High Temperature Oscillating Heat Pipe Radiator

Prime Contract no. 80NSSC24PB466

Project no. ---

Prepared for: NASA TFAWS

Prepared by: Alex Miller (Alex.Miller@ThermAvant.com)

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ThermAvant TECHNOLOGIES
2508 Paris Rd Columbia, MO 65202
(573) 397-6912
info@thermavant.com

NASA

SBIR · STTR America's Seed Fund

THERMAL & FLUIDS ANALYSIS WORKSHOP
Ames Research Center 2025

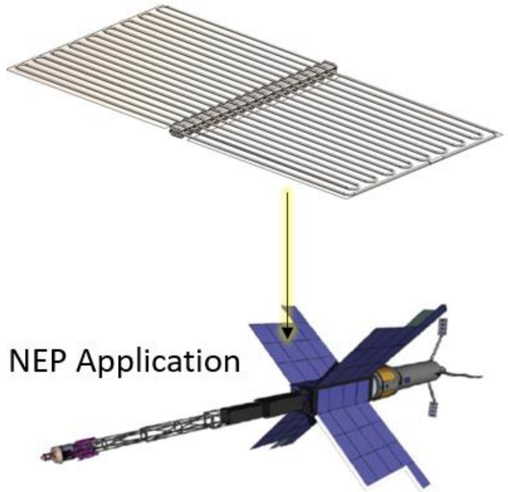
Outline

- Summary
- OHP Radiator Snapshot
- NEP Radiator Temperature Lit Review
- Prototype Design and Analysis
- Prototype Manufacturing
- Test Setup
- Thermal Results
- Phase II concepts
- Comparison to CCHP
- Participants

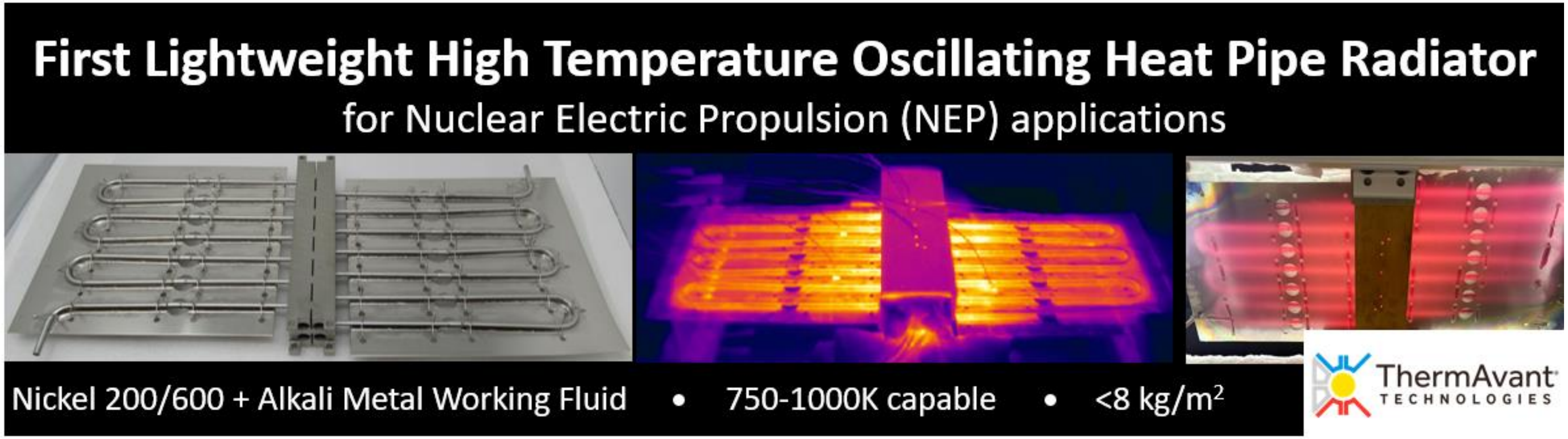
Summary

Predicted attributes after future phase II investment

Inconel/Nickel:
- 750-1000K
- 4 kg/m^2
- 1m scale

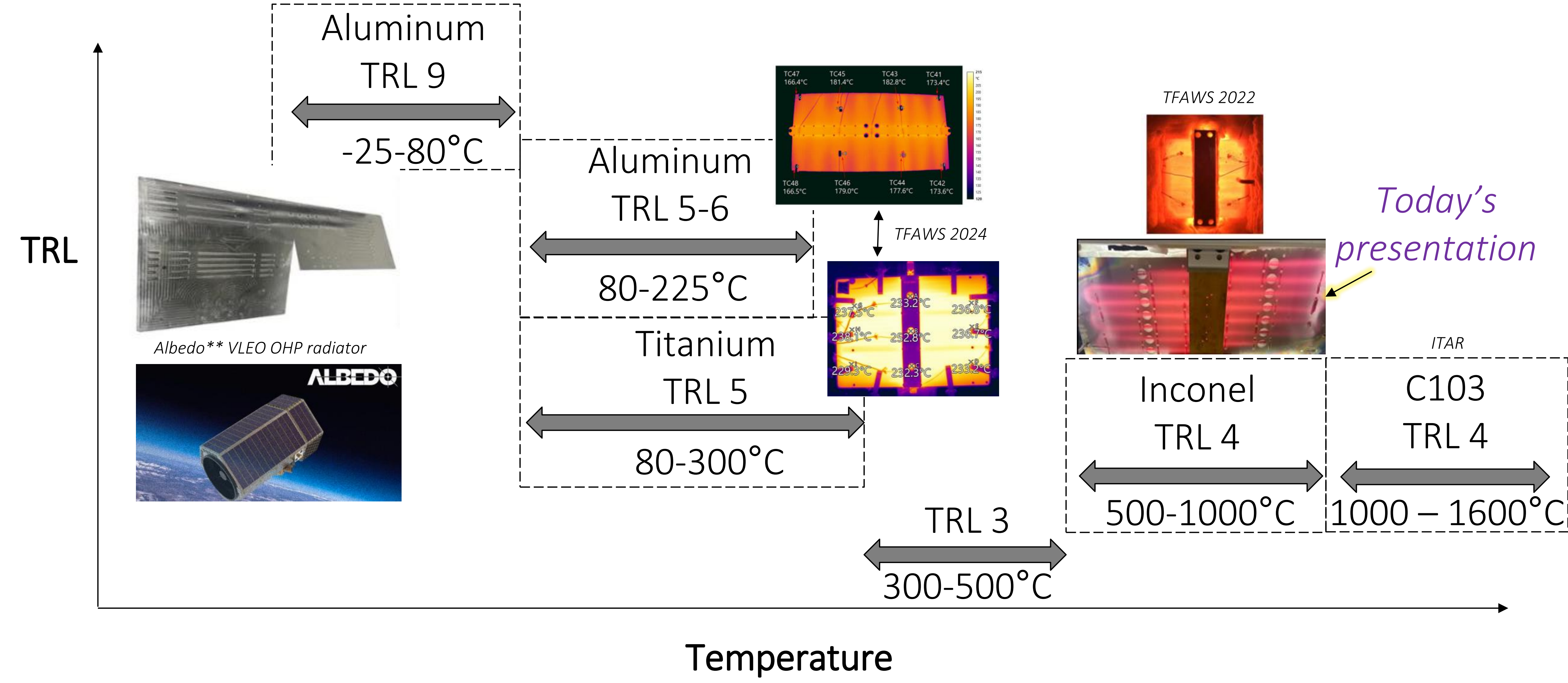


- NASA: "the large heat loads associated with nuclear power and propulsion systems require radiators that are a significant fraction of the total mass of the system, so lightweight high-temperature radiators are needed to enable such systems"
- ThermAvant Technologies (TAT) Demonstrated a first-of-its-kind 750-1000K oscillating heat pipe (OHP) radiator, positioning OHPs as an alternative to alkali metal conventional heat pipe radiator concepts
  - Testing explored (1) performance at 900K (19.5W/K or > 65x solid control), and (2) identification of lower end of operating temperature, determined to be above 723K
- Solicitation target < 6kg/m^2, industry RFIs indicate < 3kg/m^2. Phase I demonstration, which was not mass optimized was 7.65 kg/m^2, Phase II concepts predicted < 4kg/m^2.



OHP Radiator Snapshot

Maturity and materials, dependence on temperature



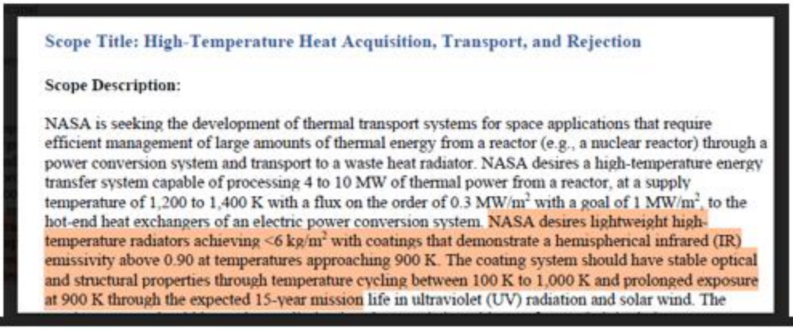
** https://www.thermavant.com/case-study/albedo-and-thermavant-tech-power-dense-ohp-based-spacecraft-thermal-control

NEP Radiator Temperature Lit Review

- Z2.01-1006 SBIR solicitation target "approaching 900K" at radiator rejection surface

- Variety of NASA references call out relevant NEP radiator temperatures: >500K input [4], 375-500K [1, 5], 450-500K input [1-3], 550-750K max input [6], 325-500K min input [6], >500K rejection [2], 500K rejection [3].
    - These are generally chosen to align with legacy Ti-water CCHPs <550K, although papers* acknowledge PHRS inlet <550K is a non-optimal constraint for PCIT >1400K
    - The JANNAF [6] technical maturation plan KPP rises to 750K max input, which aligns with AMA system-level optimization work*, and is not supported by higher TRL water-based heat pipes.

- On NASA's recent Advanced Closed Brayton Cycle (ACBC) effort, a performer designed a 25kWe power conversion system with a 1700K turbine inlet temperature, which enables efficient operation with radiators in the 700-1000K range


Scope Title: High-Temperature Heat Acquisition, Transport, and Rejection

Scope Description:

NASA is seeking the development of thermal transport systems for space applications that require efficient management of large amounts of thermal energy from a reactor (e.g., a nuclear reactor) through a power conversion system and transport to a waste heat radiator. NASA desires a high-temperature energy transfer system capable of processing 4 to 10 MW of thermal power from a reactor, at a supply temperature of 1,200 to 1,400 K with a flux on the order of 0.3 MW/m² with a goal of 1 MW/m², to the hot-end heat exchangers of an electric power conversion system. NASA desires lightweight high-temperature radiators achieving <6 kg/m² with coatings that demonstrate a hemispherical infrared (IR) emissivity above 0.90 at temperatures approaching 900 K. The coating system should have stable optical and structural properties through temperature cycling between 100 K to 1,000 K and prolonged exposure at 900 K through the expected 15-year mission life in ultraviolet (UV) radiation and solar wind. The

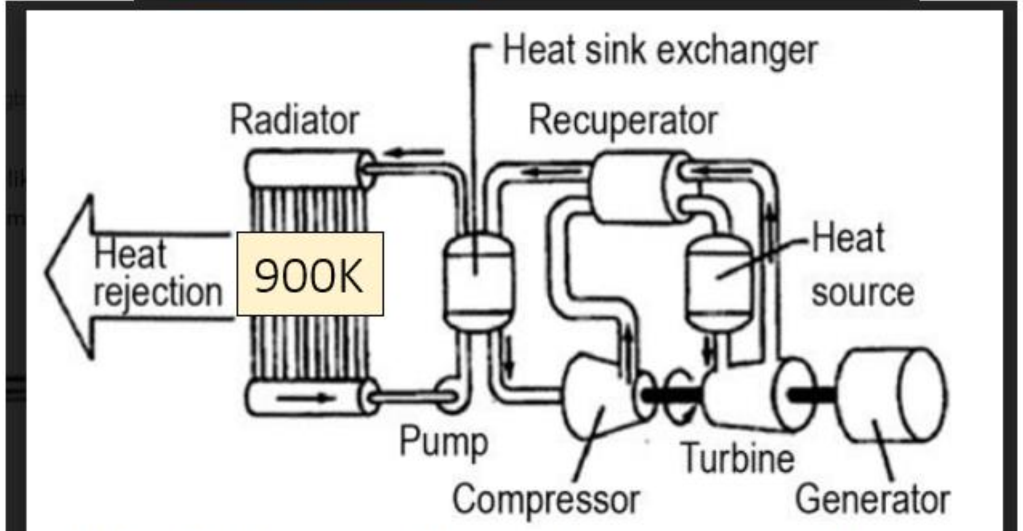


Fig. 3. Brayton Power Conversion Unit

[1] Mason et al "Nuclear Power Concepts and Development Strategies for High-Power Propulsion Missions to Mars" NASA/TM-20210016968, 2022
[2] STMD SNP Presentation (2023)
[3] Cremins, T., et al., "Mars Transportation Assessment Study," NASA, March 2023.
[4] "Space Nuclear Propulsion for Human Mars Exploration," National Academies of Sciences, Engineering, and Medicine, 2021
[5] Oleson S., et al, "Compass Final Report: Nuclear Electric Propulsion Chemical Vehicle 1.2", NASA/TM-20210017131, Sept 2021
[6] Martin, A., et al "A Technology Maturation Plan for the Development of Nuclear Electric Propulsion," JANNAF 2022

* https://ntrs.nasa.gov/citations/20220019167

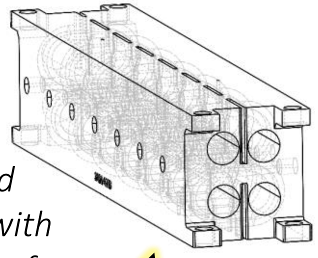
Prototype Design and Analysis

First lightweight meter-scale alkali metal OHP radiator

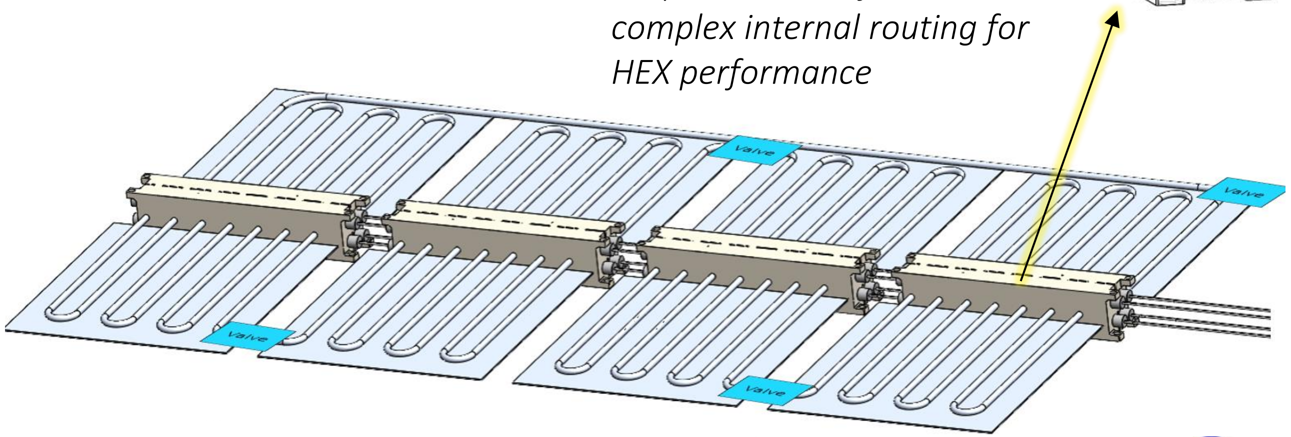
- 1m x 0.5m panel chosen for comparison to previous OHP radiator demo at 200°C, and internal oven brazing limitations

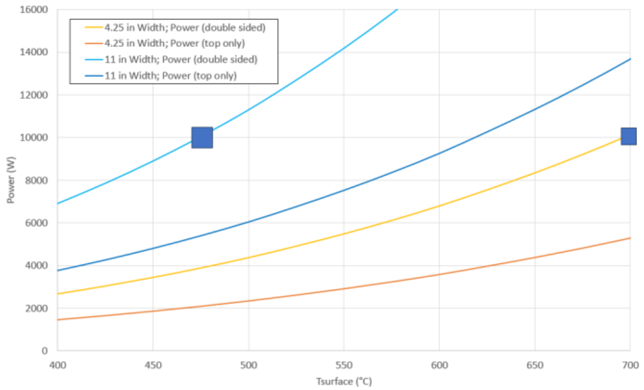
- Materials
  - IN625 AM evaporator heat exchangers
  - IN625 condenser tubing
  - Nickel 200 fin panel

- Limitations of the ph I prototype
  - Electrically heated. (Pumped NaK in final application)
  - Spacing between manifolds required for unheated length of the cartridge heaters and electrical wiring
  - Some compression fittings used to ease assembly vs fully welded

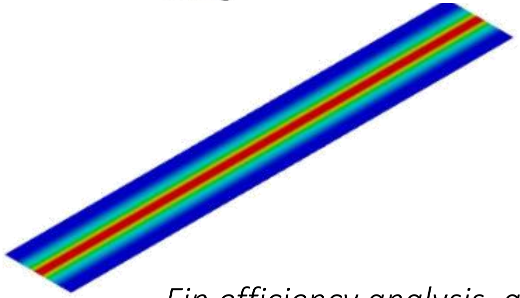


Additively manufactured evaporator manifolds, with complex internal routing for HEX performance



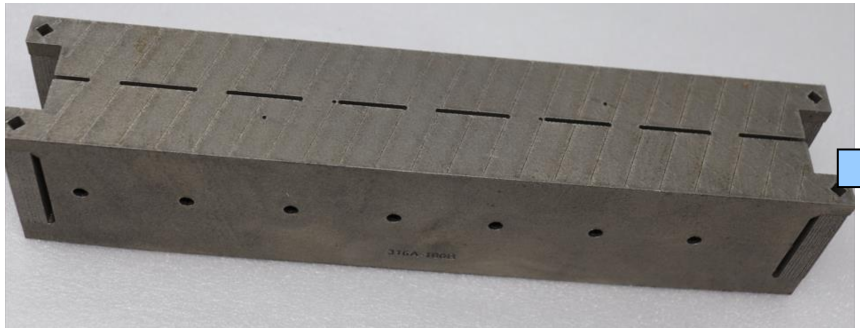


Radiative correlations to understand power at target temps as function of radiator width, emissivity, and one-sided vs two-sided view factors

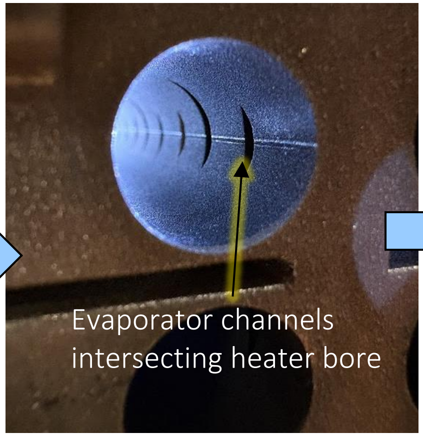


Fin efficiency analysis, as function of thermal k and thickness, to select phase I panel

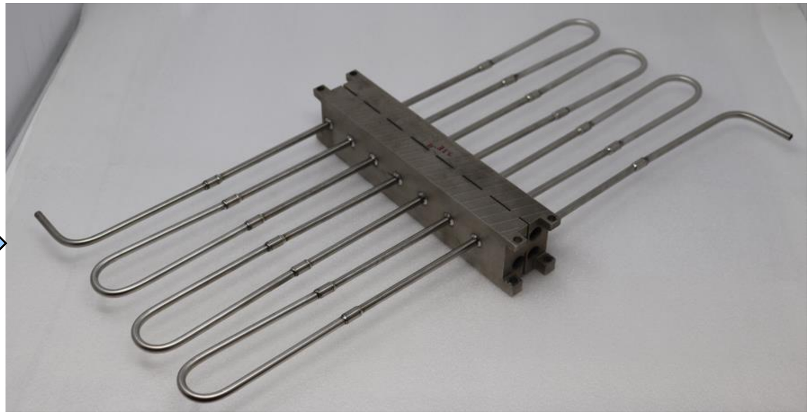
Prototype Manufacturing



Evaporator manifolds printed

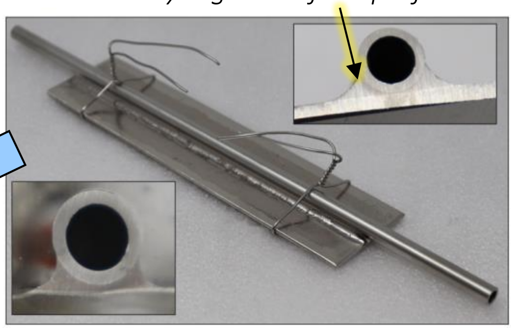


Post-AM cleanup (wire EDM), fallout on vendor setup mistake (+ not enough spares)



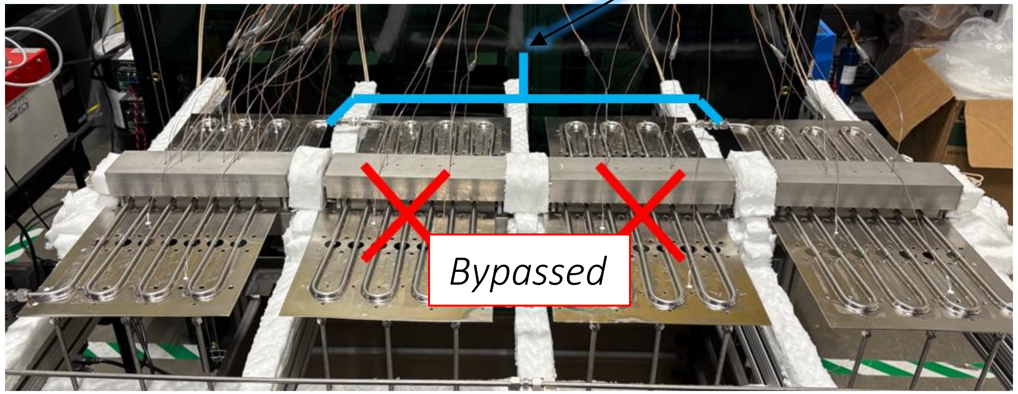
Condenser tubing formed and welded

Very high interface performance



Subscale braze optimization

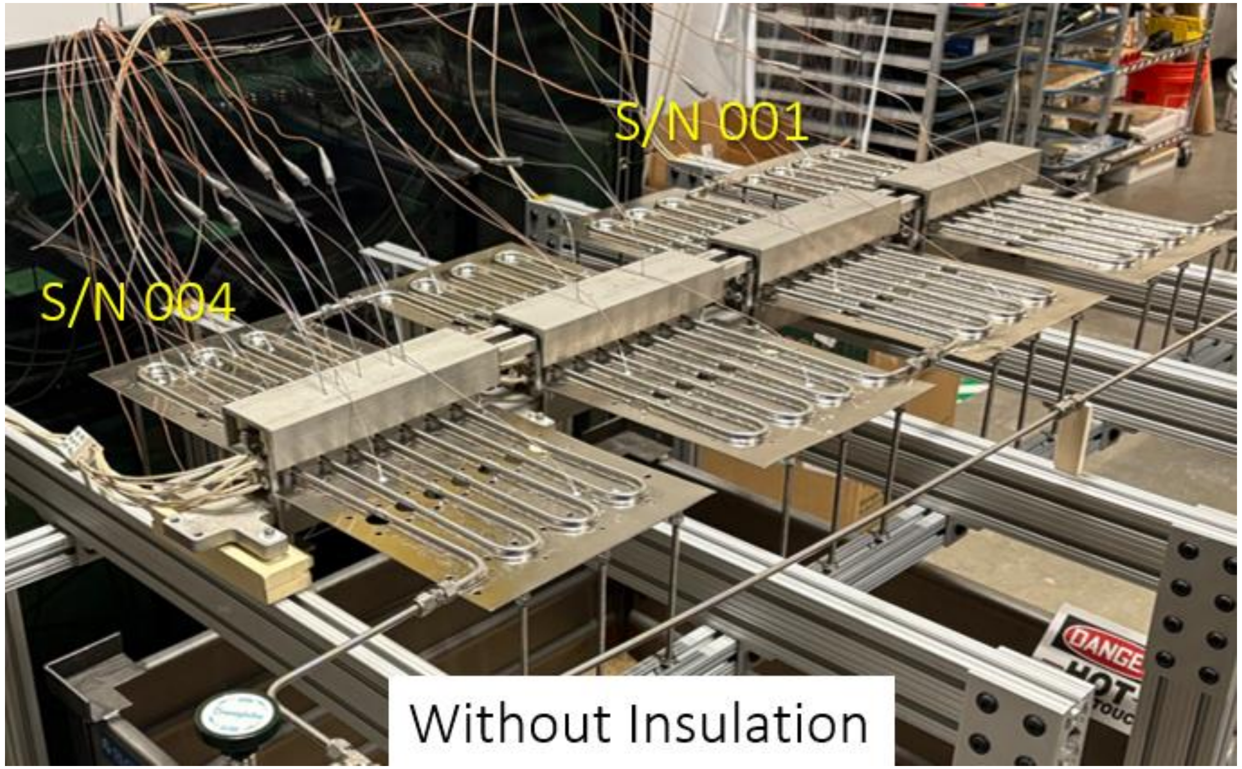
Fin panels brazed to condenser tubing



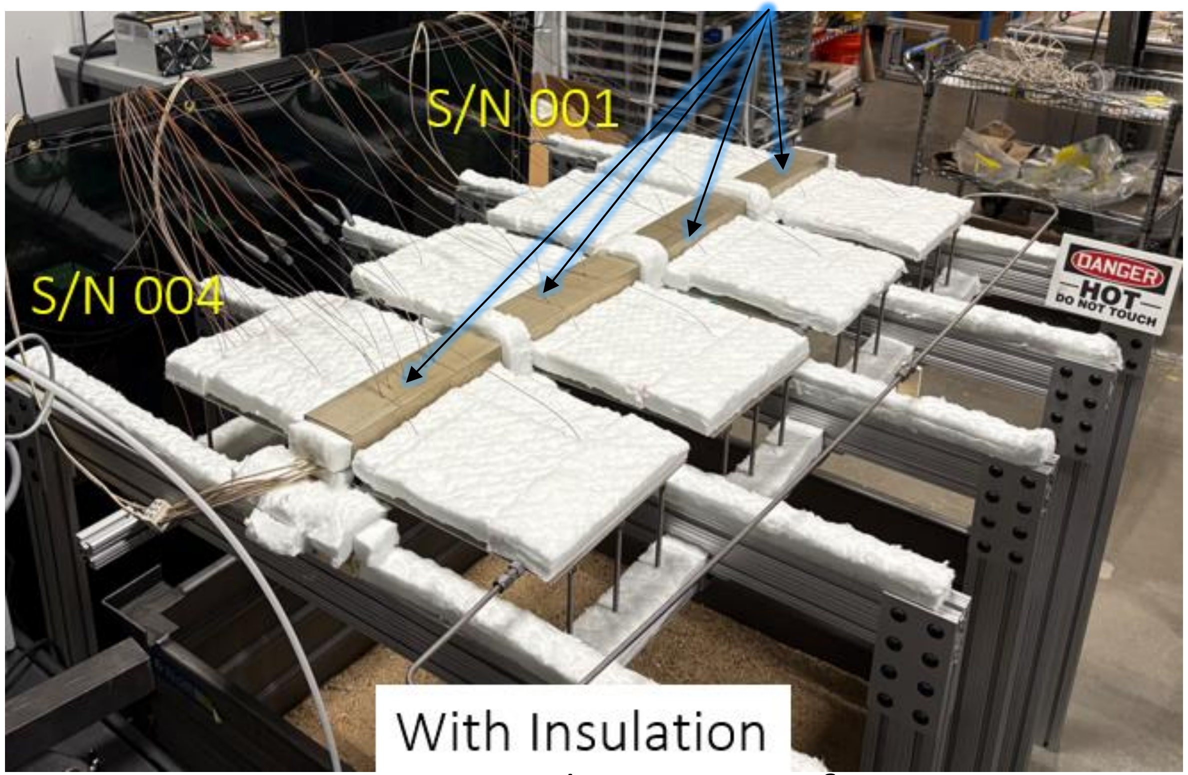
- Final OHP configuration with 50% of design channels;
- Lab demos down to 0.5m x 0.5m footprint (0.5m^2 total two-sided rejection area)

Test Setup

- Rejection by radiation + convection to 300K lab
- Insulation required on to more closely match rejection flux in space (offset free convection)



Ceramic insulators over evaporator manifolds

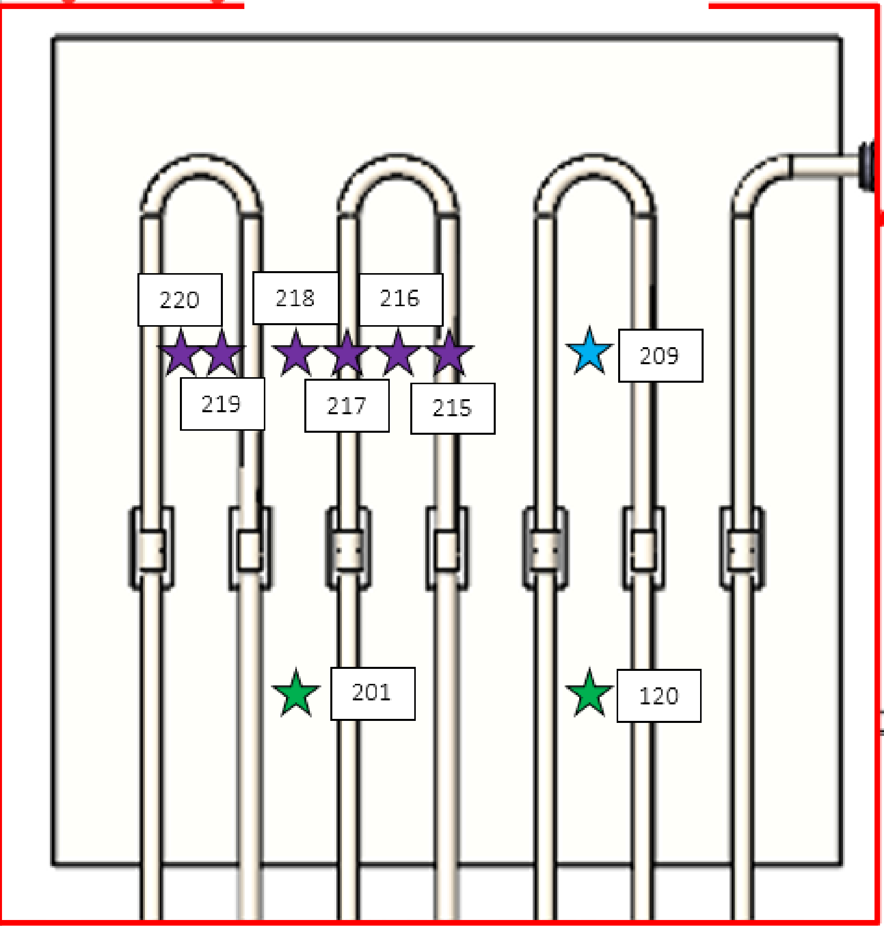


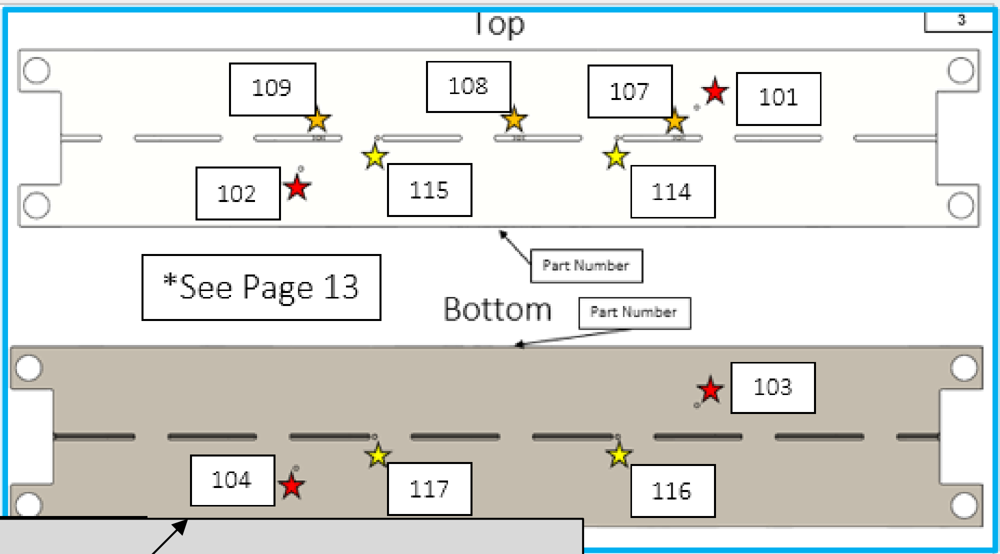
On top condenser surface

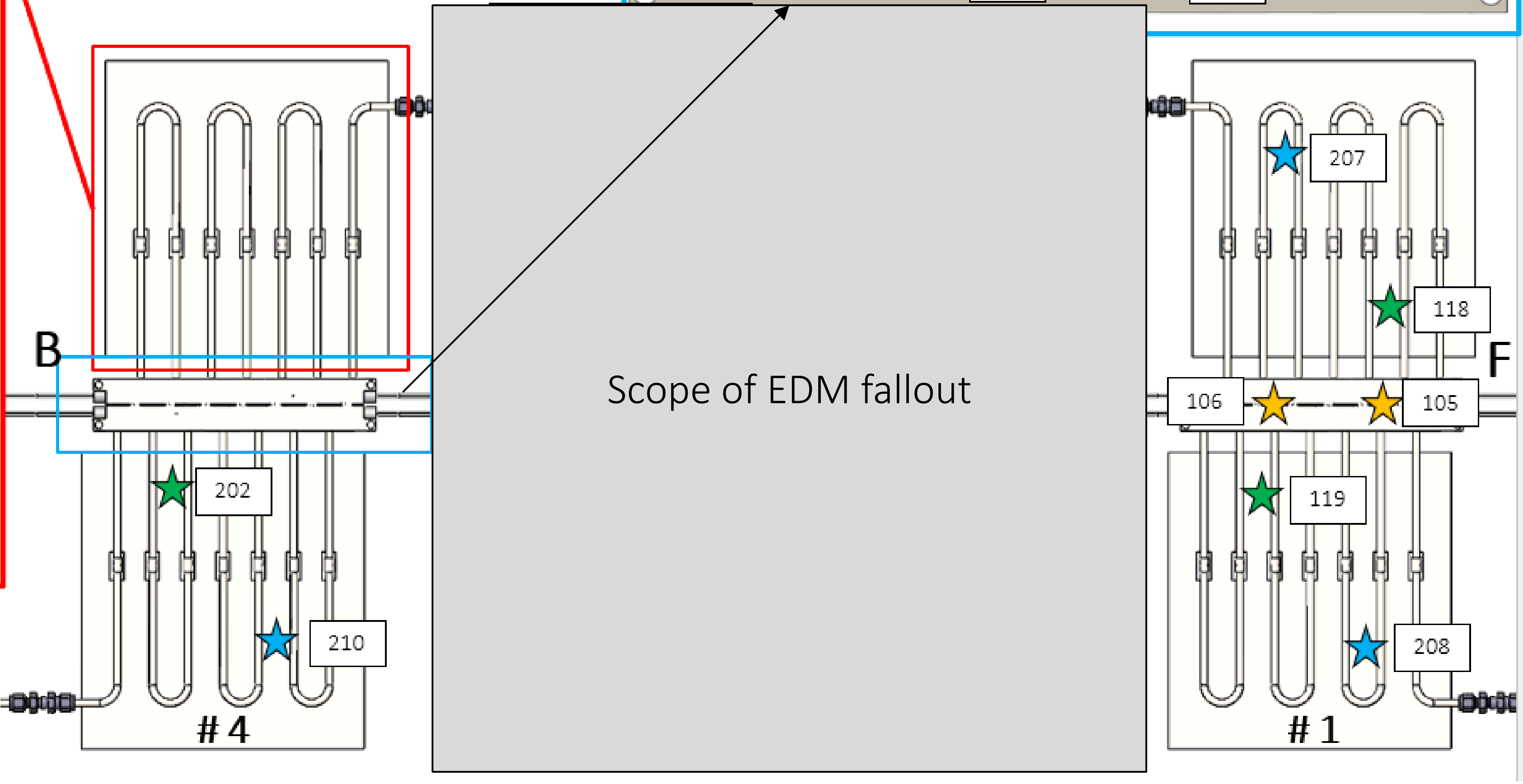
Test Setup

Thermocouple Map

★ : Overtemp Control
★ : Heater (Probe, QTY 4)
★ : Center Evap (Probe, QTY 9)
★ : Outer Evap (Probe, QTY 4)
★ : Inboard Panel (welded, QTY 9)
★ : Outboard Panel (welded, QTY 8)
★ : Panel Average (welded, QTY 6)
☆ : Ambient (Bead, QTY 1)





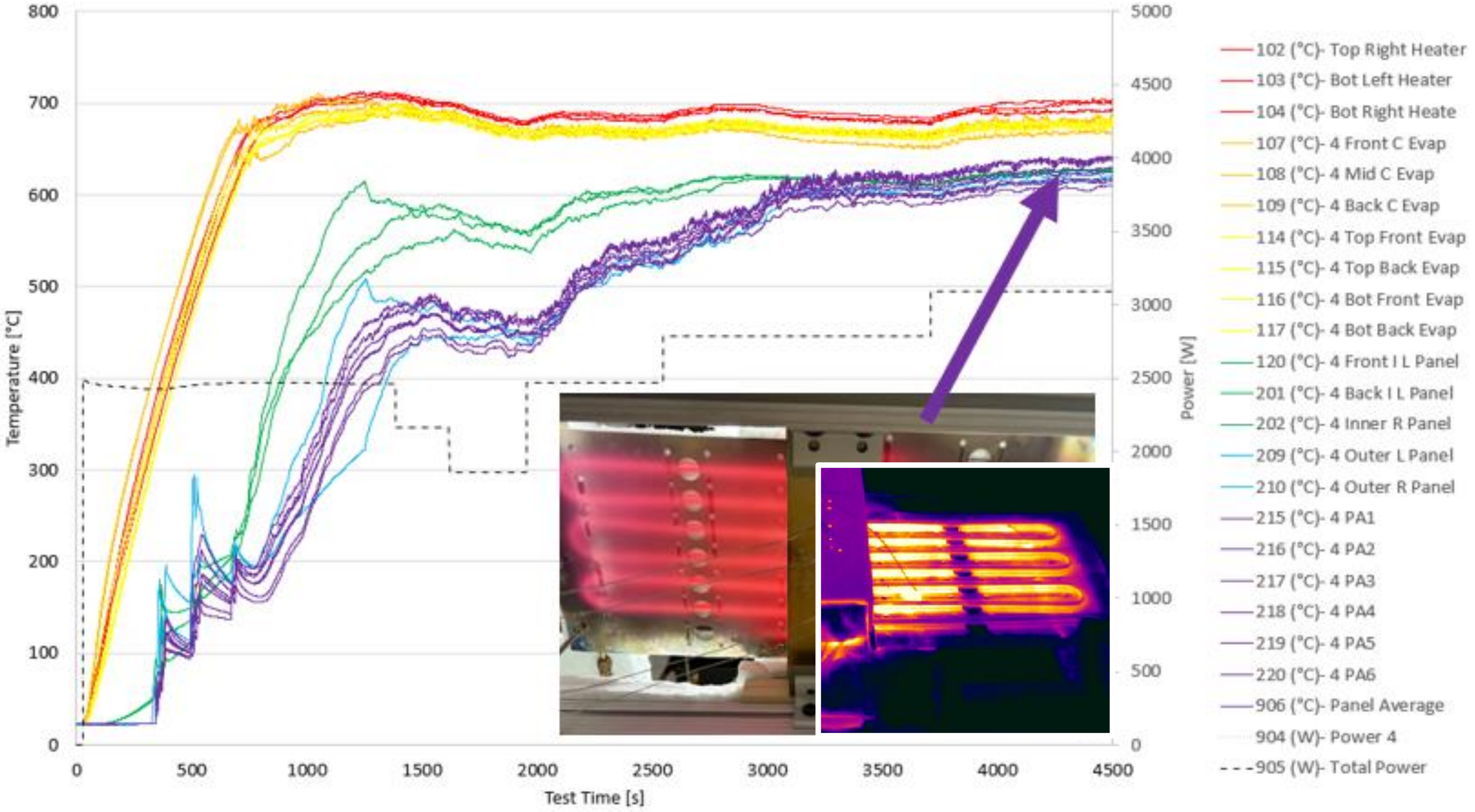


*Place where most convenient, but maintain position during testing ☆ 309

Thermal Results

Test ID 1: Startup to 900K (627 °C) condenser

- At steady-state:
  - 2.2kW thermal transport power at reference 3.1kW$_e$
  - 62 °C dT from average evaporator to average condenser
  - 17.8 W/K conductance



- Definitions:

$$Spatial\ dT = Avg\ Evap - Avg\ Cond$$

$$Conductance = \left({}^{Thermal\ transport\ power}\!/\!_{Spatial\ dT} \right)$$

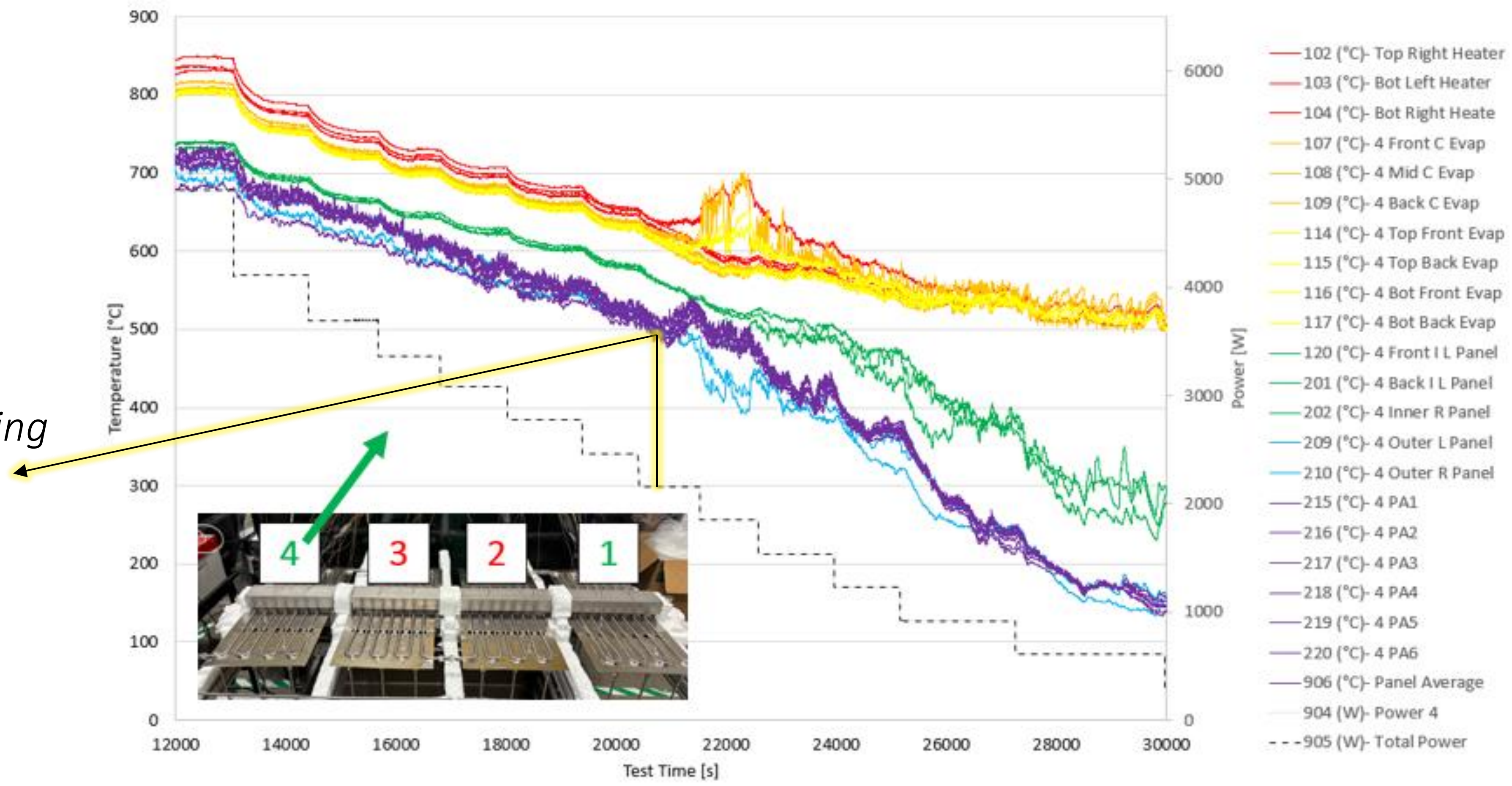
$$Thermal\ transport\ power = rejection\ power\ (at\ steady-state\ conditions) = calculated\ from\ measured\ temperatures\ of\ rejection\ surfaces$$

Thermal Results

Test ID 2: Minimum stable operating temperature

- Decreased performance (stability and conductance) as OHP brought below 500°C condenser

With same power (2.2 kW_e) applied to panel without working fluid, the average rejection surface was only 126 °C

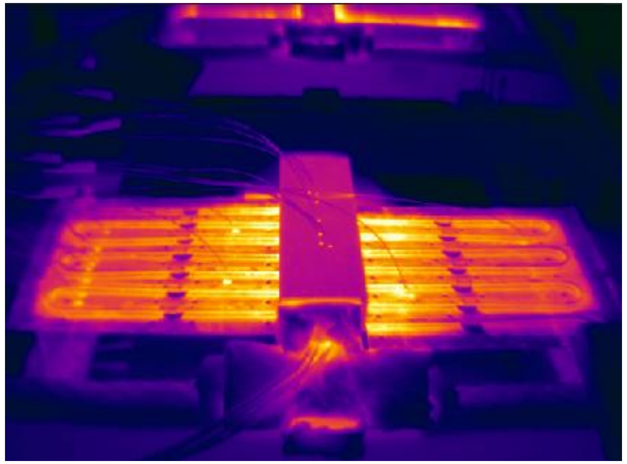


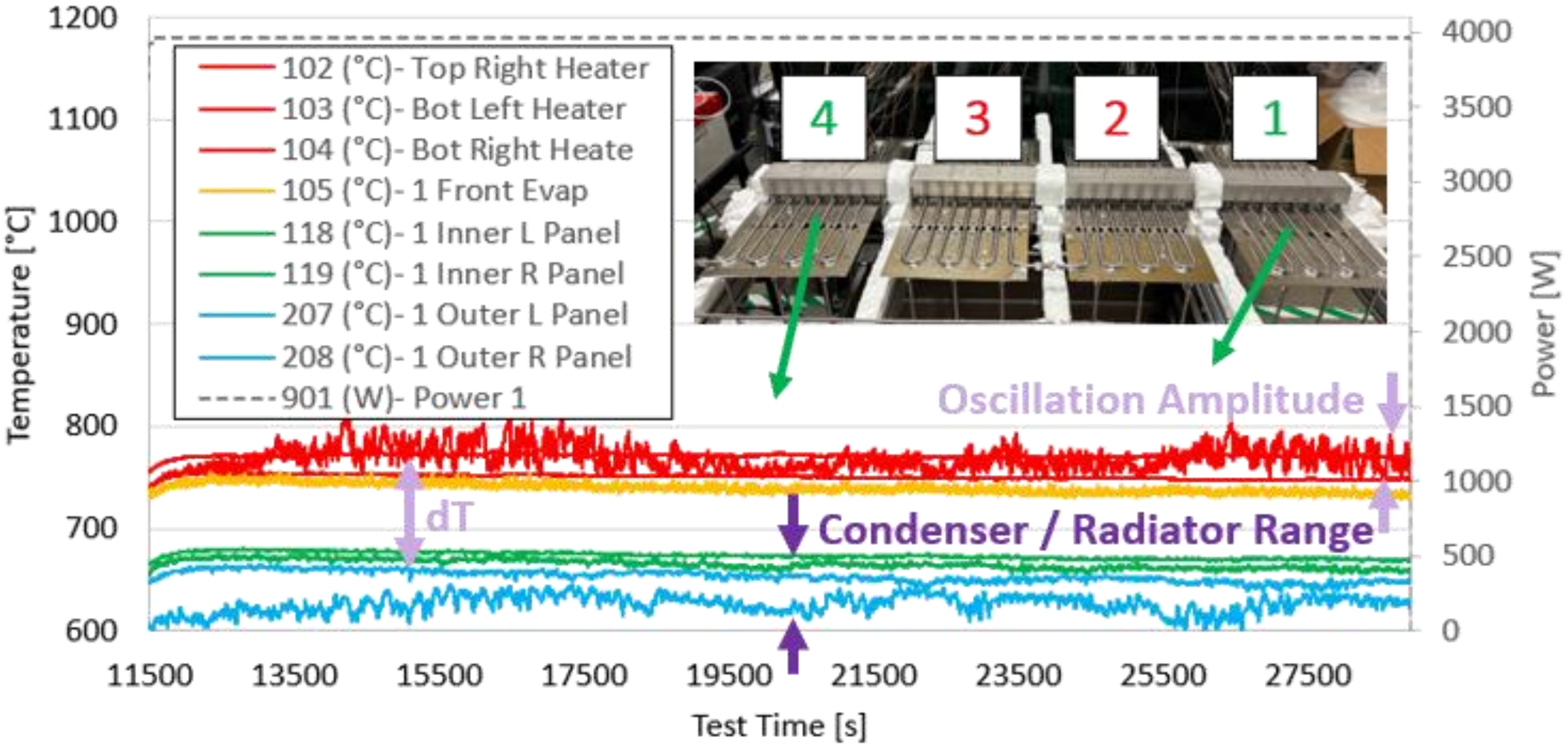
Thermal Results

Longer duration (4 hour) demonstration

- At steady-state:
  - 2.6kW thermal transport power at reference $4kW_e$
  - 68 °C dT from average evaporator to average condenser
  - 19.5 W/K conductance

IR image





Thermal Results

Tabular Summary

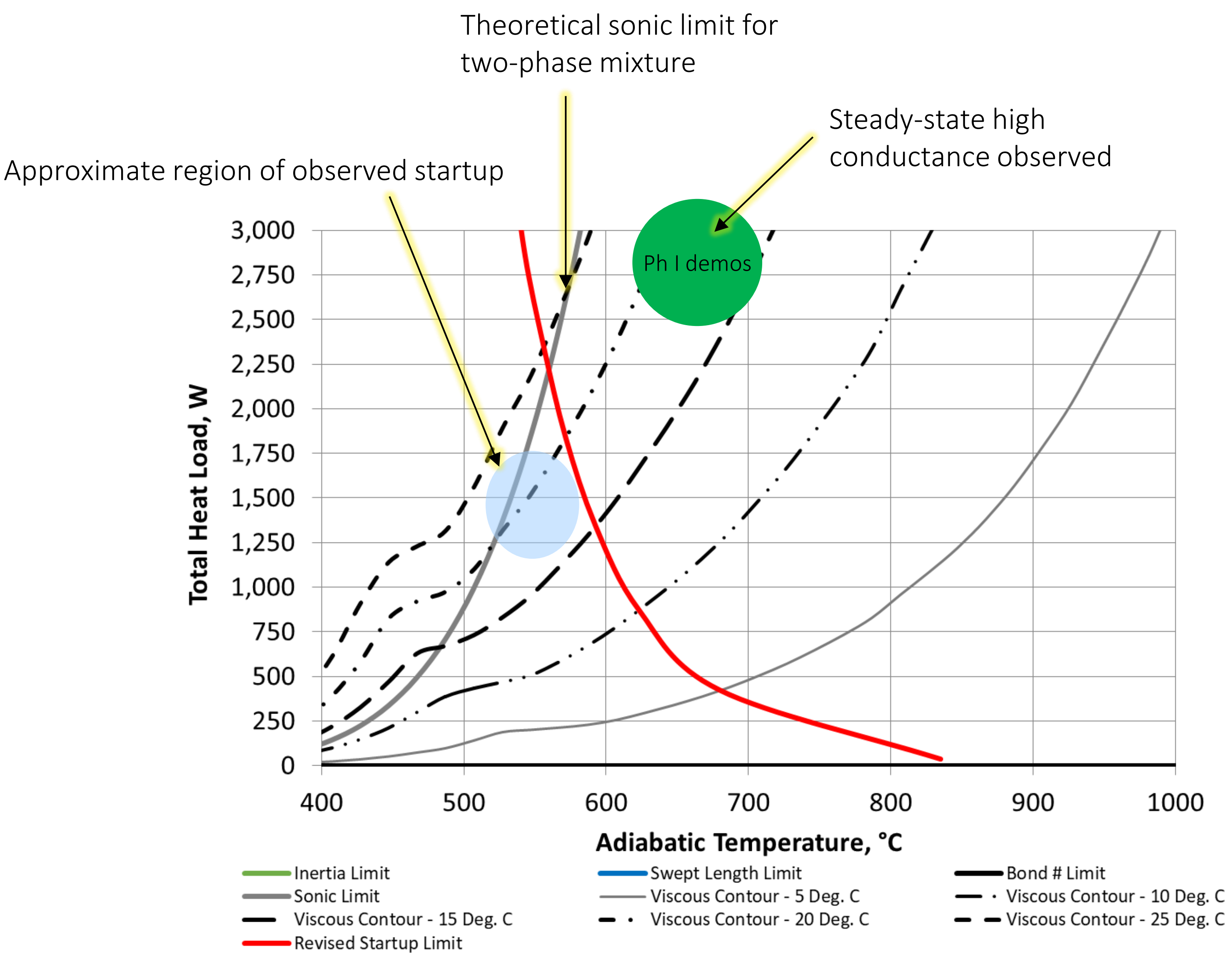
- High performance over ~500-550°C condenser predicted and observed.
  - Similar to prior demos with same fluid in different form factors
- OHP conductance (W/K) = 65x that of vented control (mass equivalent nickel radiator)
- OHP radiator specific power (W/kg) = 6.5x that of passive/conductive control

Test ID	Description	Electrical Power (kW)	Transport (rejection) Power (kW)	Avg Evaporator (°C)	Average Condenser (°C)	dT (°C)	Conductance (W/K)
0	Vented Control Test	2.2	0.4	745	126	619	0.3
1	900K Condenser	3.1	2.2	685	627	62	17.8
2	Min Stable Temp	2.5	1.2	650	525	125	9.6
3	Longer Duration	4	2.6	730	663	68	19.5

Thermal Results

Startup Limit

- First order assessment of start-up conditions showed reasonable alignment with the existing model



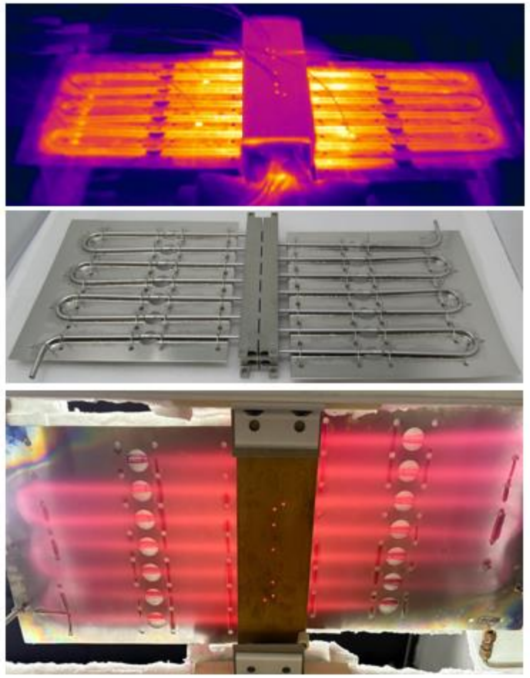
Phase II Concepts

Positive technical reviews, but not selected

High Temperature OHP Radiator Development

2022 Breadboard →
- 725-1225K
- 21 kg/m²
- 0.1m scale

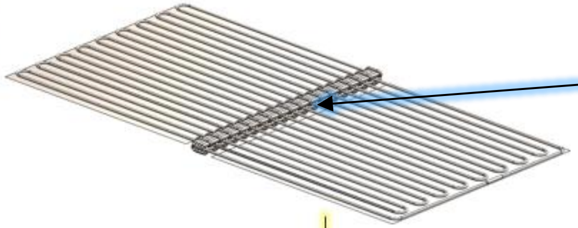
2024 NEP Phase I →
- 775-975K
- 7.7 kg/m²
- 0.5m scale



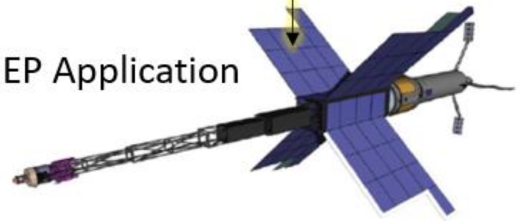
Proposed Phase II

Titanium:
- 550-750K
- 2 kg/m²
- 1m scale

Inconel/Nickel:
- 750-1000K
- 4 kg/m²
- 1m scale



NEP Application



- 750-1000K solution supported by alkali metal working fluids
- 550-750K solution requires novel working fluid development

Updated concept for fully tubular/brazed heat exchanger, no powder additive, drives areal density improvement

TRL/MRL	9/>7	9/>7	9/>7	3/2	8/>7	7/>4	6/>4	9/9	7/9	9/9	7/7
Heritage	Flown	Flown	Flown	N	Flown	N	Flown	Flown	Flown	Flown	Flown
Emissivity	>0.8	>0.8	>0.8	>0.8	0.4-0.6	~0.9	0.5	<0.63	>0.85	<0.7	<0.7
Absorptivity	0.15	High	High	Low	0.91	?	0.77-0.96	0.274	0.905	0.52-0.72	0.72-0.75
Titanium	M	?	G	G	G	M	G	?	G	G	G
Nickel	?	G	G	?	G	M	G	?	G	G	G
Charging	P	P	G	G	G	G	M	P	P	P	P
Cost	$$	$	$$$	$$	$$	$$$	$$	$$	$	$	$$

Current state of radiator coatings options from TAT partners

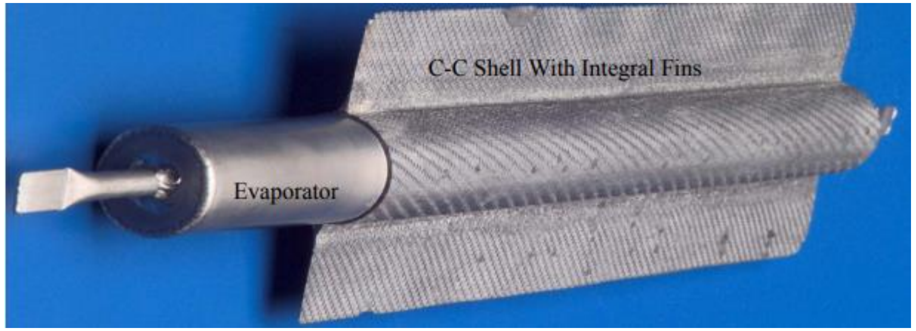
Comparison to CCHP

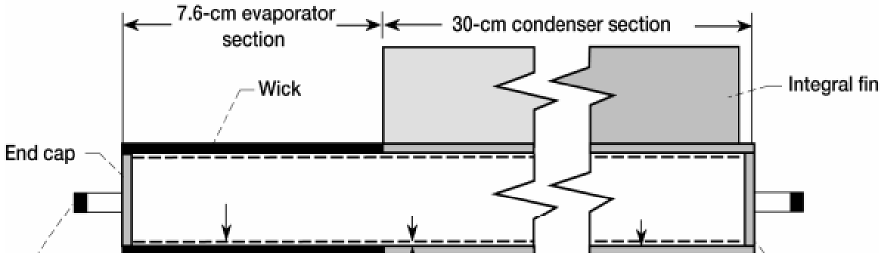
One known alkali metal CCHP radiator demo

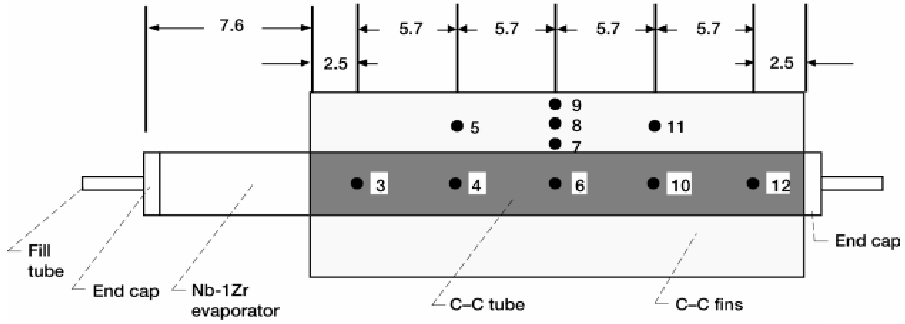
- 2.1kg/m^2 areal density with T300 C-C fin
- Potassium heat pipe performance not included… (no evaporator temperatures, conductance, or overall dTs)
- 300W @ ~600K average rejection surface.
- Sonic limited @ ~15 cm transport length under 525K condenser
- C-C fin is low density, 1.45 g/cc (1mm thick x 1” long @ k_{th}= 80W/m-K = ~80% efficient)
  - Higher thermal conductivity C-C composites exist now
- Significant and non-uniform thermal interface resistance, from condenser tube to fin
  - Note: OHP monolithic architecture has brazed interfaces from PFL to evaporator and condenser to fin. Thermal-mechanically superior to CCHP challenges, with dissimilar materials, CTE mismatches, etc. If C-C fin is proven superior, OHP integration to woven panel likely easier, due to smaller diameter tubing.
- **-> Lot of work to be done to mature alkali metal heat pipe embedded radiators (wick-based or oscillating), at component scales that support MW assemblies, especially including evaporator heat exchange interfaces to pumped NaK trunkline**

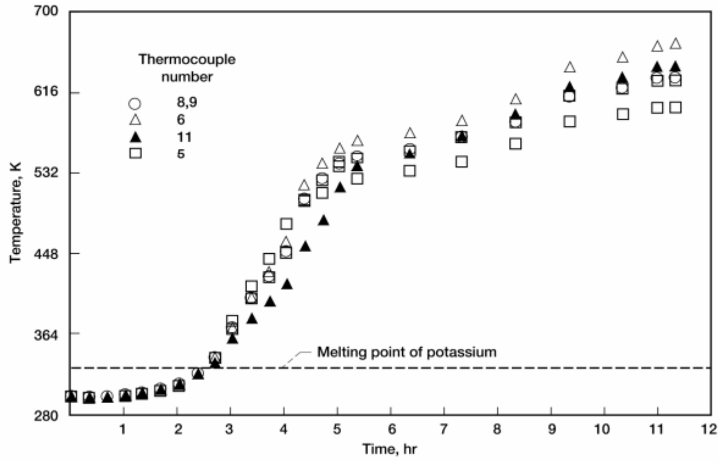
https://ntrs.nasa.gov/api/citations/20080045532/downloads/20080045532.pdf

https://ntrs.nasa.gov/api/citations/19950020948/downloads/19950020948.pdf









Participants

- ThermAvant Technologies:
    - **Alex Miller**: PI
    - **Patrick Margavio**: PM / Execution Lead
    - **Berto Aviles**: Mechanical Engineer - Thermal Analysis Support
    - **Sam Donovan:** Mechanical Engineer - Manufacturing Support
    - **Bob Ducommun:** Mechanical Engineer - Thermal Test Support
    - **Daniel Pounds**: VP – General Support

- NASA:
    - **David Bugby:** JPL Technical Monitor
    - **Greeta Thaikattil:** Supporting/informal TM

Thank you