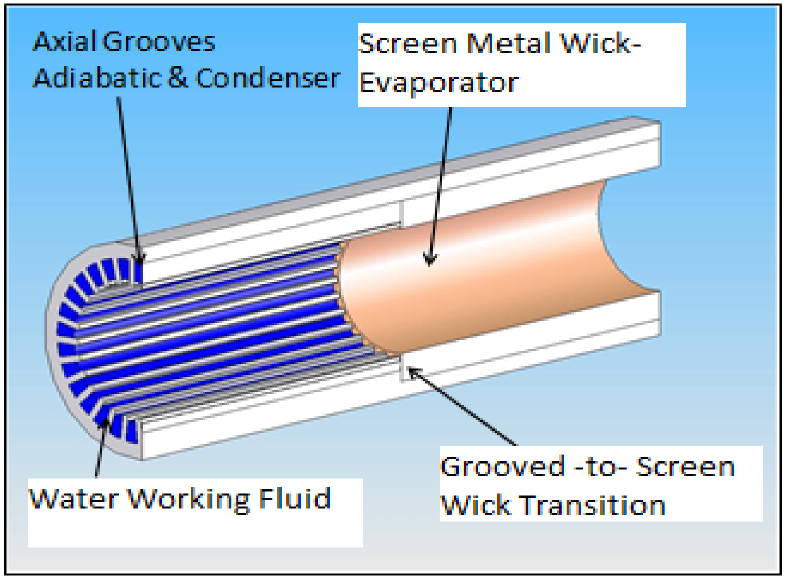
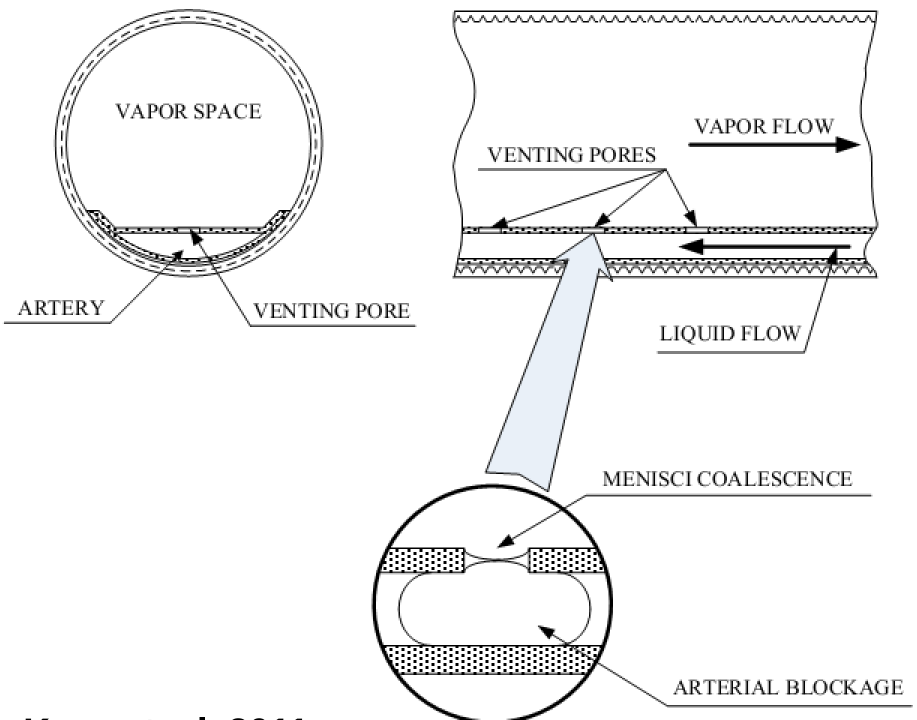
Hybrid Wick: Screened Evaporator – Grooved Condenser

- Advantages of hybrid screened/grooved wick:
  - Screened evaporator aids in startup: traps liquid in a zero-g environment, ensuring there is always fluid in the evaporator for start up
  - Screened evaporator ensures that there is fluid available to the entire heat input area during vertical testing
  - Operate in space
    - Grooved condenser has greater permeability than screened wick
    - Transports heat over longer distances



Self-Venting Arterial CCHPs

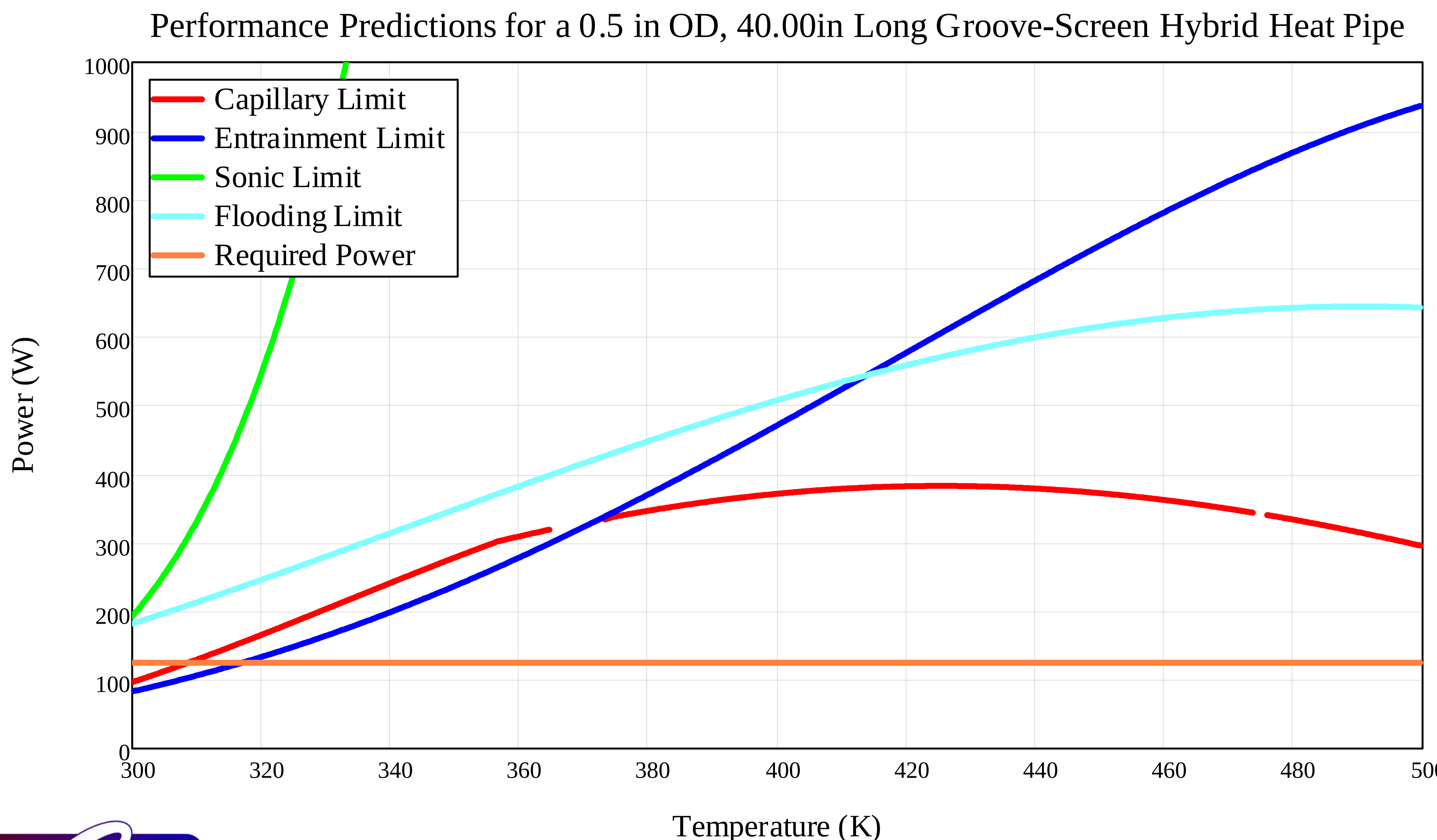


Kaya et. al, 2011

- Artery in this variation of CCHP is created using a screen wick at the base of the heat pipe that creates a single artery for the liquid return flow
- Benefit of a wick with high wick permeability and small pore size and thus a high capillary limit
- 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

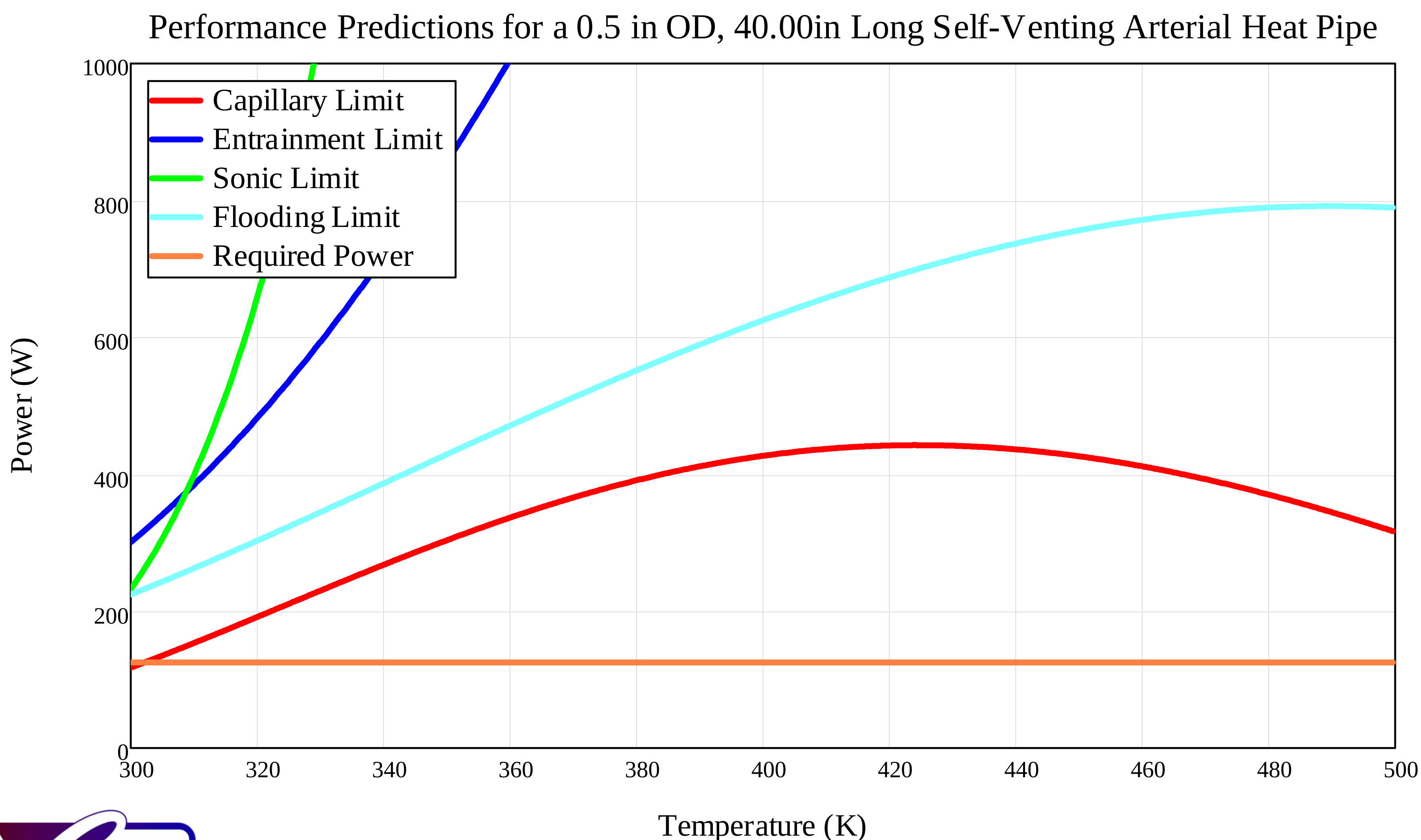
Heat Pipe Design and Fabrication

- Design and fabricate two heat pipe configurations, each roughly 1 m long
  - Self-venting arterial wick
  - Hybrid screen/grooved wick
  - Shorter than Kilopower heat pipes – time and money constraints
- Design considerations
  - Need to accommodate water during vertical testing on earth
    - Will tend to block the evaporator
  - Included a small well and dual wick in the evaporator to mitigate issues from over charging and drainage during vertical testing



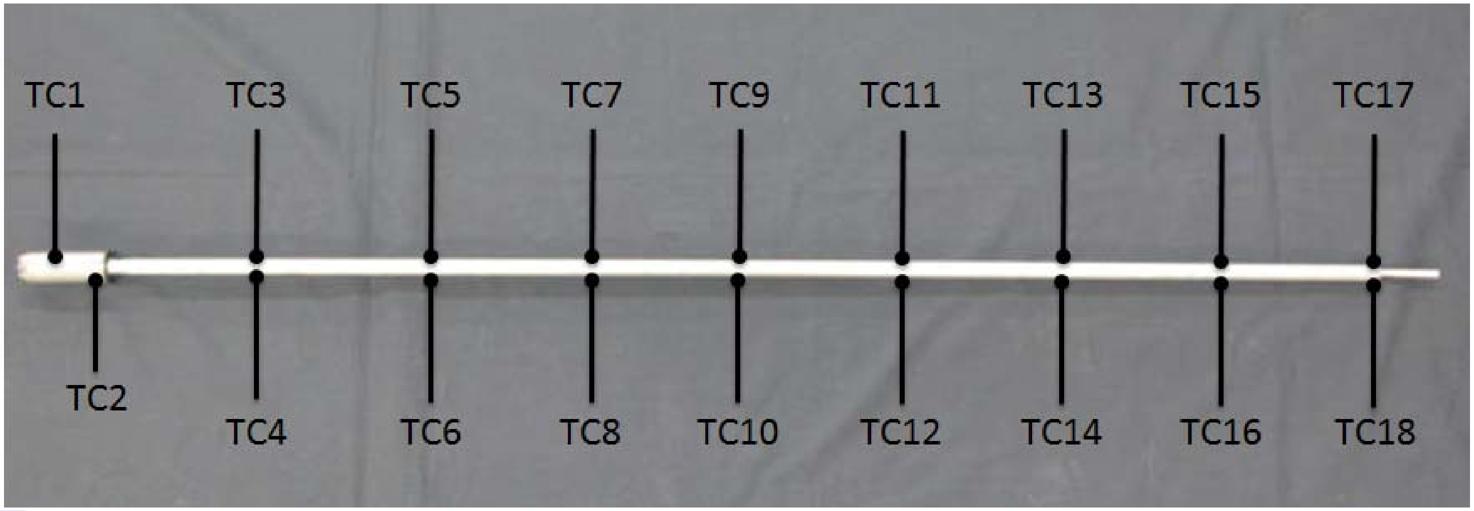
Performance Predictions for a 0.5 in OD, 40.00in Long Groove-Screen Hybrid Heat Pipe
Capillary Limit
Entrainment Limit
Sonic Limit
Flooding Limit
Required Power
Power (W)
1000
900
800
700
600
500
400
300
200
100
0
300
320
340
360
380
400
420
440
460
480
500
Temperature (K)

Heat Pipe Design and Fabrication Self Venting Arterial Heat Pipe



Performance Tests – Test Stand

- The heat pipes were installed on a tilt table capable of both against gravity and vertical testing
- The heat pipes were cooled by forced air which was controlled by the adiabatic temperature reading (TC 3 and TC 4)
- There are two thermocouples in each location for redundancy
- Power is applied to the heat pipe using an aluminum heater block
  – The temperature of the heater block is measured on the outside of the block



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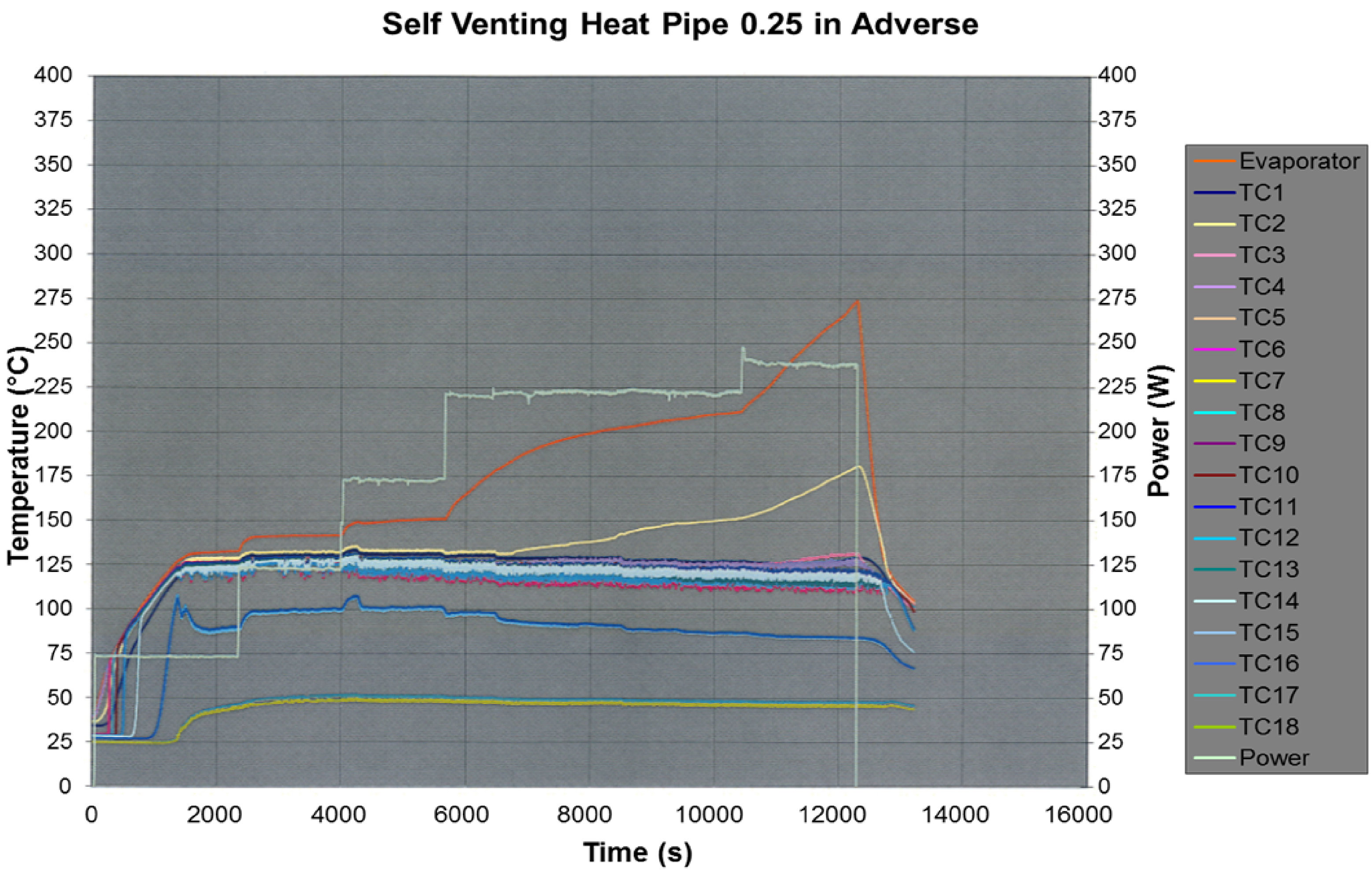
Performance Tests – Self Venting Results



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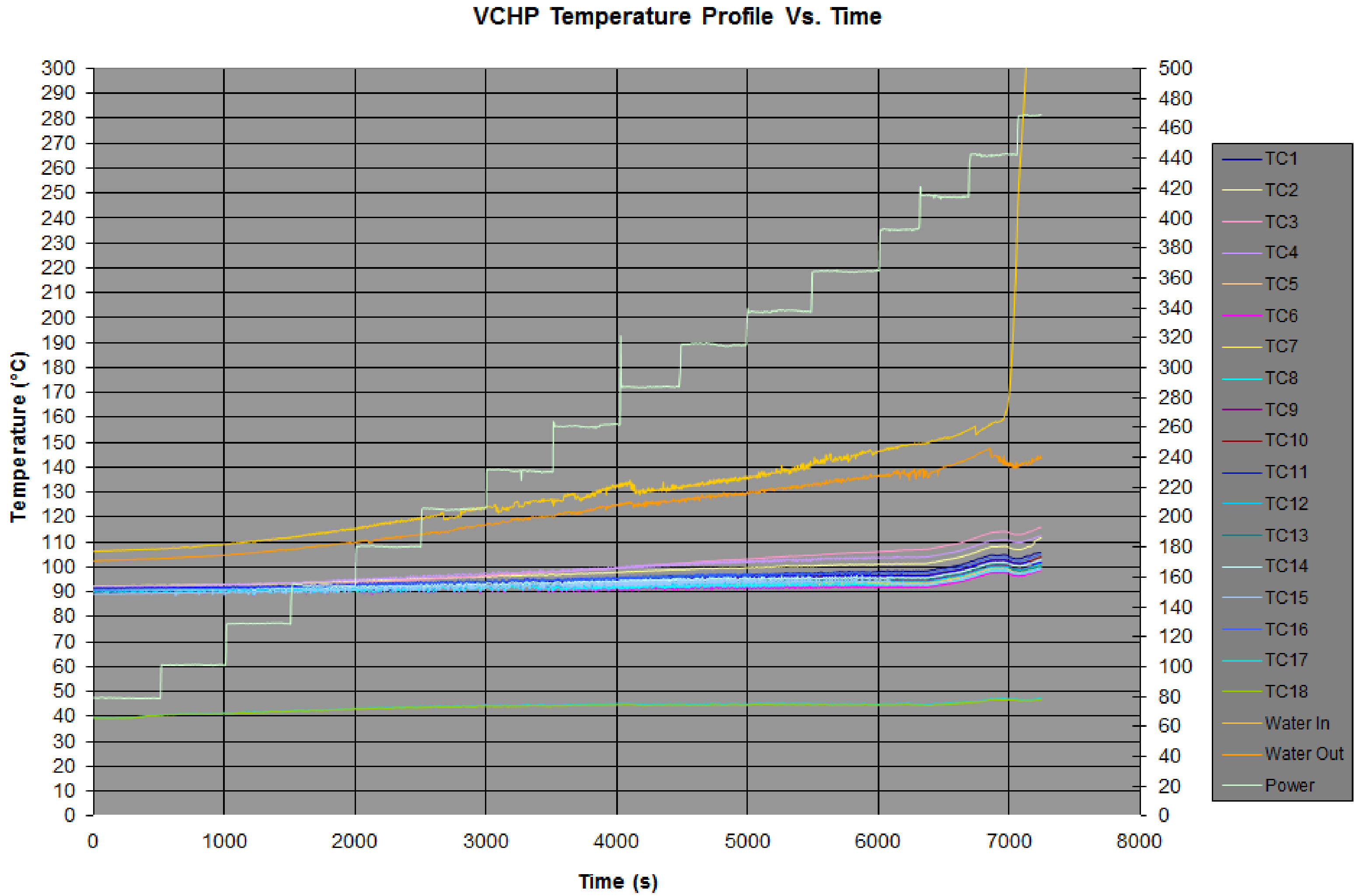
Performance Tests – Self-Venting Results

- The self-venting heat pipe dried out at 225 W at 0.25 in adverse, above the required 125 W but below the predicted 425 W
  - Recent work shows that the pipe was undercharged
- The heater block temperature was higher than the pipe temperature throughout the testing
  - The delta between the pipe and heater block temperature was due to the thermal resistance between the block and pipe
  - The increase in the delta between the block and pipe was due to the CTE mismatch between aluminum and titanium, which increased the thermal resistance with temperature
- Recent work shows that the pipe was undercharged
  - After correcting the charge, the self-venting heat pipe now dried out at ~ 430 W at 0.1 in adverse, above the required 125 W.

Increased Charge – Self-Venting Results



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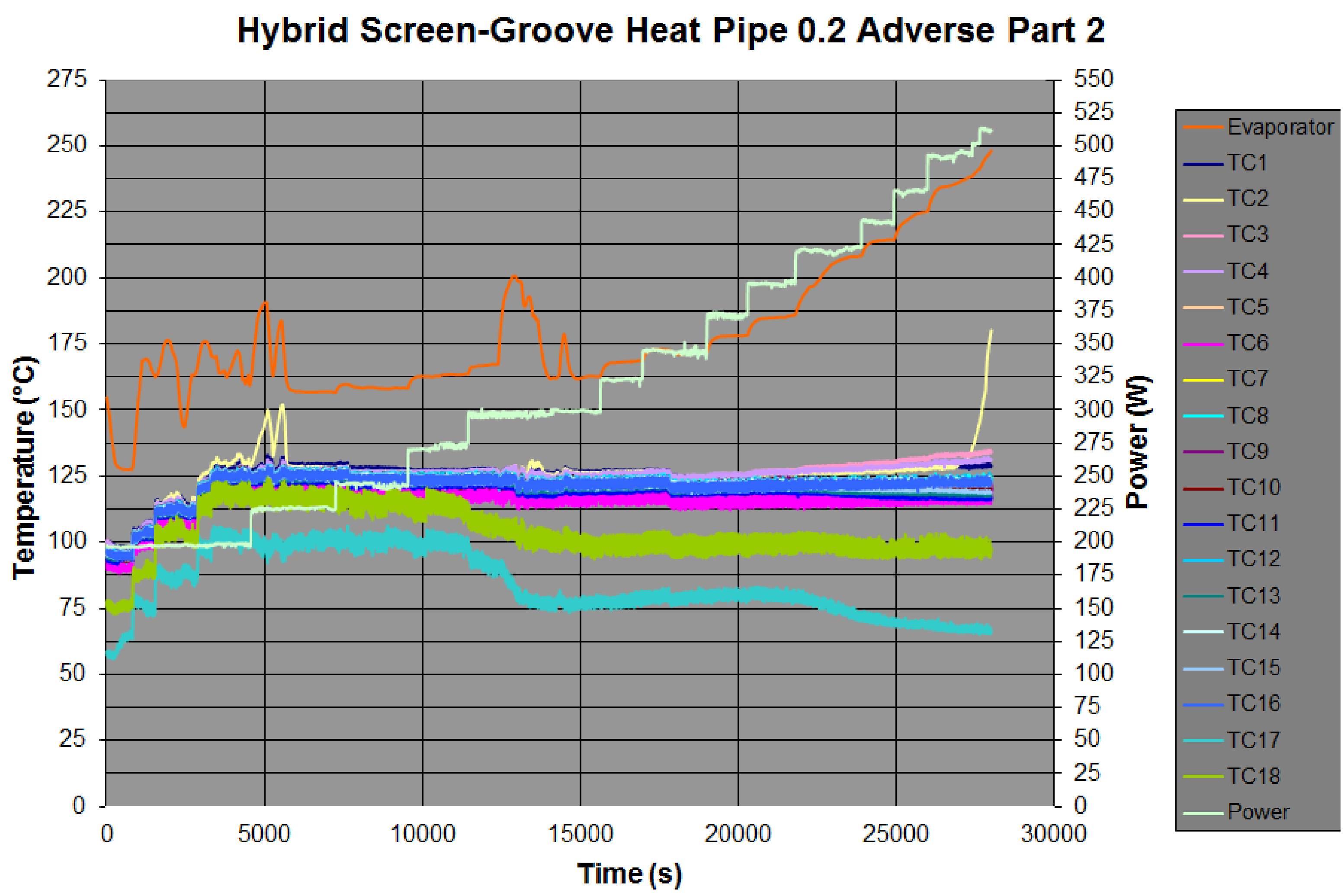
Performance Tests – Hybrid Heat Pipe Results



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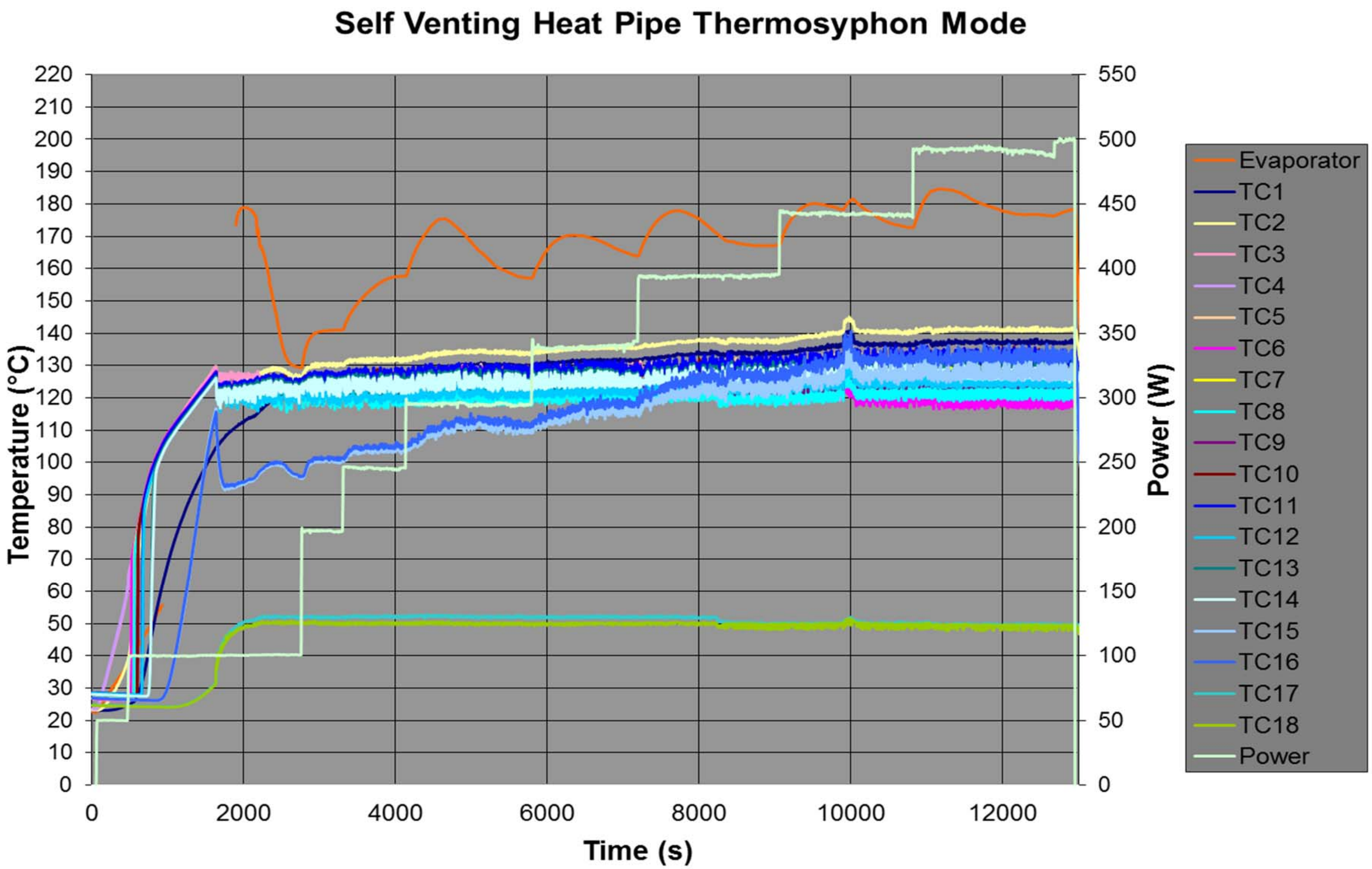
Performance Tests – Hybrid Heat Pipe Results

- The hybrid heat pipe dried out at 475 W at 0.2 in adverse, above the required 125 W and above the predicted 375 W
- The heater block temperature was higher than the pipe temperature throughout the testing
  - The delta between the pipe and heater block temperature was due to the thermal resistance between the block and pipe
  - The increase in the delta between the block and pipe was due to the CTE mismatch between aluminum and titanium, which increased the thermal resistance with temperature

Vertical and Re-priming Tests

- Test to verify the self-venting wick design will reprime after depriming
  1. Deprime the pipe by placing the pipe vertical
  2. Turn the pipe horizontal and apply power
  3. Compare operation to the original performance tests from Task 4
- Test to verify thermosyphon operation of the hybrid heat pipe using the reservoir and screened evaporator

Vertical and Re-priming Tests Self-Venting Thermosyphon Mode



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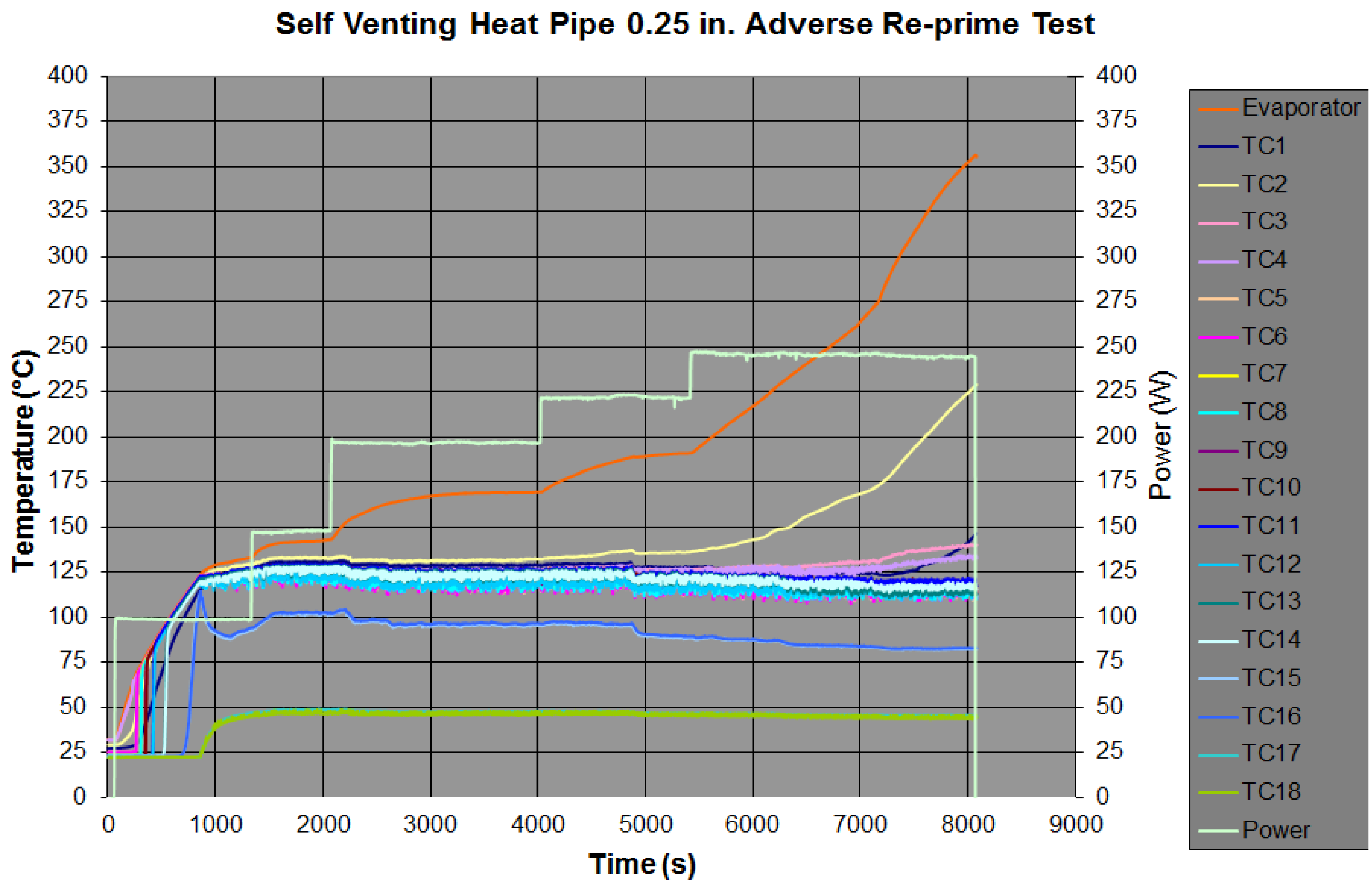
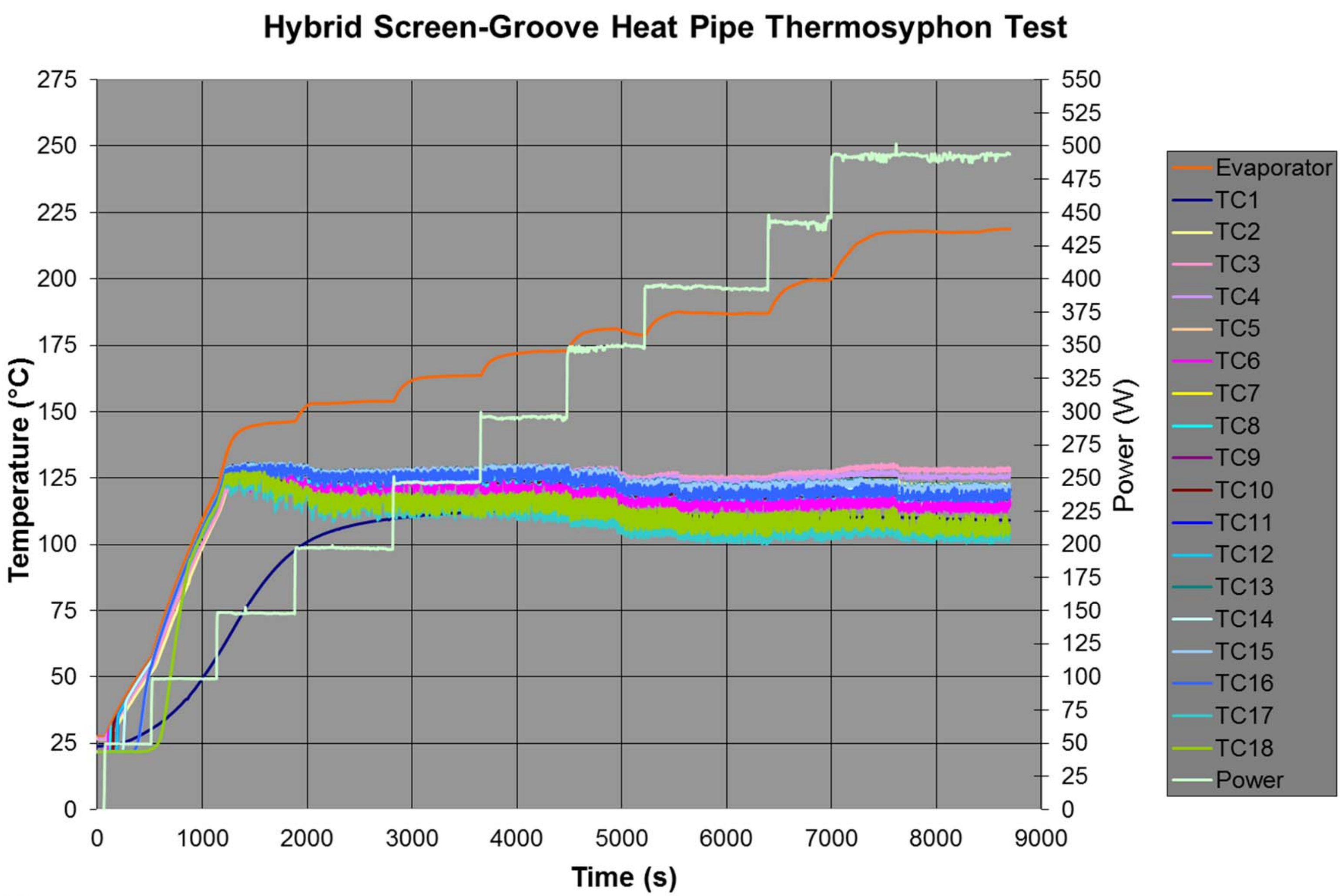
Vertical and Re-priming Tests Self-Venting Re-prime



Vertical and Re-priming Tests Self-Venting Re-Prime Results

- The self-venting heat pipe carried 500 W operating as a thermosyphon. This power was near the capacity of the cooling so the test was stopped
- After de-priming the heat pipe was turned back to 0.25 in. adverse and started
  - No problems were seen during start up
  - The pipe showed the same performance as before the de-prime, drying out at 225 W

Vertical and Re-priming Tests Hybrid Heat Pipe Thermosyphon



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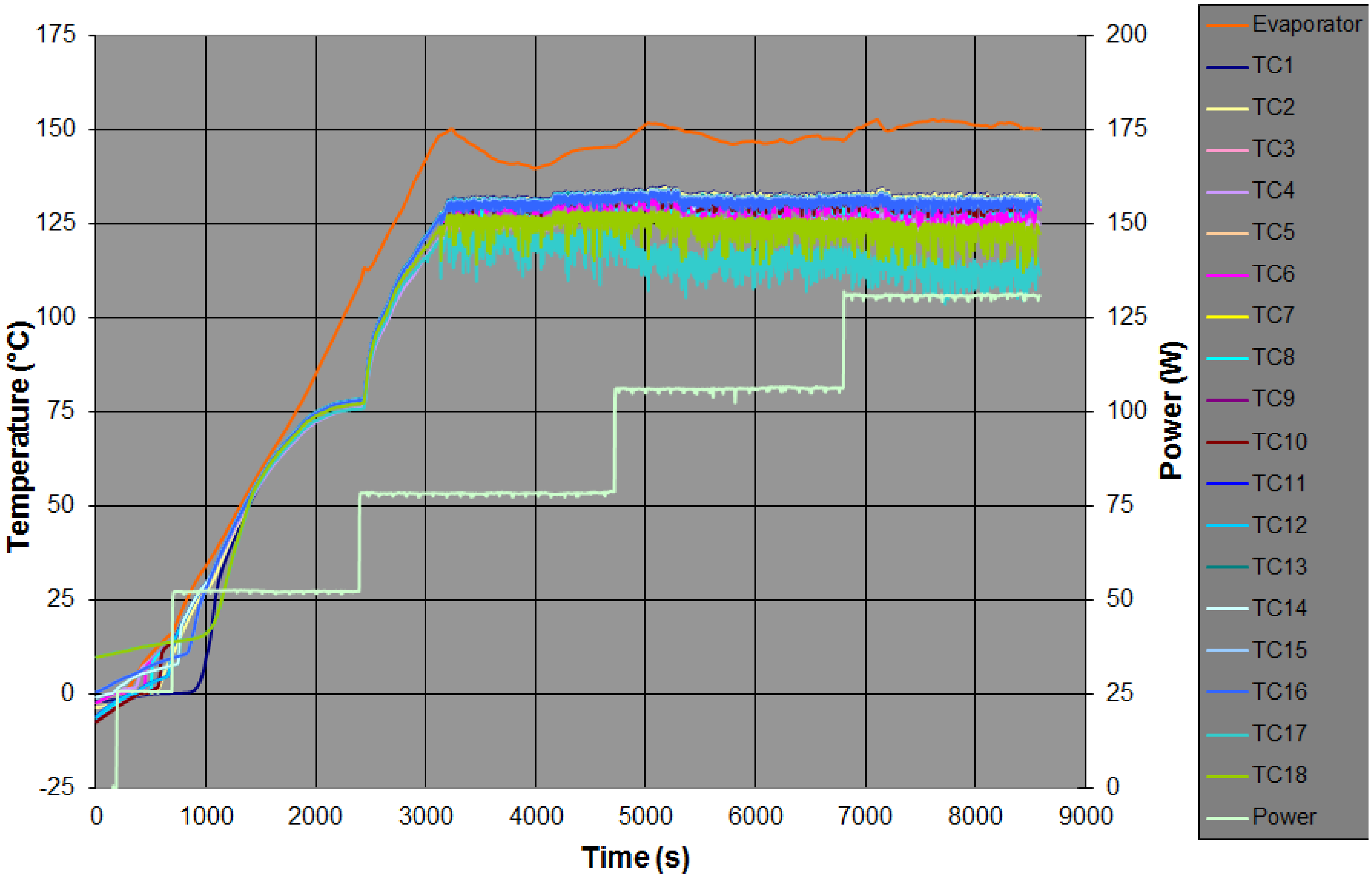
Vertical and Re-priming Tests Hybrid Heat Pipe Thermosyphon Results

- The hybrid heat pipe carried 500 W operating as a thermosyphon. This power was near the capacity of the cooling so the test was stopped
- The hybrid heat pipe showed no problems during start up or operation that would indicate pool boiling or a dry evaporator

Freeze – Thaw Testing

- The heat pipe design for Kilopower will need to withstand freezing and return to normal operation once thawed
- ACT performed freeze – thaw testing to evaluate the response of the two wick designs to a few freeze-thaw cycles
- Both heat pipe designs were evaluated through one freeze-thaw cycle and restarted without any problems

Hybrid Freeze-Thaw Test Results



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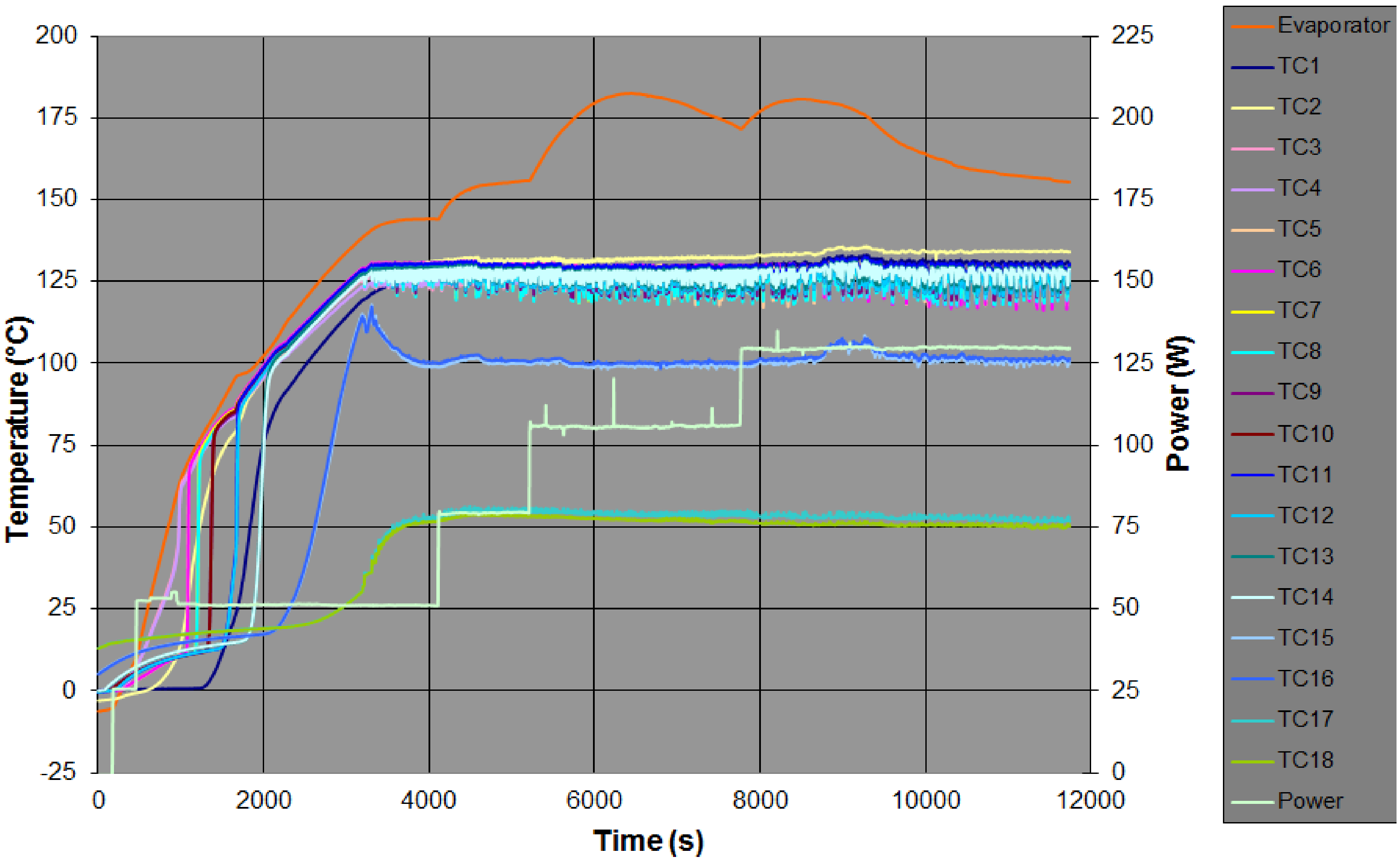
Self-Venting Freeze-Thaw Results

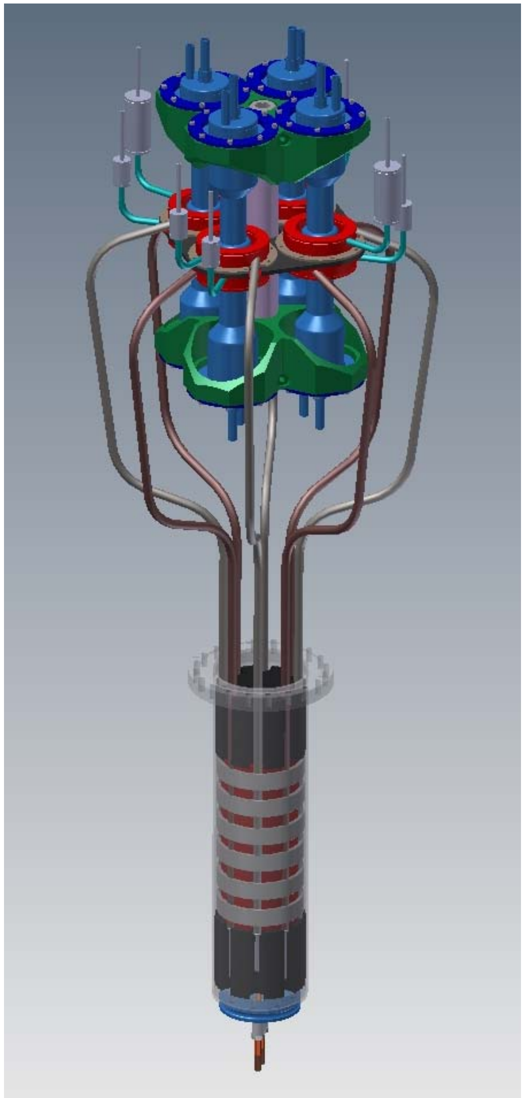


Conclusions

- Both heat pipe designs met the goals of the Phase I project
  - Both pipes successfully carried more than the required 125 W
  - Both pipes operated as thermosyphons without any start up or pool boiling issues
  - The self-venting arterial pipe successfully re-primed after de-priming without any start up issues or loss of capacity
  - Both wick designs survived one freeze-thaw cycle
- The self-venting heat pipe carried less power than predicted
  - Found to be undercharged
  - The dryout power after increasing the charge was ~430 W

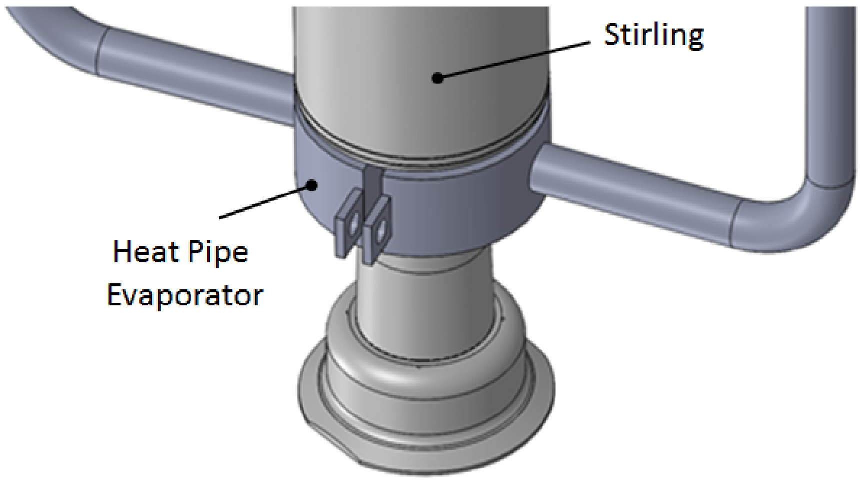
Future Work

- After discussions with NASA Glenn, the hybrid screen/groove wick was selected for future development
  - Similar performance
  - Both screen and grooved heat pipes have been shown to tolerate multiple freeze/thaw cycles.
  - Multiple freeze/thaw cycles with arteries has not been demonstrated
- Overall Phase II objective is to develop full-length titanium water heat pipes that will be suitable for testing with the Stirling convertors chosen for the Kilopower demonstration unit
  - Four Heat pipes/Two Stirling convertors



Future Work

- Design the heat pipe evaporator to interface with the cold end of the Stirling convertor
- Design the radiator
- Extensive freeze/thaw testing
- Fabricate 4 heat pipes with radiator fins



- Testing of the heat pipes at ACT, followed by testing of the heat pipes attached to Stirling convertors at Glenn
- Design of an ISS experiment
  - Simulating heat transfer to a single convertor
  - One alkali metal heat pipe
  - Two titanium/water heat pipes

Acknowledgements

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- We would like to thank Maxwell Briggs and Marc Gibson for their helpful suggestions.

Questions ?

INNOVATIONS IN ACTION
The Thermal Management Experts

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at Lewis Field