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Development of a Low-Cost Radiator for Fission Surface Power Thermal Control

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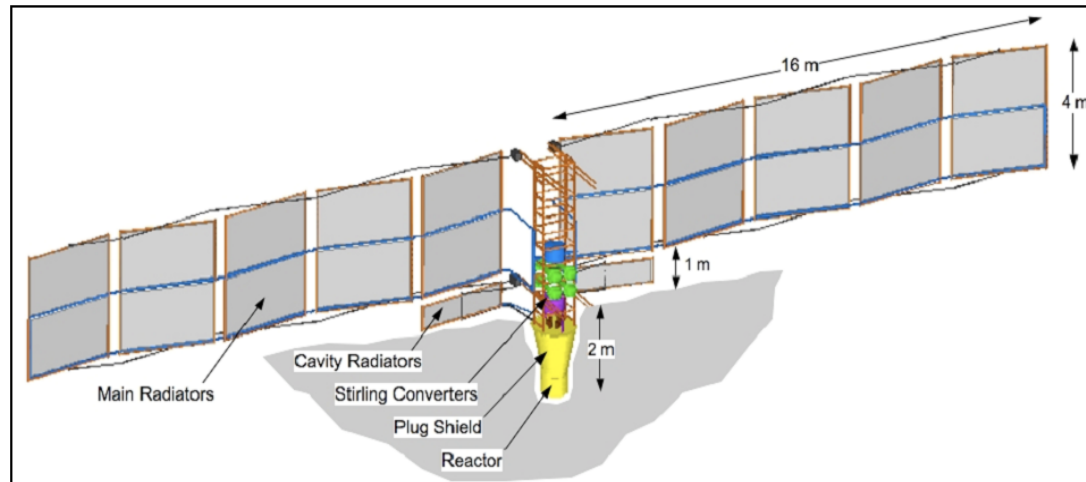
Overview

- ◆ Background
- ◆ Motivation
- ◆ Objectives
- ◆ Summary of Previous Development
- ◆ Heat Pipe Radiator Module Development
- ◆ Radiator Cluster Development
- ◆ Conclusions and Future Steps

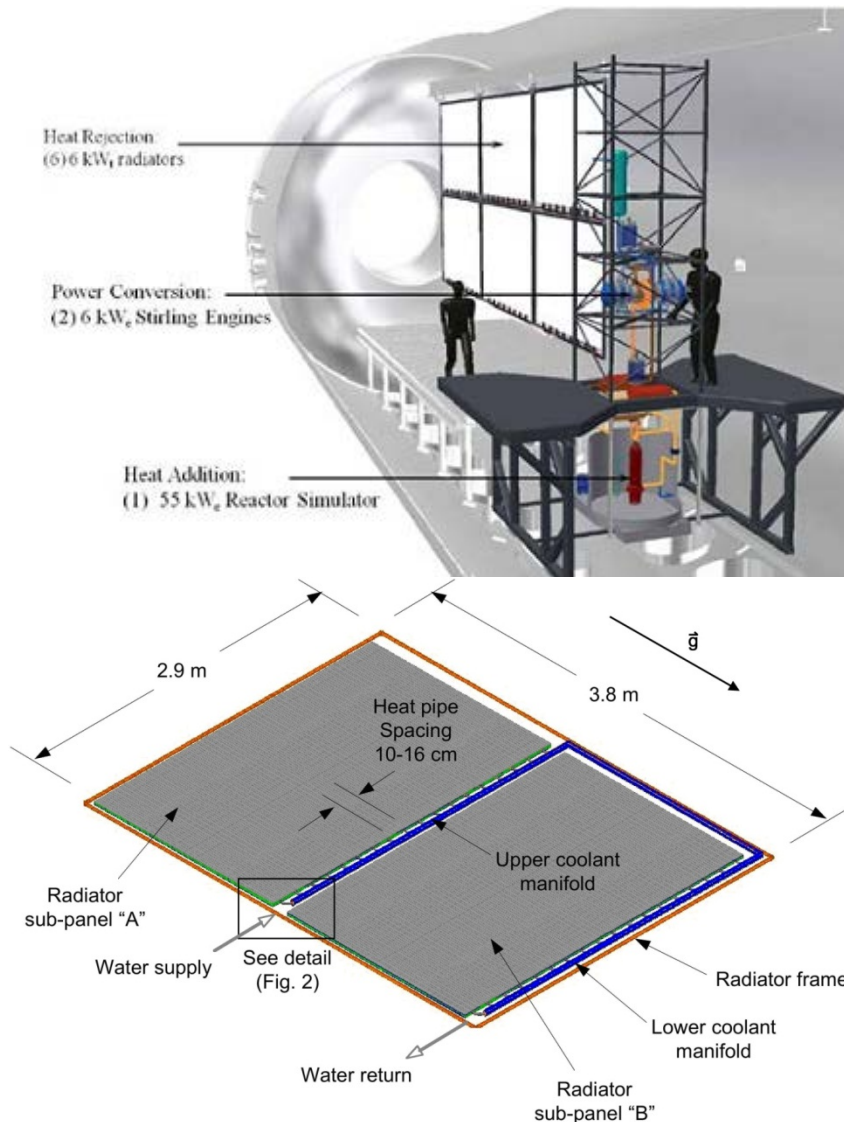


Background

- ◆ NASA Glenn Research Center (GRC) is developing fission power system technology for future space transportation and surface power applications
 - A nuclear reactor supplies thermal energy to electrical convertors and uses a heat pipe radiator to reject the waste heat
 - Heat pipes are vertical thermosyphons due to the need to reject heat from both sides for optimum efficiency
- ◆ The surface systems were envisioned in the 10 to 100kW_e range and have an anticipated design life of 8 to 15 years with no maintenance
- ◆ Goals for the surface systems are light weight, high reliability and long life



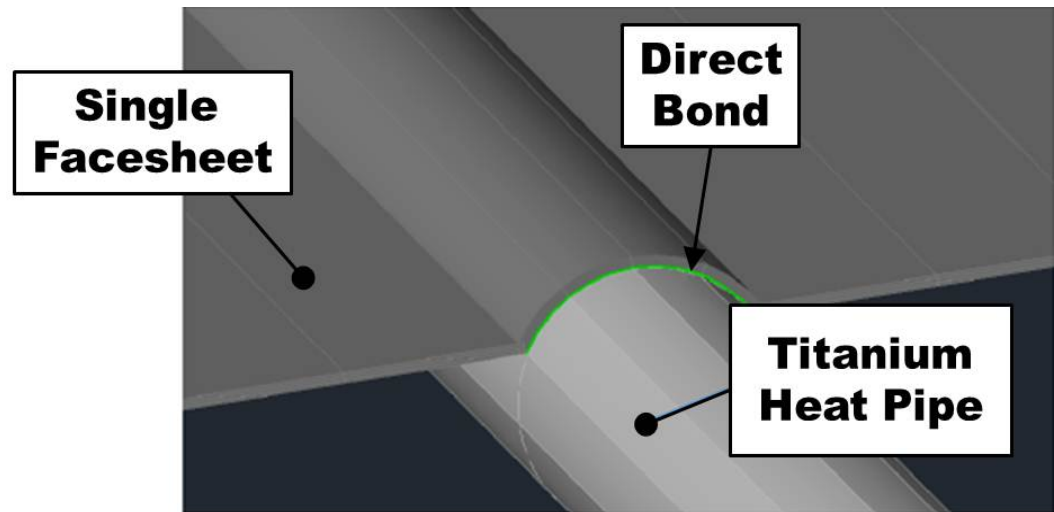
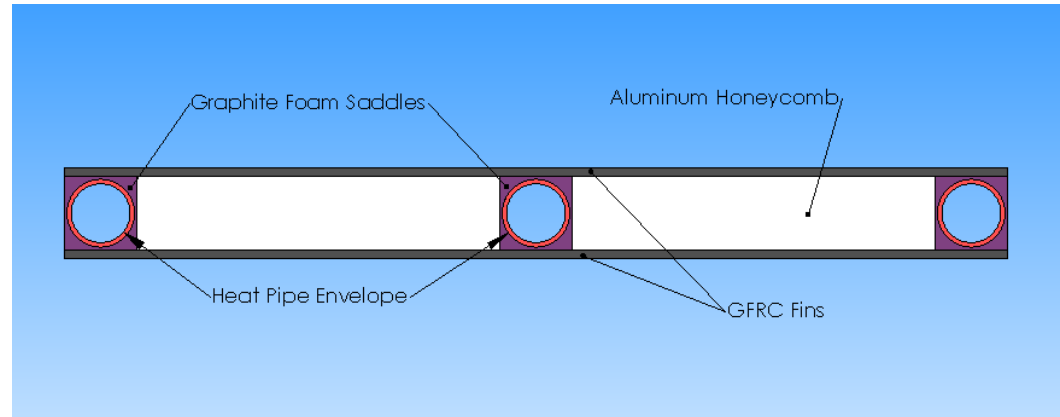
Background



- ◆ NASA GRC is developing a Fission Power System Technology Demonstration Unit (TDU)
 - Non-nuclear unit that will be tested in thermal vacuum to demonstrate integrated system performance
- ◆ Radiator Requirements for TDU
 - Nominal heat load: 36kW
 - Nominal sink temp.: 250K
 - Coolant inlet temp: 400K
 - Max. panel area: 55m²
 - Radiator will experience temperature and power cycling
 - * CTE mismatch must be minimized
 - Specific power must be maximized to reduce associated mass and cost

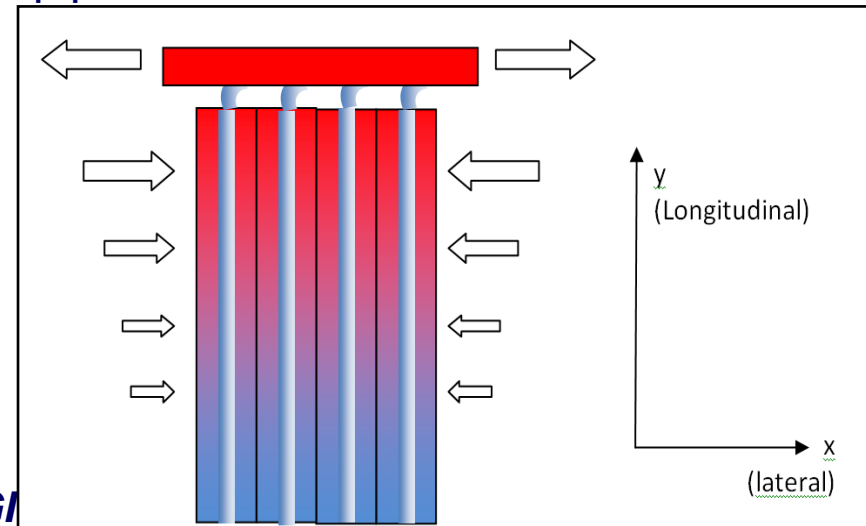
Motivation

- ◆ An improved VCHP radiator for fission power applications will help achieve the OCT goals of reduced mass, improved specific power and reduced cost
- ◆ ACT previously developed a dual-facesheet VCHP radiator for a similar Phase I and Phase II program
- ◆ Mechanical stress testing of a dual-facesheet radiator under the Phase II program demonstrated that direct bonding may be possible
- ◆ A single direct-bond facesheet radiator reduces the overall cost and mass of the assembly



Considerations

- ◆ The VCHP radiator needs to do the following:
 - Operate in the temperature range from 370 to 400 K
 - * Too hot for ammonia
 - Minimize mass
 - Survive multiple freeze/thaw cycles.
 - Accommodate the Coefficient of Thermal Expansion (CTE) mismatch between the titanium heat exchanger and the Graphite Fiber Reinforced Composite (GFRC) panel face sheets
- ◆ Titanium CTE: $8.6 \mu\text{m/m-K}$
 - GFRC CTE must be matched along heat pipe axis
- ◆ Negative CTE in GFRC perpendicular to heat pipes
 - Coiled adiabatic section to accommodate CTE mismatch



Objectives

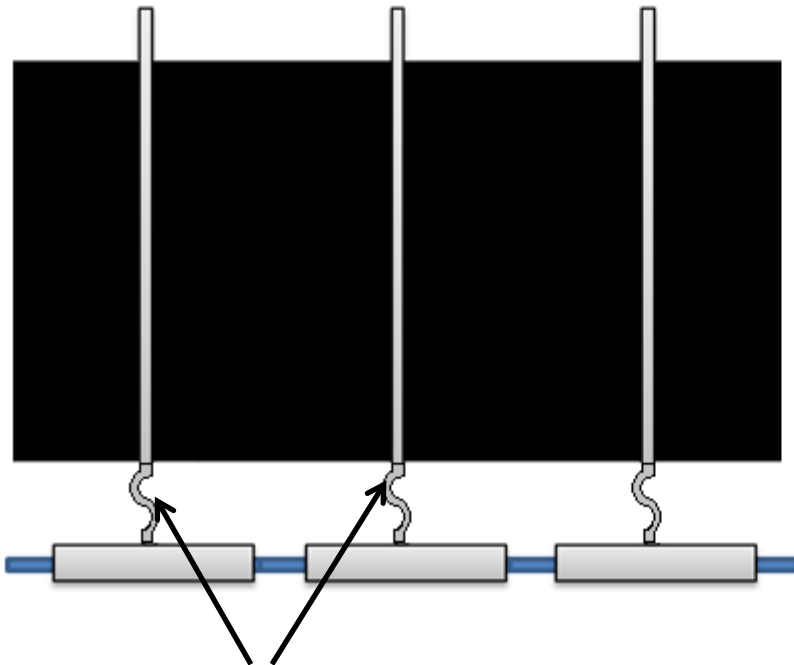
- ◆ **Overall Objective:** Develop low-cost radiator panels that are suitable for integration in NASA's TDU.

- ◆ **Phase II Objectives:**
 - Validate the design developed in Phase I
 - Demonstrate a heat pipe radiator module
 - Demonstrate one cluster by testing in vacuum at GRC
 - Fabricate and test in ambient the full the set of clusters



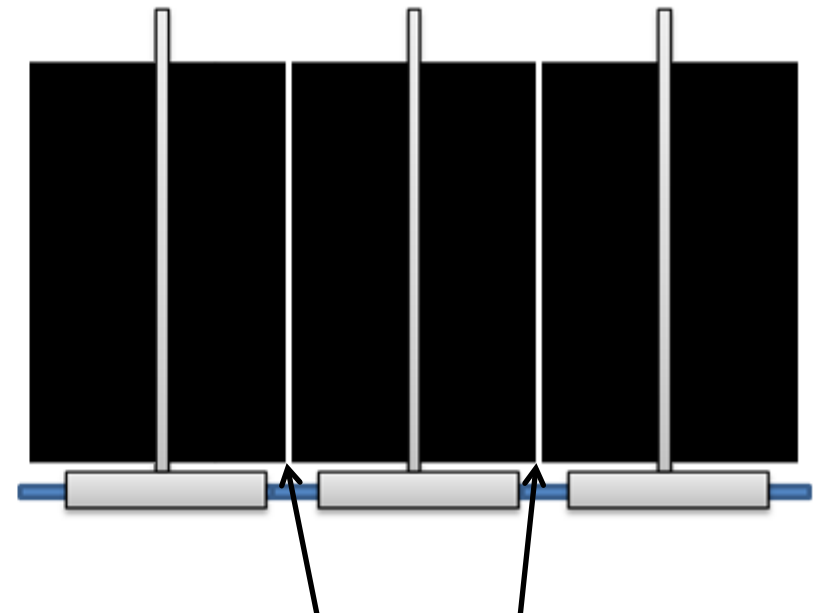
Preliminary Design: Sub-Panel vs. Modular Radiator Design

Continuous Sub-Panel Design
(More efficient if a heat pipe fails)



Helical adiabatic bends used to compensate for CTE mismatch between facesheet and manifold

Modular Sub-Panel Design
(Cheaper to fabricate and no CTE mismatch issues)



Minimal gap between adjacent modules



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Advantages of Modular Sub-Panel Design

◆ Thermal/Structural Advantages

- CTE mismatch in the horizontal direction (along the manifold) is no longer a concern
- The adiabatic section can be straight (no helical bends) and the length can be minimized or eliminated
- Modular units are easier to test and validate proper VCHP operation, since there is no thermal influence from adjacent modules

◆ Fabrication, Cost, and Logistical Advantages

- Eliminates cost of helical bends
 - * No alignment issues
- Minimizes risk of damaging the radiator when installing into TDU
 - * Avoids stresses in large continuous sections of facesheet
 - * If a module is damaged, it is easier and cheaper to replace
- During lamination and bonding, waste of GFRC is minimized
- Modular units are easier to ship



Disadvantages of Modular Sub-Panel Design

◆ Disadvantages

- If one pipe/fin module fails, the fins are useless since they don't offer a heat conduction path to the neighboring pipe/fin modules
 - *As a consequence, the level of redundancy must be increased

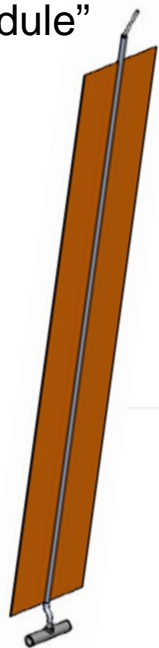
◆ Solution

- Since the elimination of the adiabatic sections would increase the specific power beyond the original (continuous sub-panel) design, there is potential to add redundancy to the system by adding more heat pipe/radiator modules

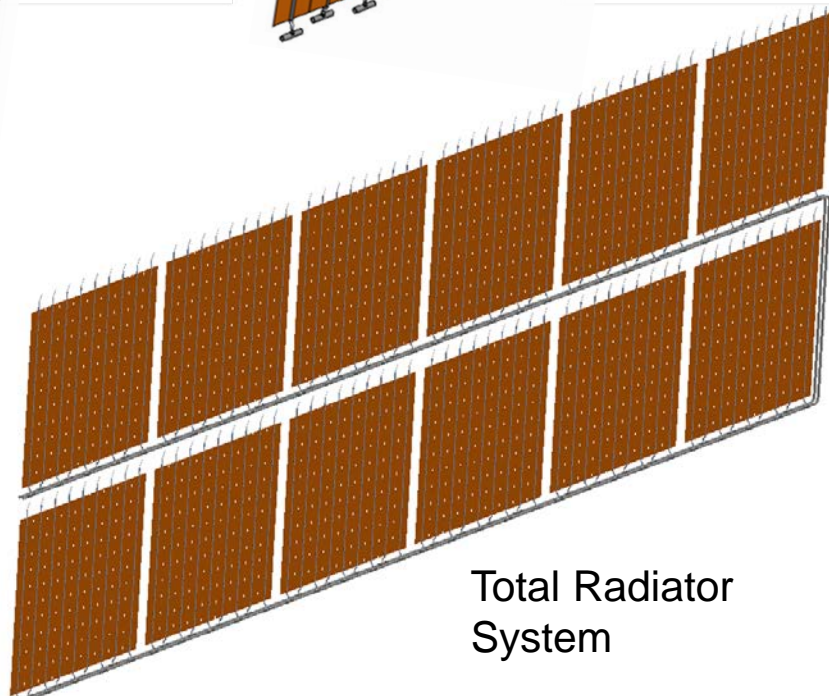
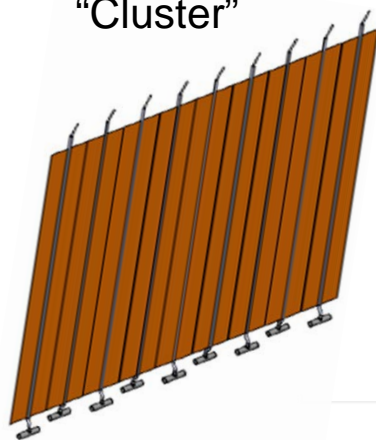


Full Scale Design

“Module”



“Cluster”



Total Radiator System

Geometry

Evaporator Length (cm)	12.67
Adiabatic Section Length (cm)	5.08
Condenser Length (cm)	170
Fin Width Overhang (cm)	12
Total GFRC Area (m ²)	46.5
Total Number of Heat Pipe Modules	108
Total Number of Heat Pipe Clusters	12
Number of Redundant Heat Pipes	3

Thermal Performance and Mass

Total Power Output (kW)	41.8
Specific Power (W/kg)	741.7
Mass of Single Heat Pipe/Fin Module (kg)	0.523
Total System Mass (kg)	56.38
Total Temperature Drop from Coolant to GFRC Root (°C)	19.1

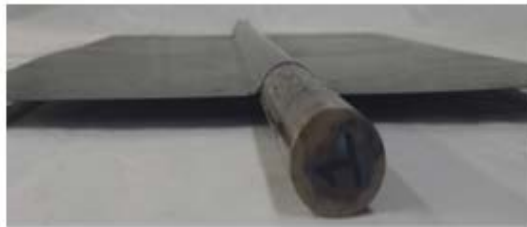
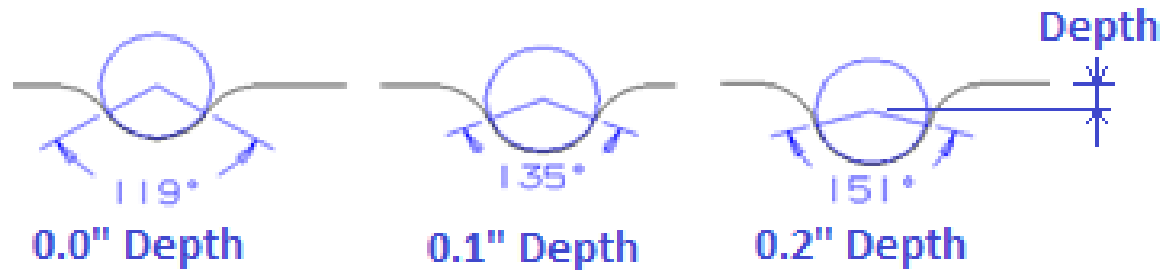


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Direct Bond Development - Summary



0.00" Depth



0.10" Depth

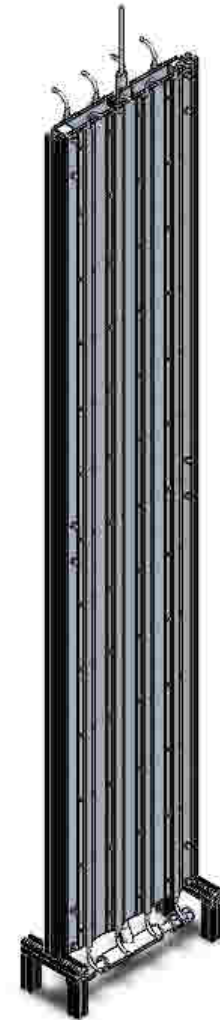


0.20" Depth

Vanguard process optimization focus was to maximize the bond contact area and minimize composite fiber breakage. Three designs were evaluated by fabricating one short pipe-radiator section of each design. This required tooling the plate used for module and cluster assembly.

Module Performance Testing

The module was tested inside the vacuum chamber with an aluminum cold wall on either side of the pipe. The pipe was tested under vacuum before and after thermal cycling, and also under ambient conditions.



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Module Performance Testing

- Summary -

Vacuum

- ◆ Testing in vacuum before thermal cycling. Power delivered ~ 380 W in nominal conditions – Sink: -23°C, Water inlet temperature: 127°C, Water flow rate: 3GPM
- ◆ Testing in vacuum - thermal cycling – 7 cycles
- ◆ Testing in vacuum – post thermal cycling, Power delivered ~ 380 W
 - Evaporator length was 5.5 inches

Ambient

- ◆ Testing in ambient the 5.5 inch evaporator module – 500W (sink was ambient)
- ◆ Testing in ambient the 7 inch evaporator module: 25% higher than the 5.5 inch evaporator module (sink was ambient)



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Radiator Cluster Development

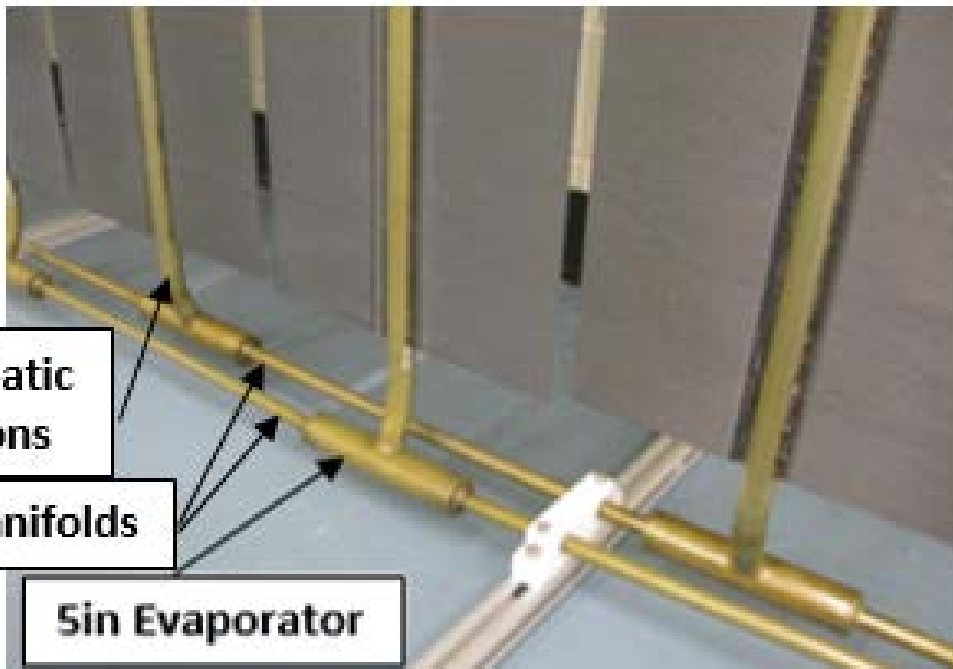
- ◆ Eight Clusters were delivered to NASA GRC (twelve was the initial number)
 - Two Clusters have short evaporators
 - Six Clusters have long evaporators
- ◆ Cluster 1 was tested in:
 - Ambient at ACT
 - Vacuum at GRC
- ◆ Clusters 2-8 tested in ambient at ACT (including thermal imaging)
 - Before pinching
 - After pinching



Cluster Fabrication and Testing

The first cluster (short evaporator) was tested in:

- Ambient at ACT
- Vacuum at GRC

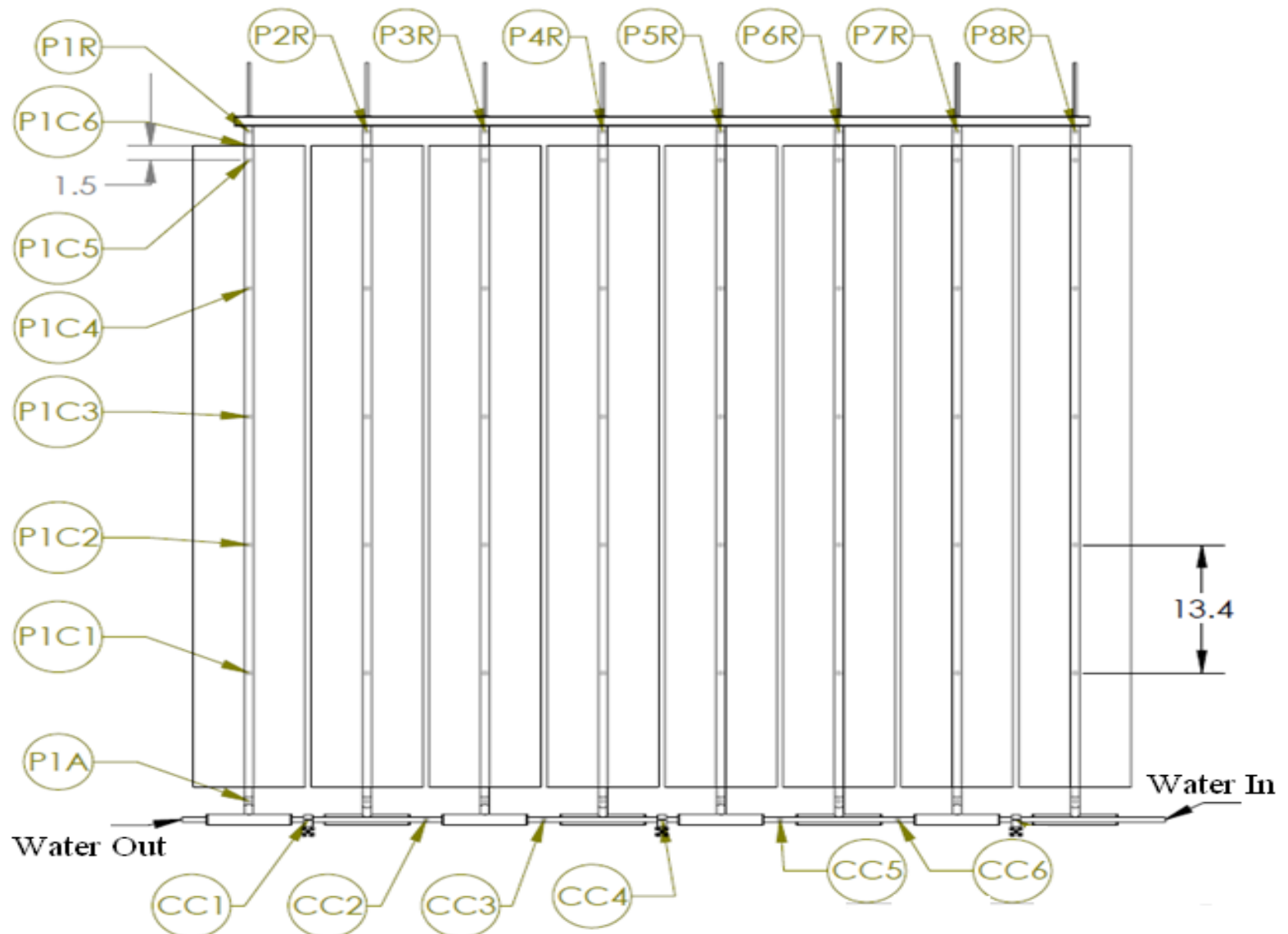


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Cluster Testing – Thermocouple Map



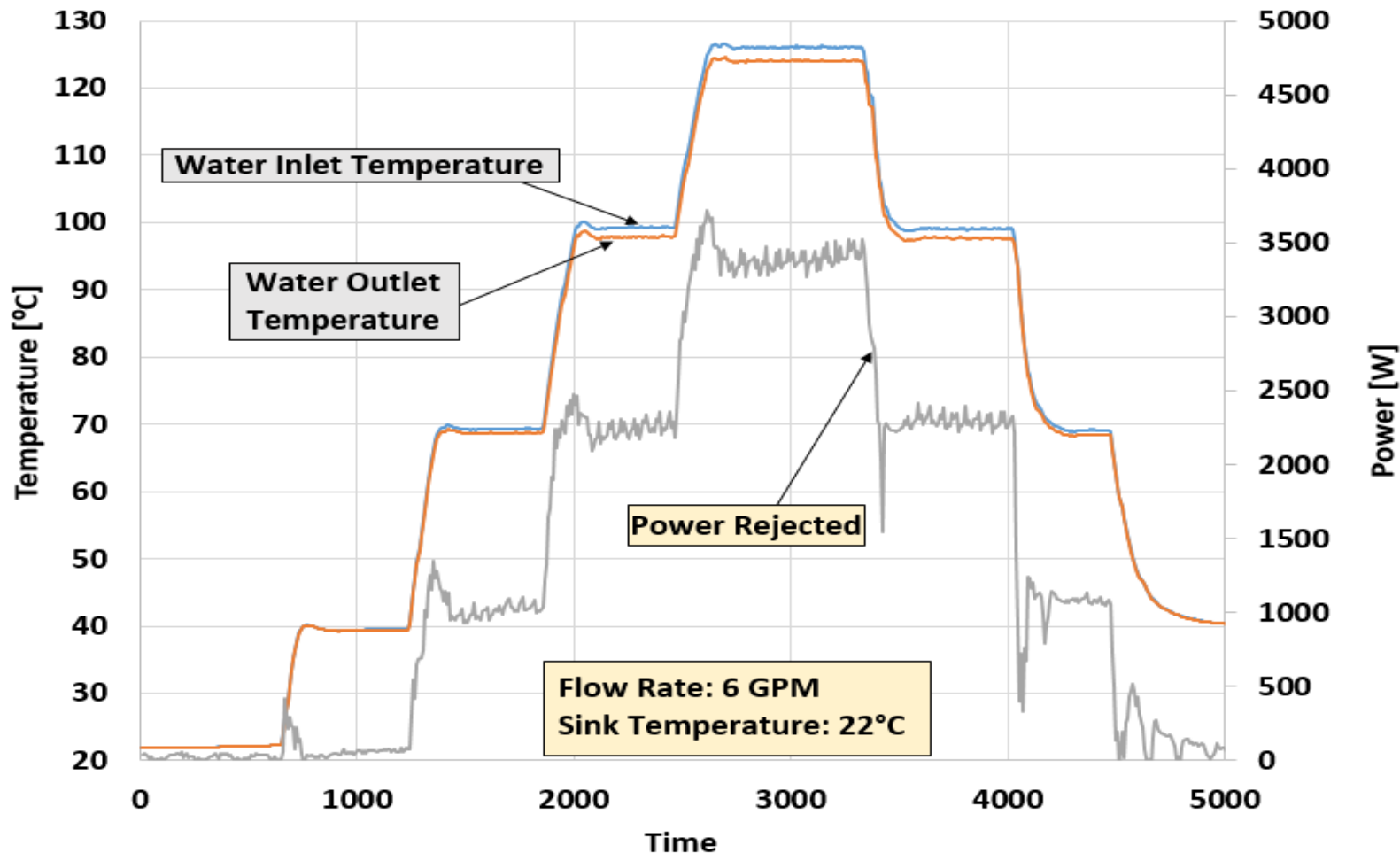
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Module Development Cluster Testing at ACT - Ambient

- ◆ 3.5 kW of power are rejected into ambient
 - NCG charge is slightly larger – 3.5 KW is conservative



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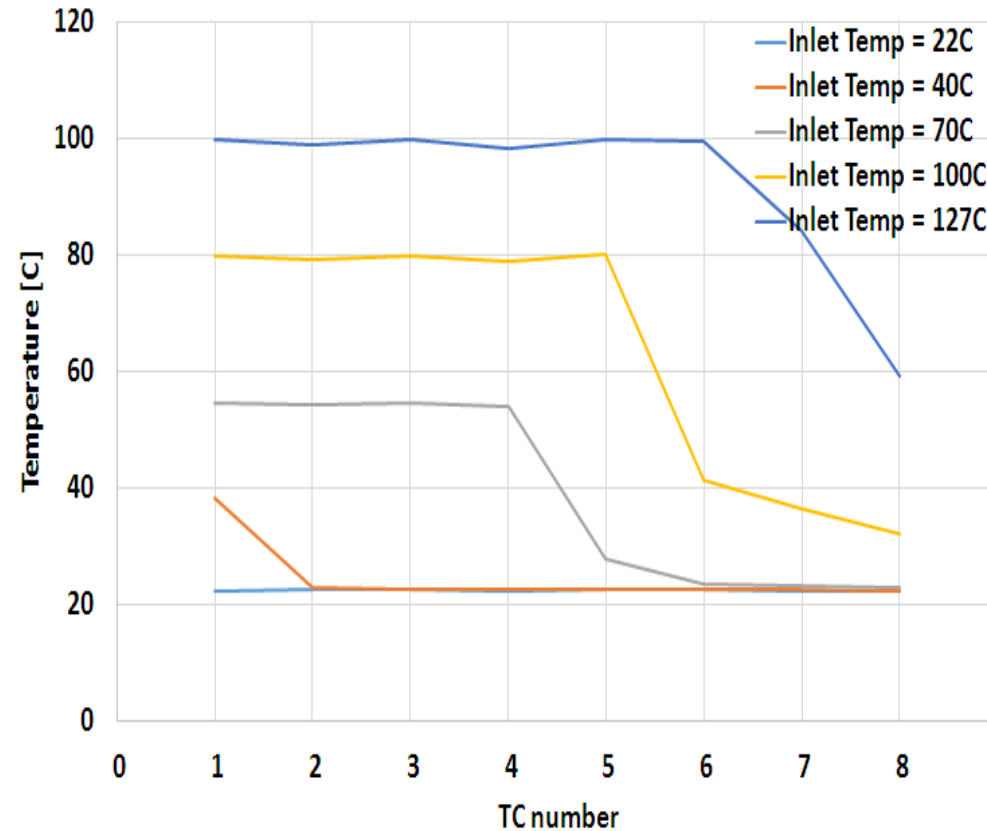
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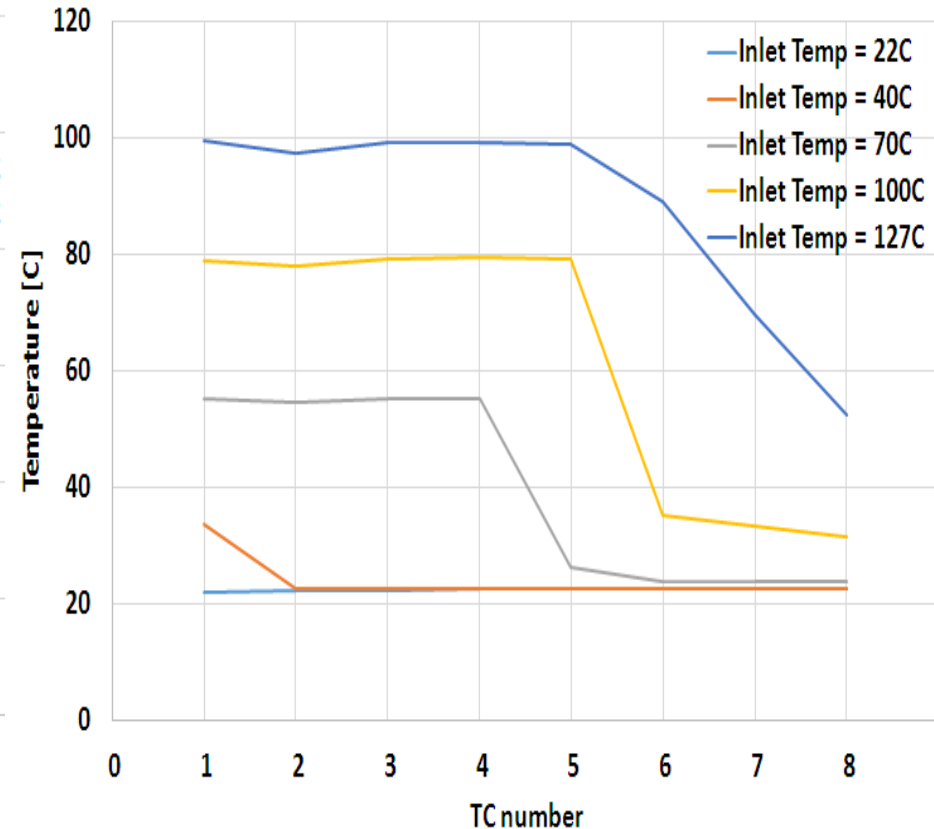
Cluster Testing at ACT - Ambient

◆ VCHP behavior

Pipe 1



Pipe 2



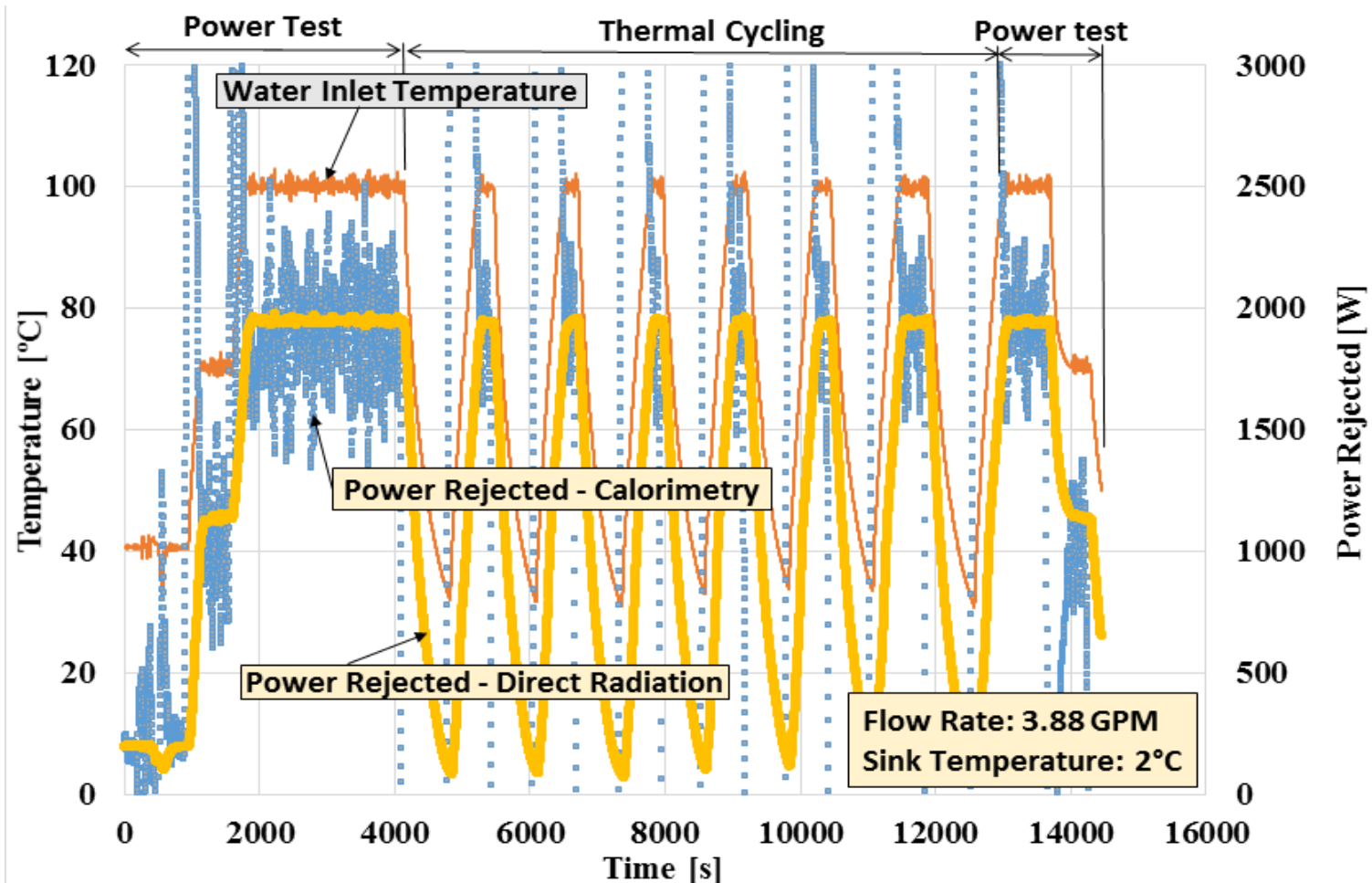
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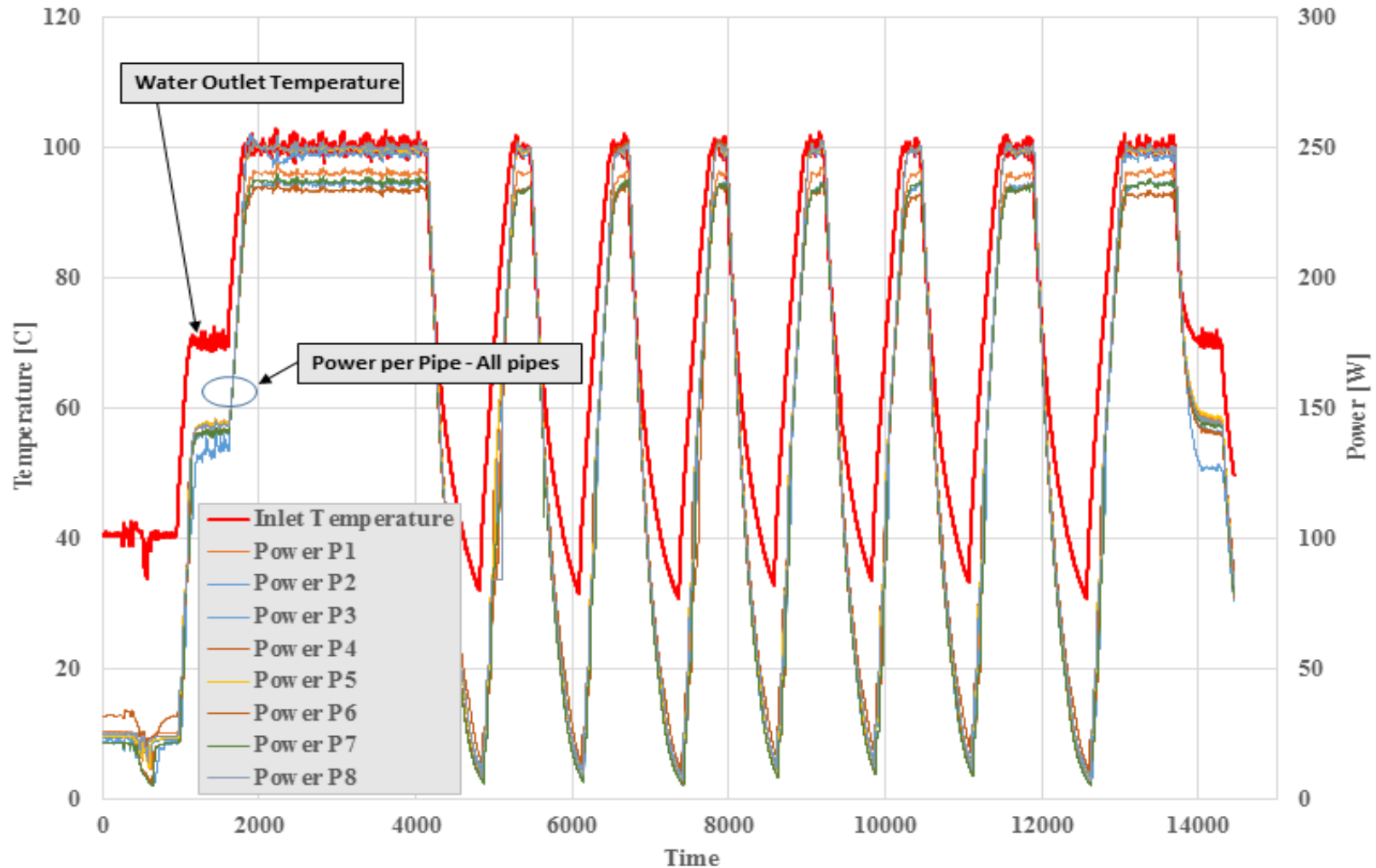
Cluster 1 Performance Testing – Vacuum First Round

- Conservative factors: lower inlet temperature, higher sink temperature, small evaporator, lower flow rate, too much NCG – **1.95 kW** of rejected power before and after thermal cycling



Cluster 1 Performance Testing – Vacuum First Round

- Conservative factors: lower inlet temperature, higher sink temperature, small evaporator, lower flow rate, too much NCG



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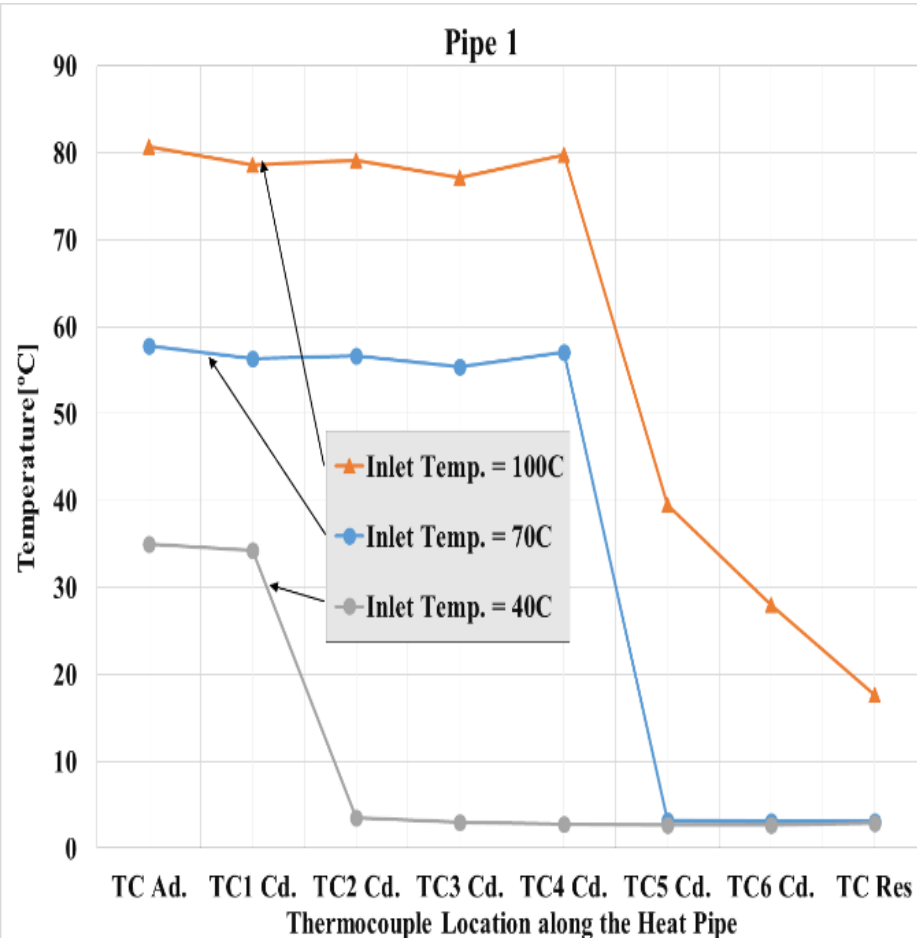


Cluster 1 Performance Testing – Vacuum

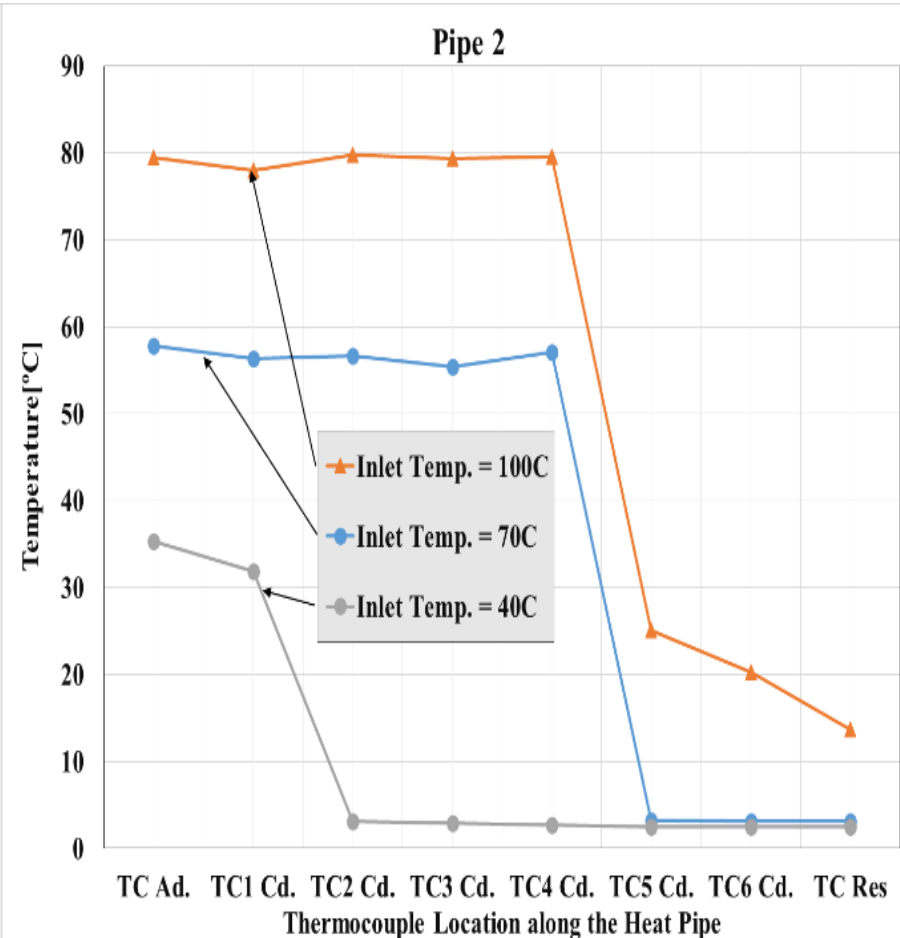
First Round

◆ VCHP behavior

Pipe 1



Pipe 2



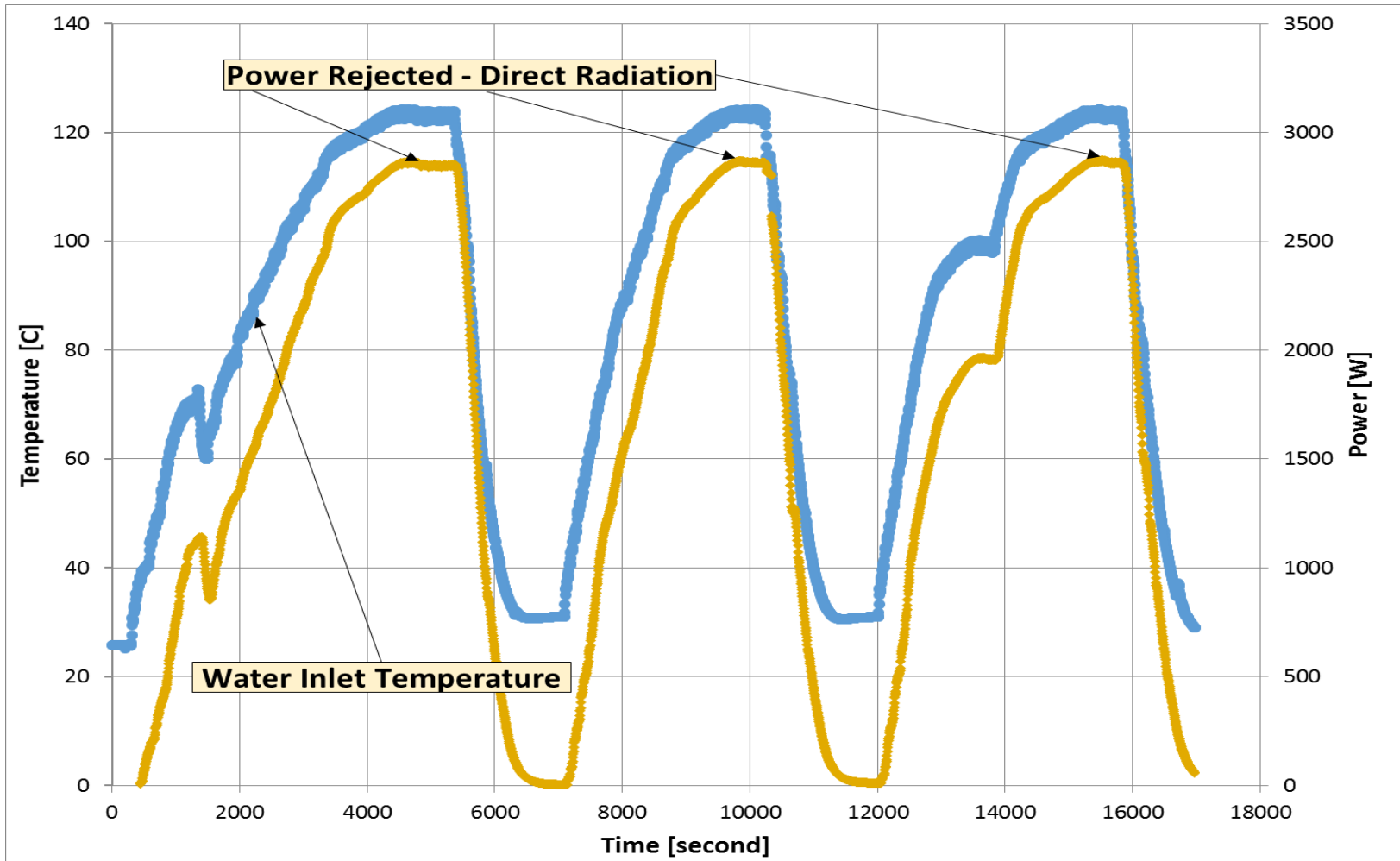
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Cluster 1 Performance Testing – Vacuum Second Round

- Conservative factors: higher sink temperature, small evaporator, lower flow rate, too much NCG – 2.87 kW of rejected power



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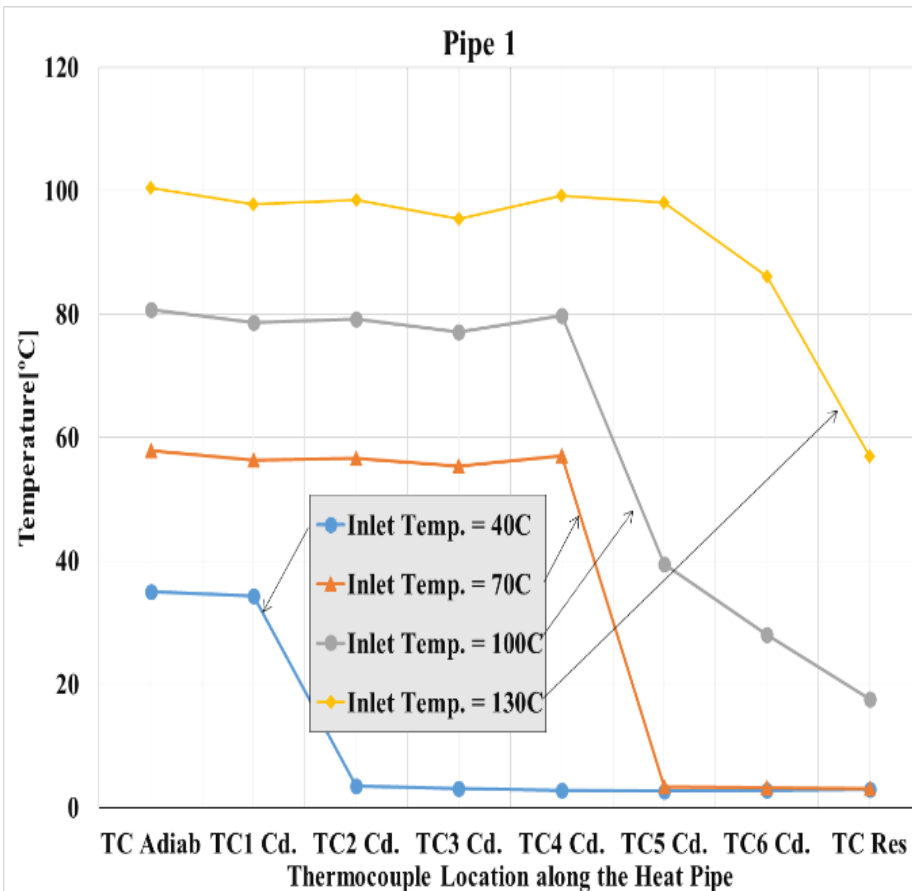


Cluster 1 Performance Testing – Vacuum

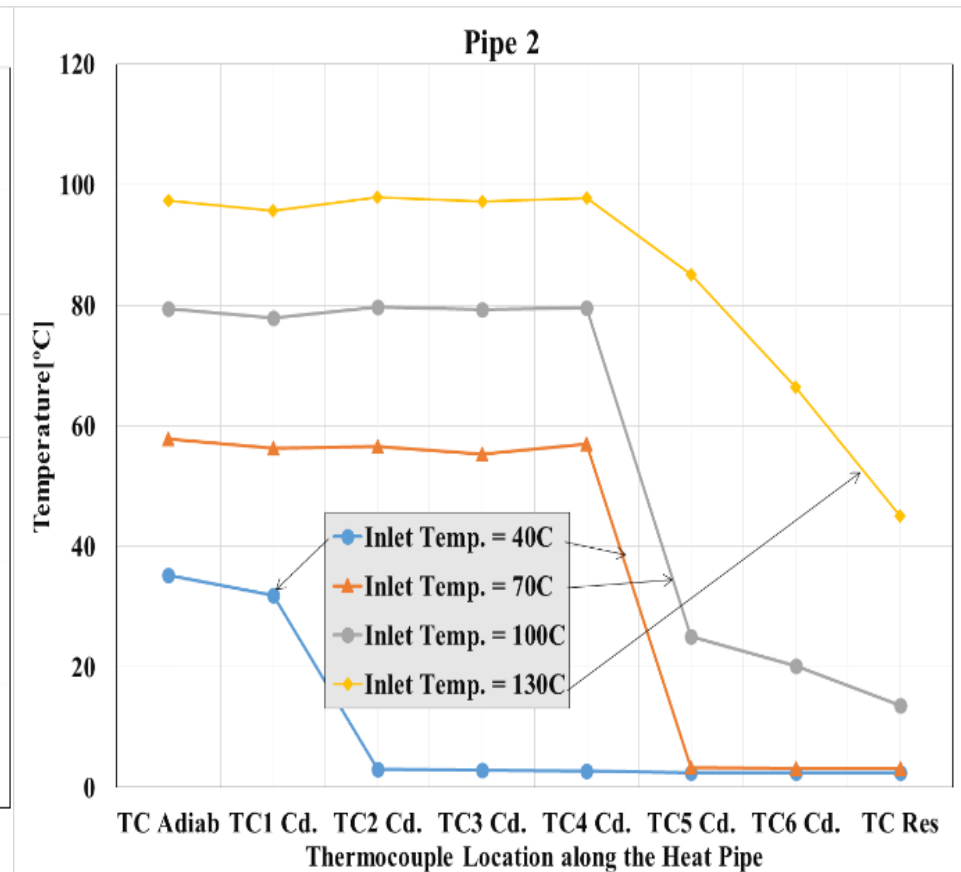
Second Round

◆ VCHP behavior

Pipe 1



Pipe 2



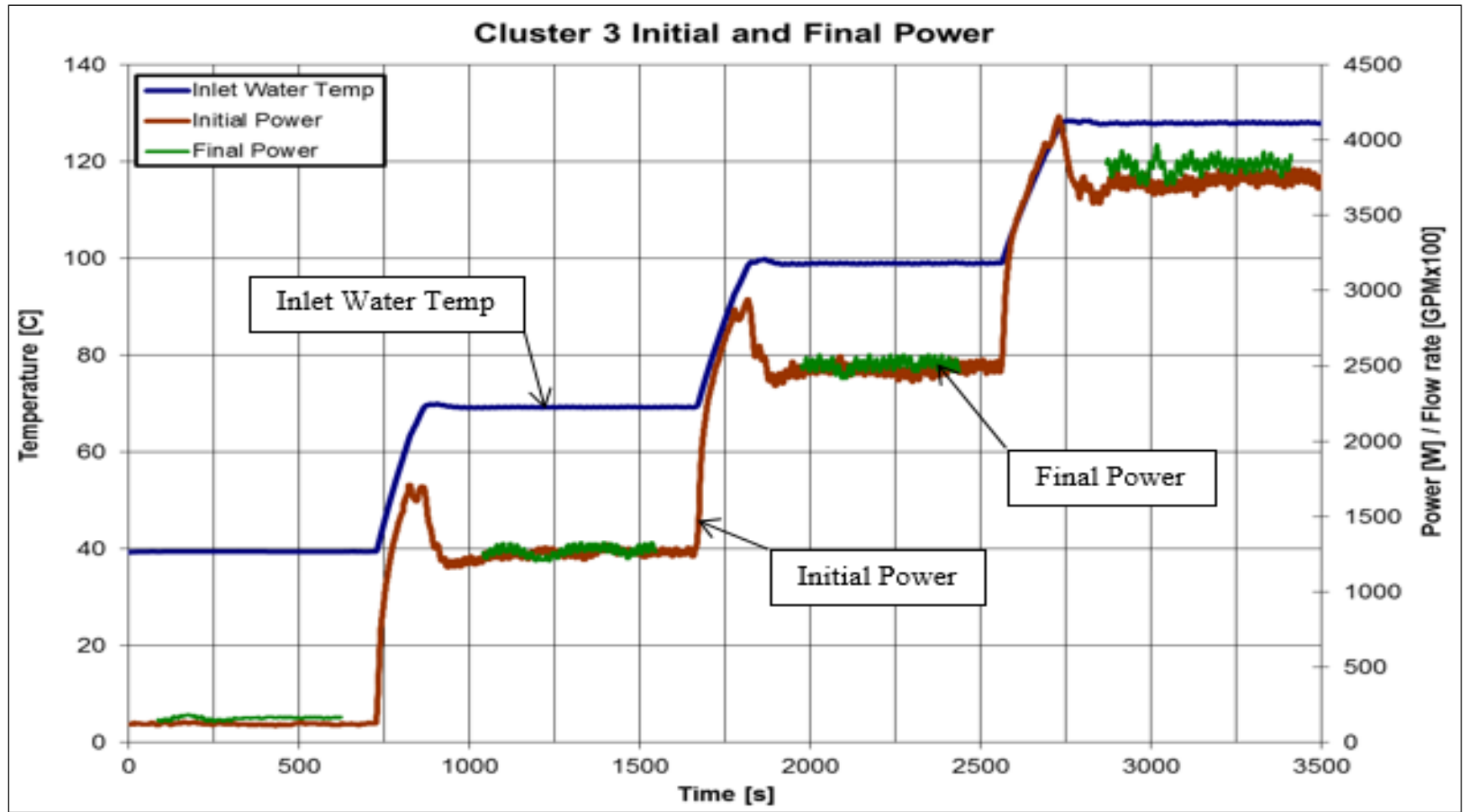
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Cluster 3 Performance Testing

Power test in ambient with **short** evaporator (5.5" length) – **3.75 kW** of rejected power
Before and after pinching



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Cluster 3 Performance Testing

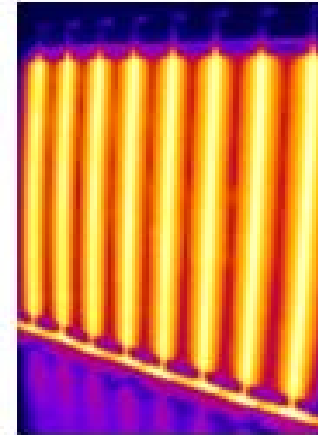
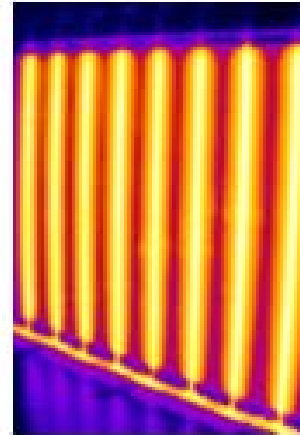
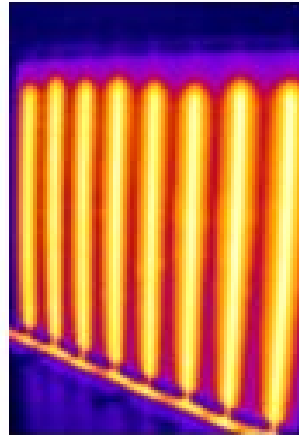
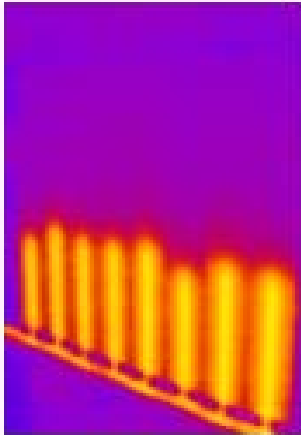
Thermal results for cluster 3 pre pinch weld at 40, 70, 100, and 127°C respectively

40°C

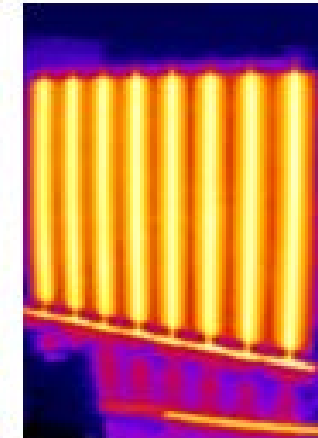
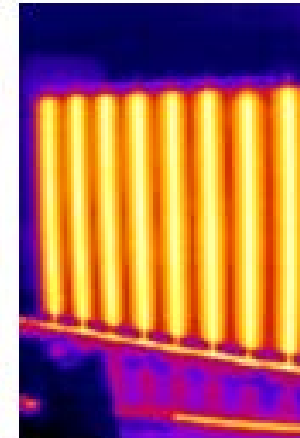
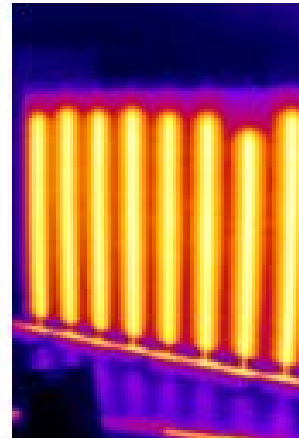
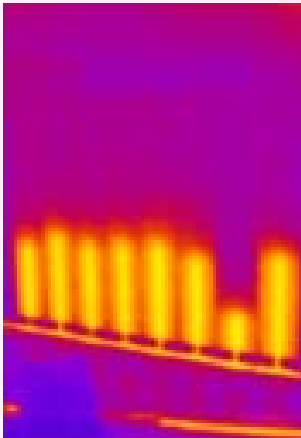
70°C

100°C

127°C



Thermal results for cluster 3 post pinch weld at 40, 70, 100, and 127°C respectively



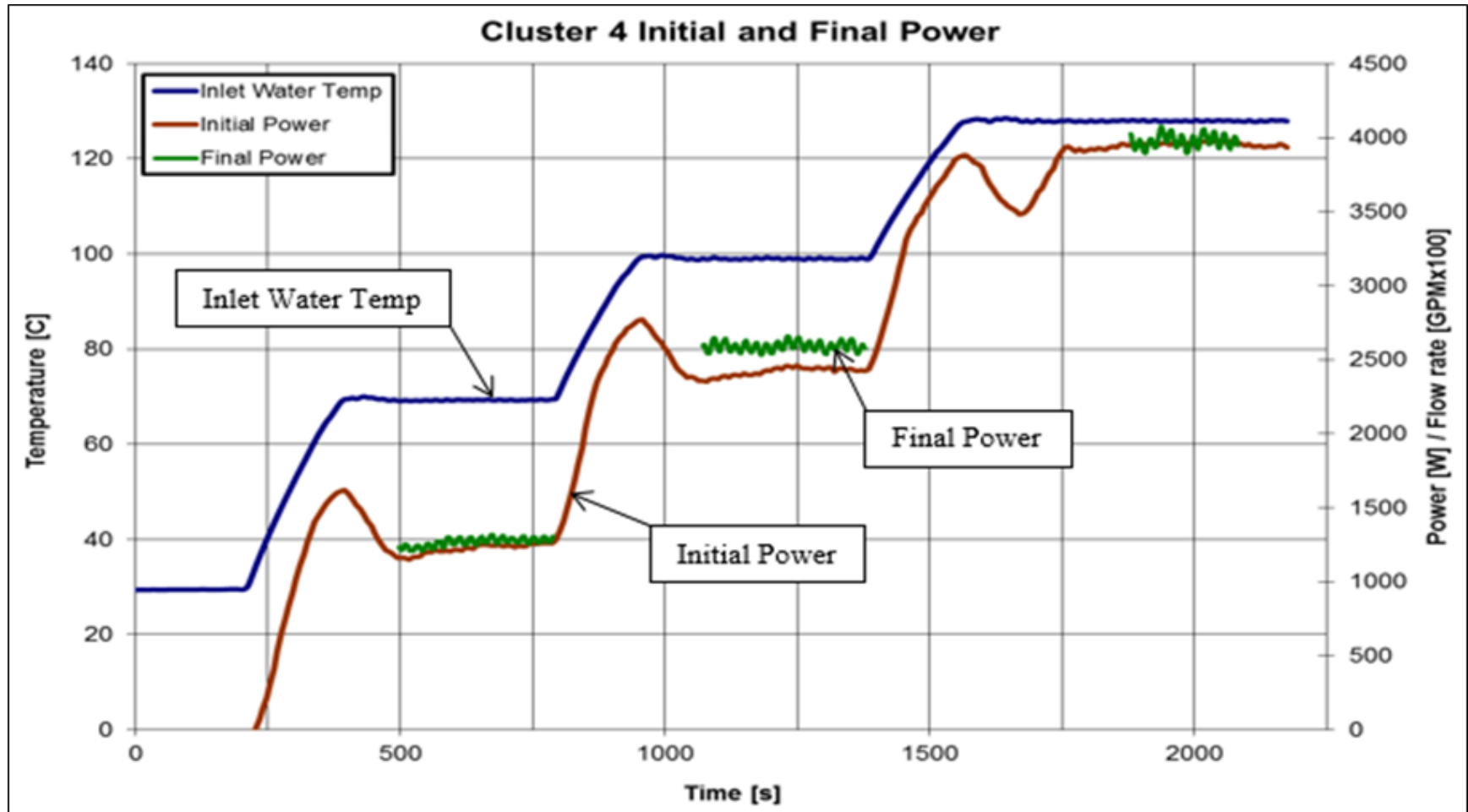
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Cluster 4 Performance Testing

Power test in ambient with **long** evaporator (7" length)) – **3.97 kW** of rejected power
Before and after pinching



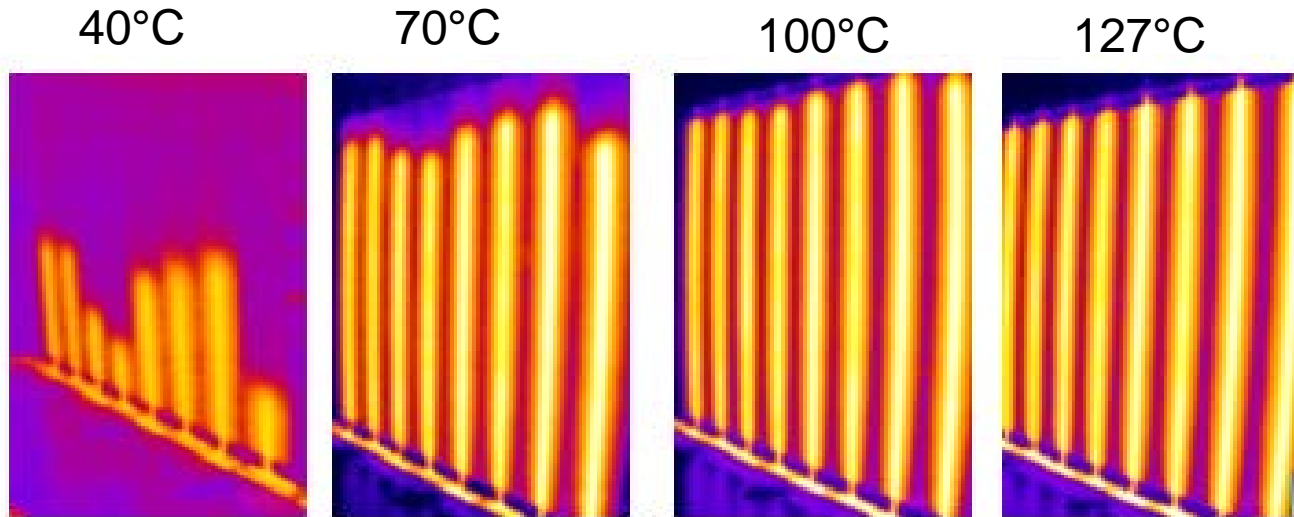
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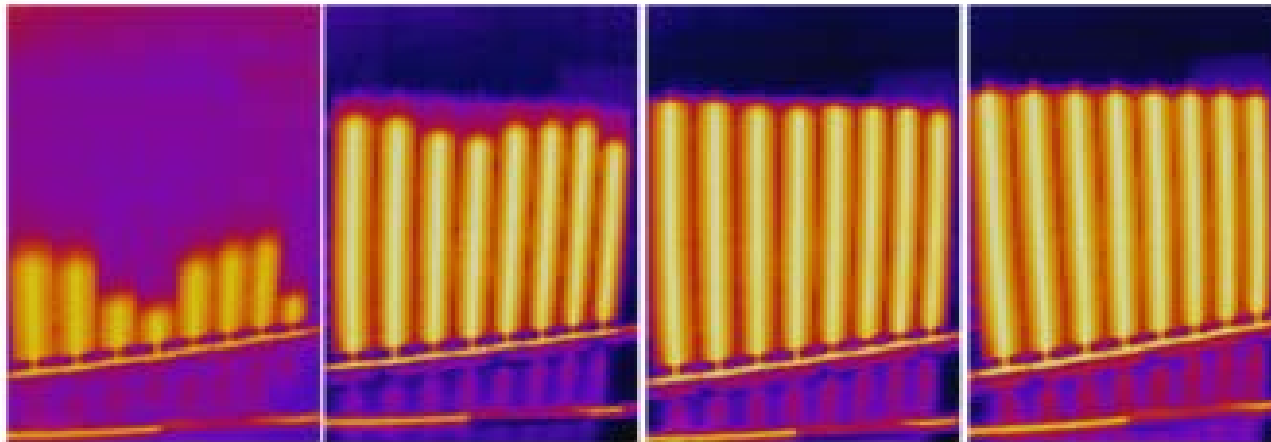


Cluster 4 Performance Testing

Thermal results for cluster 4 pre pinch weld at 40, 70, 100, and 127°C respectively



Thermal results for cluster 4 post pinch weld at 40, 70, 100, and 127°C respectively



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Conclusion

- Module with short evaporator delivered 380W in nominal conditions
- Module with long evaporator showed 25% increase in power ... however, at cluster level, the increase was less
- Cluster performance in vacuum was 2.9 kW in conservative conditions
 - Flow rate was ~4 GPM lower than nominal (6GPM)
 - Sink temperature was 2°C, higher than nominal (-23°C)
 - Evaporator was shorter compared to the rest of the clusters
- Thermal cycling did not affect the direct bond integrity for the module or cluster 1.
- All clusters were tested before and after pinching the fill tubes
 - Power
 - Thermal imaging
- Few heat pipes showed NCG increase after pinching.
 - However, at nominal inlet temperature, power delivered was nominal for all the heat pipes/clusters
- A cost assessment was performed and delivered to NASA



Acknowledgements

- ◆ Both Phase I and the ongoing Phase II SBIR programs have been sponsored by NASA Glenn Research Center under Contract NNX13CC45P.
 - ACT would like to thank **Maxwell Briggs, Marc Gibson, Jim Sanzi, and Lee Mason** for their support and helpful discussions during both programs.



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