

Production and Characterization of Additively Manufactured Radiator Panels with Integral Branching Heat Pipes for High-Temperature Heat Rejection

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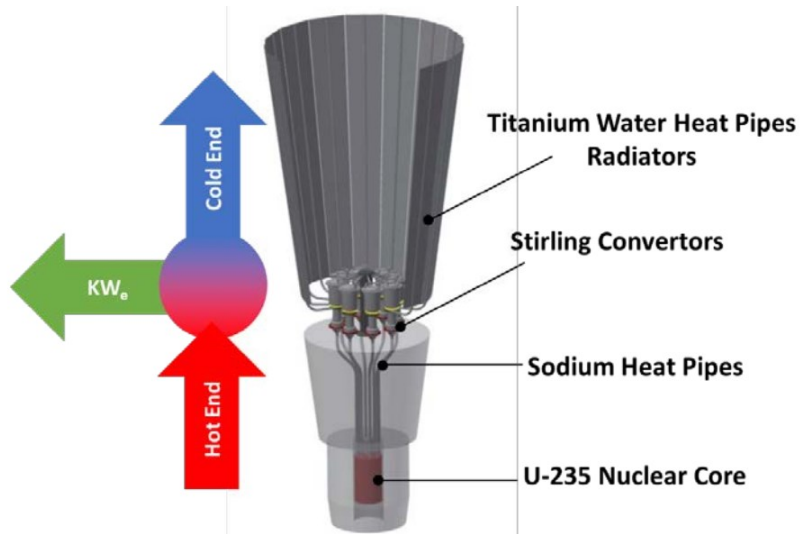
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Presented By
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Mission and Technical Needs for High Temperature HPRs

Kilo-Power Concept

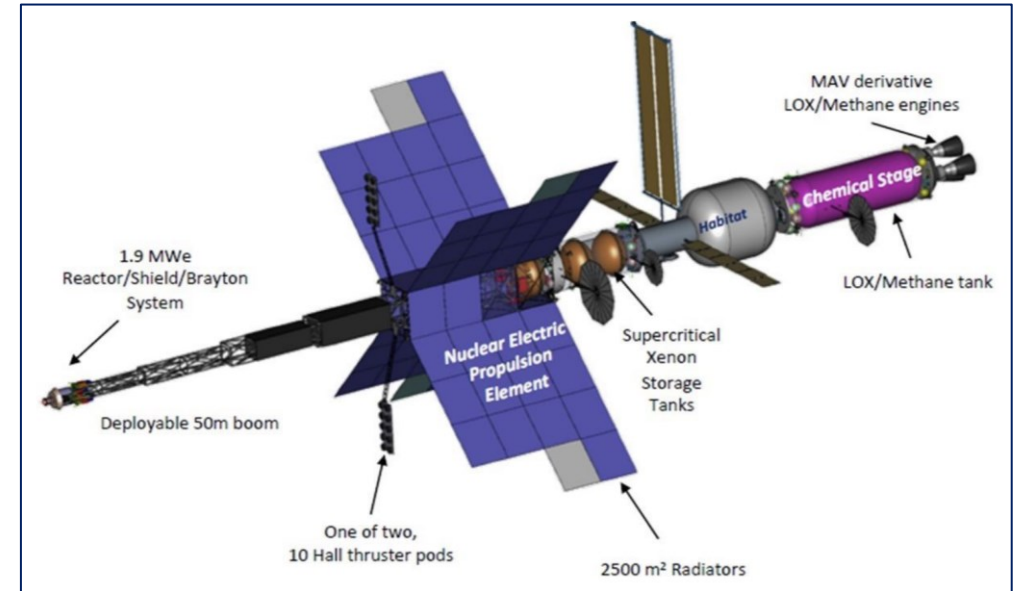


Lee et al. 2018 (ACT, NASA Glenn, LANL)

- 1-10+ kW electric power output
- High operating temperatures required
- Need for mass optimized heat rejection

NASA calls for lightweight ($\rho_s = 2 - 4 \text{ kg m}^{-2}$), high temperature ($T_H = 500 - 550 \text{ K}$), thermally efficient ($\eta_f \geq 70\%$) heat rejection systems.

Nuclear Electric Propulsion

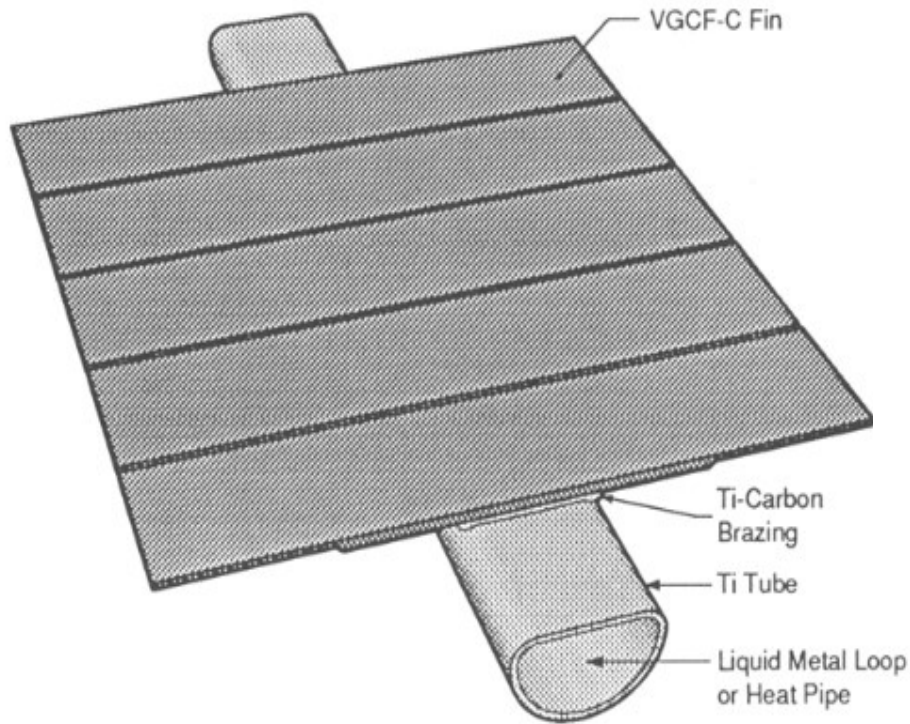


(Kludze et al., 2023)

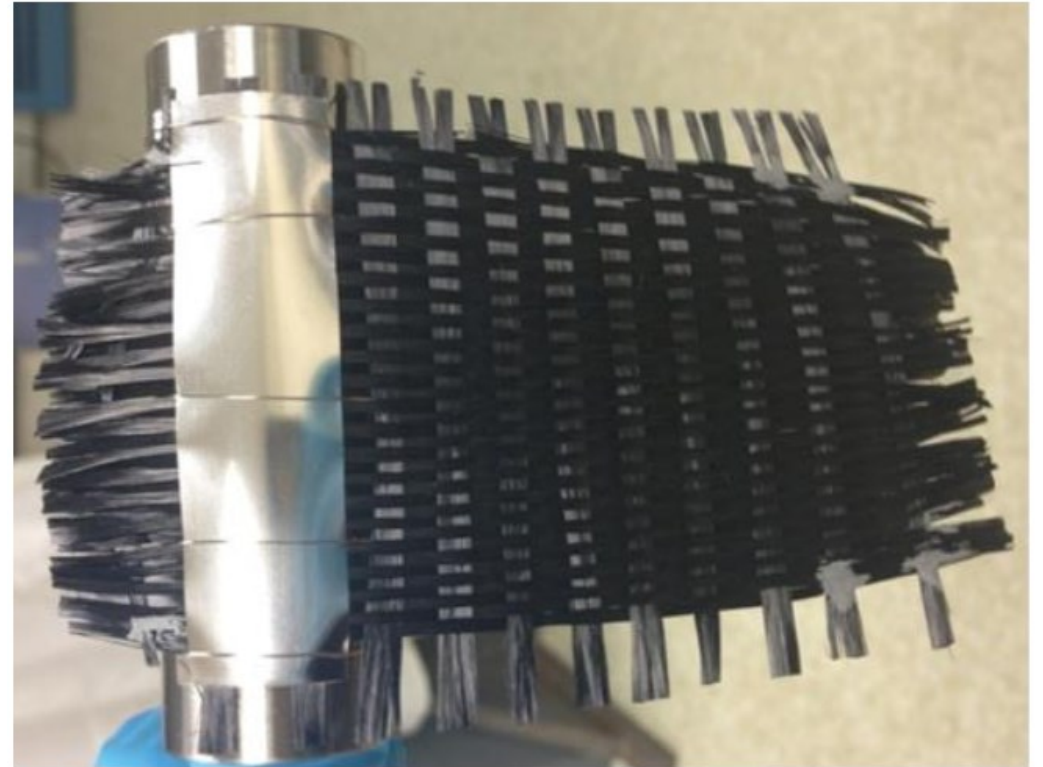
MTAS Mission:

- Generate up to 4 MWe of electric power
- Call for large radiators ($\sim 2500 \text{ m}^2$) operating at at $T_H \sim 500\text{K}$

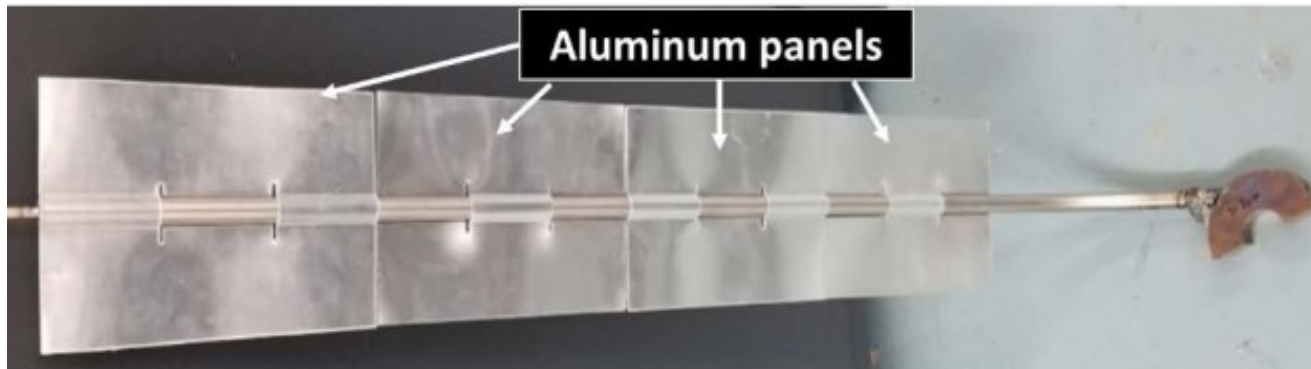
1. Carbon fiber fin wrapped over metal heat pipes (600-850 K), specialty braze, delamination challenges (Denham *et al.*, 1994)



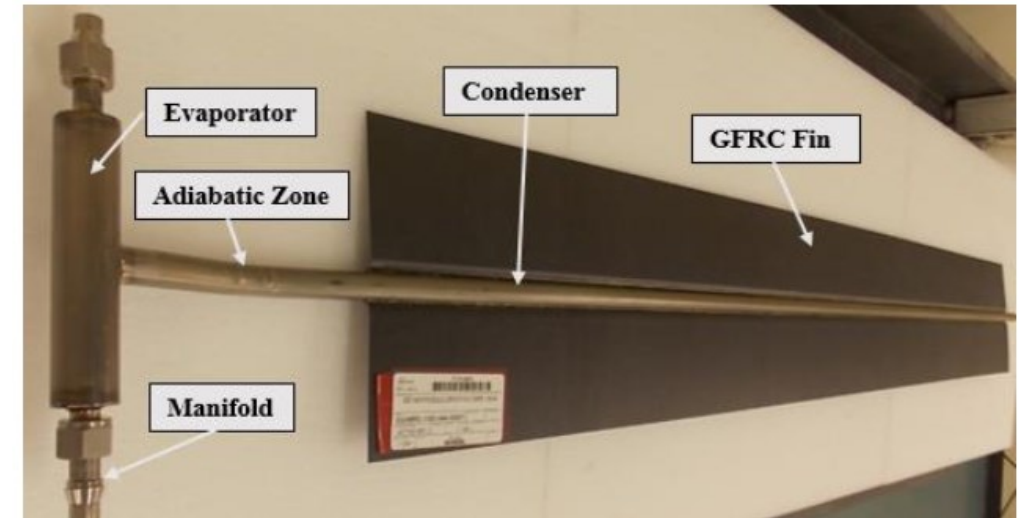
2. Bare carbon fiber panel: discrete fibers, optically dense, brazed to metal HPs (Tomboulain, 2014)



3. ACT: H₂O-Ti heat pipes (400 K), bonded to aluminum radiator panels with ultrasonic soldering process (Lee *et al.*, 2018)

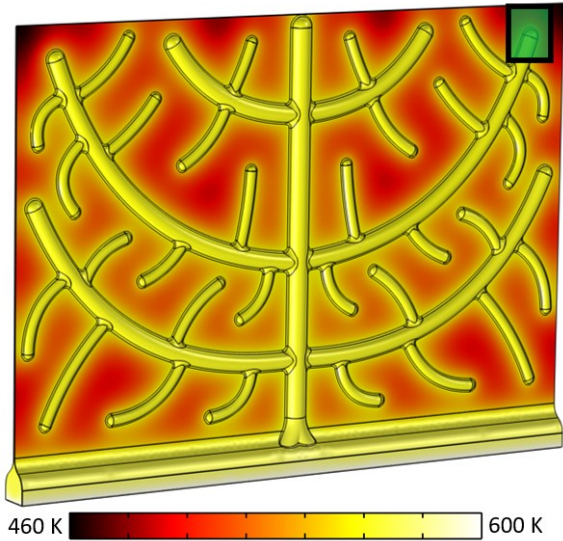


4. Graphite fiber reinforced composite (GRFC) adhesively bonded to Ti heat pipes (Tarau *et al.*, 2016)



Common Challenges:

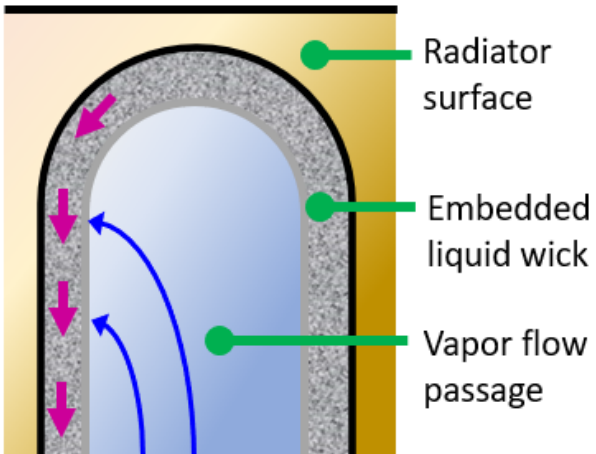
- **Metal-metal bonding:** high thermal stresses at high T_H due to CTE mismatch
- **Polymer-based adhesive bonding:** more compliant, but greater thermal interface resistance, limited operating temperature



Proposed solution:

- Avoid braze and dissimilar material joints through additively manufacturing with single material
- Integral branching heat pipe network to achieve high effective thermal conductivity
- Design for: $T_H = 500 - 550 \text{ K}$, $\rho_S < 3 \text{ kg m}^{-2}$, $\eta_f \sim 70\%$
- CP-Ti construction with water as heat pipe fluid

Embedded heat pipe network



Penn State University:

Design of radiator panels, assessment of thermal performance in relevant conditions

Arizona State University:

Developing AM strategies to produce porous metal wicks

Presentation Outline

1. Develop AM production strategies and characterization for embedded wick specimens and heat pipes

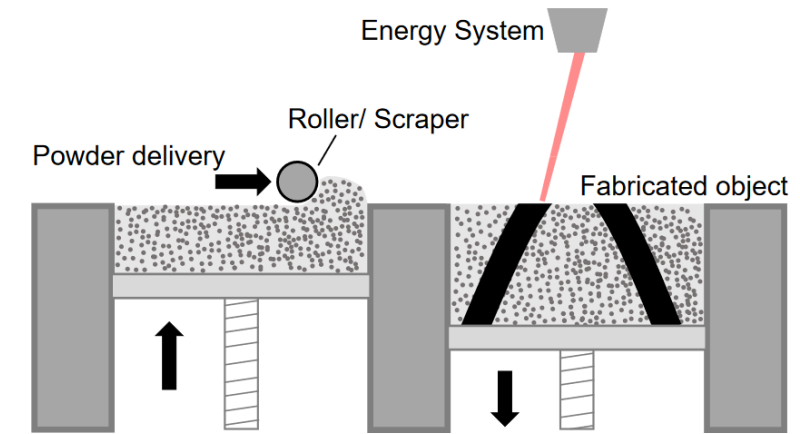
2. Identify treatments to enhance the surface wettability of CP-Ti specimens

3. Implement findings to produce small-scale heat pipe radiator (HPR) prototype

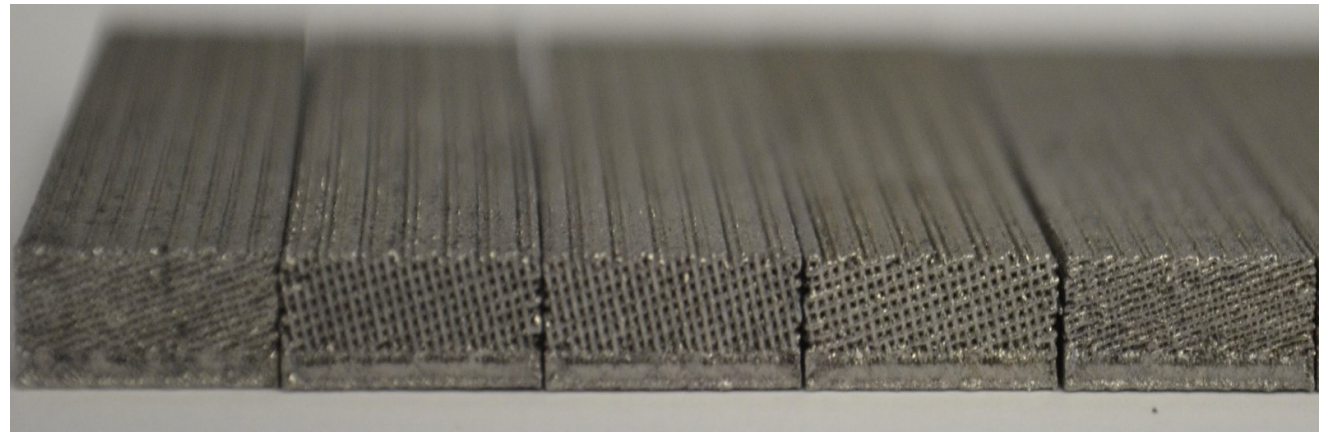
4. Validate HPR performance in relevant cryo-vacuum environment

Goals:

- Develop LPBF build strategies and parameters for porous wicks
- Develop post-build treatments for wetting (hydrophilic) surfaces
- Characterize capillary properties (ϵ , K , r_{pore}), down-select for full heat-pipe radiators (HPRs)

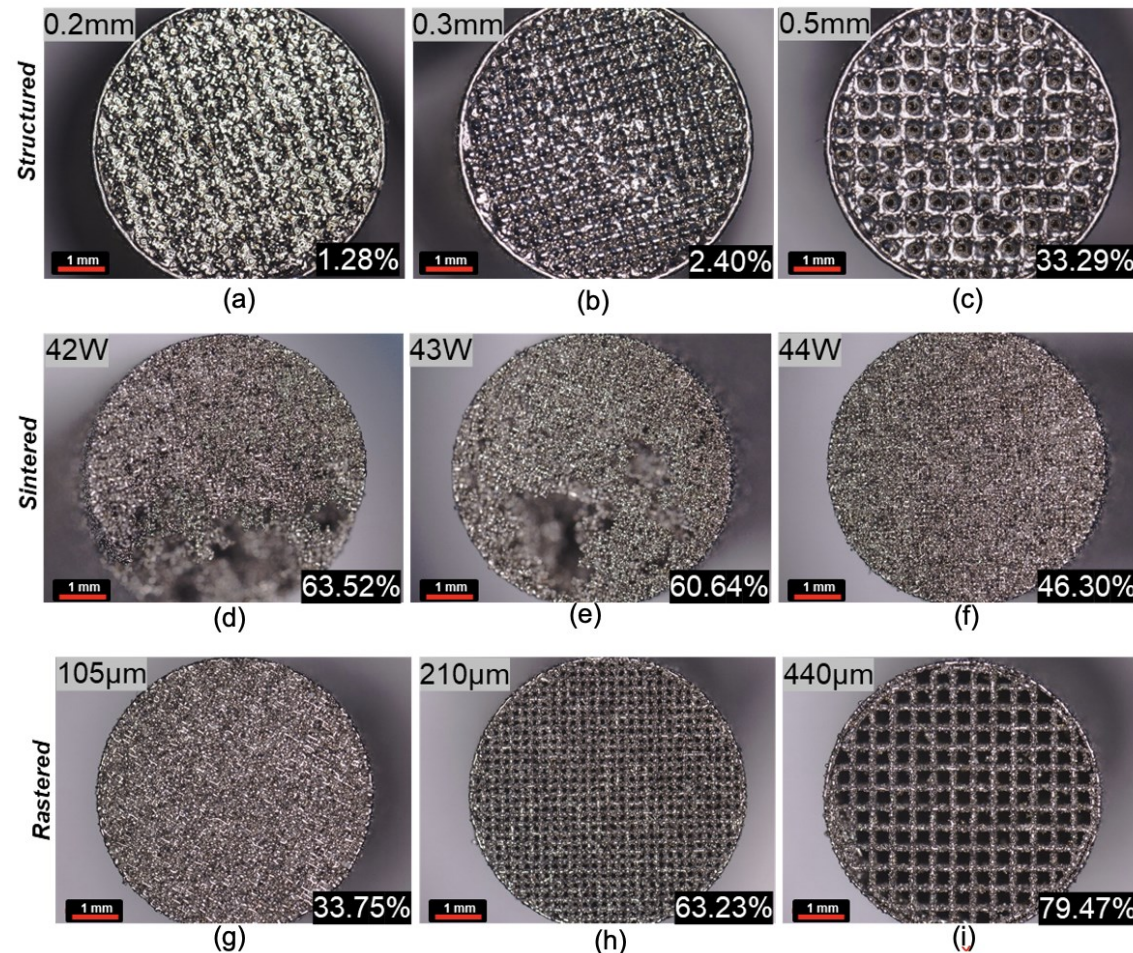
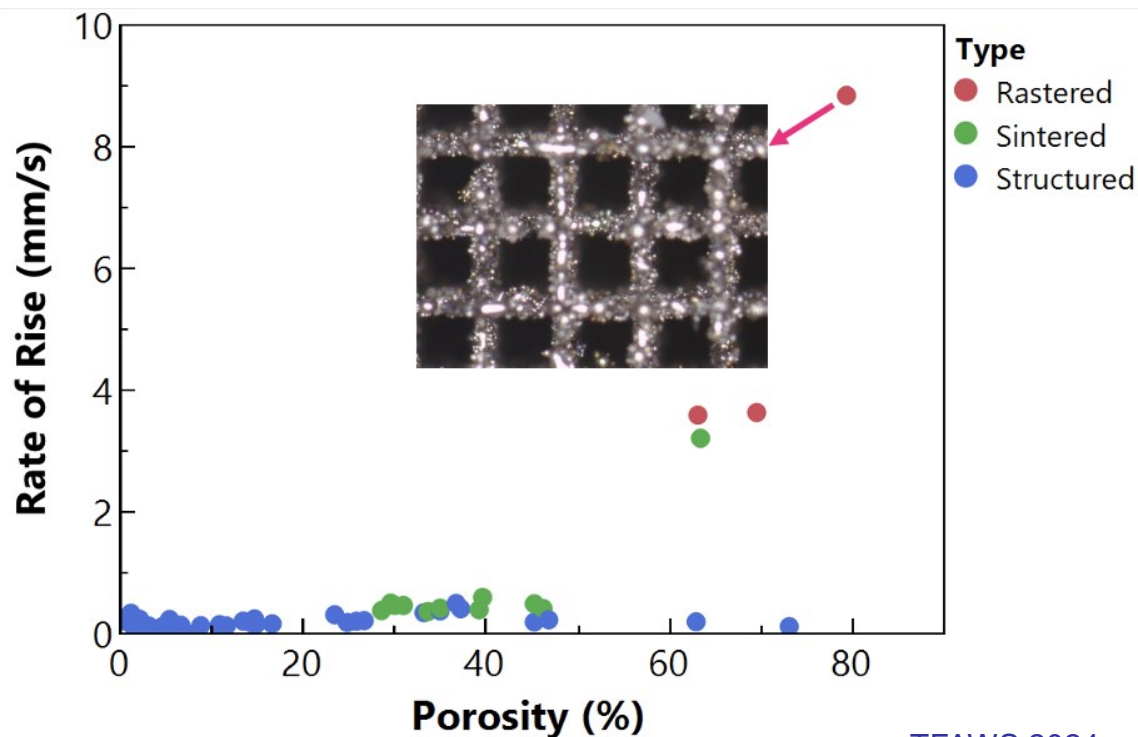


Wiberg, 2019



Printing Strategies Investigated:

- Structured Wicks.
- Sintered Wicks.
- Rastered Wicks:** Demonstrated high permeability, more isotropic properties



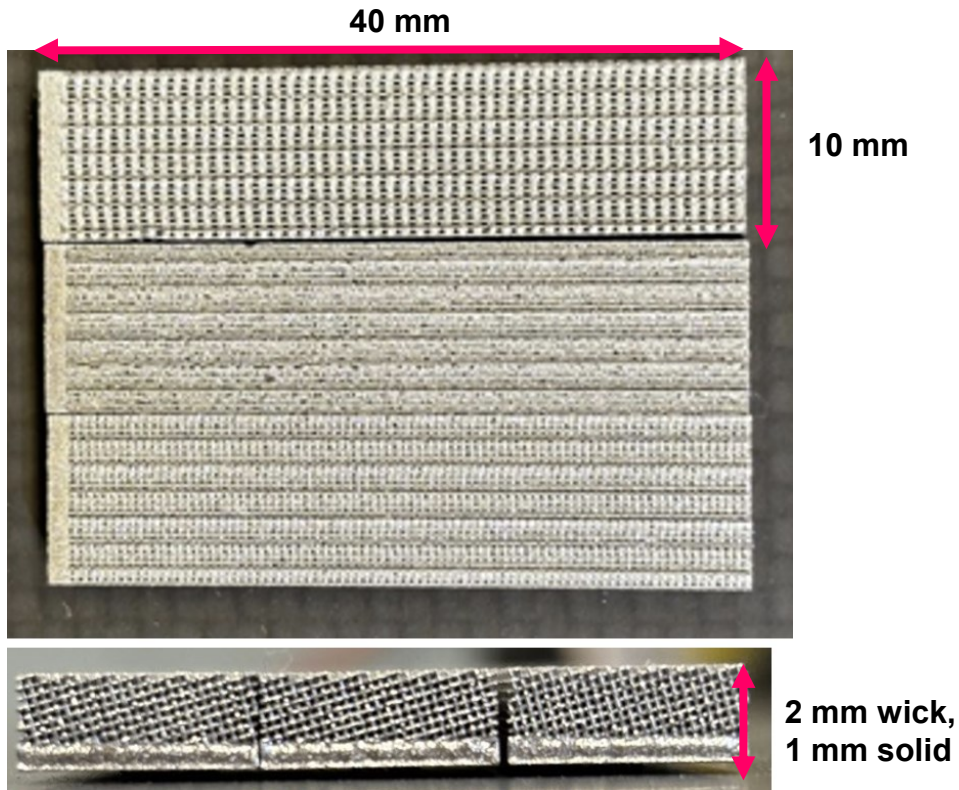
Representative images of prior Inconel 718 wicks fabricated using these approaches.

Wick porosity indicated in the lower right corners

Printing Strategies and Parameters:

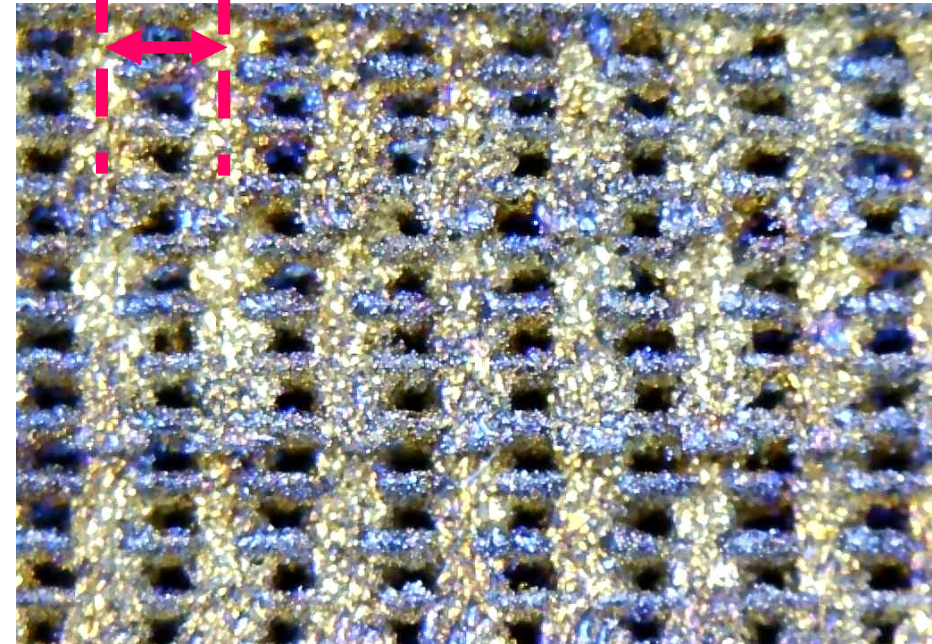
Hatch Spacing (μm)	Hatch Pattern	Laser Power (W)
275	Alternating every 1, 3 or 6 layers between X and Y axes	50%, 60%, 75% of baseline
400		

Example: for hatch spacing **275 μm** , **75%** laser power, alternating X and Y rastering directions every **3 Layers**, Coupon label would be : **H275-75-3L**



Face and end views of Ti wick sticks

Raster line spacing



Picture of a wick structure showing the open pores

Treatment	Results
Heat Treatment in an air furnace at 400, 500, 550, 600 and 750°C for 1 hr (Lim et al., 2001)	Increased wettability initially, but rapid degradation
5 wt% NaOH chemical treatment (24 hr) followed by heat treatment at 600°C (1 hr) (Lim et al., 2001)	Improved wetting, but residual deposits
5 wt% KOH chemical treatment (24 hr) followed by heat treatment at 600°C (1 hr) (Kim et al., 2014)	
15 wt% H₂O₂ chemical treatment followed by heat treatment at 600°C (1 hr) (Khodaei et al., 2020)	Improved wetting, Mild to no degradation in wettability over time

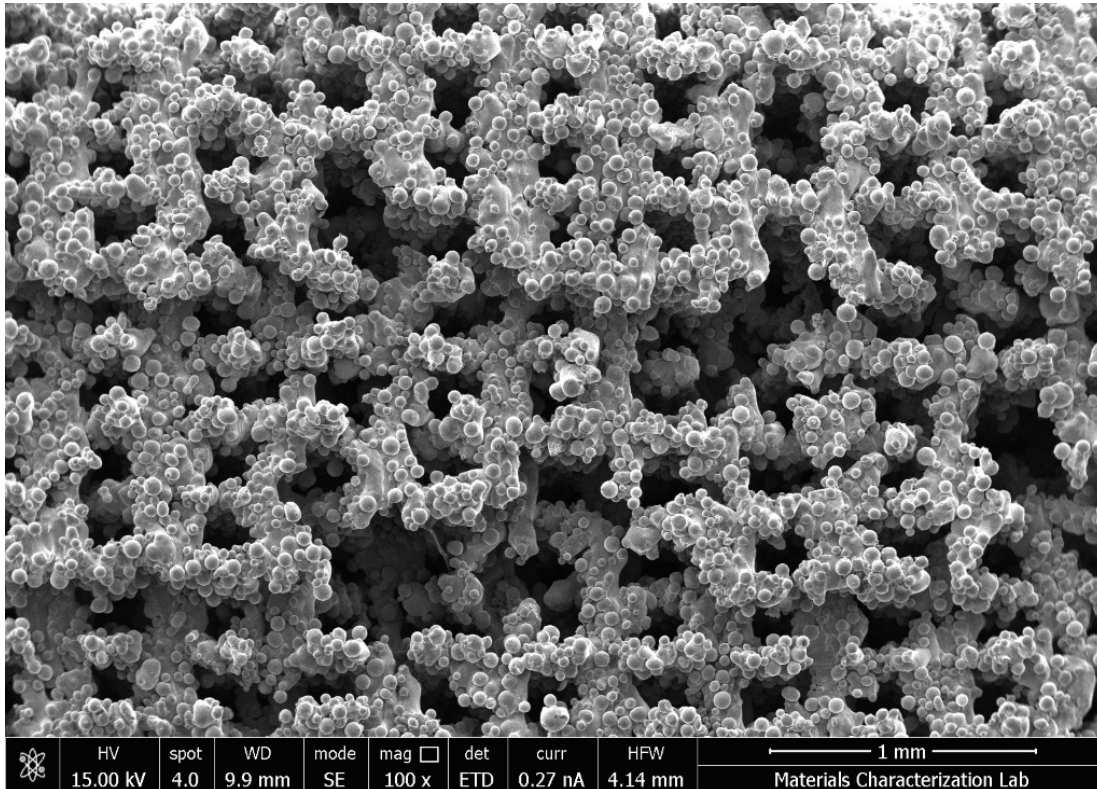


Example of a hydrophobic CP-Ti specimen

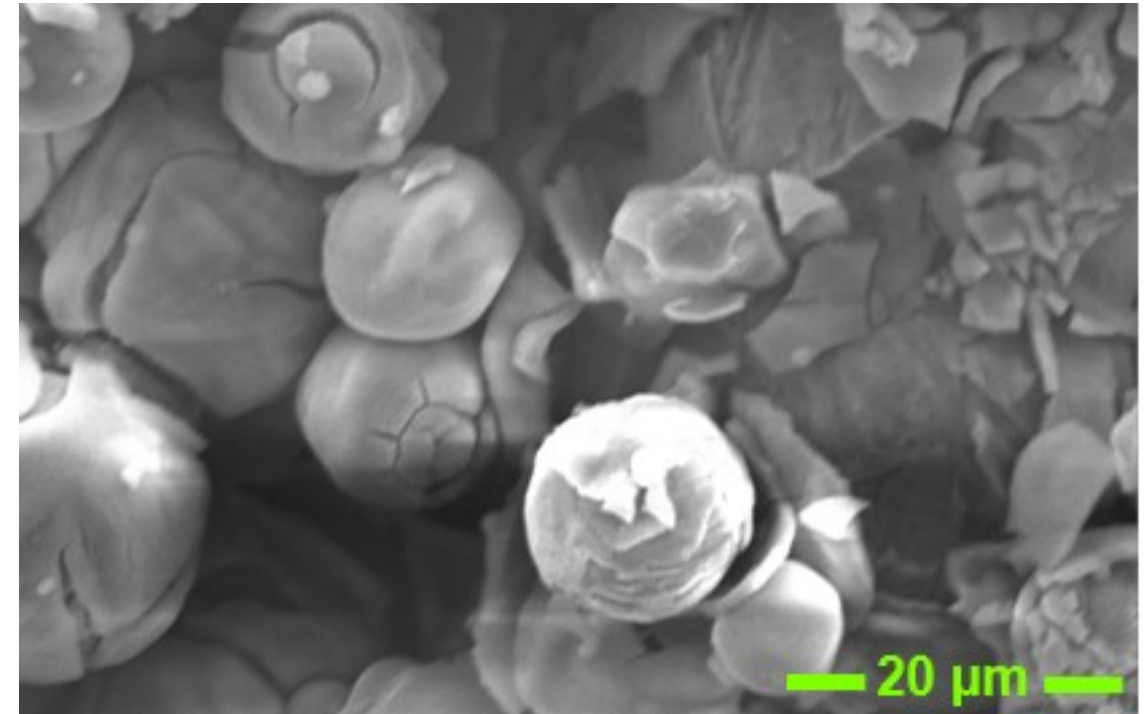


H₂O₂ + Thermal treatment

- EDS + XPS measurements indicated H_2O_2 treatment increased surface oxygen concentration significantly in CP-Ti
- SEM showed the formation of a flakey oxide layer on treated CP-Ti



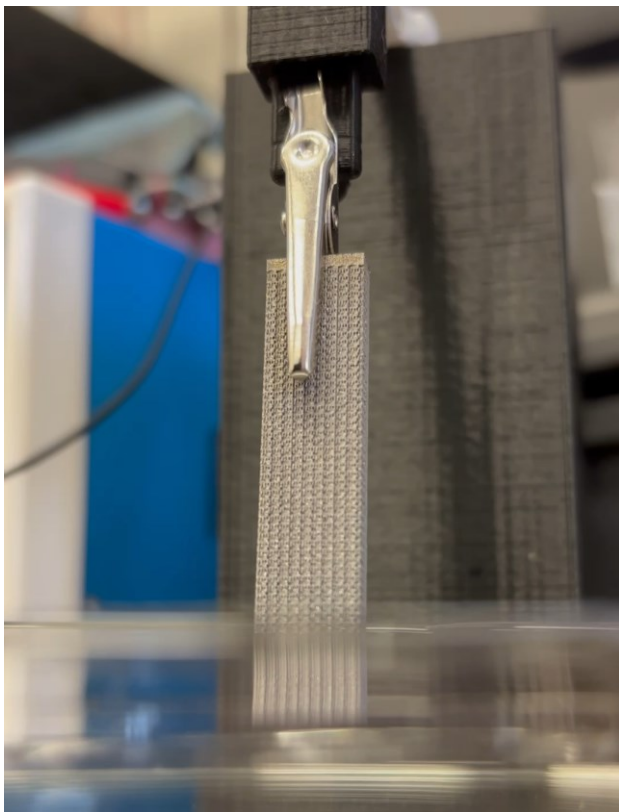
SEM imaging showing the pores and rastered pattern of representative AM wick specimen



SEM imaging showed flakey TiO_2 layer formation resulting from the H_2O_2 treatment

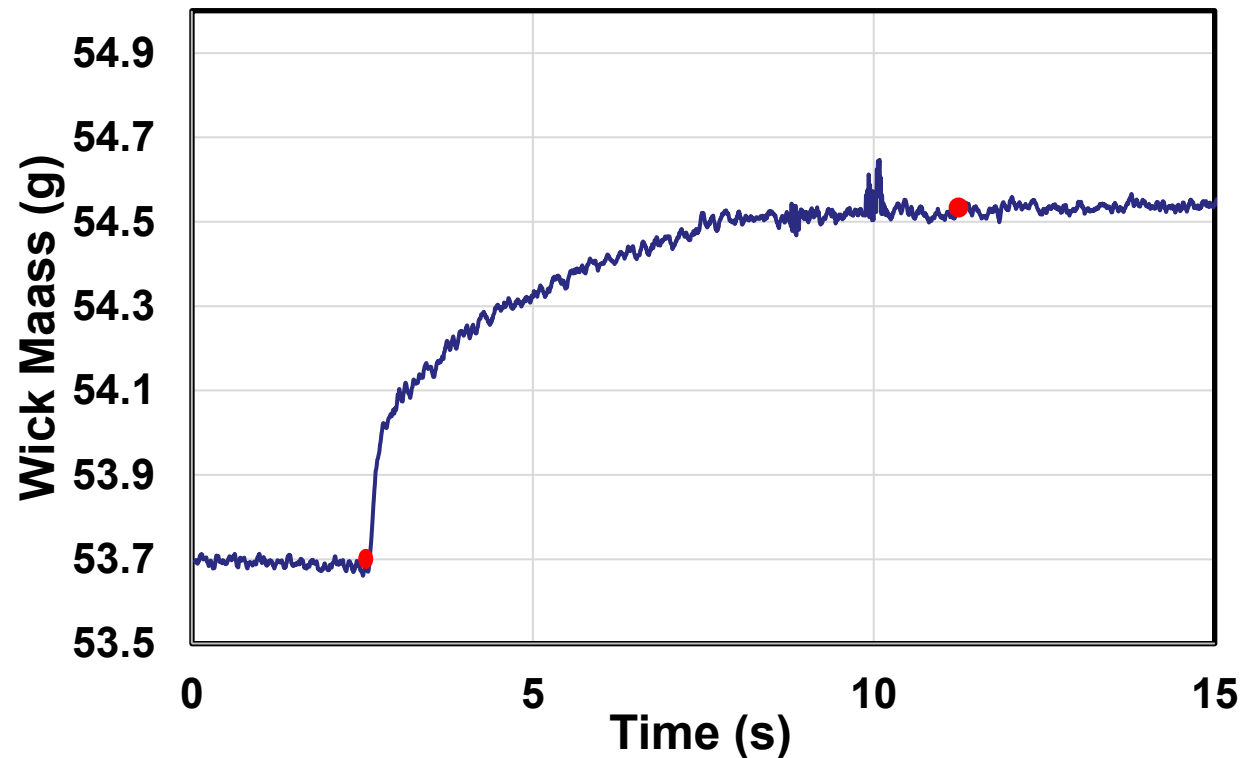
Measurements of Capillary Parameters: Mass-Based RoR

- Rate-of-rise experiment to measure effective K , r_{pore} values for CP-Ti wicks



CP-Ti mass-based ROR test

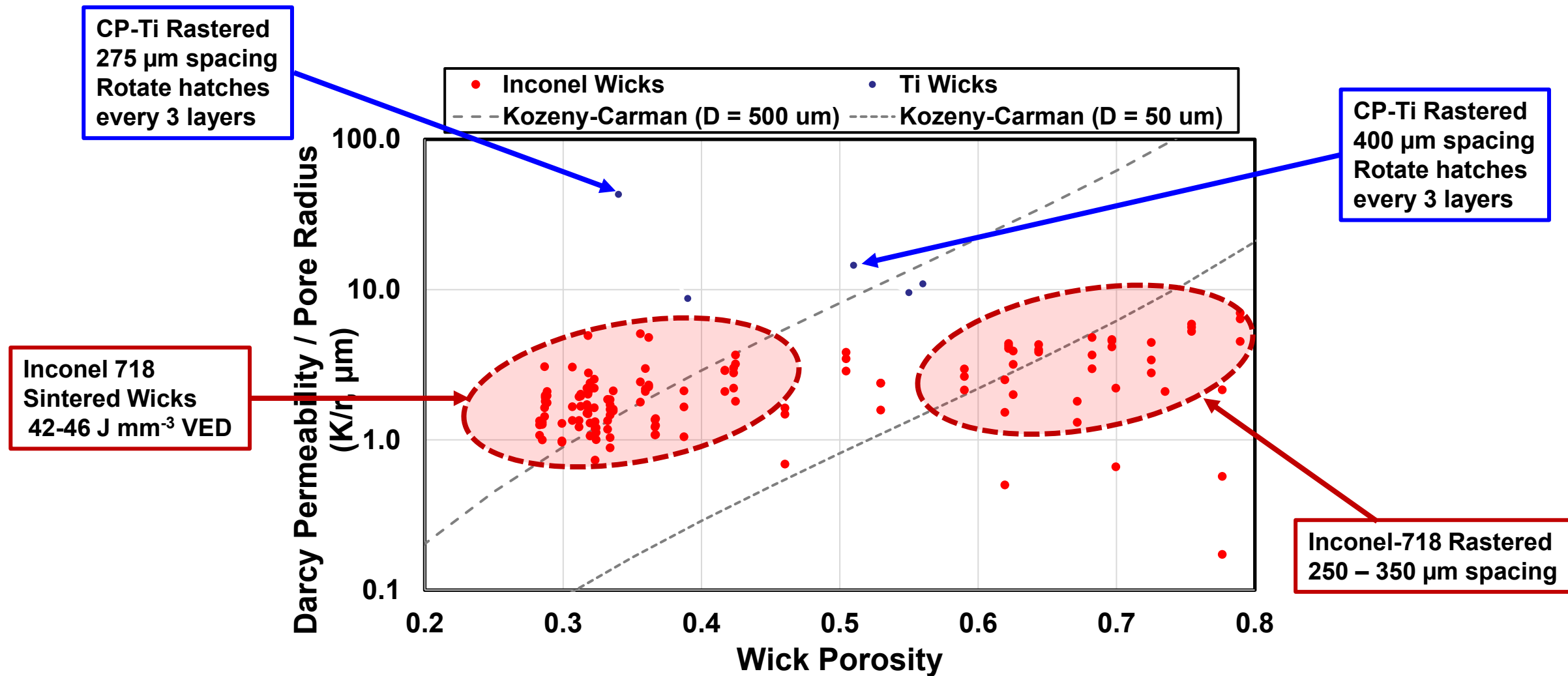
Mass-based ROR measurement



Solving iteratively for K and r_{pore} :

$$\frac{\rho \epsilon d^2 h(t)}{2} \frac{d^2 h(t)}{dt^2} = \underbrace{\frac{2\sigma \cos\theta \epsilon}{r_{pore}}}_{F_{capillary}} - \underbrace{\frac{\mu d(h^2(t))}{K dt}}_{F_{Darcy}} - \underbrace{\rho_L g \epsilon h(t)}_{F_{gravity}}$$

- Wick Properties Extracted from Water Rate of Rise Data (Post-Treatment)

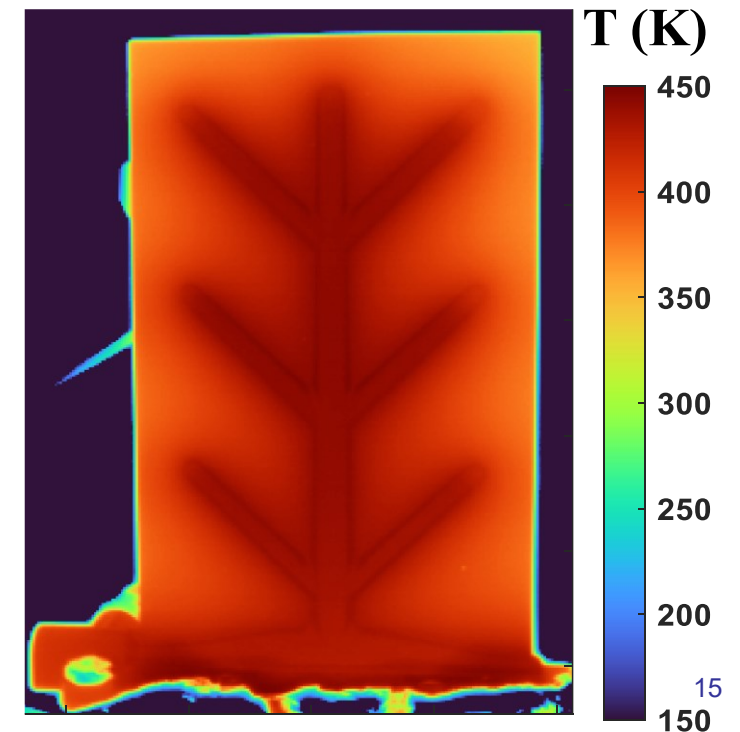
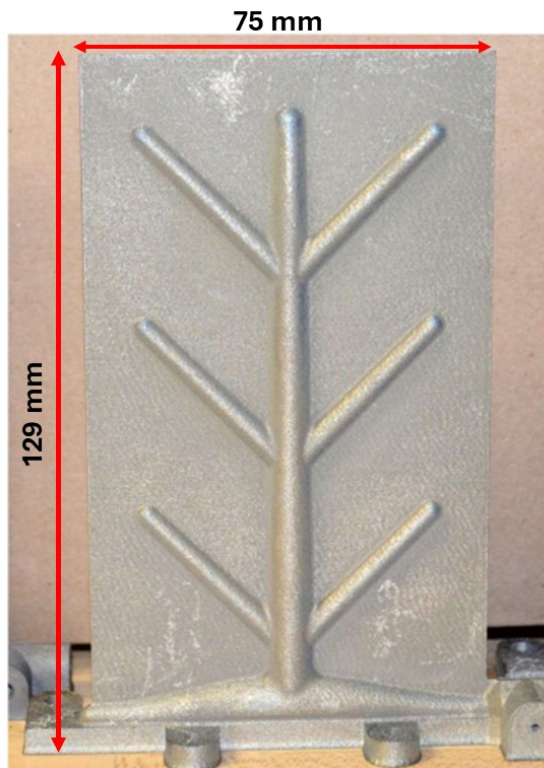


Summary of Findings

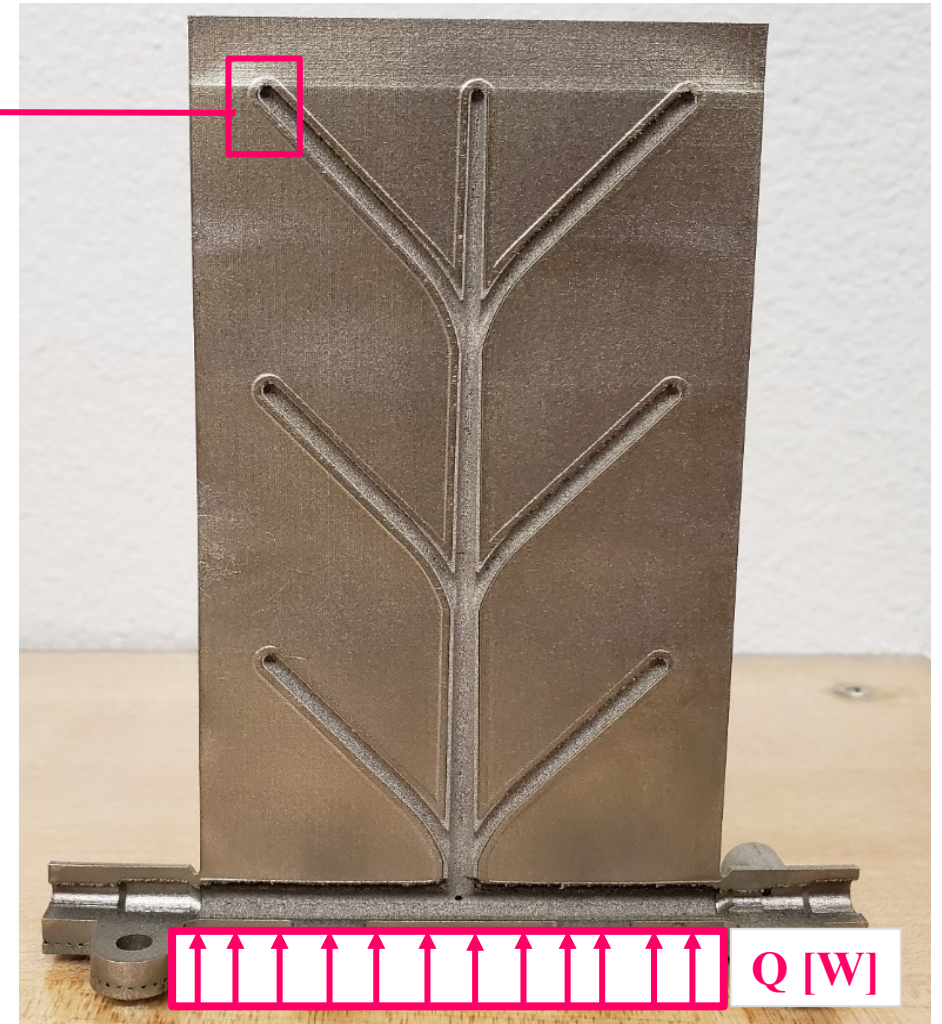
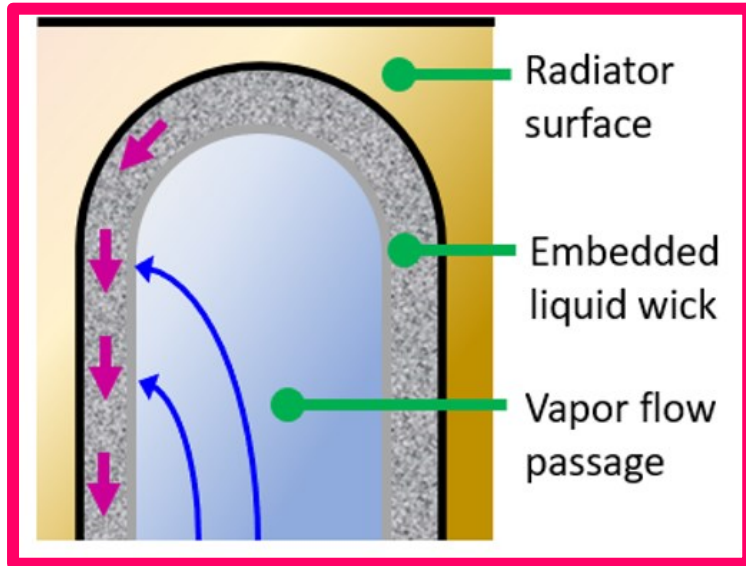
- Identified effective AM titanium wick manufacturing approaches for highly permeable porous wicks.
- Oxidation process developed for CP-Ti wick wettability
 H_2O_2 solution treatment and subsequent heat treatment
- From rate-of-rise tests, the best performing wicks had raster line spacings of **(275, 400 μm)**, porosity of **34 – 56%**, permeability **$K \sim 1000 \mu\text{m}^2$** , average pore radius r_{pore} of **90 – 200 μm** .
- Wick parameters and treatment employed for full HPR prototypes

Goals:

- Design and production of full AM HPR panel prototypes
- Embed high performing AM wicks in branching heat pipes
- Adapt wettability treatment for enclosed branching networks
- Thermal characterization in relevant cryogenically cooled vacuum environment

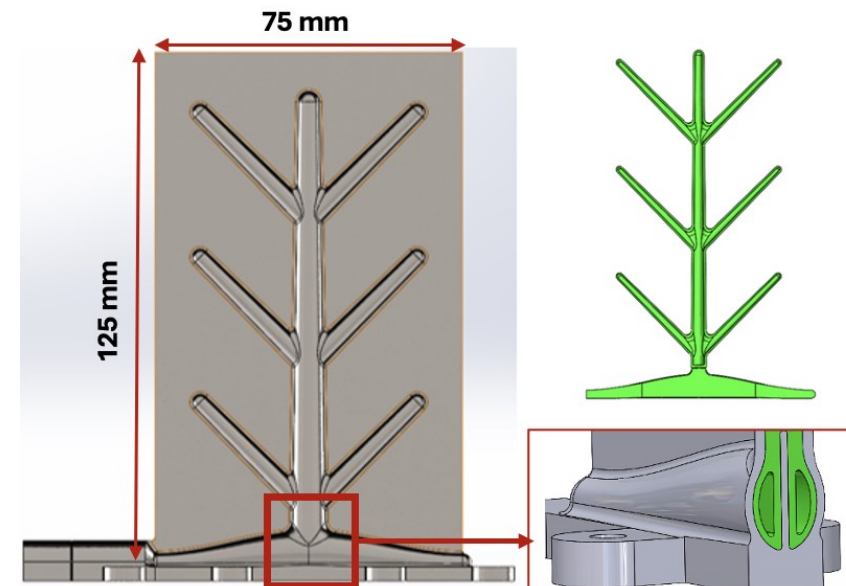


Prototype Heat Pipe Radiator Configuration

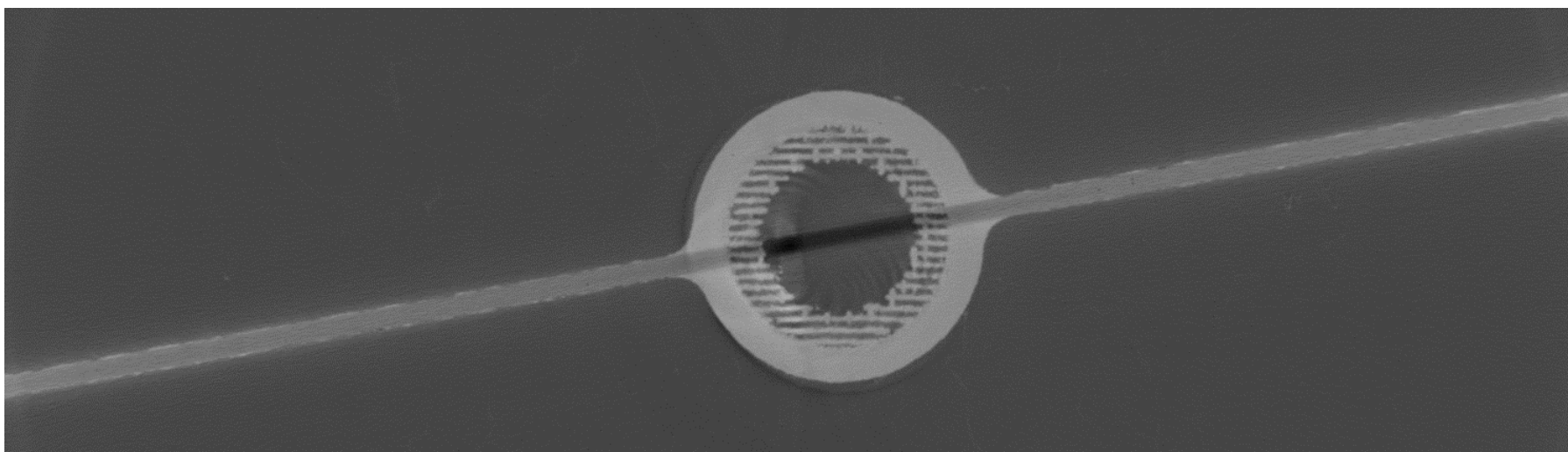


Sintered-wick HPR prototype, Inconel 718, cross-section showing vapor passages and wick

Geometrical and Thermal Properties	Values
Fin Thickness (μm)	500
Wick Thickness Range (mm)	0.49 – 0.95
Vapor Diameter Range (mm)	1.5 – 4.6
Theoretical Panel Mass (g)	87.5
Wick Production Strategy	Alternating between X and Y directions every 3 layers
Wick Hatch Spacing (μm)	275 and 400

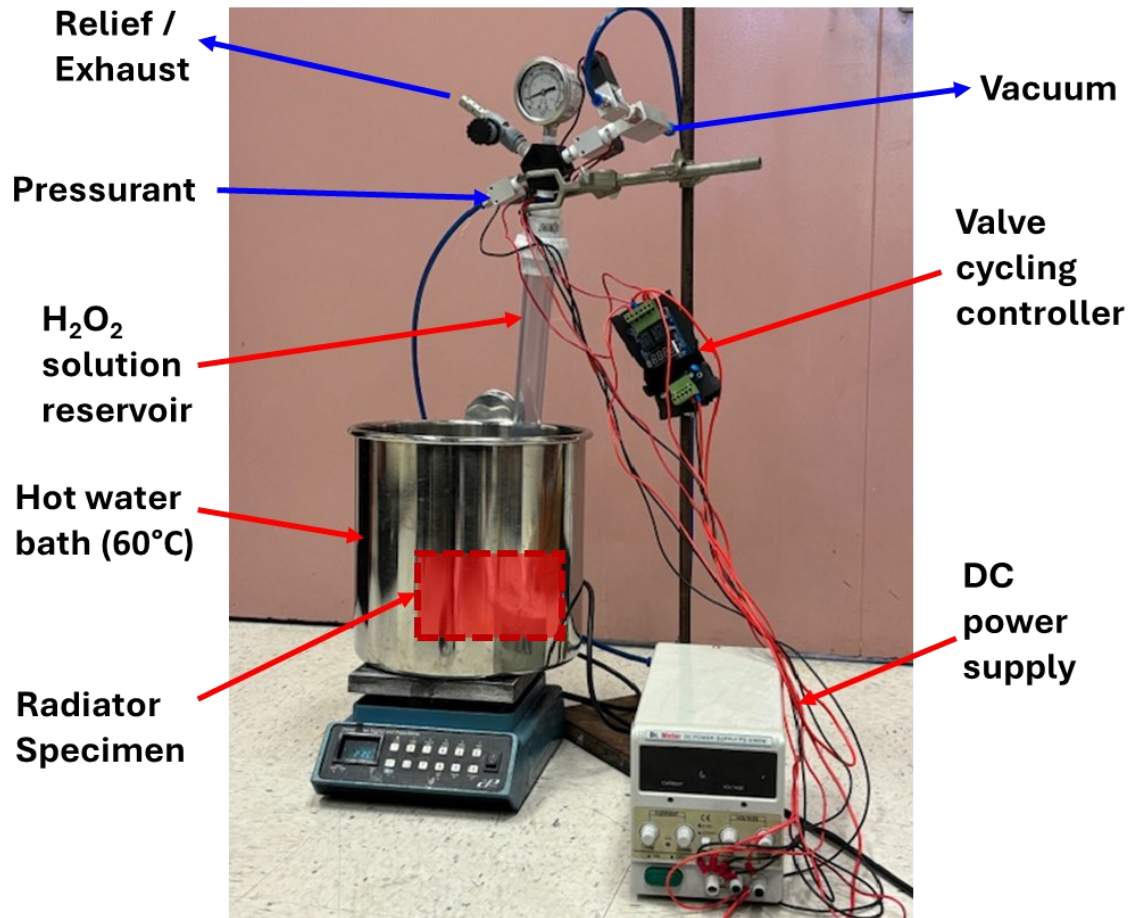


CAD design of the radiator panel



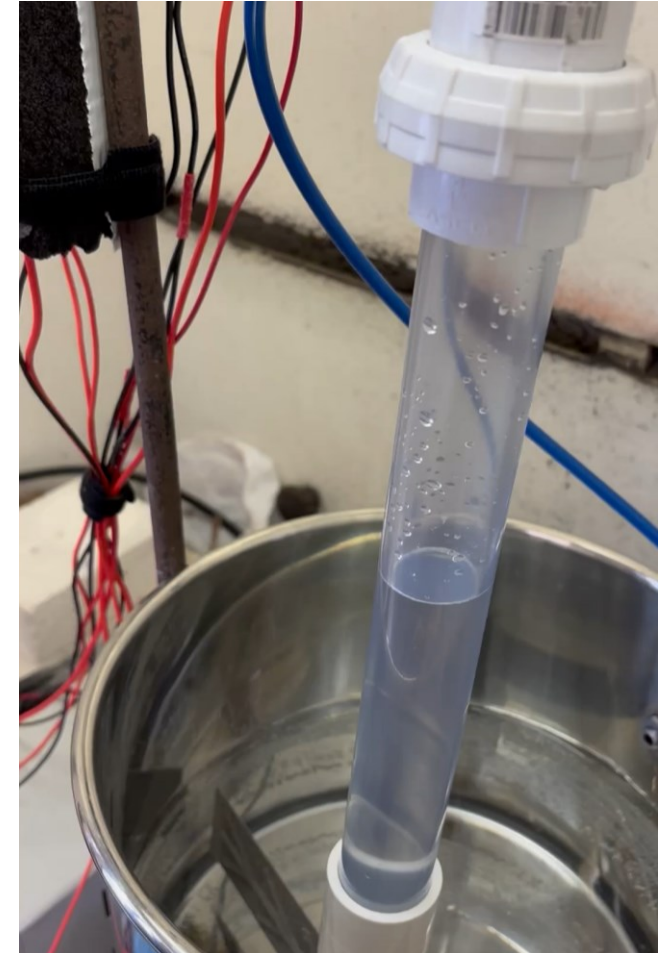
CT-scan of CP-Ti HPR

- Cyclic surface treatment using hydrogen peroxide followed by heat treatment at 600°C to ensure that the treatment reaches the entire HP network.



Oxidation Process Set-Up

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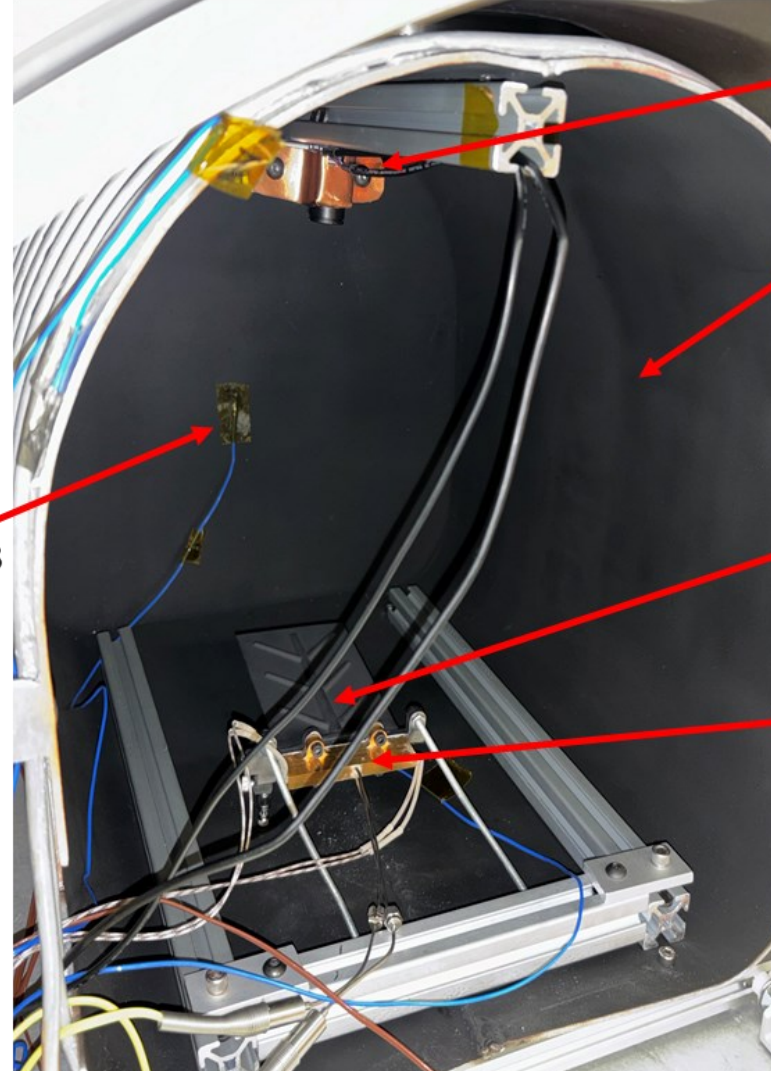


Cyclic H₂O₂ Oxidation Process



CP-Ti HPR Specimen

**Environment
Thermocouples**



**Thermal
Camera**

**LN2-Cooled
Enclosure
(front panel off)**

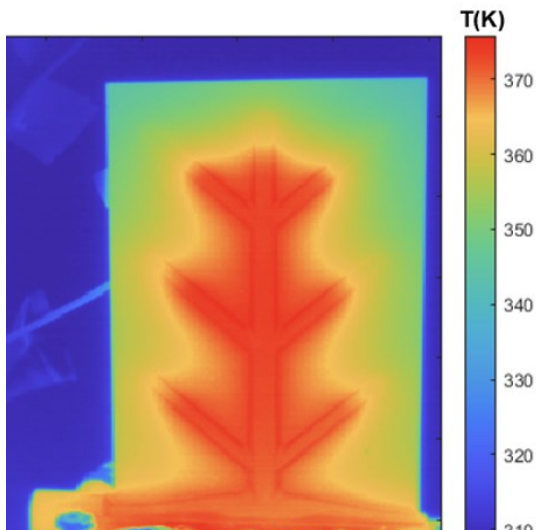
**Radiator
Specimen**

**Copper heater
(Foil-wrapped
during testing)**

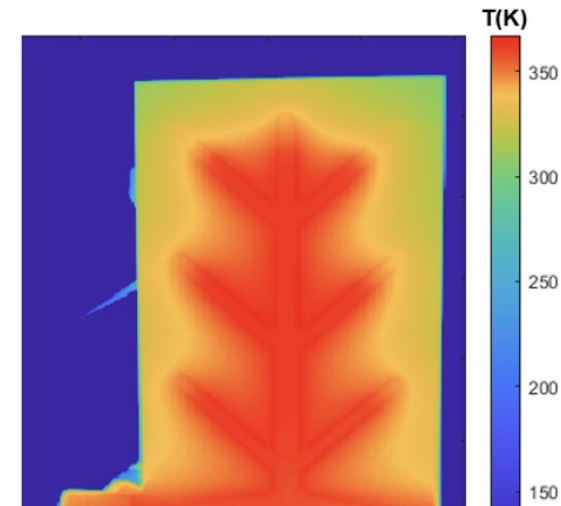
CP-Ti Cryo-Vacuum Test Results

- Cryo-vacuum test results for $T_H = 376 \text{ K}$ (103°C) to 510 K (237°C)

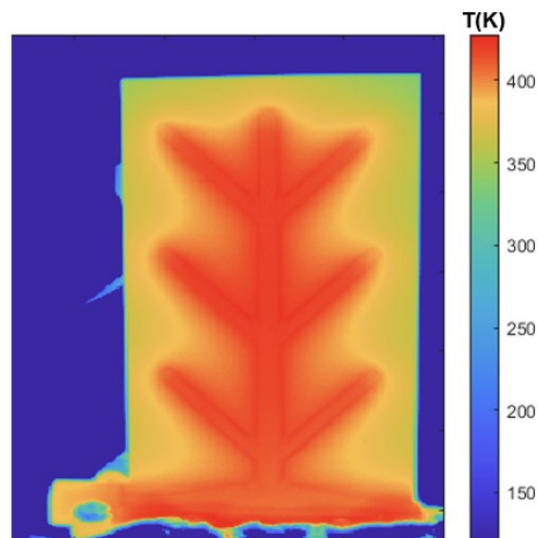
$T_H = 376 \text{ K}$
(103°C)



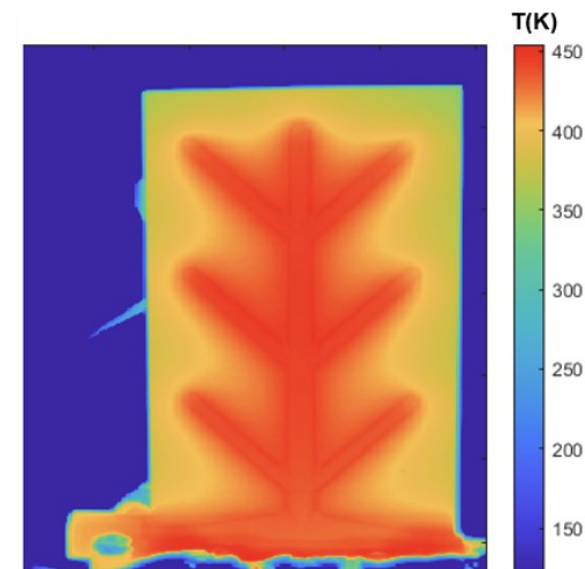
$T_H = 425 \text{ K}$
(152°C)

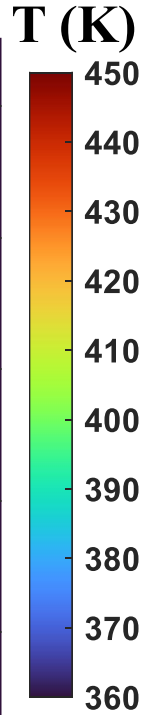
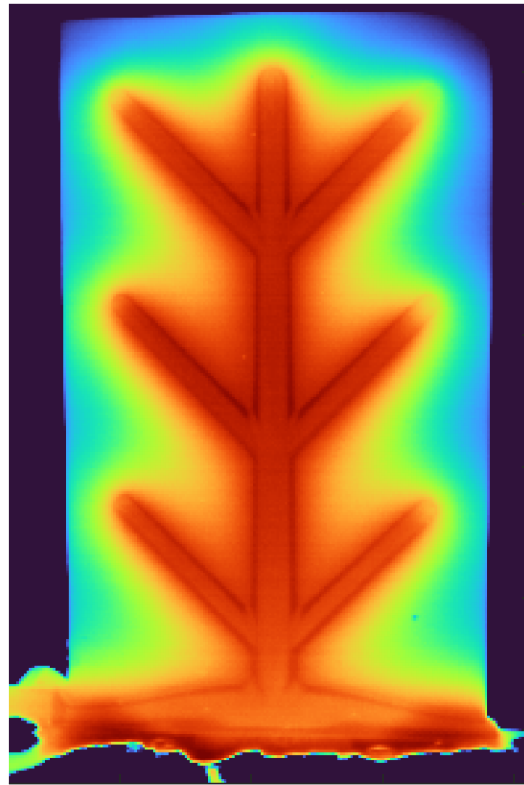
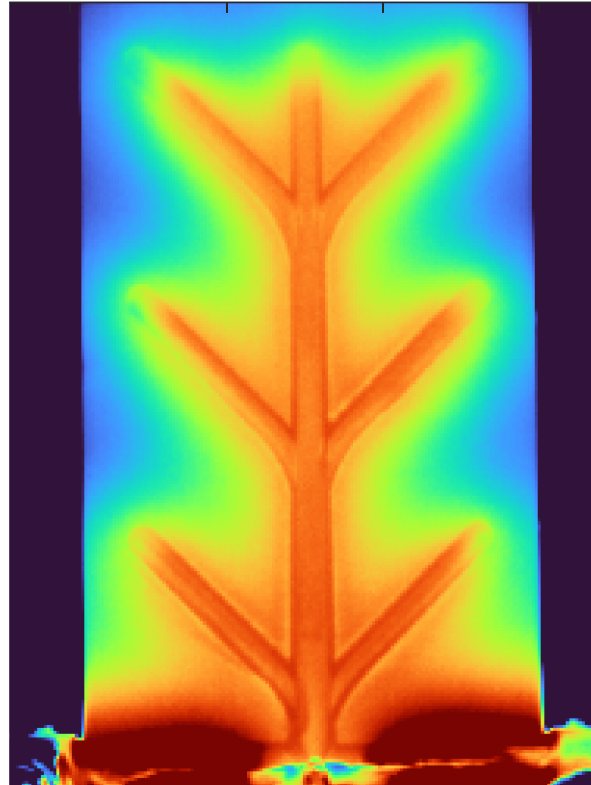


$T_H = 475 \text{ K}$
(202°C)



$T_H = 510 \text{ K}$
(237°C)





Inconel 718 HPR

$\rho_s = 3.80 \text{ kg m}^{-2}$
 $T_H = 508 \text{ K}$
 $Q_{rad} = 30.1 \text{ W}$
 $\eta_f = 51\%$

CP-Ti HPR

$\rho_s = 2.13 \text{ kg m}^{-2}$
 $T_H = 510 \text{ K}$
 $Q_{rad} = 44.9 \text{ W}$
 $\eta_f = 67\%$

- Net Radiated Heat:**

$$Q_{rad} = Q_{heater} - Q_{loss,heater}$$

$$= \epsilon_{paint} \sigma A_s (T_{avg,rad}^4 - T_{\infty}^4)$$

- Fin efficiency:** $\eta_f = Q_{rad} / \epsilon_1 \sigma (T_H^4 - T_{\infty}^4)$

T_H (K)	Q_{rad} (W)	$Q_{loss,heater}$ (W)	T_{∞} (K)	$T_{avg,rad}$ (K)	η_f (%)
376 ± 1	16.5 ± 1.1	1.39 ± 0.5	145 ± 5	361 ± 8	85 ± 7
425 ± 1	25.9 ± 1.3	2.29 ± 0.8	139 ± 5	403 ± 7	80 ± 6
475 ± 1	35.2 ± 1.6	3.59 ± 1.3	140 ± 5	434 ± 8	70 ± 5
510 ± 1	44.9 ± 2.0	4.79 ± 1.7	140 ± 5	461 ± 8	67 ± 5

Summary of findings:

1. Identified AM printing strategies and design parameters for highly permeable porous CP-Ti wicks
2. Developed durable surface treatment to enhance CP-Ti wetting properties.
3. Design, characterization and manufacturing of monolithic CP-Ti/H₂O HPR prototype for NASA target:
 $T_H = 500 - 550 \text{ K}$, $\rho_S < 3 \text{ kg m}^{-2}$, $\eta_f \sim 70\%$.

Upcoming Project Activities:

1. Developing branching optimization algorithm for mass efficient scaled-up HPR panels
2. System-level design study for FSP and NEP missions: deployment mechanisms, MMOD effects...

