Intermediate Temperature Ceramic Heat Pipe Modeling and Optimization

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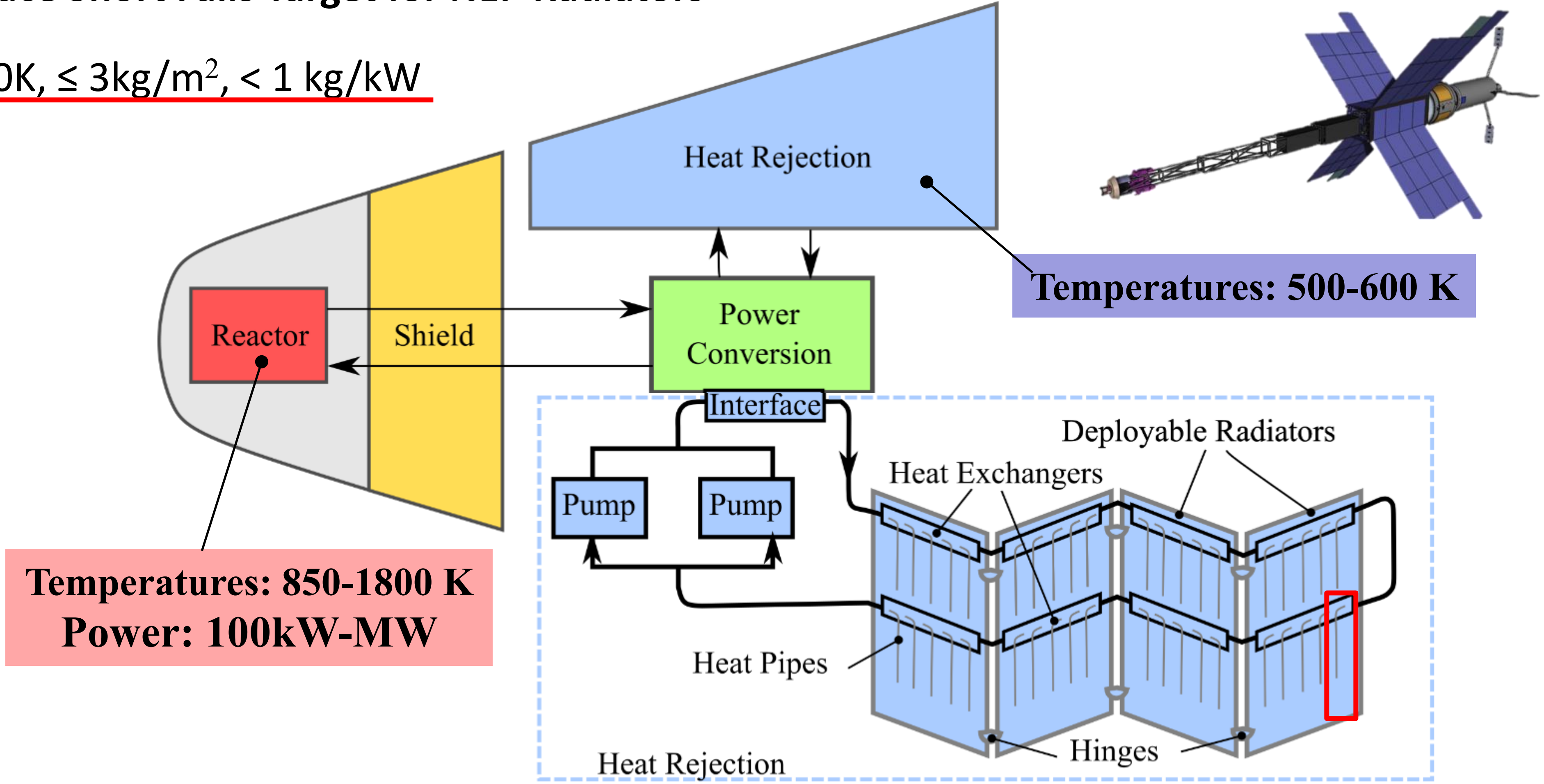
Thermal & Fluids Analysis Workshop
TFAWS 2024
August 26-30, 2024
NASA Glenn Research Center
Cleveland, OH

Motivation

Civil Space Short Falls Target for NEP Radiators

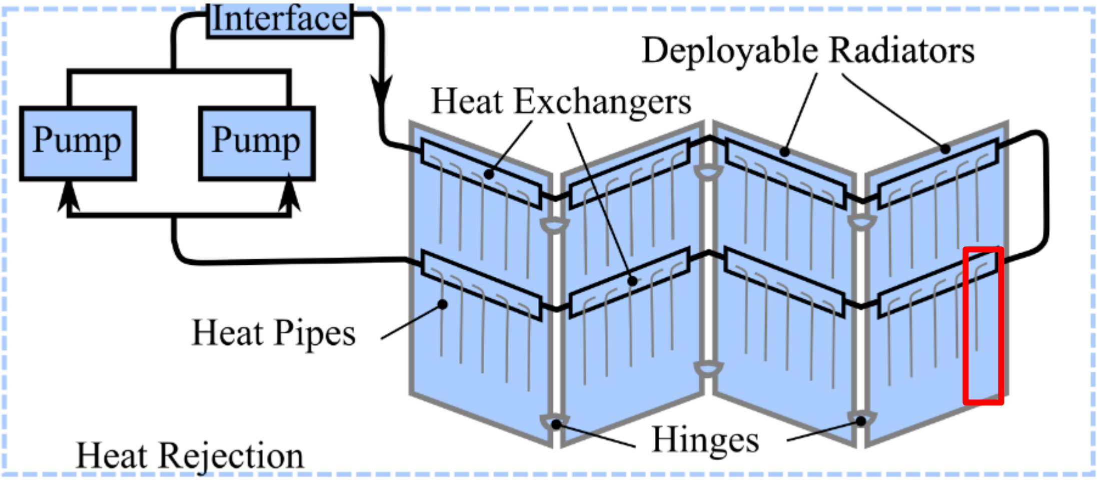
- >500K, ≤ 3kg/m^2, < 1 kg/kW

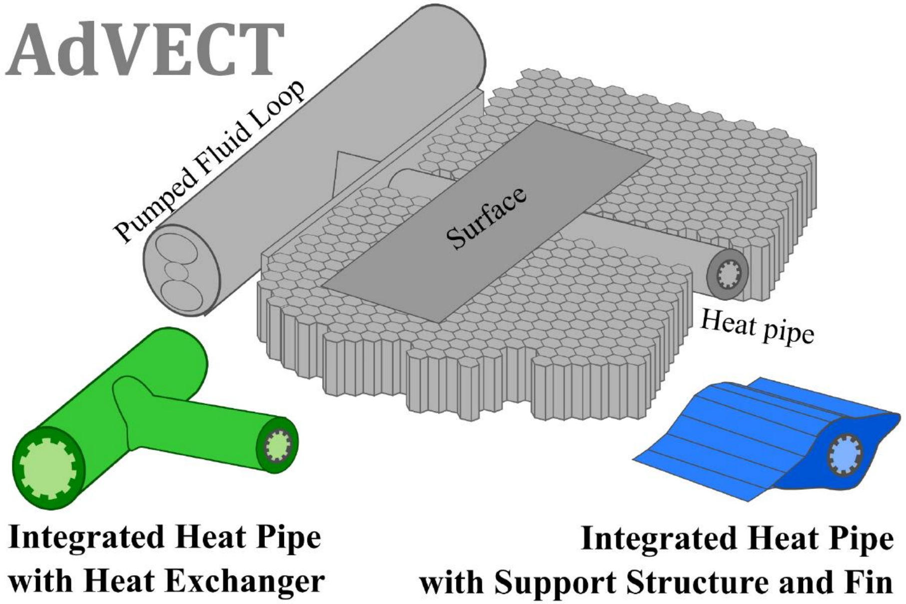


AdVECT: Additive Vehicle-Embedded Cooling Technologies

Porous Ceramic Radiators with embedded Heat Pipes

- Operating @ 500-600K
- Areal Density ≤ $2 kg/m^2$
- Specific weight < 1 kg/kW



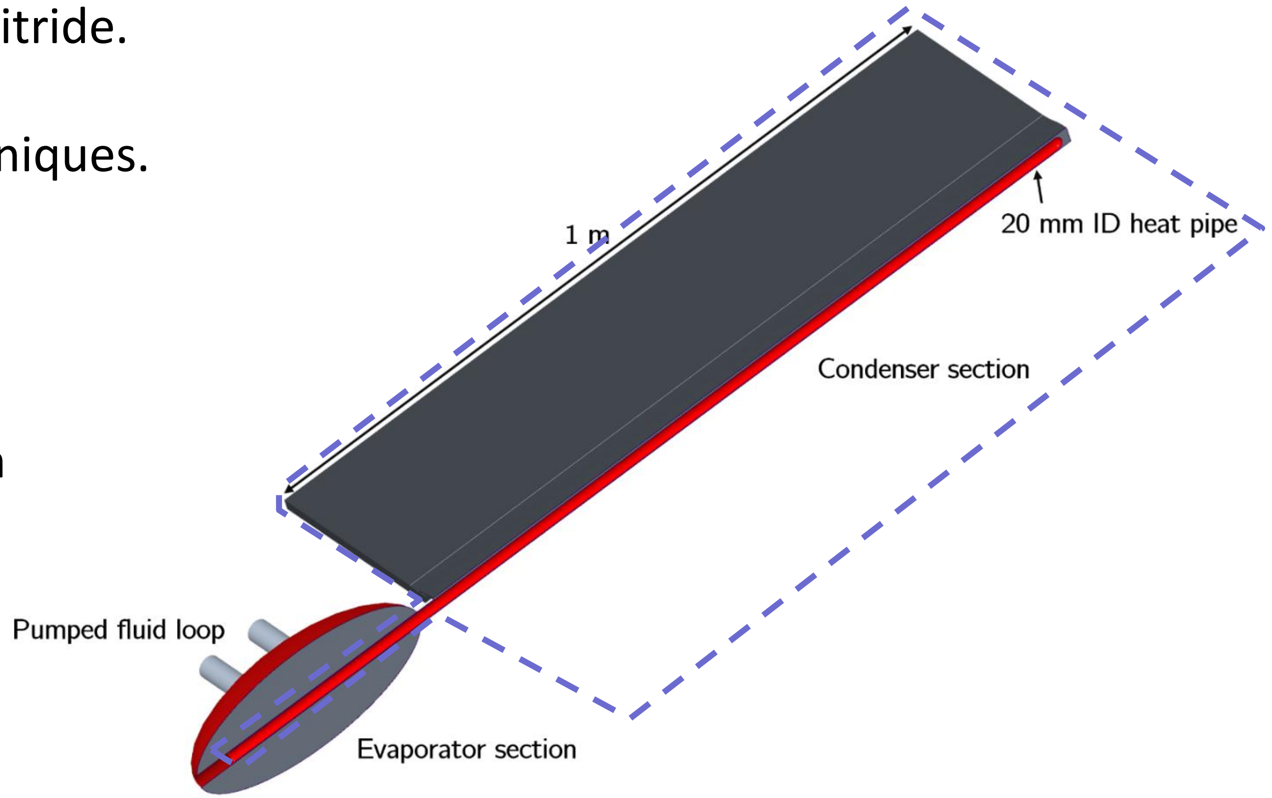


Scope

Approach

- Develop new ceramic resins using Aluminum Nitride.
- Parametric study of printing and sintering techniques.
- Performance testing;
  - Print prototype ceramic heat pipes.
  - Establish feasible, full scale design through simulation.
  - Experimentally validate solutions.

→ **Elevate TRL of technology to level 3**



Scope

Why ceramics?

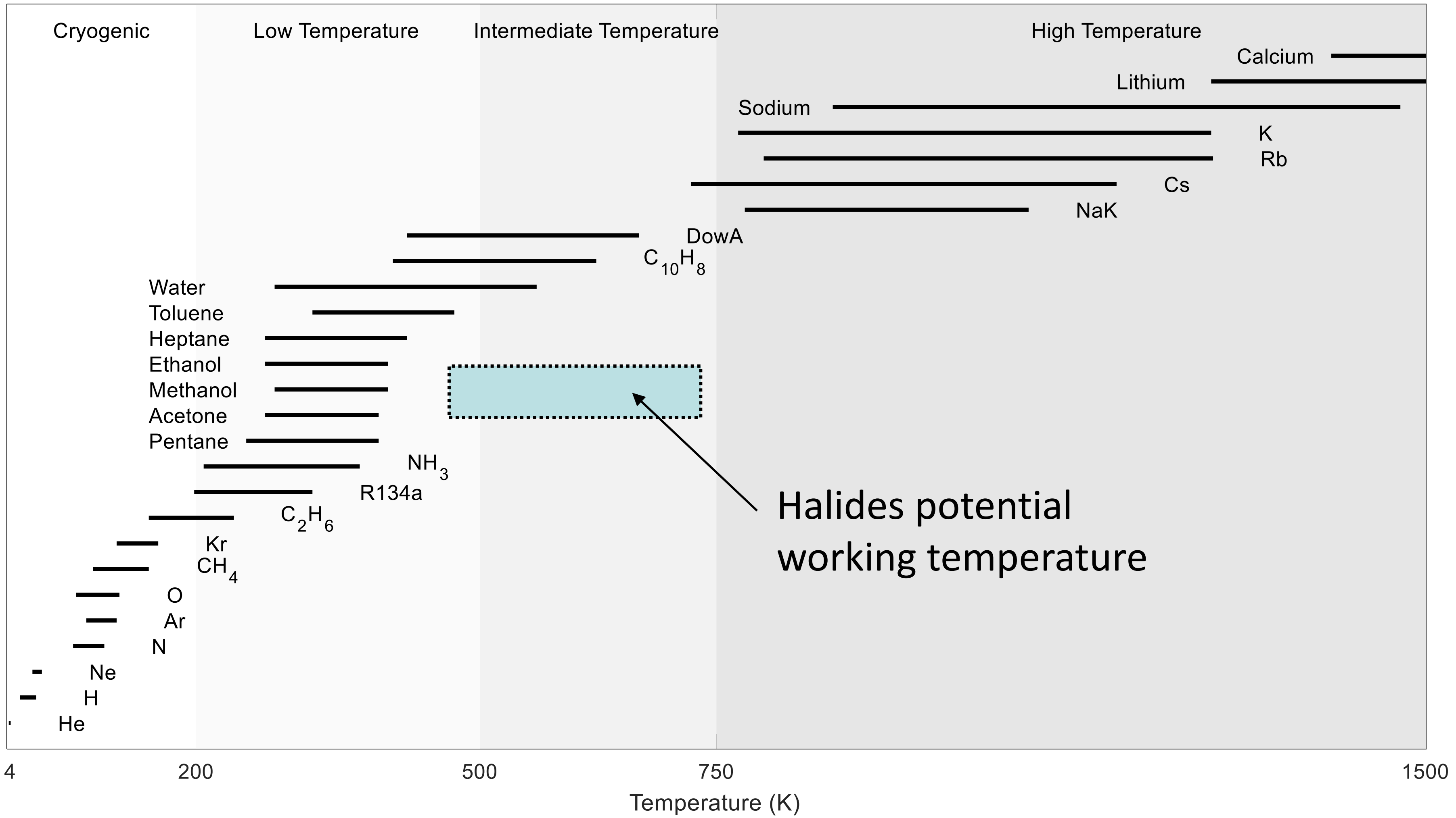
Expanded choice of working fluids

+

Novel Form Factors and Topology Optimization

Why Ceramics

Existing state-of-the-art for heat pipe working fluids



Additively Manufactured Ceramics

- Three primary fabrication methods
  - Binder Jetting
    - Low resolution (50-200 μm layers,
    - Requires large ceramic particles (generally ≥ 50 μm), porous
  - Direct Ink Writing
    - Low resolution (minimum feature size tip dependent, generally > 100 μm, > 50 μm layer height)
    - Can use small or large ceramic particles
  - Digital Light Processing (DLP)/Stereolithography
    - High resolution (≤ 50 μm minimum feature size, ≤ 50 μm layer height)
    - Small ceramic particles (< 1 μm)
    - Slurry of photosensitive resin + ceramic

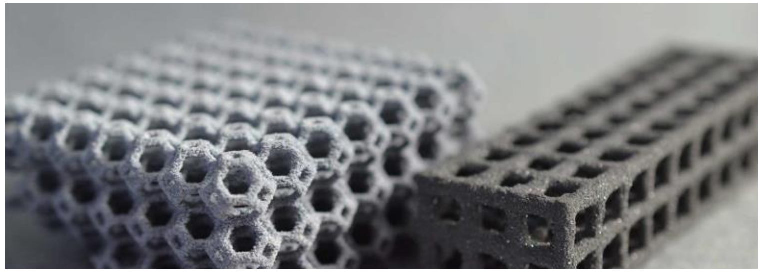
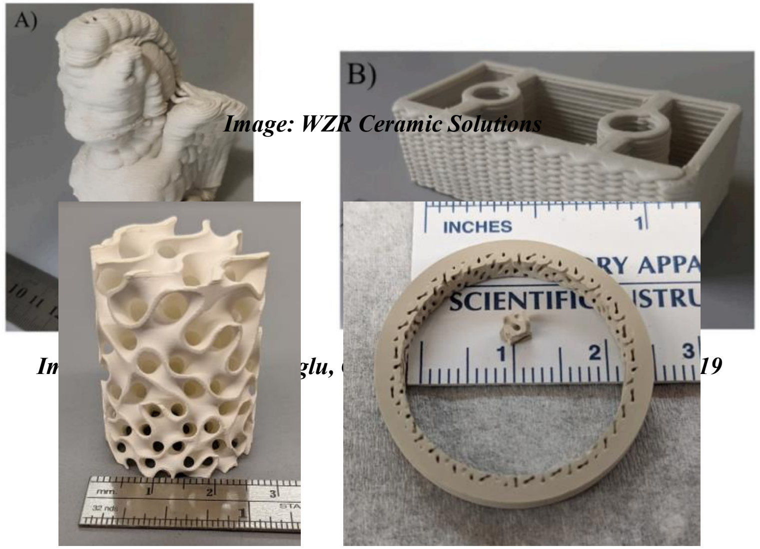


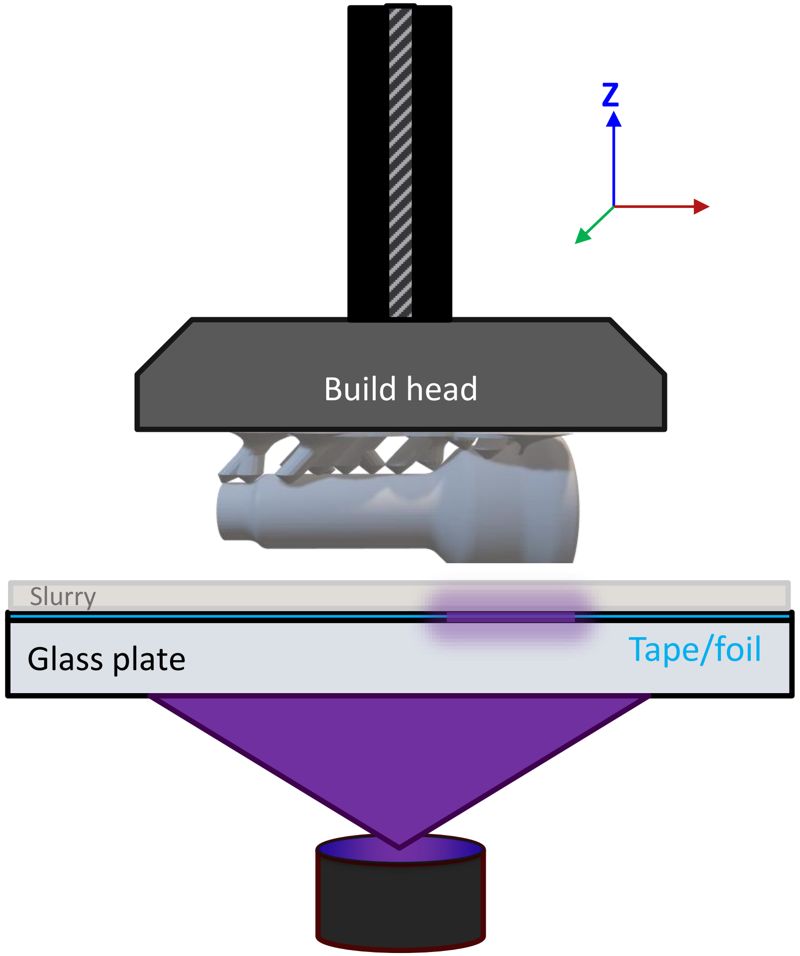
Image: WZR Ceramic Solutions



The Story So Far…

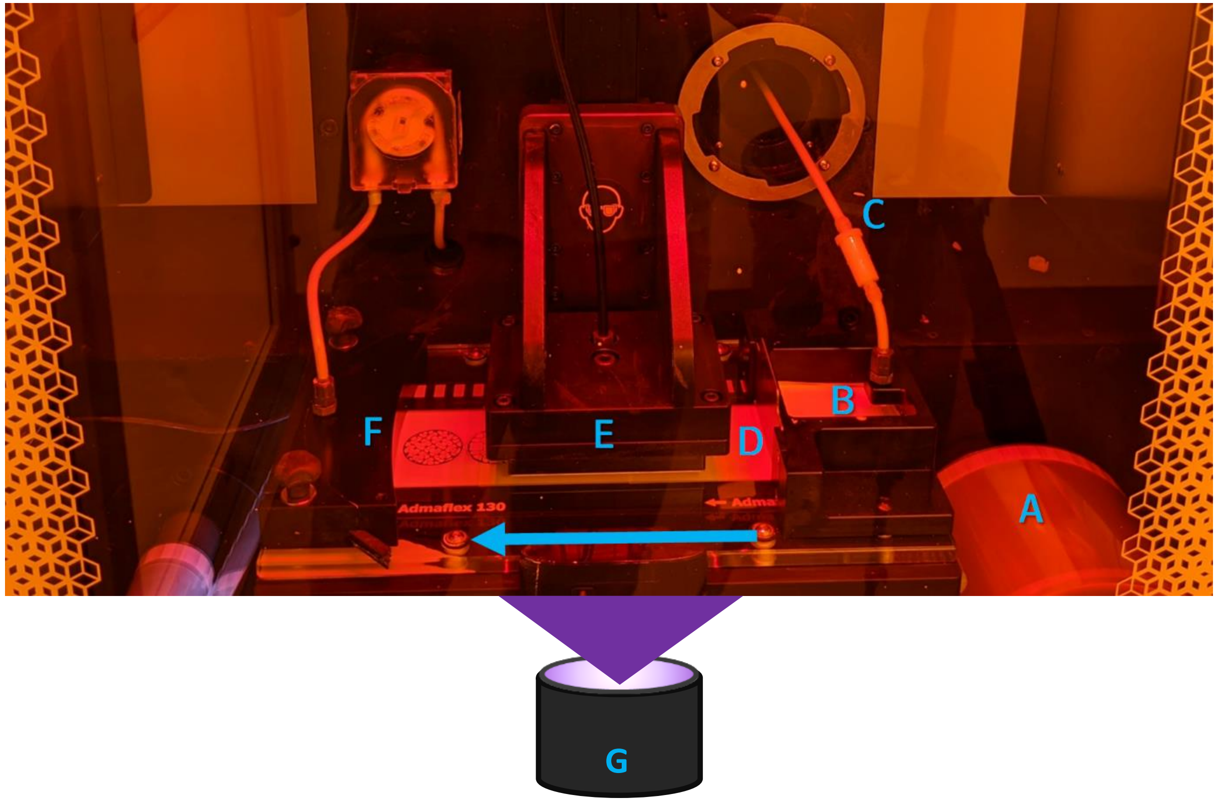
DLP Printing – Admatec A130

- Layerwise printing method
  - 10-50 µm typical
  - 2-5 mm/hr build rate (Z direction)
- 96 x 54 x 110 mm build volume



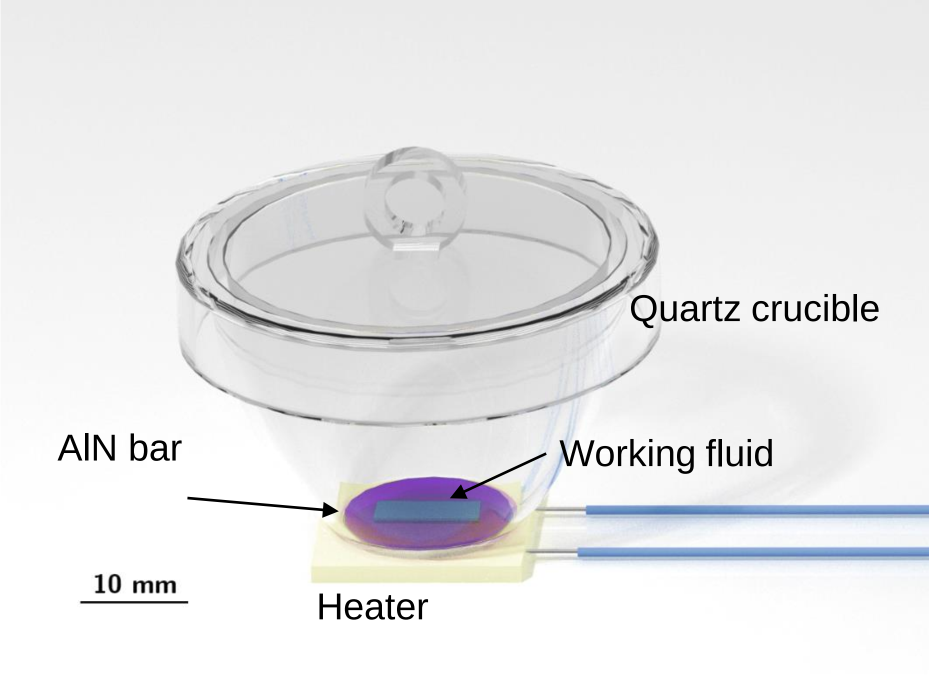
DLP Printing – Admatec A130

A. Foil roll
B. Slurry vat
C. Recirc filter
D. Doctor blade
E. Build head
F. Wiper (recirc)
G. Projector

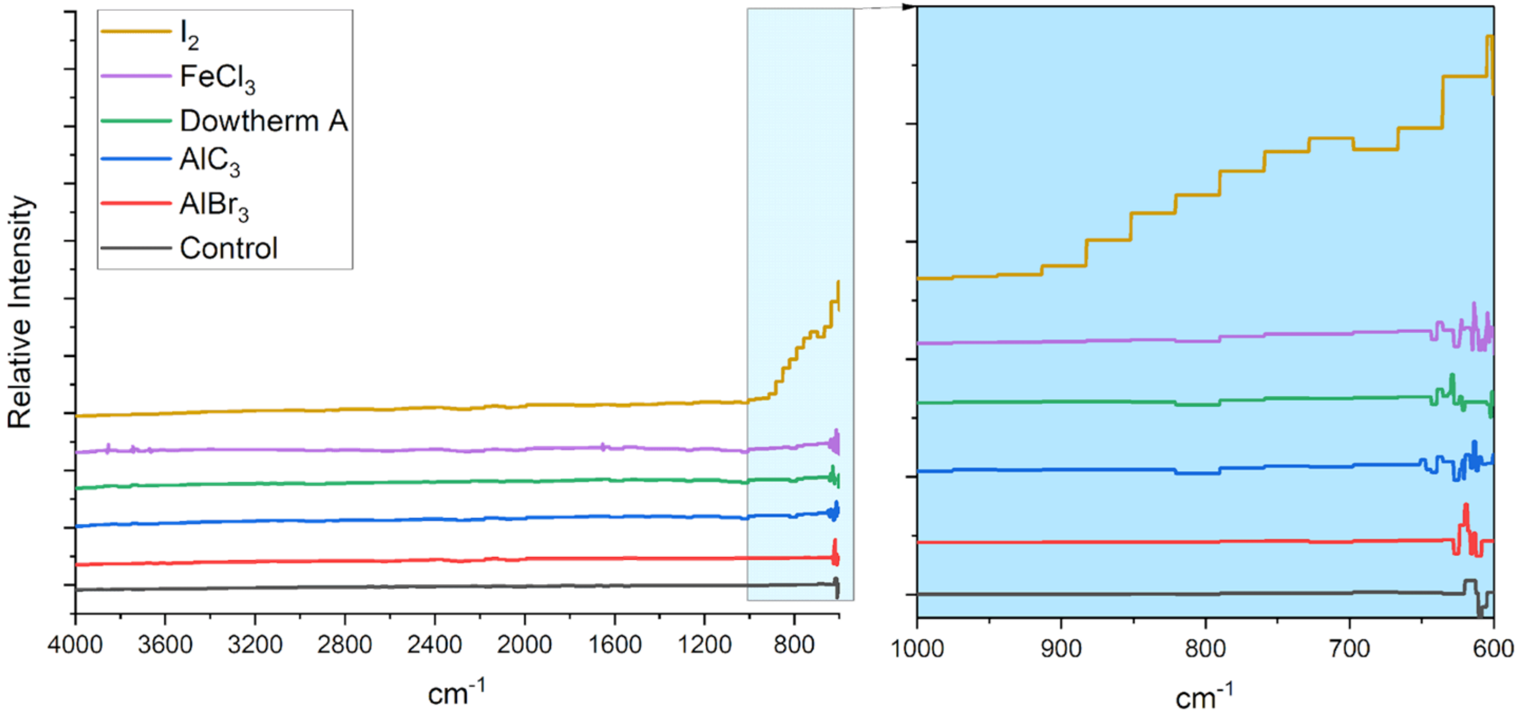


Working Fluid Compatibility Testing

- Fluid heated to melting point in inert atmosphere
- AlN bar immersed
- Fourier transform infrared spectroscopy (FTIR) & SEM after immersion & cleaning



Working Fluid Compatibility Testing

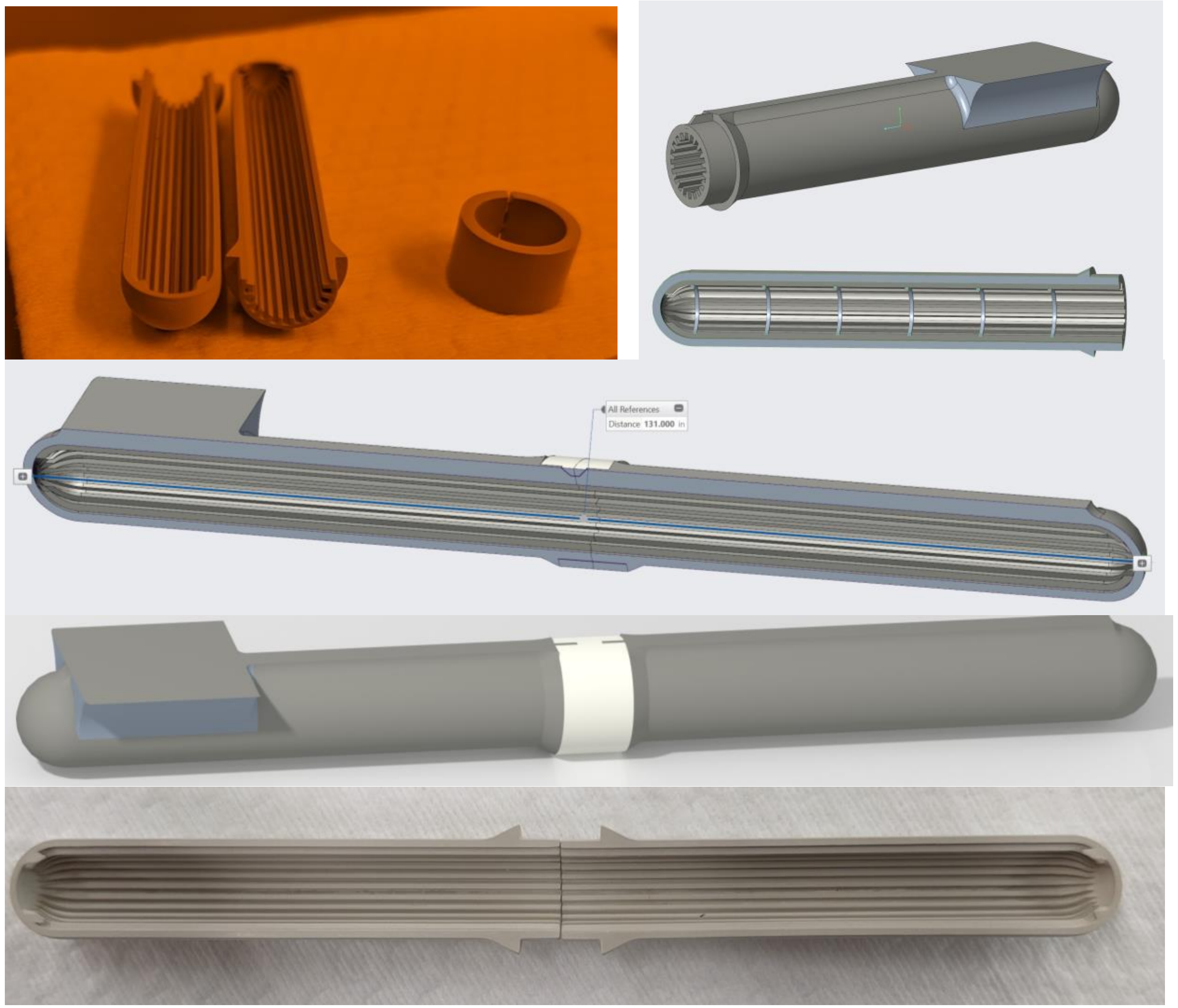


Fourier transform infrared spectroscopy (FTIR)

The story so far…

AdVECT

- Design iteration of grooved heat pipes



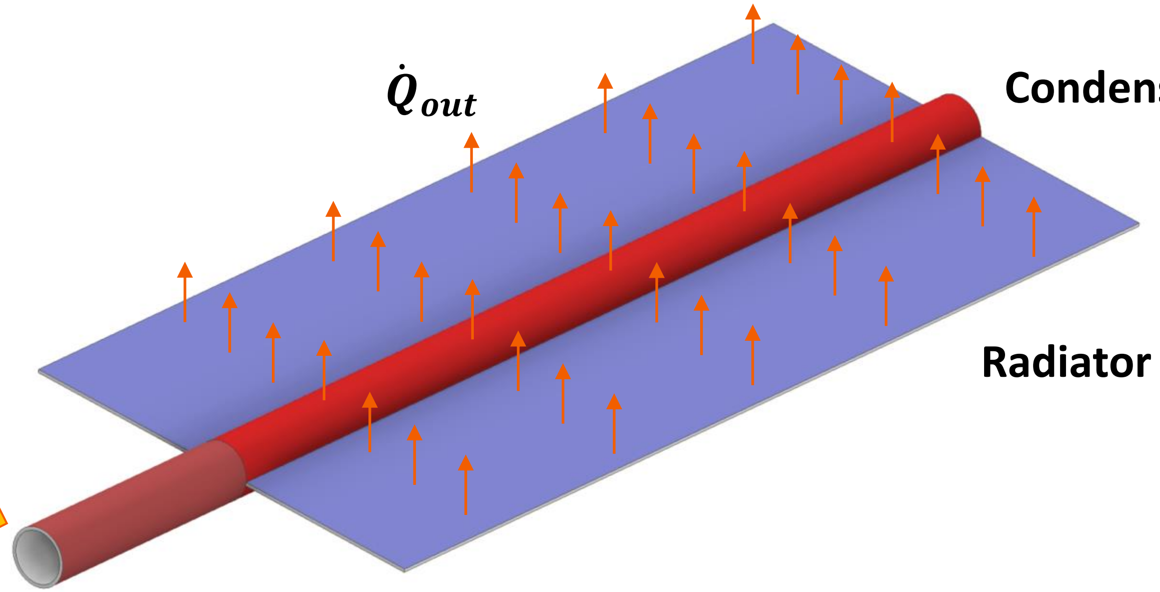
Modeling

What are the potential benefits to an Aluminum Nitride-Aluminum Bromide Embedded Heat Pipe Radiator?

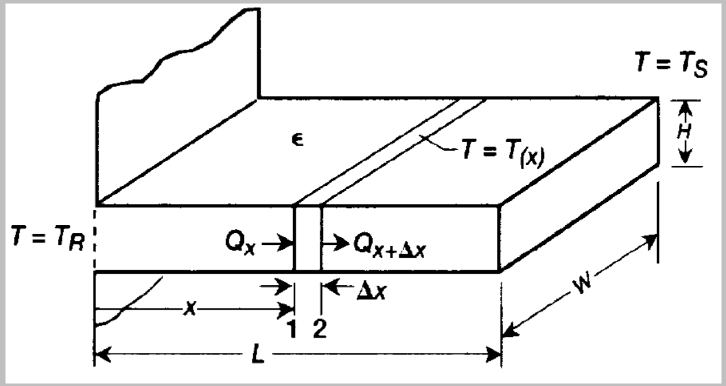
Find out through modeling performance

Reduced Order Thermal Model

1D model of heat pipe

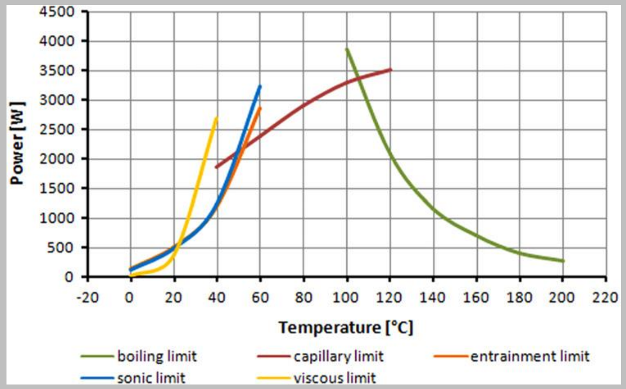


Radiation Model of Fins + HP Surface



$$\dot{Q}_{rad}(T) < \dot{Q}_{env}(T)$$

Performance Limit of Heat Pipe



Reduced Order Thermal Model

Performance Limits of Heat Pipes

Capillary Limit

$$\dot{Q}_c = \frac{\rho_l \sigma h_{fg}}{\mu_l} \frac{K A_w}{l_{eff}} \left(\frac{2}{r_{eff}} - \frac{\rho_l g l_t}{\sigma} \cos(\theta) \right)$$

Boiling Limit

$$\dot{Q}_b = \frac{4\pi(l_e) k_{eff} \sigma T_v}{h_{fg} \rho_l \ln\left(\frac{r_s}{r_i}\right)} \left(\frac{1}{r_n} - \frac{1}{r_{eff}} \right)$$

Viscous Limit

$$\dot{Q}_v = \frac{\pi r_i^4 h_{fg} \rho_v P_v}{12 \mu_l l_{eff}}$$

Sonic Limit

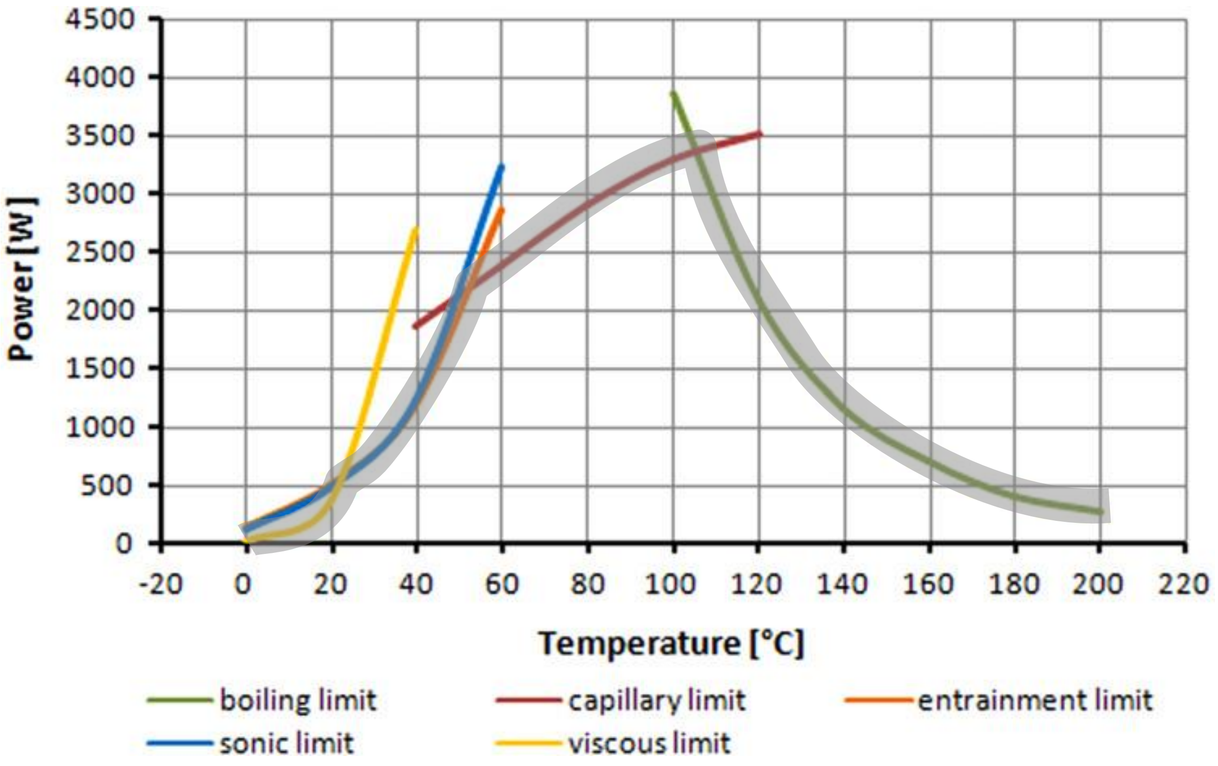
$$\dot{Q}_s = 0.474 A_v h_{fg} (\rho_v P_v)^{0.5}$$

Entrainment Limit

$$\dot{Q}_e = A_v h_{fg} \left(\frac{\rho_v \sigma}{2 r_{cav}} \right)^{0.5}$$

Limit Envelope

$$\dot{Q}_{env}(T) = \min\left(Q_i(T)\right)$$



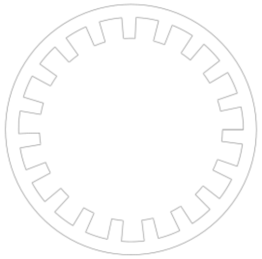
P. Nemec, A. Čaja, and M. Malcho, "Mathematical model for heat transfer limitations of heat pipe," *Mathematical and Computer Modelling*, vol. 57, no. 1, pp. 126–136, Jan. 2013.

Experimental Scale

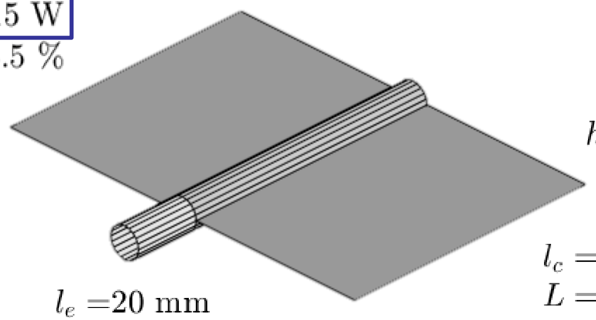
AlN – Ethanol Heat Pipe

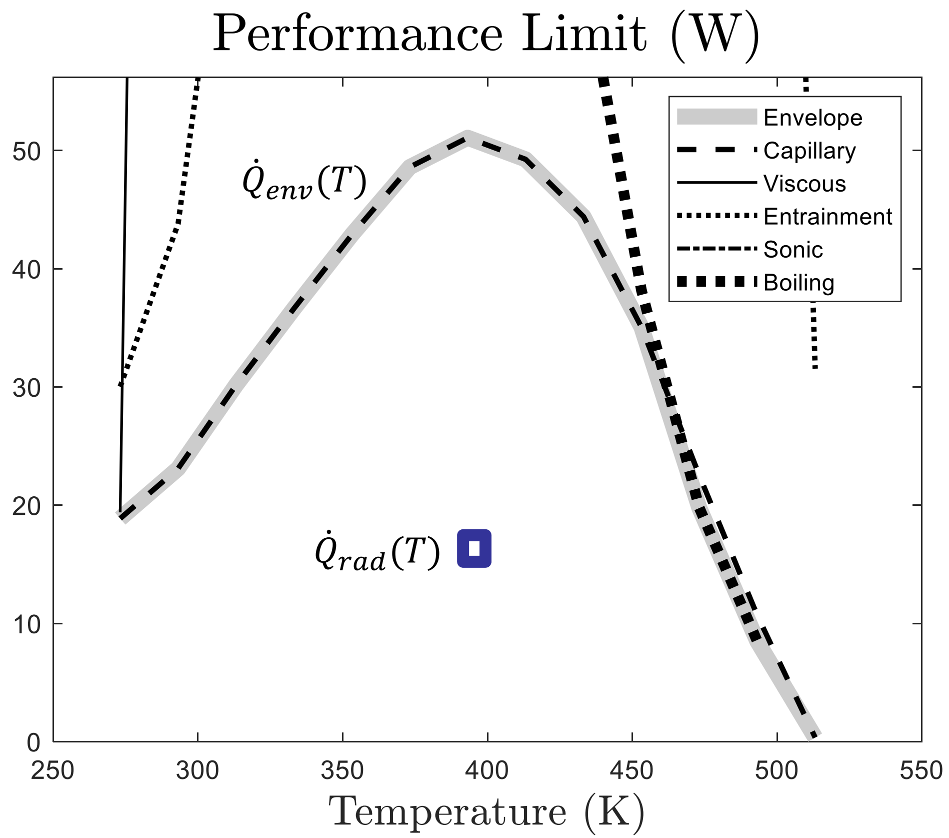
Radii (mm)
$r_o = 4.8$
$r_s = 4.3$
$r_i = 3.5$

Grooves (mm)
$w = 0.8$
$t = 0.5$
$d = 0.8$



Heat Pipe Performance
$r_{eff} = 0.79\text{mm}$
$K = 1520\mu\text{m}^2$
$k_{eff} = 50\text{W/m·K}$





Key Performance Metrics

$m = 38$ g, $\frac{A}{m} = 3.9$ kg/m^2, $\frac{\dot{Q}}{A} = 1548$ W/m^2, $\frac{m}{\dot{Q}} = 2.54$ kg/kW

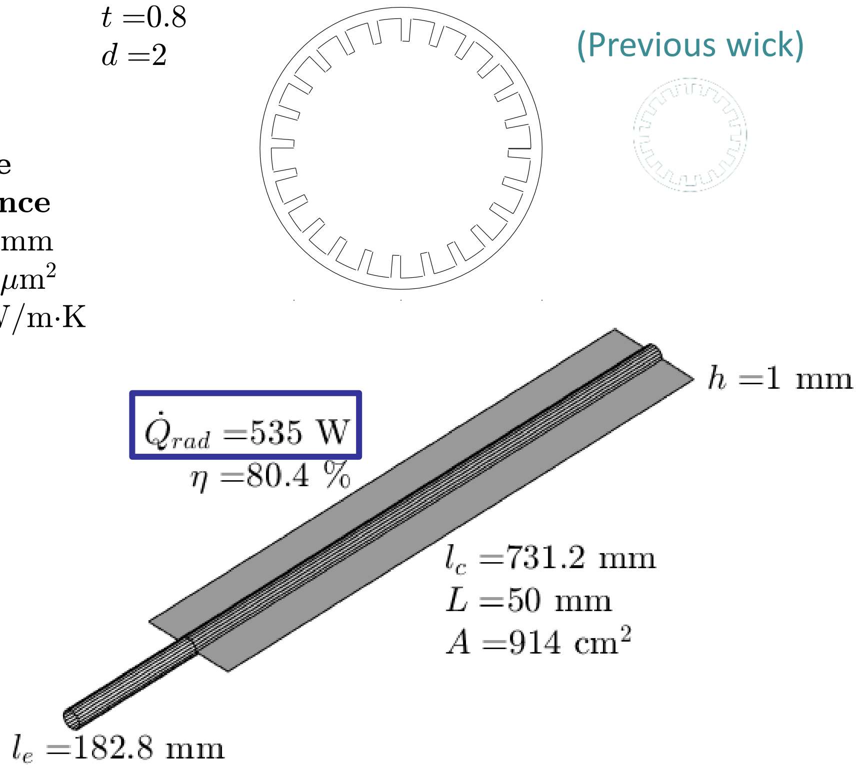
Spacecraft Scale

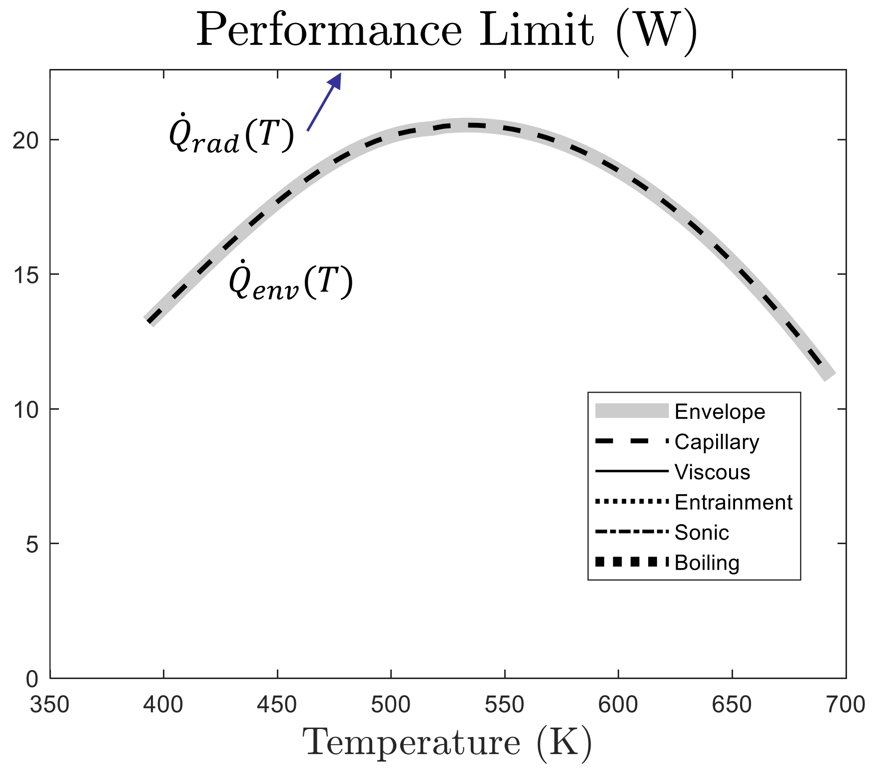
AlN – $AlBr_3$ (Using geometry without alteration)

Radii (mm)
$r_o = 12.5$
$r_s = 11.5$
$r_i = 9.5$

Grooves (mm)
$w = 2$
$t = 0.8$
$d = 2$

Heat Pipe Performance
$r_{eff} = 1.96\text{mm}$
$K = 10868\mu\text{m}^2$
$k_{eff} = 37\text{W/m}\cdot\text{K}$





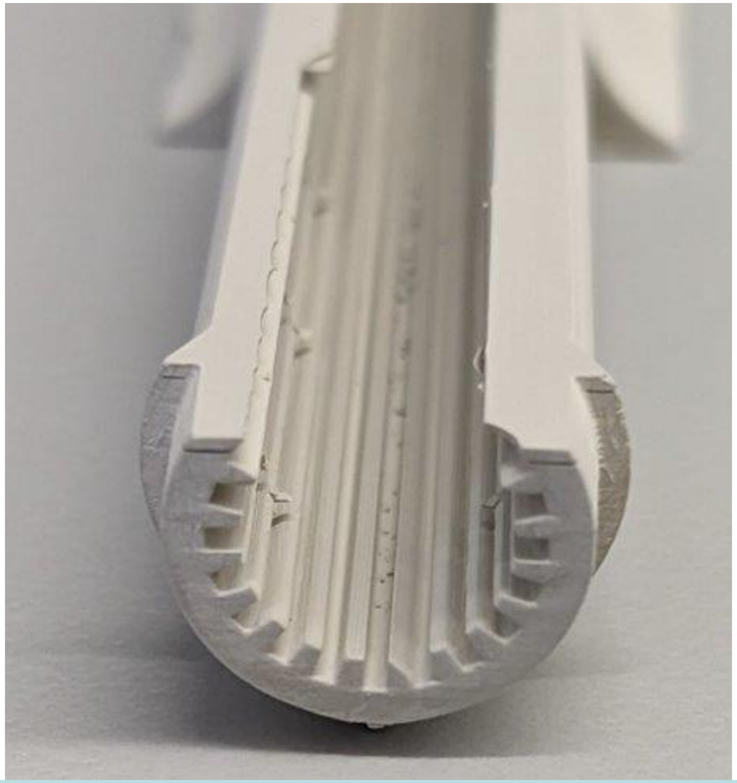
Groove wick cannot meet heat load requirements

Key Performance Metrics

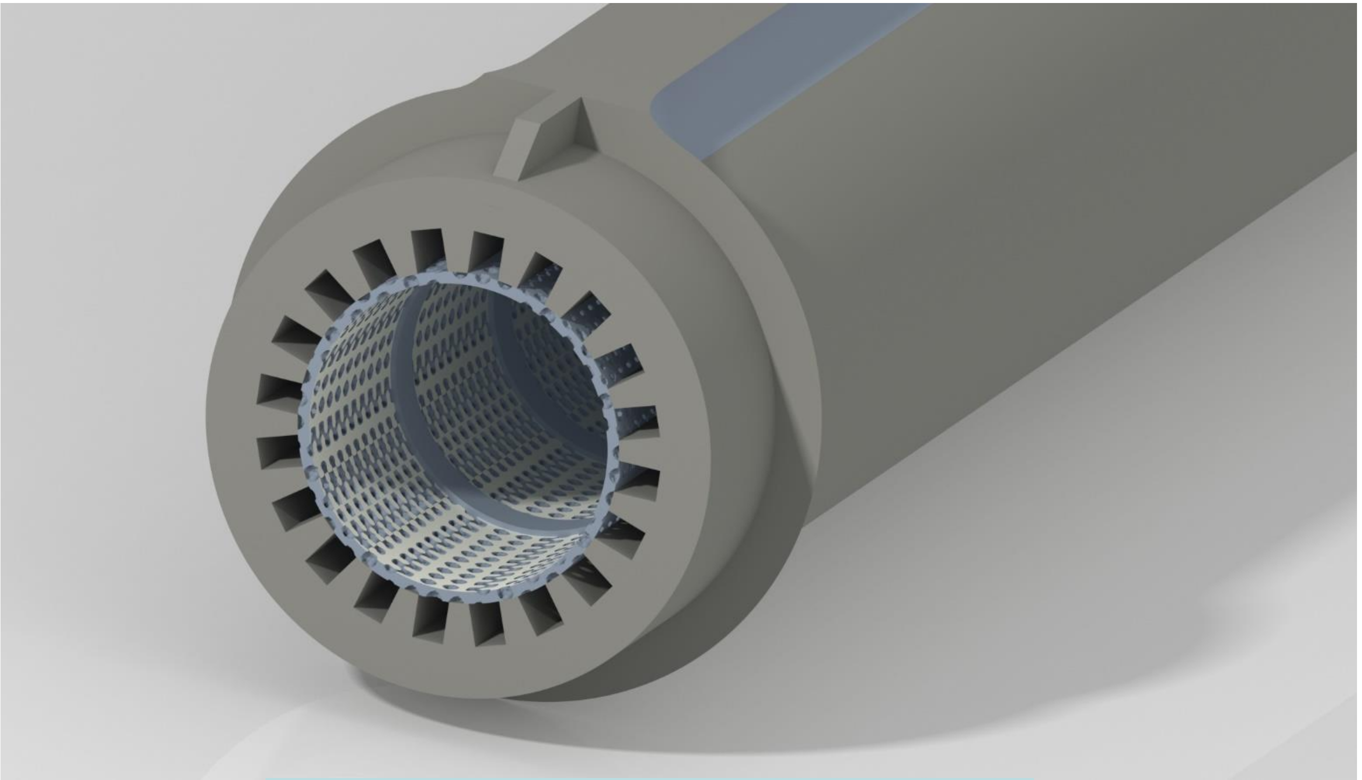
$$m = 804 \text{ g}, \ \frac{A}{m} = 8.8 \text{ kg/m}^2, \ \frac{\dot{Q}}{A} = 5849 \text{ W/m}^2, \ \frac{m}{\dot{Q}} = 1.5 \text{ kg/kW}$$

Results

New Biporous Groove Design – Mesh Screen Cover (lattice)



Facilitate printing overhanging features



Reduce r_{eff} without significant K losses

Results

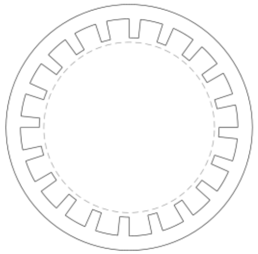
Spacecraft Scale

AlN – $AlBr_3$ (biporous wick)

Radii (mm)
$r_o = 8.5$
$r_s = 7.5$
$r_i = 6.2$

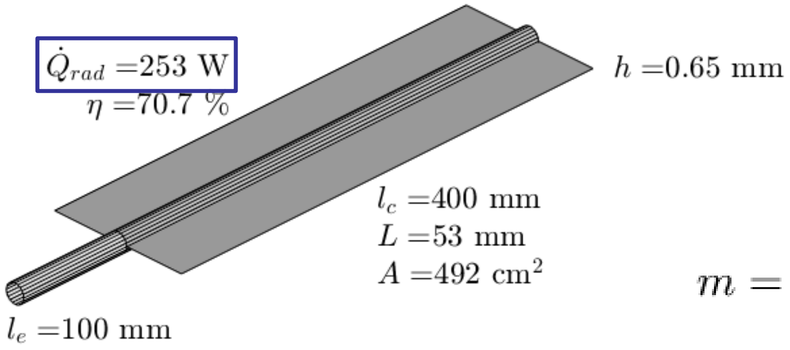
Grooves (mm)
$w = 1.4$
$t = 0.7$
$d = 1.3$

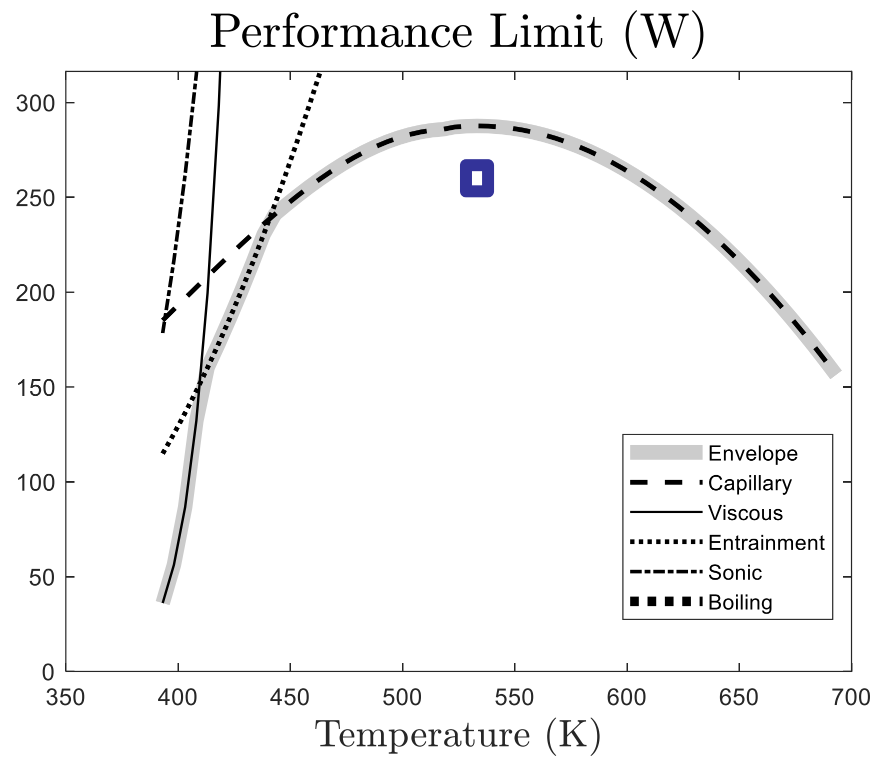
Mesh (μm)
$w_m = 50$
$d_m = 50$



Performance

$r_{eff} = 0.05\text{mm}$ (1.96mm)
$K = 5013\mu\text{m}^2$ (10868μm^2)
$k_{eff} = 43\text{W/m}\cdot\text{K}$ (37W/m.K)





Key Performance Metrics

$$m = 254 \text{ g}, \ \frac{A}{m} = 5.2 \text{ kg/m}^2, \ \frac{\dot{Q}}{A} = 5141 \text{ W/m}^2, \ \frac{m}{\dot{Q}} = 1 \text{ kg/kW}$$

(8.8kg/m^2) (1.5kg/kW)

Future Work

Model Refinement

- Many equations for limits are based on different manufacturing techniques.
    - Use experiments to refine and validate the formulas
- Geometry is not yet optimized for structural strength
    - Use experiments to define yield and stability.
- Geometry uses basic shapes only
    - Explore tapering profiles for radiators and targeted wick structures.
- Only Aluminum Bromide evaluated so far
    - Continue compilation of halide properties to expand model parameters

- Eventually build out COMSOL model for final validation.