Low-Cost Radiator for Fission Power Thermal Control

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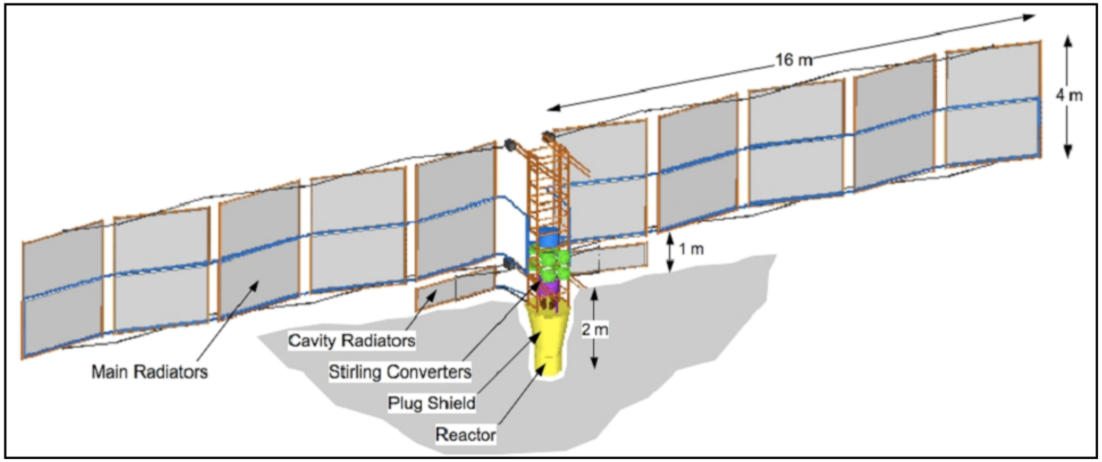
Thermal & Fluids Analysis Workshop
TFAWS 2014
August 4 - 8, 2014
NASA Glenn Research Center
Cleveland, OH

Overview

- Background
- Motivation
- Objectives
- Radiator Trade Study
- Preliminary Design
- Proof-of-Concept Fabrication and Testing
- Program Summary and Future Considerations

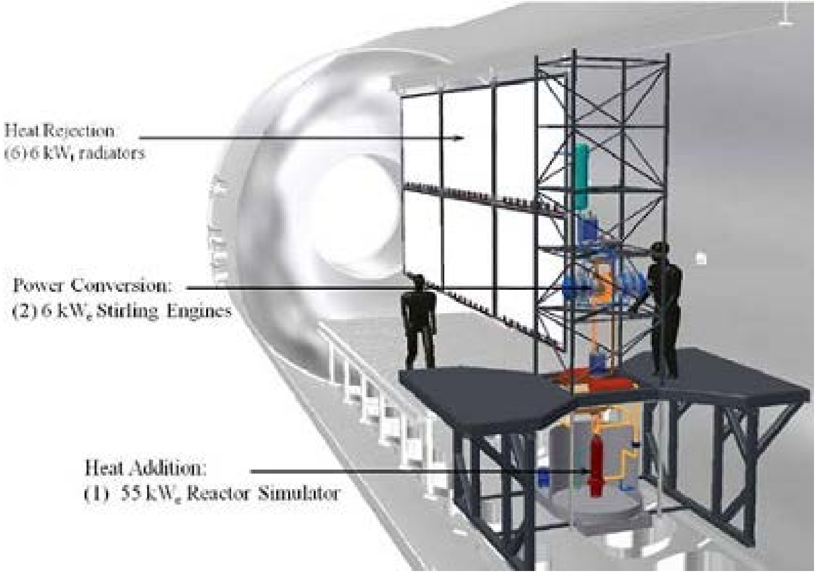
Background

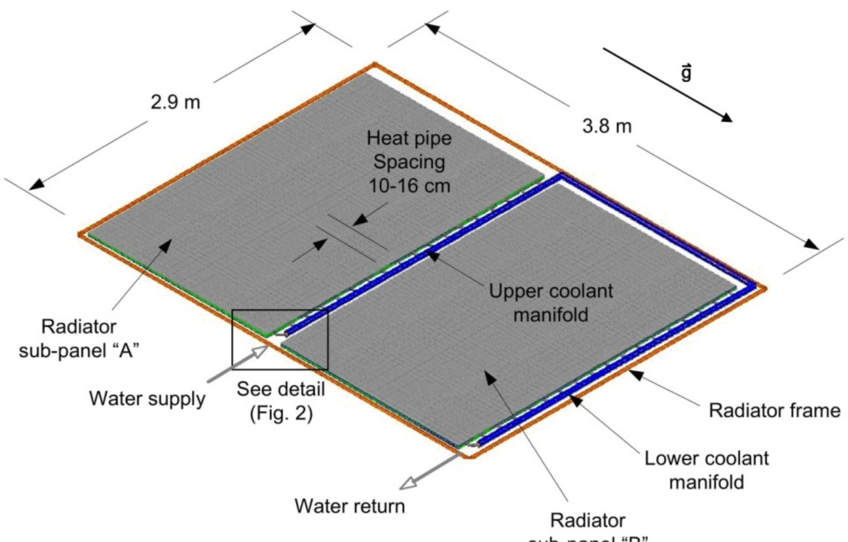
- NASA Glenn Research Center (GRC) is developing fission power system technology for future space transportation and surface power applications
  - A nuclear reactor supplies thermal energy to electrical convertors and uses a heat pipe radiator to reject the waste heat
  - Heat pipes are vertical thermosyphons 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



Geng, Mason, Dyson, and Penswick, STAIF 2008

Background



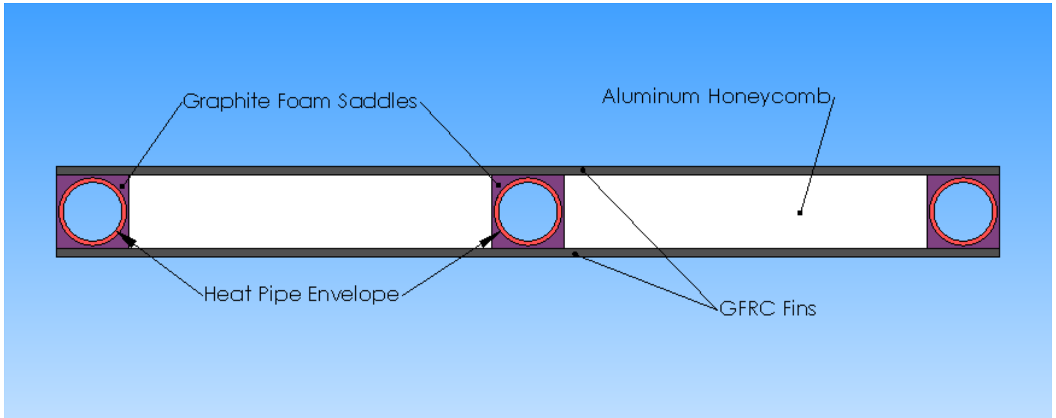


- NASA GRC is developing a Fission Power System Technology Demonstration Unit (TDU)
  - Non-nuclear unit that will be tested in thermal vacuum to demonstrate integrated system performance
- Radiator Requirements for TDU
  - Nominal heat load: 36kW
  - Nominal sink temp.: 250K
  - Coolant inlet temp: 400K
  - Max. panel area: 55m^2
  - Radiator will experience temperature and power cycling
    - CTE mismatch must be minimized
  - Specific power must be maximized to reduce associated cost

Motivation

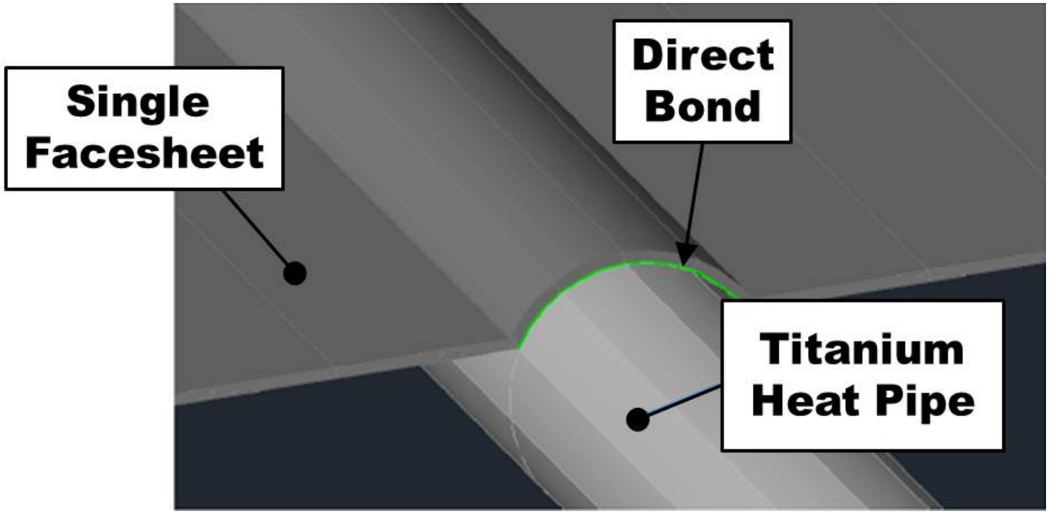
- An improved VCHP radiator for fission power applications will help achieve the OCT goals of reduced mass, improved specific power and reduced cost

- ACT previously developed a dual-facesheet VCHP radiator for this application



- Mechanical stress testing of a dual-facesheet radiator under the Phase II program demonstrated that direct bonding may be possible

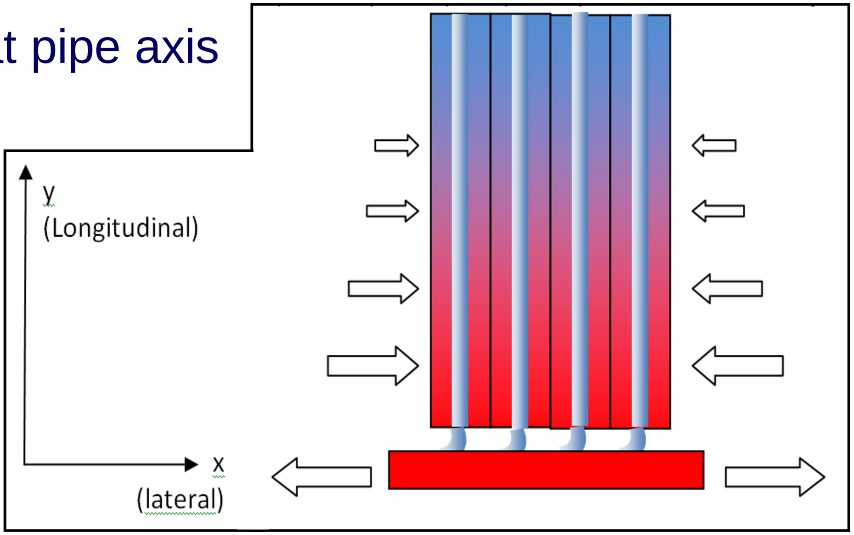
- A single direct-bond facesheet radiator reduces the overall cost and mass of the assembly



Design 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 μm/m-K
  - GFRC CTE must be matched along heat pipe axis
- Negative CTE in GFRC perpendicular to heat pipes
  - Coiled adiabatic to accommodate CTE mismatch

CTE Stresses

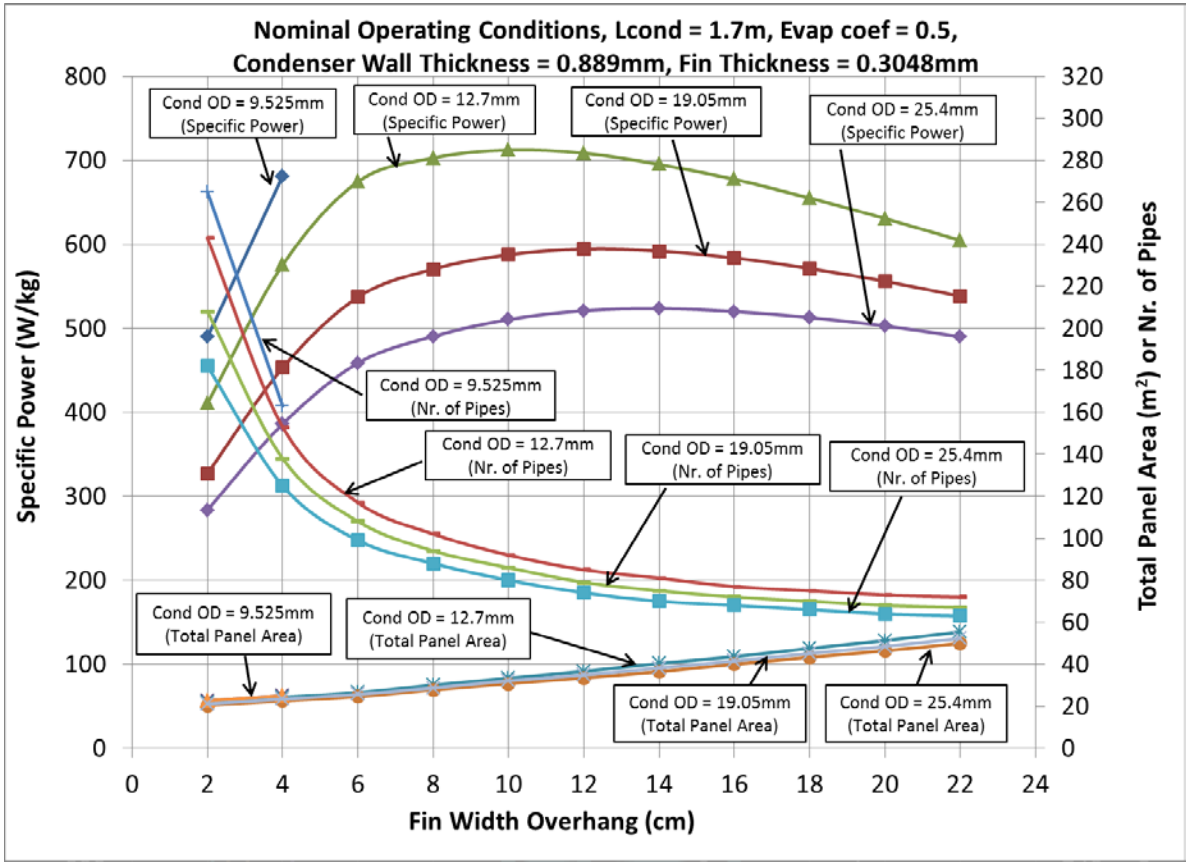


Objectives

- **<u>Overall Objective:</u>** Develop low-cost radiator panels that are suitable for integration in NASA's TDU.
- **<u>Phase I Objective:</u>** Demonstrate that a single facesheet radiator is feasible.
- **Specifically,**
  - Demonstrate that the GFRC facesheet can be directly bonded to titanium heat pipes, with no problems from the C.T.E. mismatch.
    - Verify through thermal cycle testing of protoype
  - Modify the VCHP radiator design to incorporate new flooding data.
  - Conduct a trade study to determine the effect of various geometrical parameters on the performance of a single-facesheet radiator.
  - Develop a complete preliminary design for a single-facesheet radiator, including estimates of panel performance and weight.

Radiator Trade Study

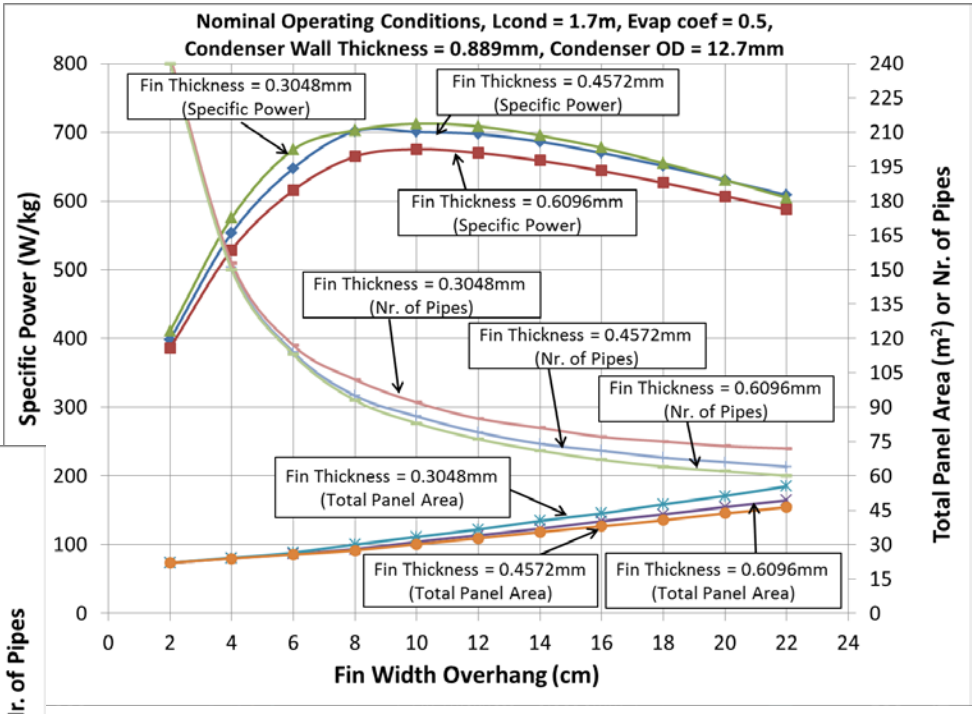
- Variables of interest
  - Condenser OD
  - Condenser wall thickness
  - Fin thickness
  - Condenser height
  - Evaporator length
- Approach
  - Each heat pipe and associated fins studied in isolation from rest of system
  - For a range of fin widths, the number of heat pipes was adjusted to obtain 36 kW output
  - With power output fixed (36kW), the specific power was dictated by system mass

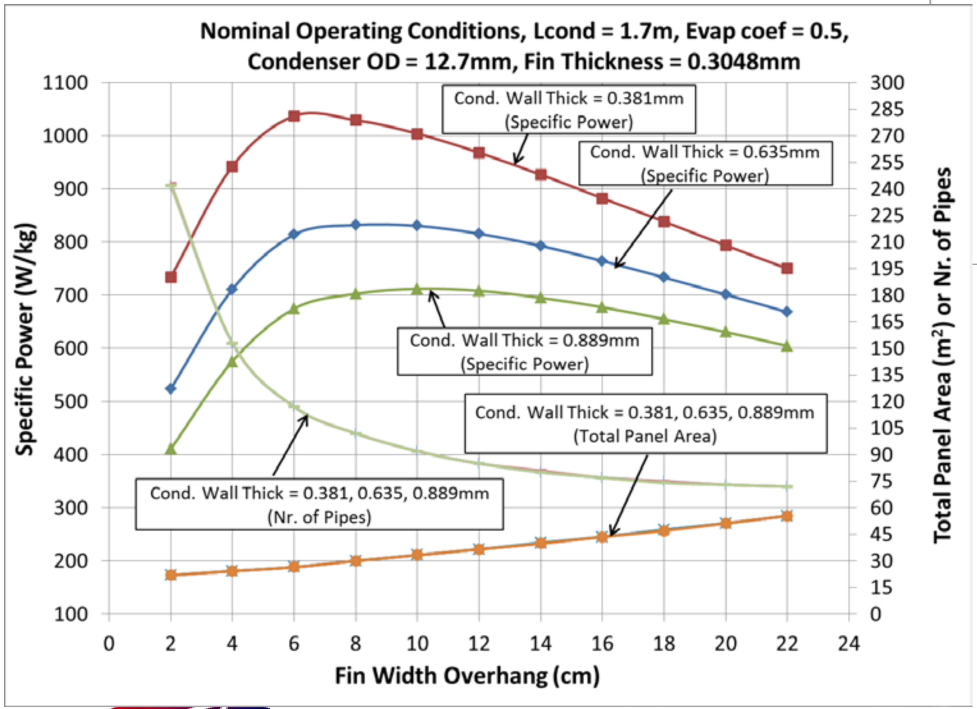


- Effect of condenser OD
  - For a given fin width, specific power increases for decreasing condenser OD
  - For condenser OD ≤ 9.525 mm, the power is limited by the thermosyphon flooding limit
  - The maximum specific power occurs for 12.7 mm OD and 10 cm fin width overhang

Radiator Trade Study Results (Continued)

- Effect of condenser wall thickness
  - Specific power increases significantly with decreasing wall thickness due solely to the reduction of envelope mass
  - Number of heat pipes per unit fin width is the same for each condenser wall thickness

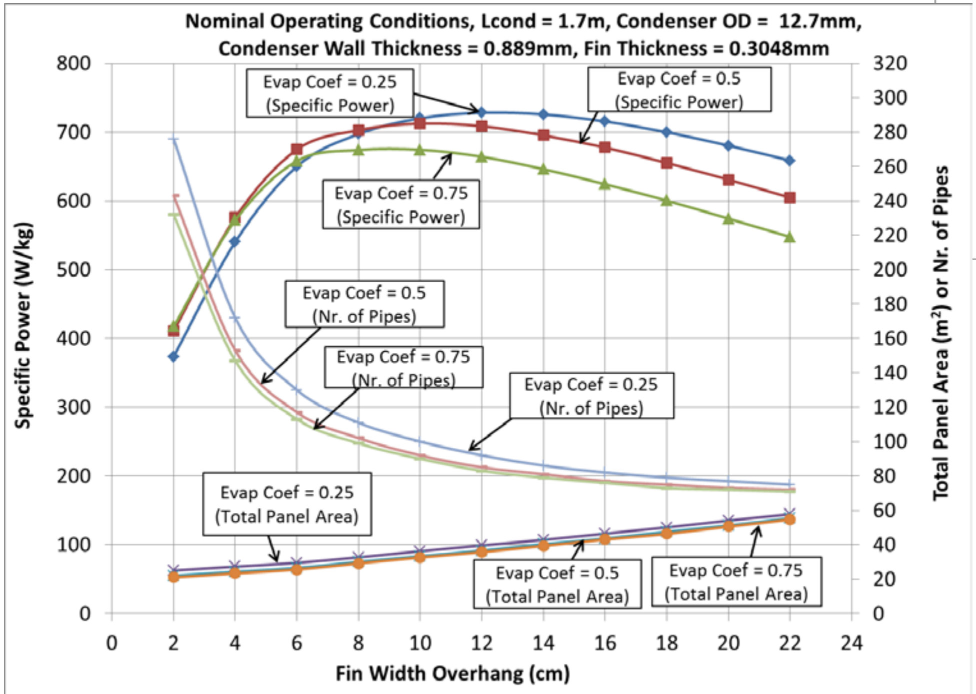


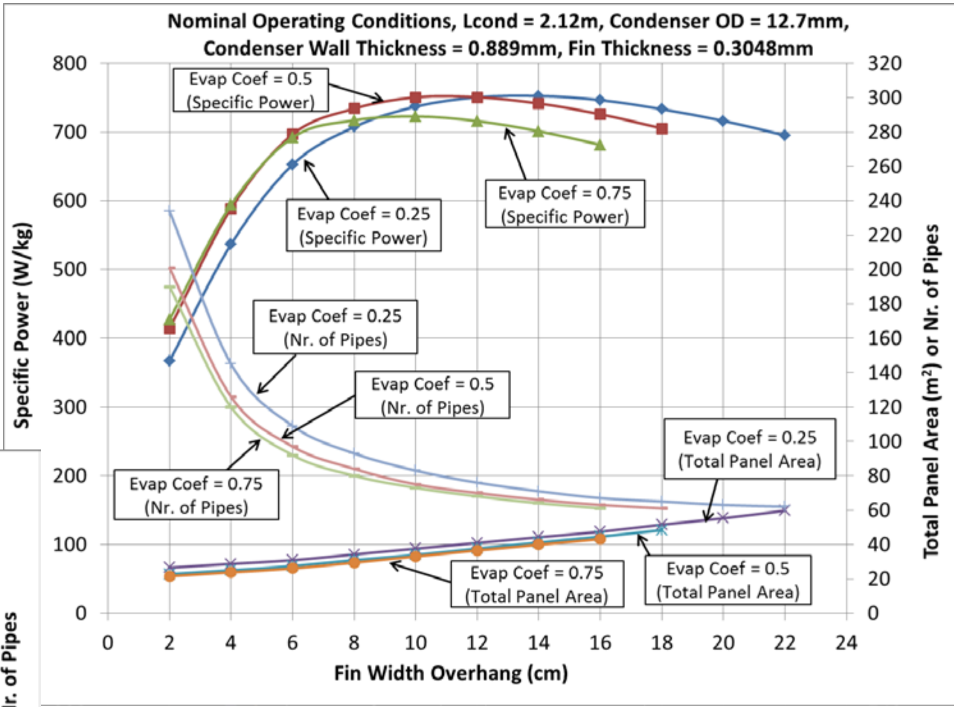


- Effect of fin thickness
  - Specific power increases minimally with decreasing fin width
  - Performance primarily dependent on mass, not fin efficiency

Radiator Trade Study Results (Continued)

- Effect of evaporator length
  - Evaporator length defined in terms of maximum allowable length
  - For a given fin width, specific power is dictated by competing effects between mass and heat transfer area of the evaporator
  - Evaporator coefficient of 0.25 resulted in largest specific power





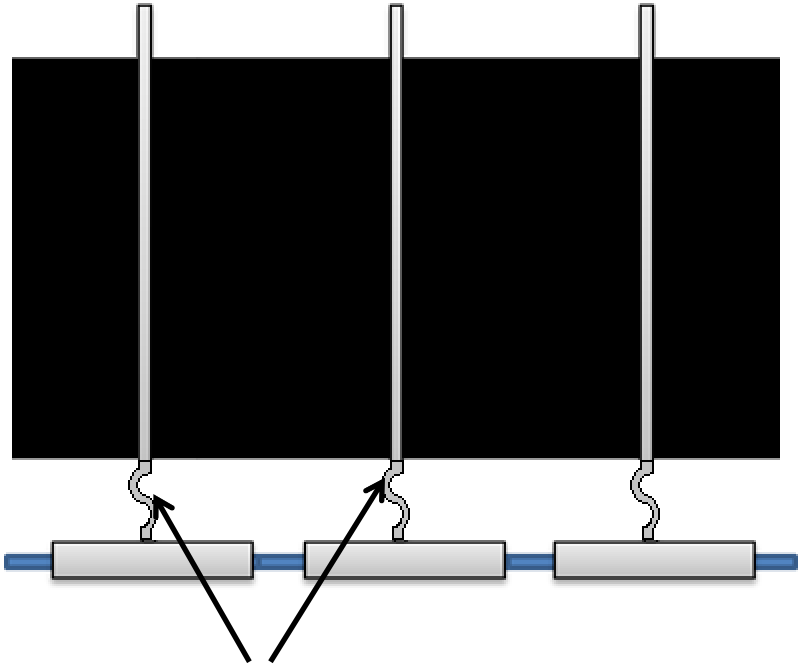
- Effect of condenser length
  - Condenser length was increased by 25% of original length
  - Similar maximum specific powers for evaporator coefficients of 0.25 and 0.5
  - Overall, increasing the condenser length resulted in a minimal increase in specific power per fin width

Summary of Radiator Trade Study

- The effect of geometry on specific power was studied over a range of fin widths for a fixed power output
- Specific power per unit fin width increases with decreasing condenser OD
  - Flooding limit exceeded for OD ≤ 9.525 mm when fin widths are greater than 4cm
- Specific power per unit fin width significantly increases with decreasing condenser wall thickness
  - Reducing wall thickness below 0.889 mm may not be feasible for applications requiring Micrometeroid and Orbital Debris (MMOD) protection
- Larger fin thicknesses result in slightly lower specific power, due to mass of GFRC material
- Specific power per unit fin width is largest when evaporator coefficient is 0.25
- Increasing the condenser length by 25% results in minimal increase in specific power per unit fin width

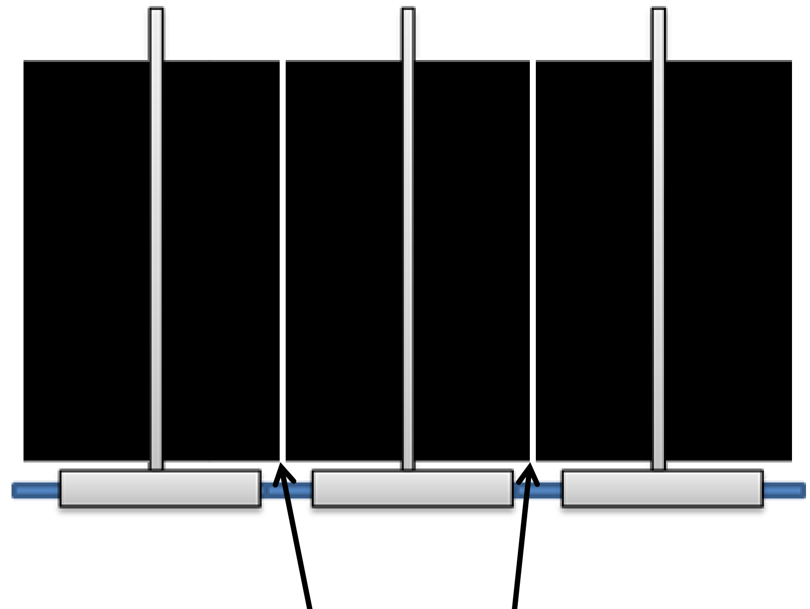
Preliminary Design: Sub-Panel vs. Modular Radiator Design

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

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

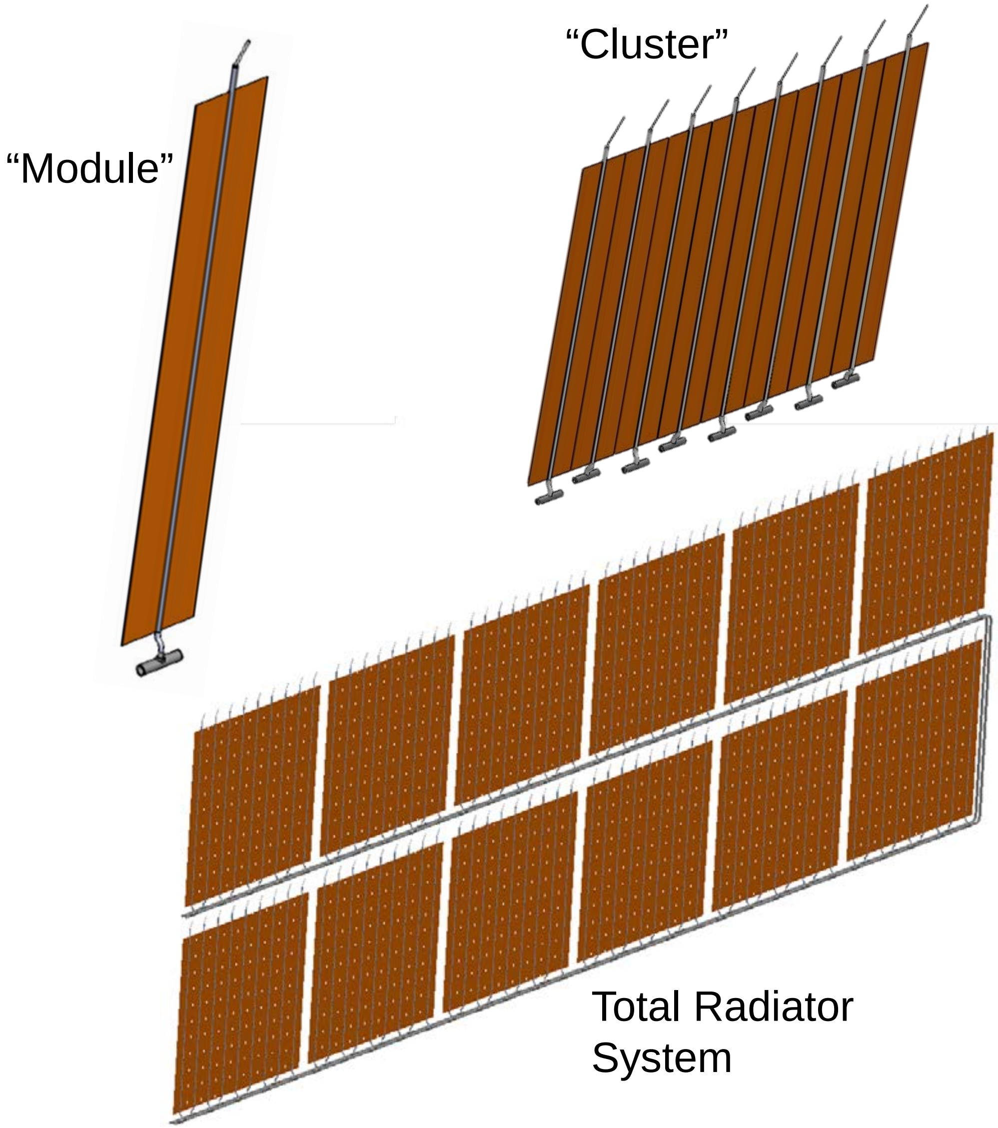
- Disadvantages
  - If one pipe/fin module fails, the fins are useless since they don't offer a heat conduction path to the neighboring pipe/fin modules
    - As a consequence, the level of redundancy must be increased
- Solution
  - Since the elimination of the adiabatic sections would increase the 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

Design Case Study Showing Potential System Redundancy

Design Case	Length of Adiabatic Section (cm)	Overhang Width (cm)	No. of Pipes	System Mass w/out Coolant (kg)	System Power (kW)	Specific Power (W/kg)	Total Panel Area (m^2)
1. Continuous Sub-Panel Design	17.78	12	103	55.8	40	719	44.3
2. Modular Design w/Reduced Adiabatic Length	2.54	12	103	53.4	40	751.5	44.3
3. Modular Design w/Reduced Adiabatic Length (Constant Specific Power)	2.54	12	142	73.6	53	719.8	61.1
4. Modular Design w/Reduced Adiabatic Length (Constant Panel Area)	2.54	10	122	58.6	43.2	738	44.2

- **Design Case Description**
  - Design 1 corresponds to the maximum specific power achievable for the continuous sub-panel with helical adiabatic section bends.
  - Design 2 shows how the specific power increases by ~30 W/kg, if the helical bends are removed and the adiabatic sections are reduced from 17.8 cm to 2.5 cm.
  - Design 3 shows that by reducing the adiabatic length, 39 redundant heat pipe modules can be added to the system and still achieve the original specific power of the continuous sub-panel design. The VCHPs would prevent excess heat rejection at nominal conditions.
  - For Design 4, the fin width was reduced slightly to allow for redundant heat pipe modules within the original area of the continuous sub-panel design.
- **For this application, the preferred design requires a trade-off between the desired number of redundant heat pipes and available radiator area (i.e. design 2 and 3)**

Final Radiator Design

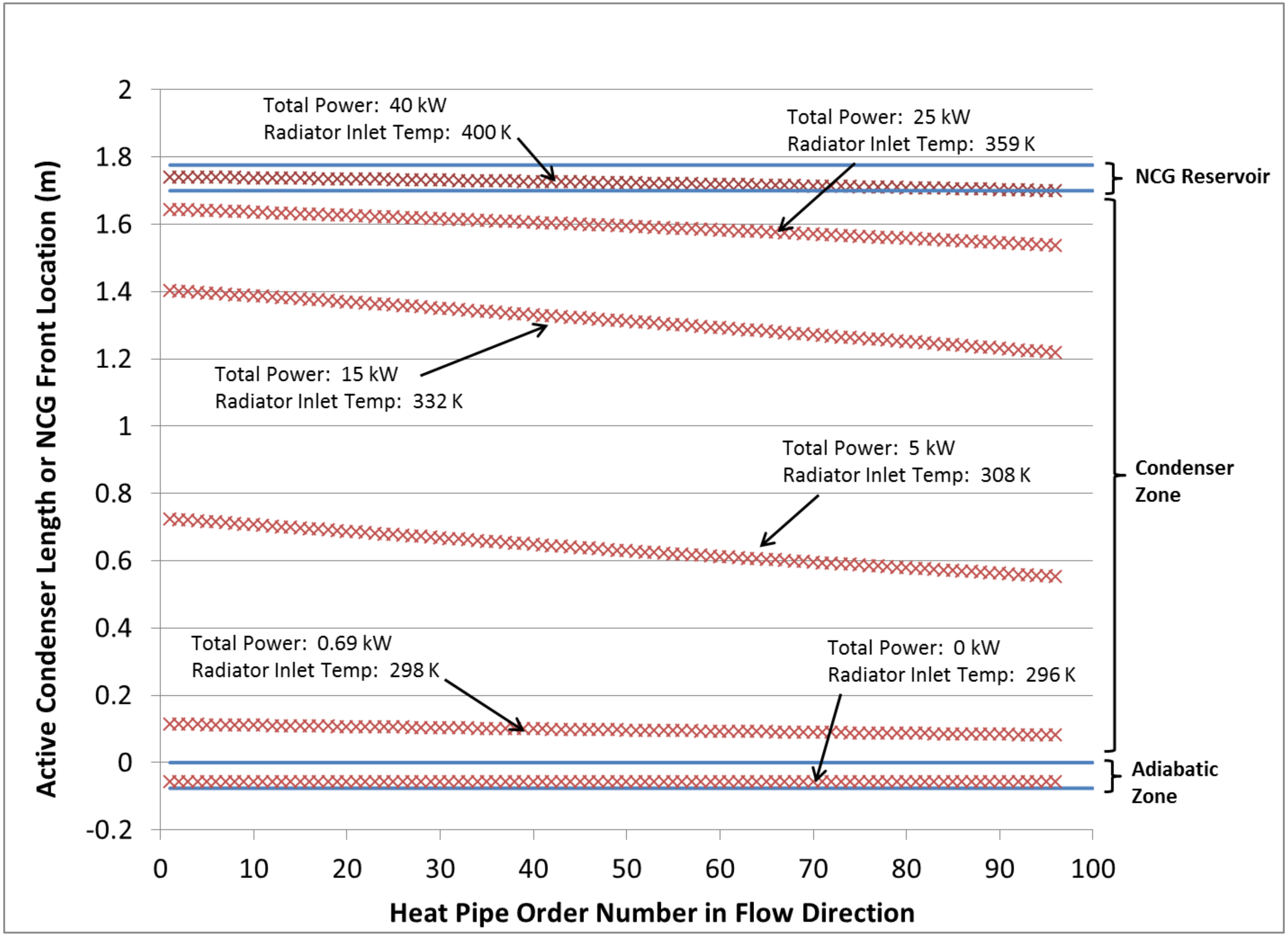


Geometry	
Condenser OD (mm)	19.05
Evaporator Length (cm)	13
Adiabatic Section Length (cm)	7.62
Condenser Length (cm)	170
NCG Reservoir Length (cm)	7.62
Fin Width Overhang (cm)	12
Total GFRC Area (m^2)	42.36
Total Number of Heat Pipe Modules	96
Total Number of Heat Pipe Clusters	12
Heat Pipe Redundancy Compared to Nominal Radiator (i.e. 36kW, 175K Sink, 400K inlet)	23
% Margin by Area Compared to Nominal Radiator	24
Thermal Performance & Mass	
Total Power Output (kW)	40
Specific Power (W/kg)	609.0
Dry Mass of Single Heat Pipe/Fin Module (kg)	0.685
Total Dry Mass of Radiator System (kg)	65.74

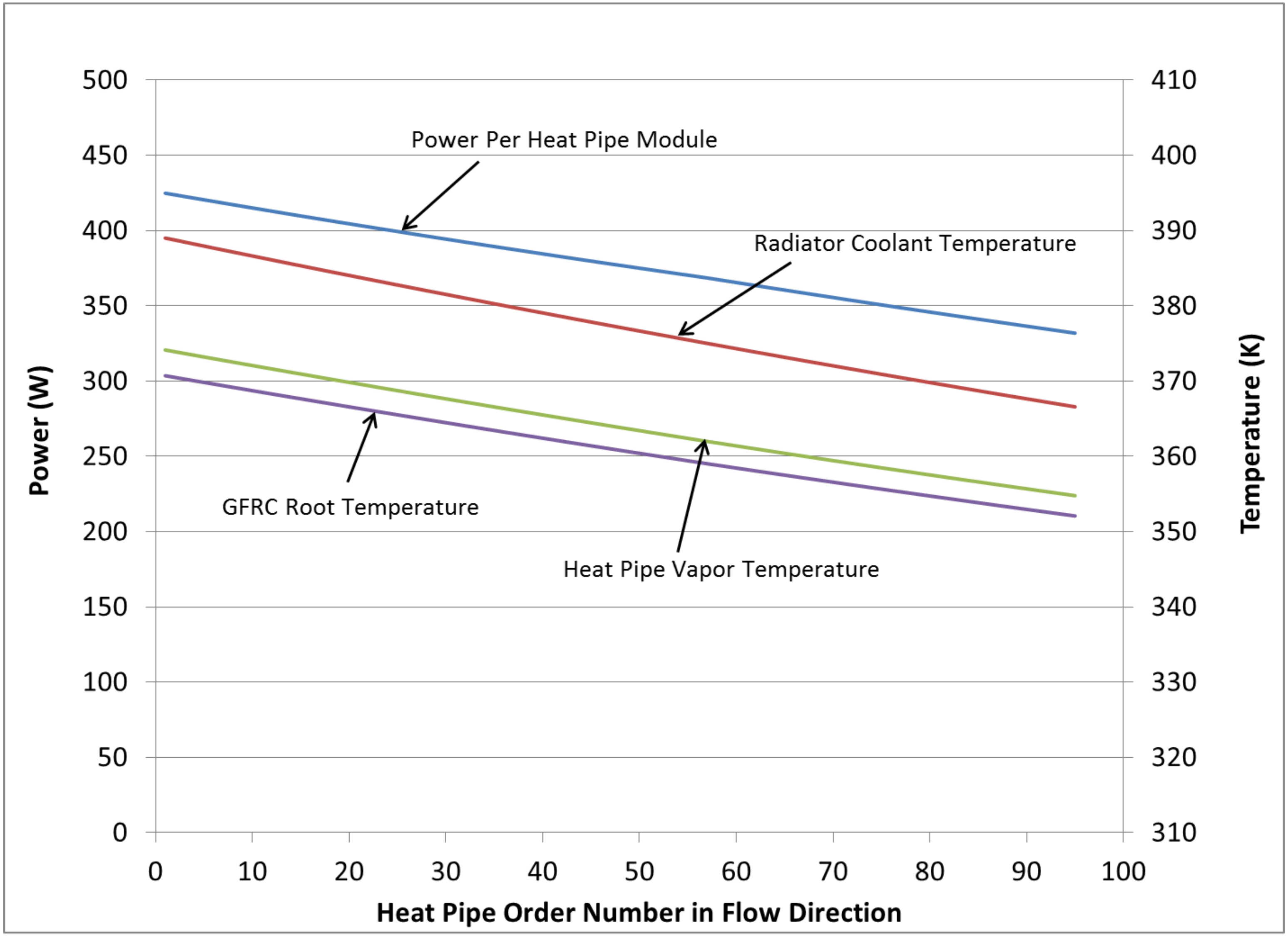
VCHP Modeling Approach

- Model based on flat front theory
- Reservoir length is constant throughout (7.62cm or 3in)
- The amount of NCG is constant and based on the vapor temperature of the coldest heat pipe during “hot” conditions (40kW, 400K inlet, 250K sink)
  - This ensures all condensers are fully active during “hot” conditions with the NCG front pushed deeper into the reservoir for the hotter pipes
- The model assumes a constant waste heat load from the Stirling converter and adjusts the coolant temperature (and NCG front) to accommodate the heat load

VCHP Performance for Final Radiator Design at Various Waste Heat Loads and Constant Sink Temperature (T_{sink} = 250K)



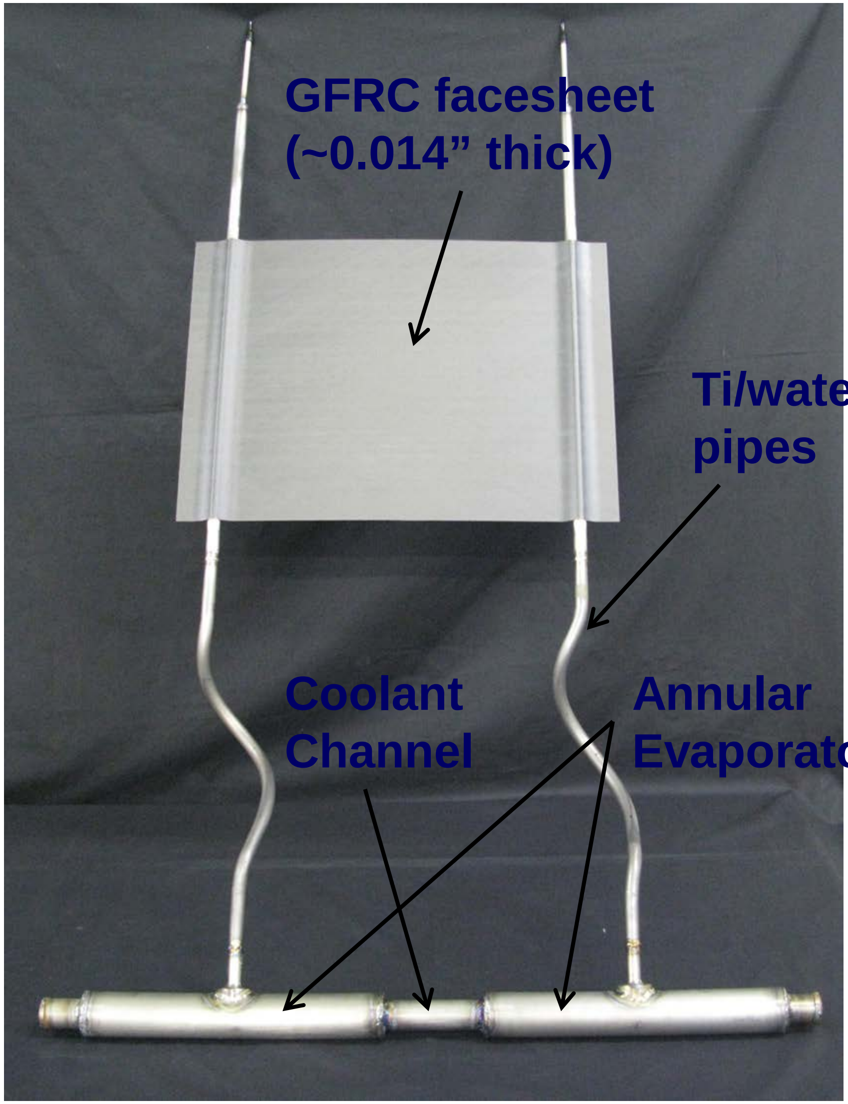
VCHP Power & Temperature Distribution for Final Radiator Design (36kW, 250K Sink, 389K Inlet)

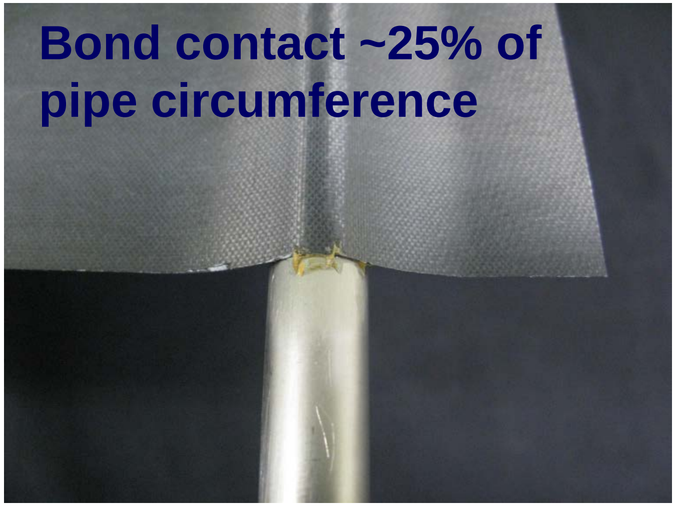


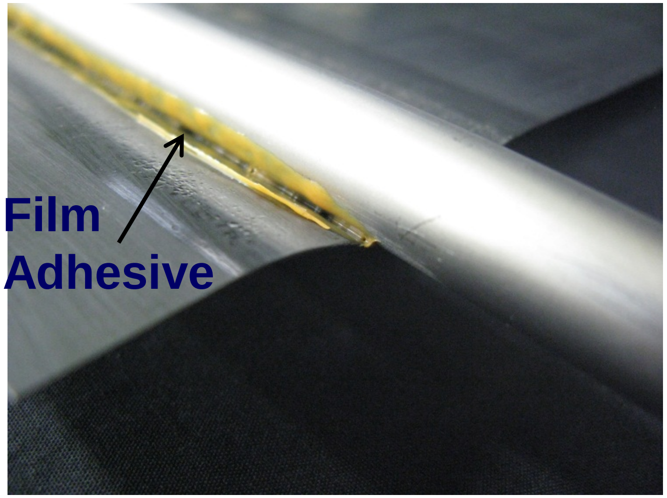
Thermal Performance/Cycling Test for Proof-of-Concept Radiator

- Primary Objectives
  - To evaluate the uniformity of the adhesive bond along both heat pipes
  - To determine if the bonds can withstand thermal cycling without degradation
- Secondary Objectives
  - To evaluate VCHP and radiator performance
- Approach
  - Conducted two identical thermal performance tests before and after thermal cycling
  - Compared the bond delta temperatures across the bond along each heat pipe to determine if thermal cycling causes the bond to degrade
  - Use IR camera to verify bond uniformity
  - Thermal cycling consists of ramping the coolant and sink temperature together between hot and cold conditions

Proof-Of-Concept Radiator

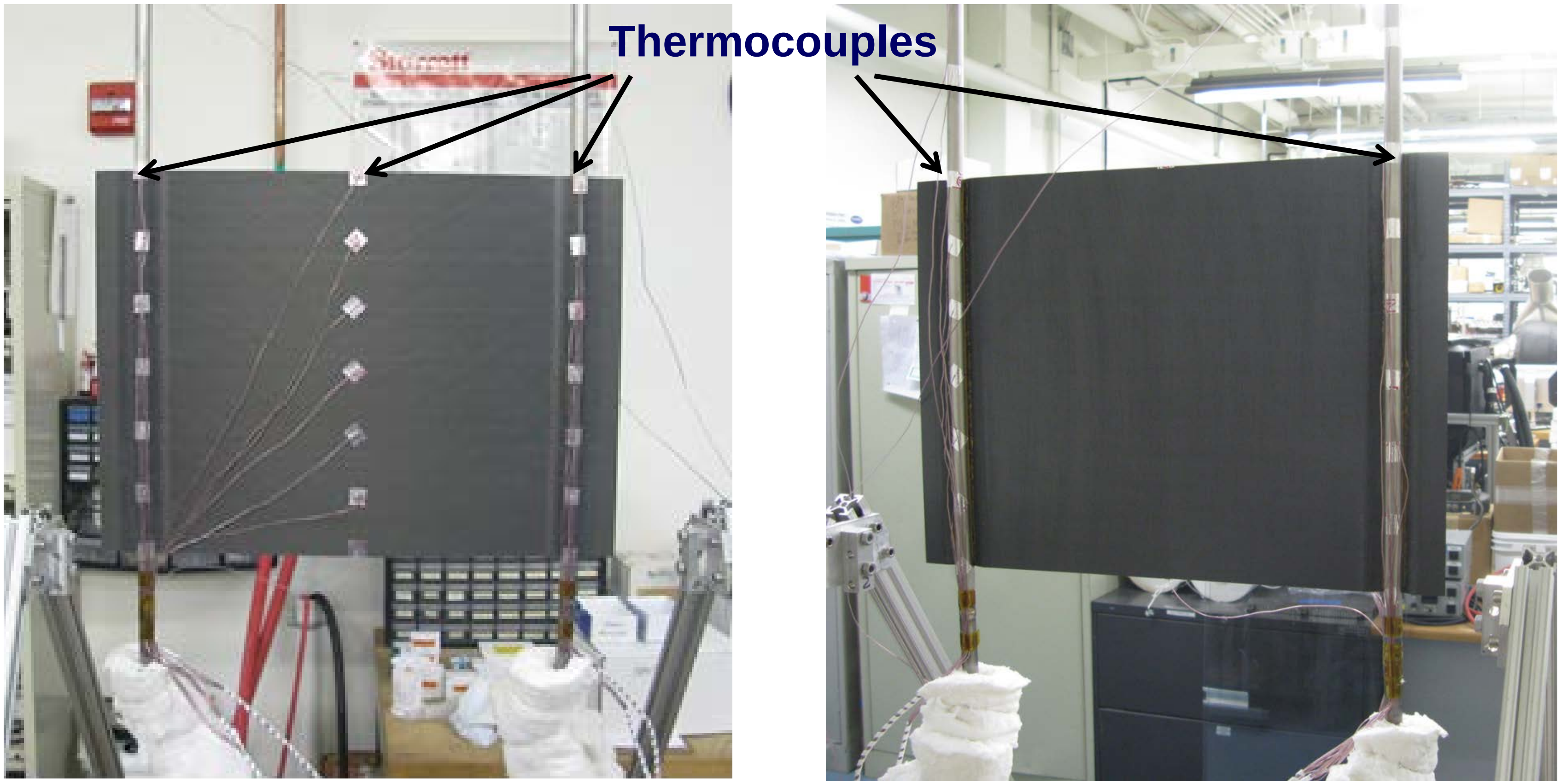




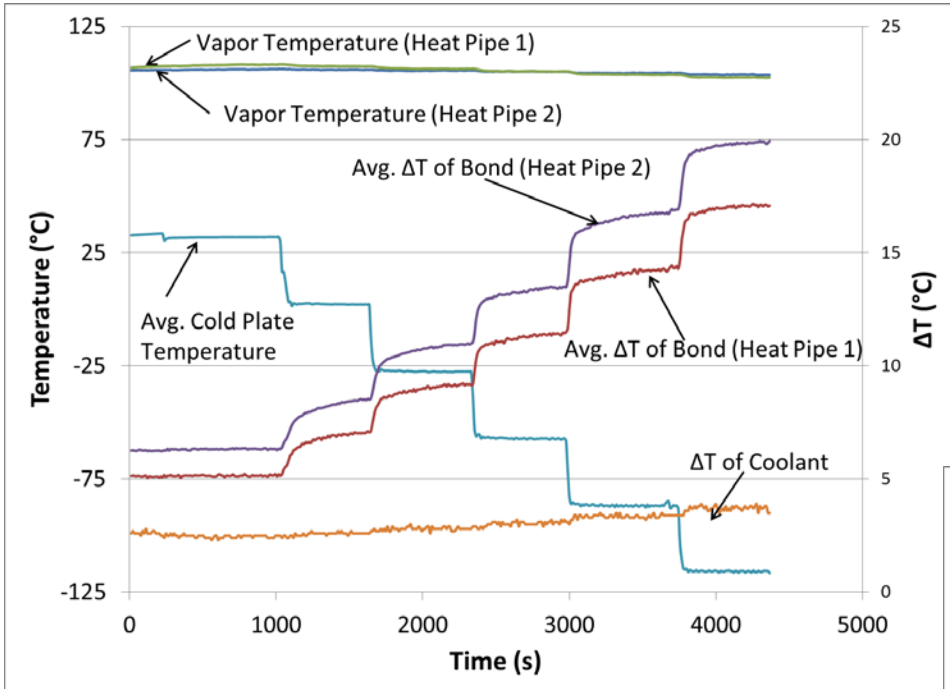


Test Set-Up

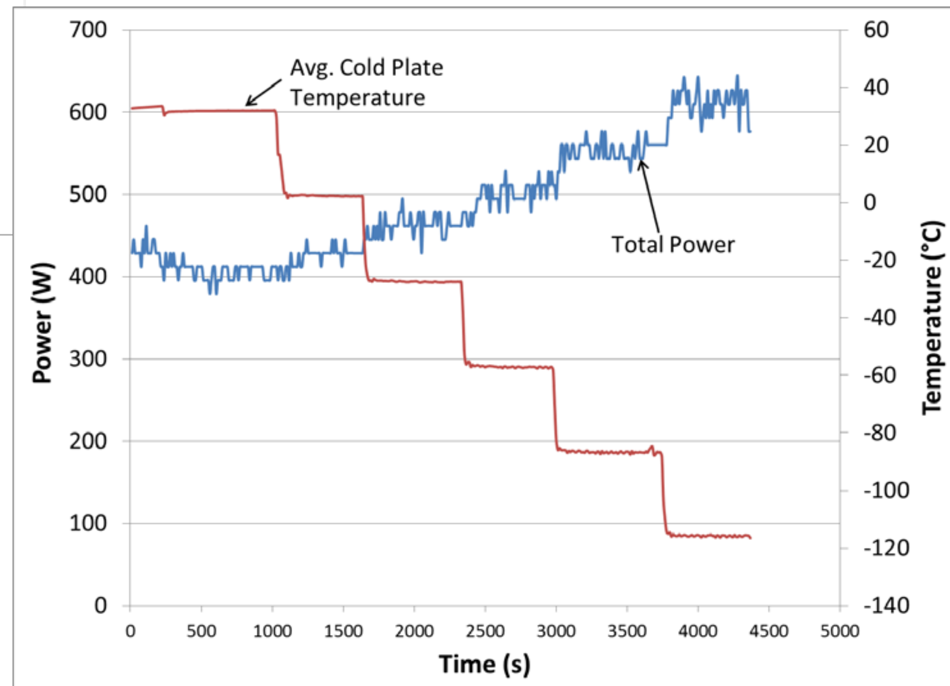
- Tape-on thermocouples used to measure effective temperature difference across direct bond joint



Thermal Performance Test Results

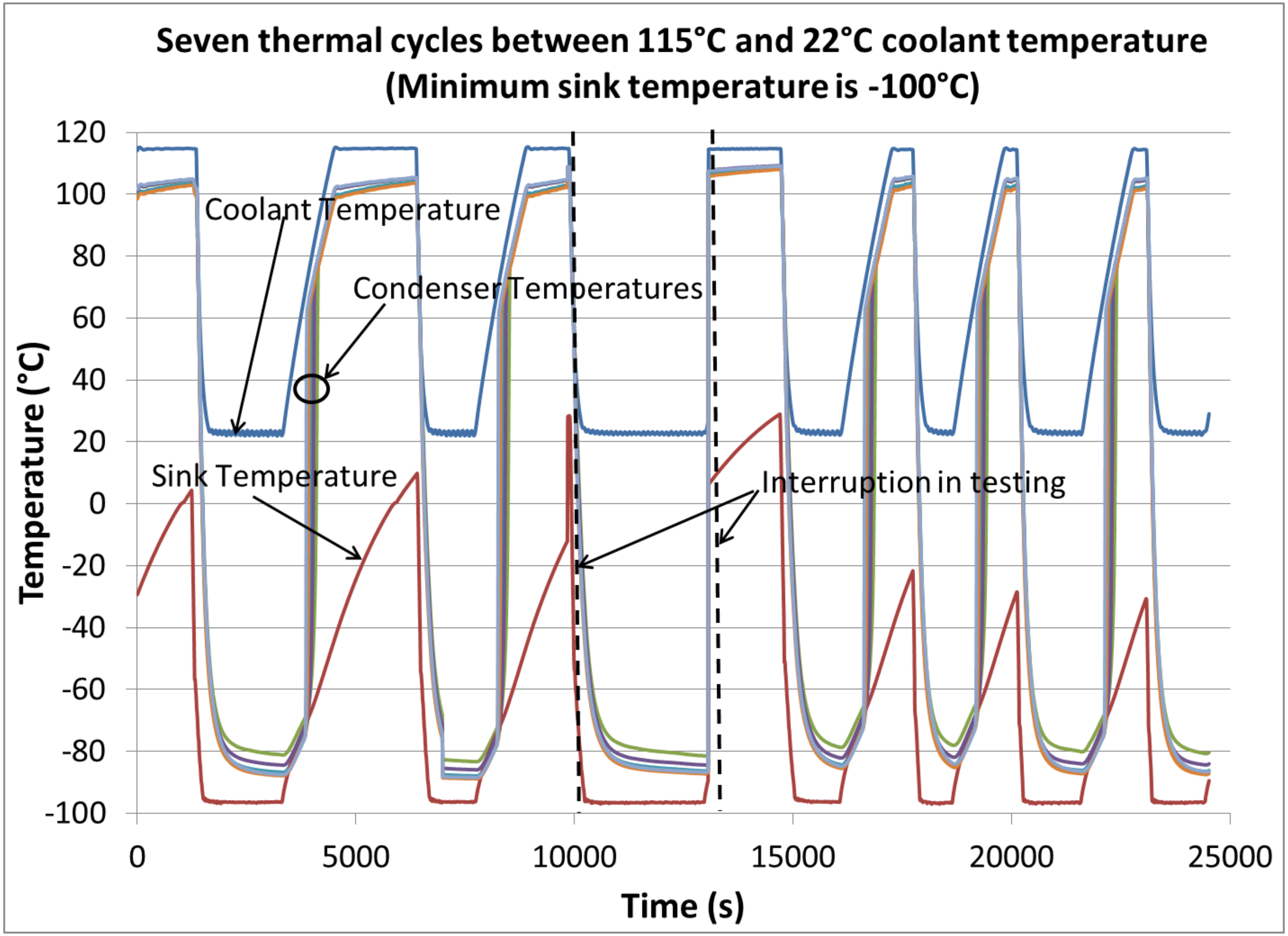


- Heat pipes charged as CCHPs
- Liquid nitrogen cold plates used for controlling sink temperature
- Total power measured from calorimetry of the coolant

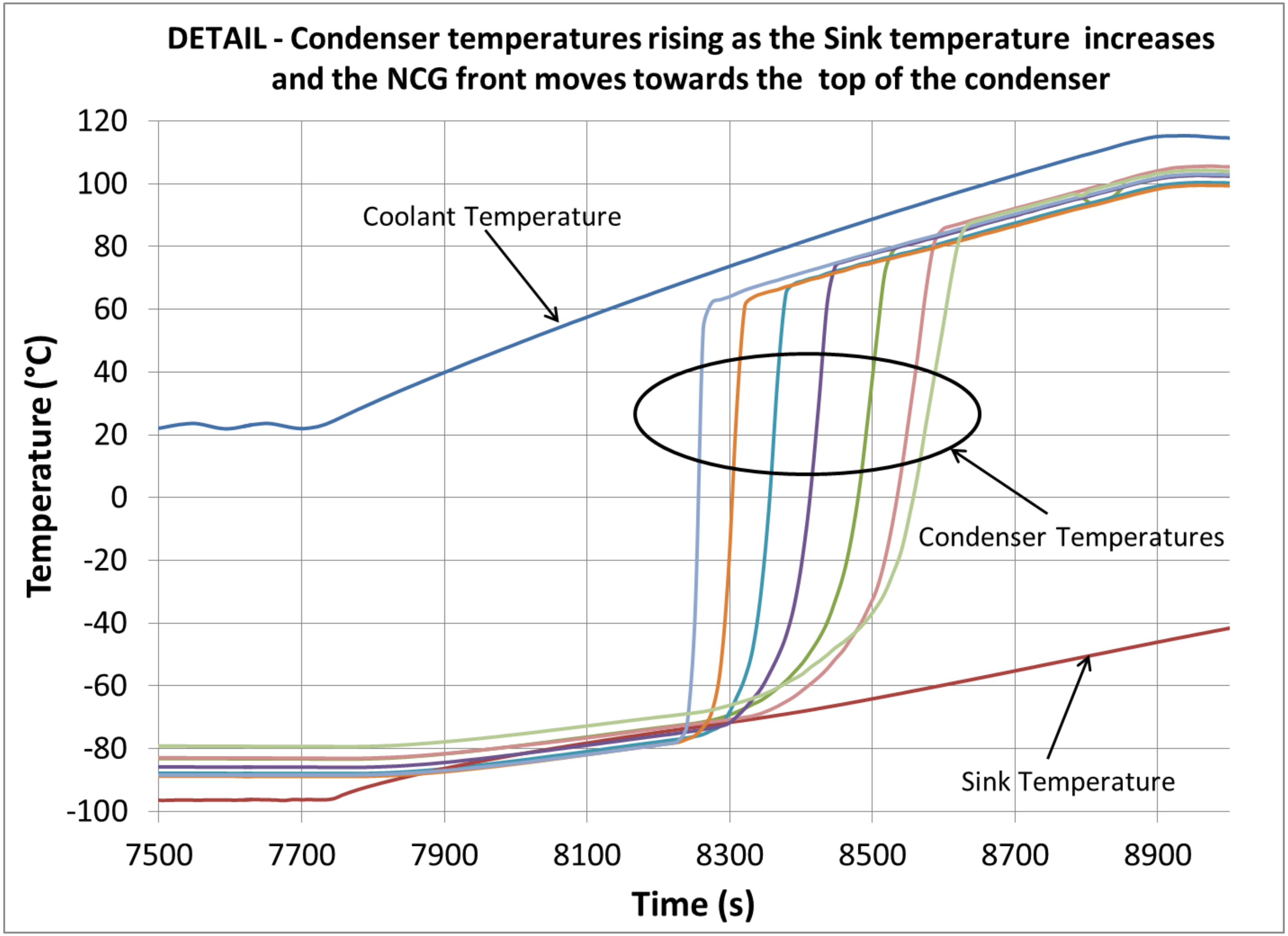


- Sink temperatures ranged from 30°C to -115°C
- Significant convective losses caused the heat pipe vapor temperature to be nearly independent of sink temperature

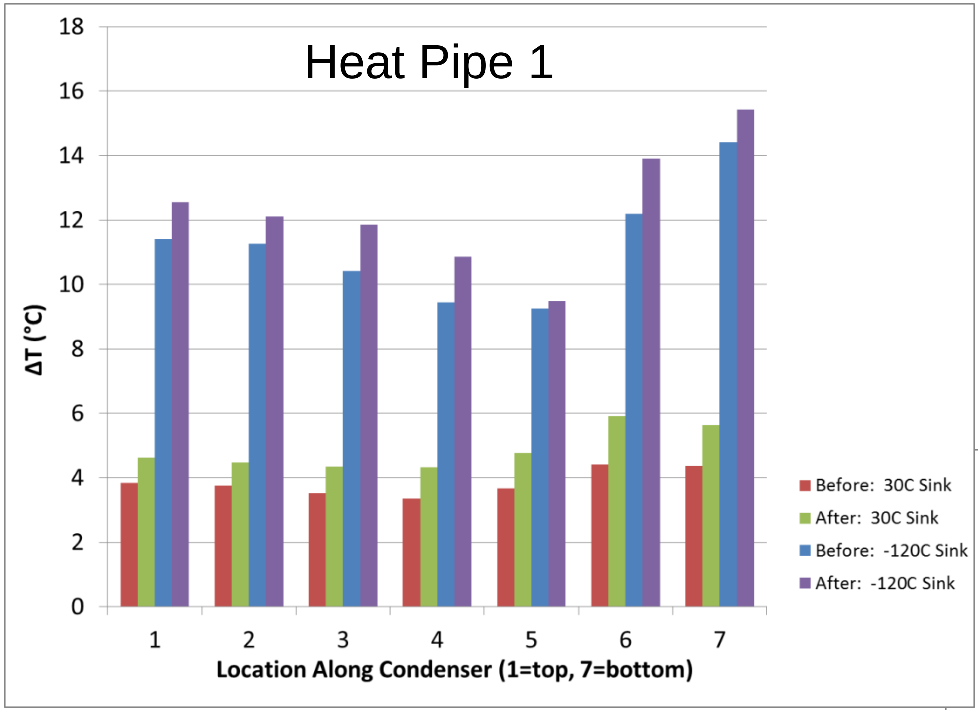
Thermal Cycling Test Results



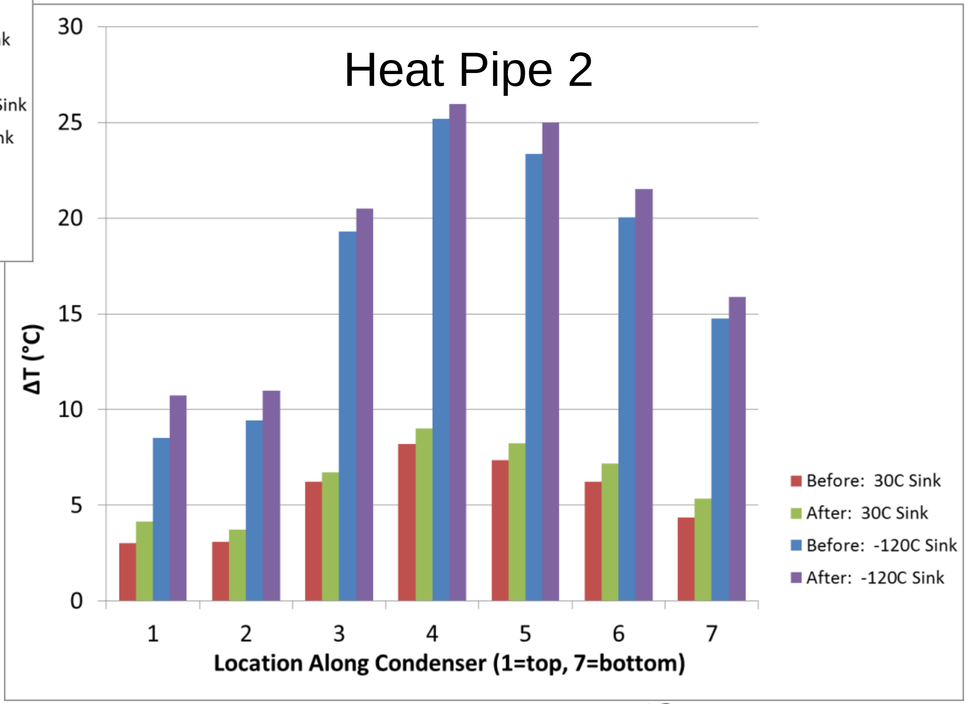
Thermal Cycling Test Results Continued



Delta Temperature Profile of Direct Bond (Before and After Thermal Cycling)

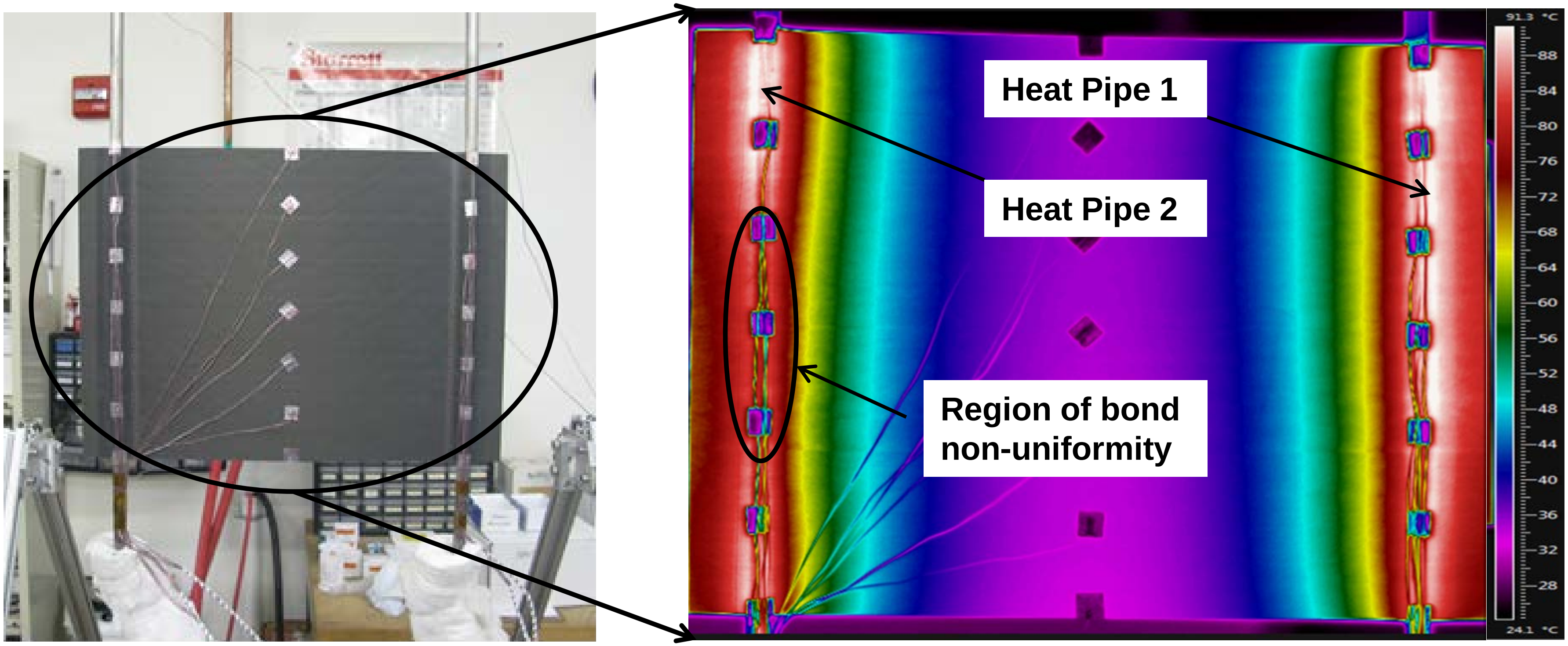


- Methodology
  - Thermal performance tests repeated for the two sink temperature extremes (30°C and -120°C)
  - Compared ΔT profiles before and after thermal cycling for each heat pipe



- Results
  - The bond adhesive appeared more uniform for heat pipe 1
    - Verified with IR camera
  - Both heat pipe bonds showed no sign of degradation after a total of 13 thermal cycles

Thermal Imaging of Radiator Panel



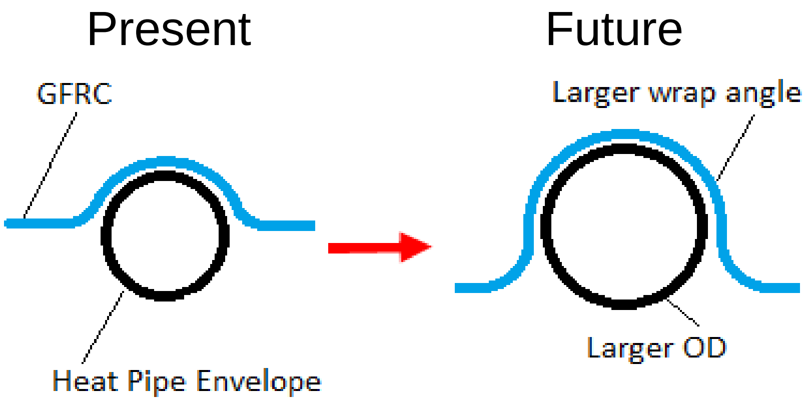
- Thermal imaging taken on facesheet side of radiator (Ti pipes not exposed)
- Non-uniform temperature distribution along heat pipe 2 indicates poor bond adhesion
  - Larger delta temperatures between heat pipe vapor and facesheet root

Program Summary

- Overall, the Phase I program was considered a success
  - Single Facesheet Radiator Design
    - Studied the effect of various geometry parameters on thermal performance and mass
    - Examined modular design vs. continuous panel
    - Developed preliminary design based on modular geometry
    - Reduced mass of radiator by ~65%, compared to previous dual-facesheet design
    - Reduces costs and simplifies fabrication – POCO is difficult to machine and expensive
  - Experiments
    - Demonstrated the titanium heat pipes could be directly bonded to the GFRC facesheet
    - Tested the thermal performance of the sub-scale radiator
    - Verified that the sub-scale radiator could withstand the CTE mismatch for several thermal cycle tests

Recommendations

- More development is needed to improve the quality of the direct bond
  - Bond adhesive was not uniform along the length
  - Resulting contact area between pipes and facesheet was small (~25%)
  - However, both heat pipe bonds showed no sign of degradation after a total of 13 thermal cycles
- Future Work
  - Development will focus on improving the integrity of the direct bond
    - Larger wrap angle
    - Larger condenser OD
    - Adhesive type and application
  - Conduct flat sample lap shear to down-select adhesive type and cure process
  - Representative pipe/facesheet samples will also undergo lap shear testing



Acknowledgements

- The Phase I SBIR program was 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 regarding the program.

TFAWS Active Thermal Paper Session

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