Additive Manufacturing and Working Fluid Characterization of Ceramic Heat Pipes

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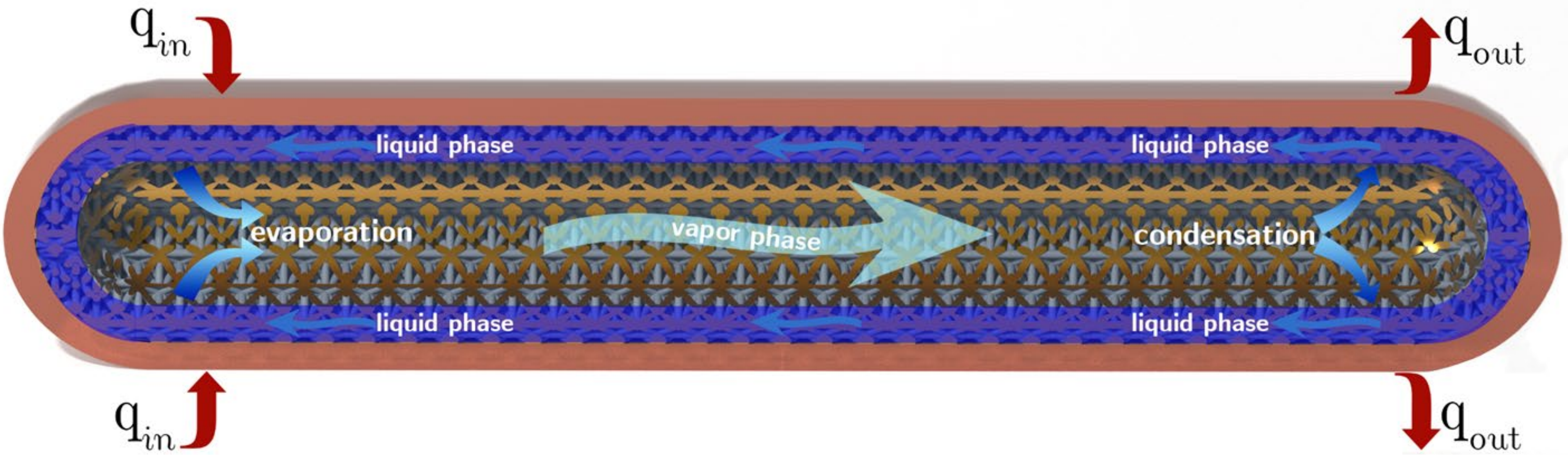
Background

- Heat pipes are **passive** thermal heat transfer devices
  - No moving parts & significantly higher rejection than pure conduction
- Used extensively in spacecraft
  - Developed by NASA in 1960s
- Broadly split into three temperature categories

	Temperature	Example Working Fluids
Low	200-550 K	H_2O, NH_3
Intermediate	450-750 K	$AlBr_3$, I_2
High	675-1000 K	Na, K

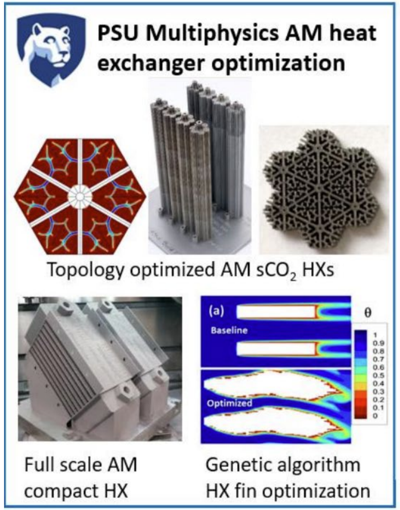
Background

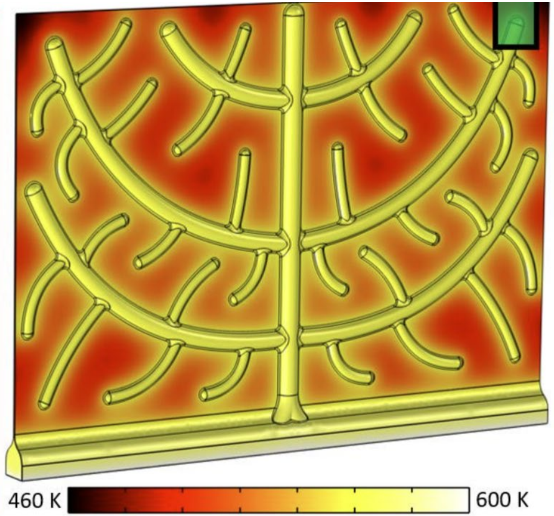


1. Envelope (commonly Cu, Al, Ti)
2. Wick (commonly sintered, grooved, or mesh)
3. Working fluid liquid phase (e.g. water)
4. Working fluid vapor phase

Background

- State of the art research exploring additive manufacturing (AM)
  - Tailored wick structures
  - Optimization of integrated heat pipes & radiator

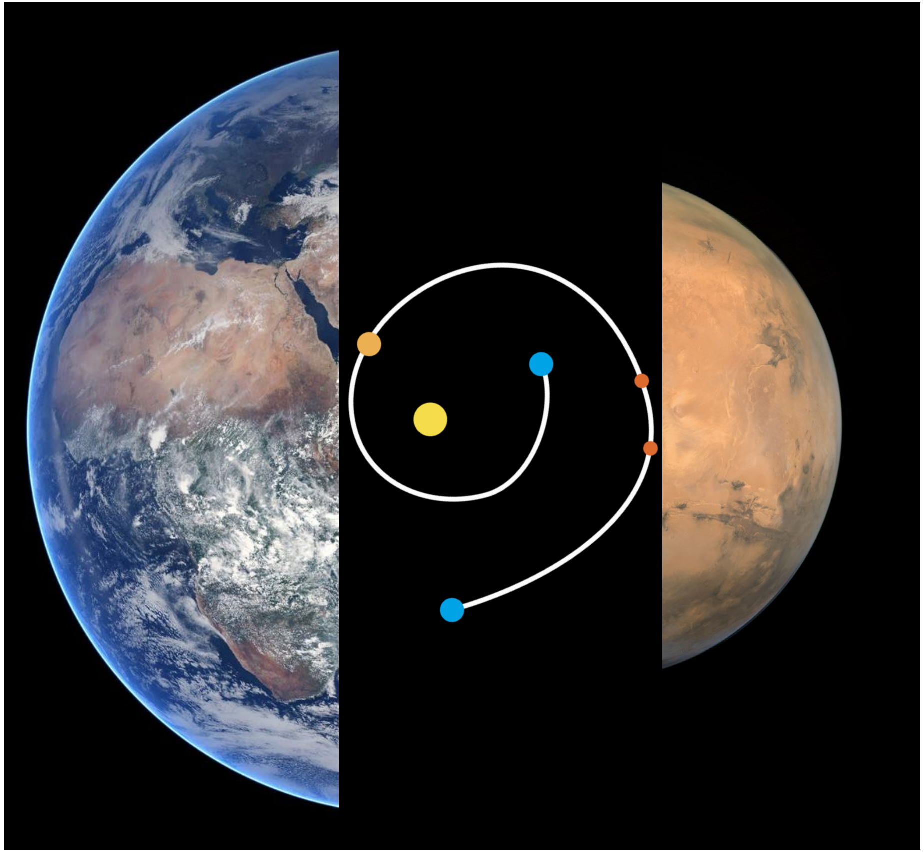




NASA ESI 2021: Lynch et al., High Temperature Additively Manufactured Monolithic Heat Pipe Radiators

Motivation for Heat Pipe Development

- NASA plans crewed missions to Mars ~2040
    - Builds on Artemis lunar missions
- Mission profiles 650 – 916 day duration
- Technology not fully developed



Nuclear Electric Propulsion

- Nuclear electric propulsion gets crewed mission to Mars
  - Getting there quickly & efficiently = more energy
  - More energy = more heat
- Estimates of 4,030 m^2 radiator area for 2 MW_e reactor*
- Radiators are significant mass fraction of vehicle

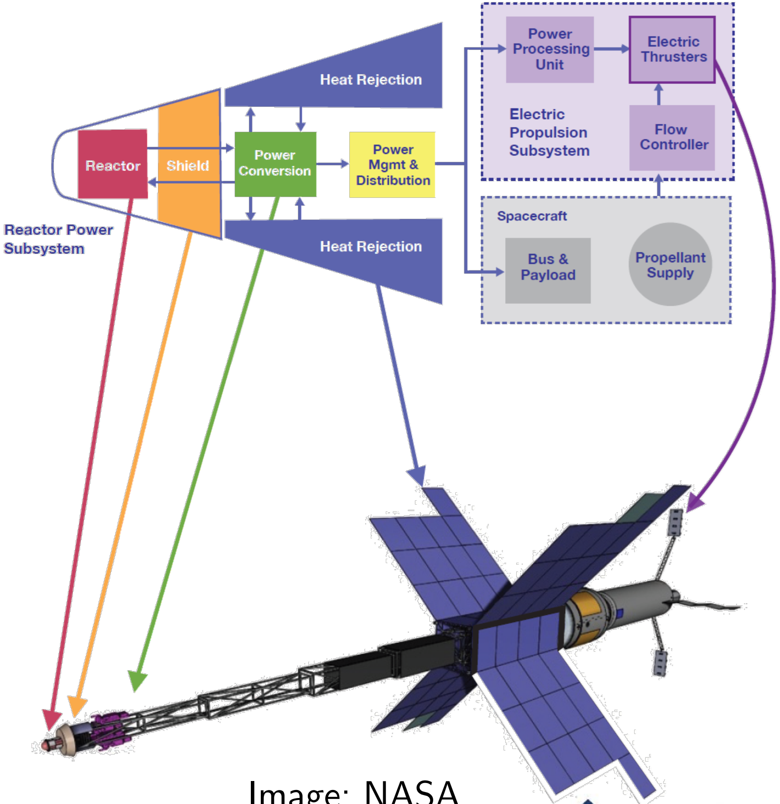
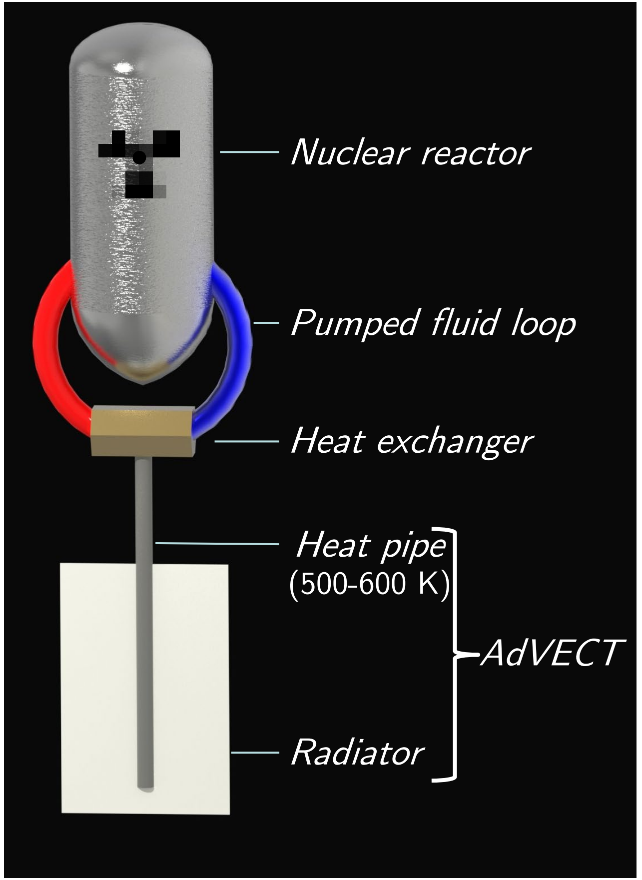


Image: NASA

*W. S. Machemer, et al, 2023.

Additive Vehicle-Embedded Cooling Technology (AdVECT)

- Reject heat via additively manufactured (AM) heat pipes
  - Consolidate parts
- Target operating temperature of 500-600 K for working fluid
  - Intermediate temperature range
- Uses AM ceramics
  - Aluminum nitride (AlN) → high thermal conductivity

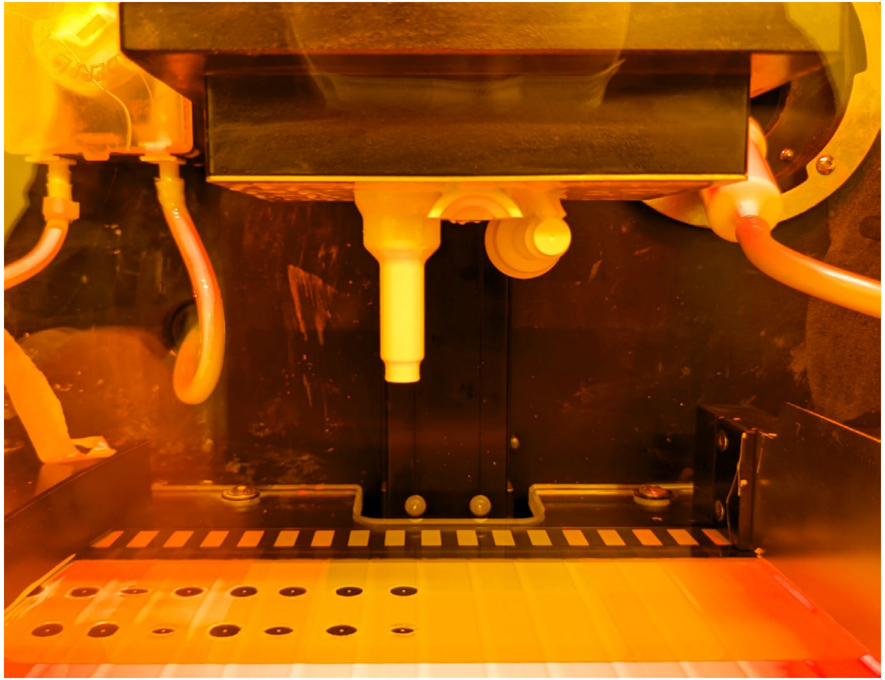


Working Fluid Selection

- Intermediate temperature range
  - High vapor pressure for H_2O
  - Too low for common metals (Na, K)
- Four halide compounds selected
  - $AlBr_3$, $AlCl_3$, $FeCl_3$, I_2
- Commercially available eutectic also trialed
  - Dowtherm A (DTA)
- Previously investigated for use in intermediate temp systems (W.G. Anderson, et al. 2013.)

AM Ceramic Fabrication and Methodology

- Use layer-wise digital light processing (DLP) printing
  - Photosensitive resin + ceramic particles
- High resolution, high final density
  - 20 µm layer height, 50 µm feature size
- AM AlN developed to print heat pipe/radiator



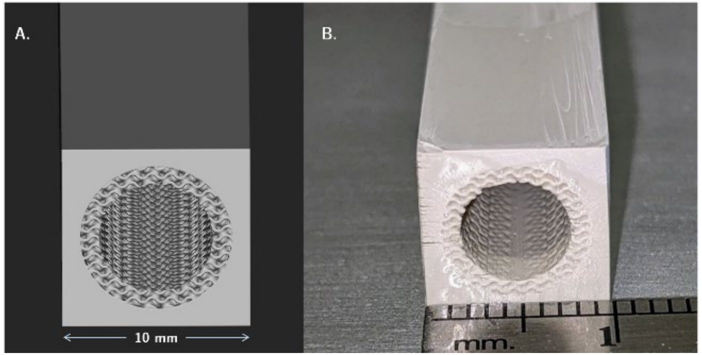
Comparison of AM AlN Formulations

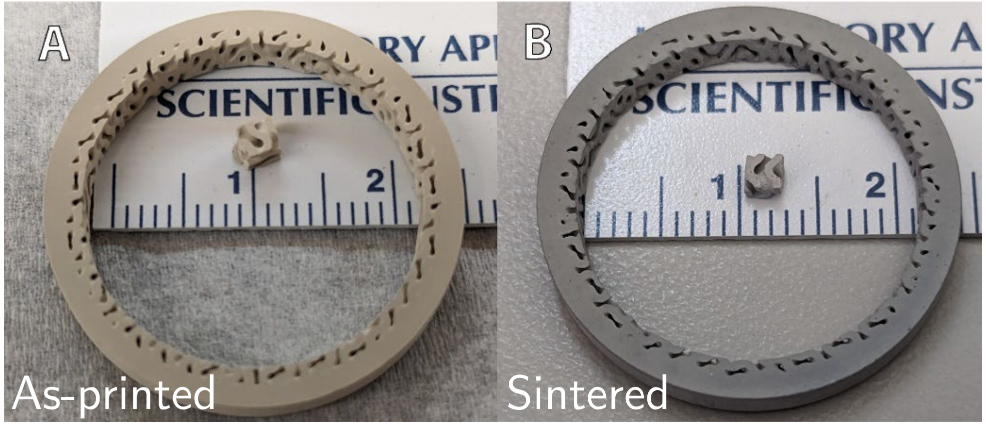
	Composition (wt %)	Sintering Temperature (°C)	Flexural Strength (MPa)	Thermal Conductivity (W/m·K)
Duan et al. 2020	95:5 $AlN:Y_2O_3$	1845	265 ± 20	155
Ożóg et al. 2020	90:6:4 $AlN:Y_2O_3:Al_2O_3$	1800	Not tested	4.34
Lin et al. 2022	100:5 $AlN:Y_2O_3$	1850	365-400	135-150 (appr)
Rauchenecker et al. 2022	96:3:1 $AlN:Y_2O_3:CaO$	1700	320-498	162.1-166.2
Lee and Kim 2014* (Basis for this work)	98:1:1 $AlN:Y_2O_3:CaZrO_3$	1600	579	120

*Conventional ceramics

Development of Low Sintering Temperature Formulation

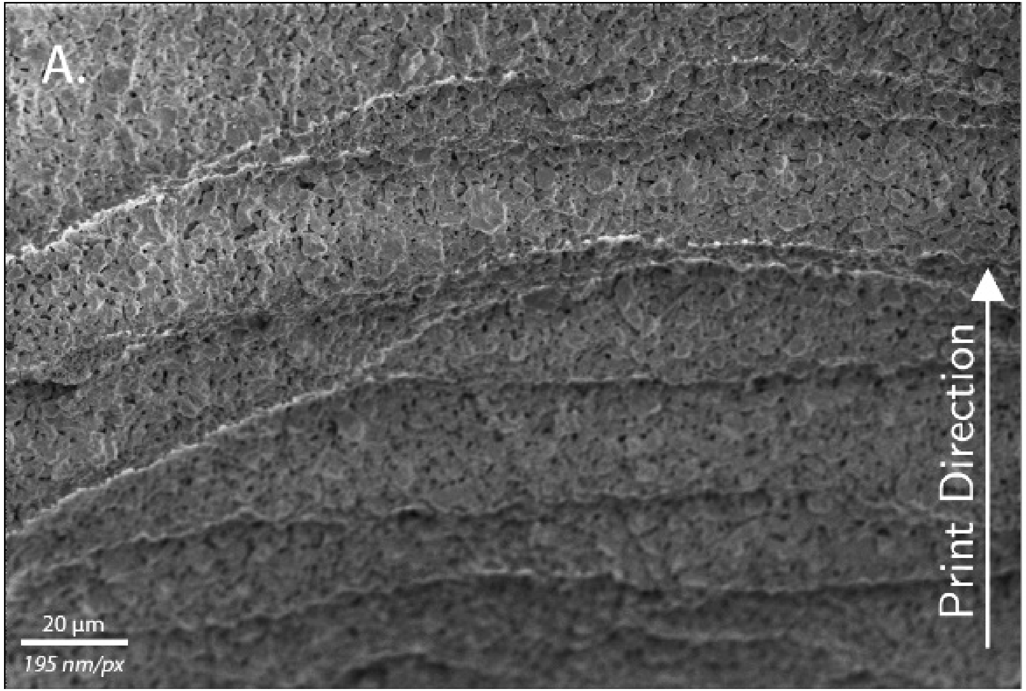
- Debinding in N_2 atmosphere
  - Potential for oxidation in air
- Sintering in N2 at 1600°C (2hrs) & 1400°C (3 hrs)
- Good final part quality
  - Fine details preserved,
  - Lower than expected density





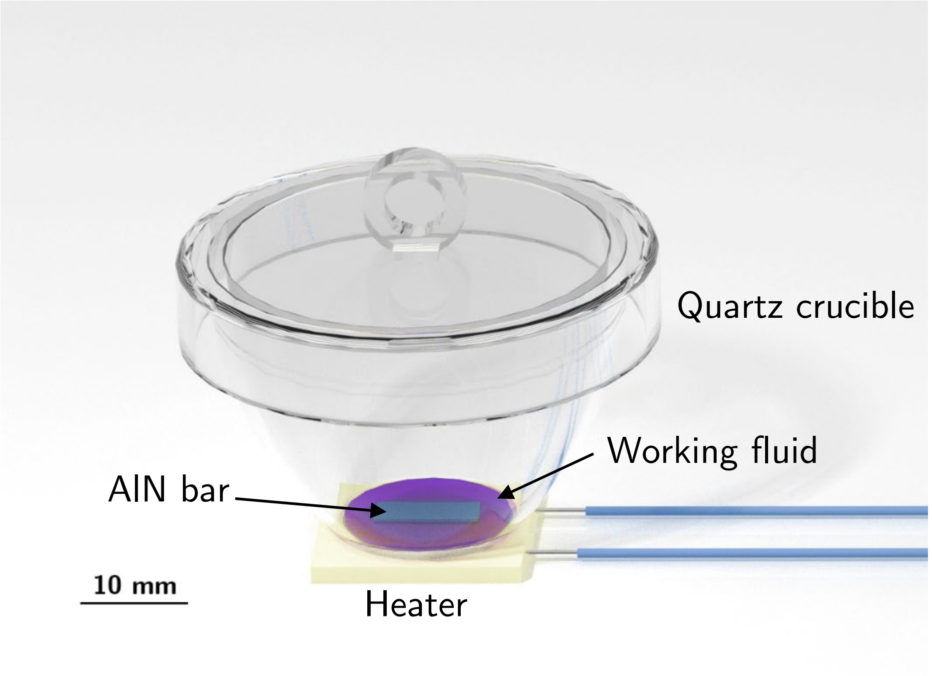
SEM - Surface Microporosity

- Visible porosity in final part
  - 18.6% surface porosity, 301 nm mean pore size
  - Optimizations to thermal processing to enhance final density



Working Fluid Compatibility Testing

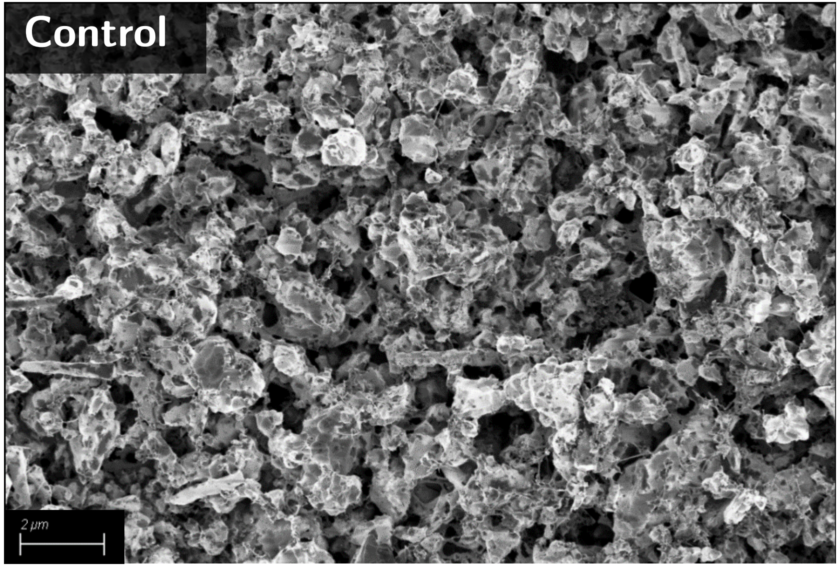
- Fluid heated to melting point in inert atmosphere
- AlN bar immersed
- Fourier transform infrared spectroscopy (FTIR) & SEM after immersion & cleaning



Working Fluid – SEM Results

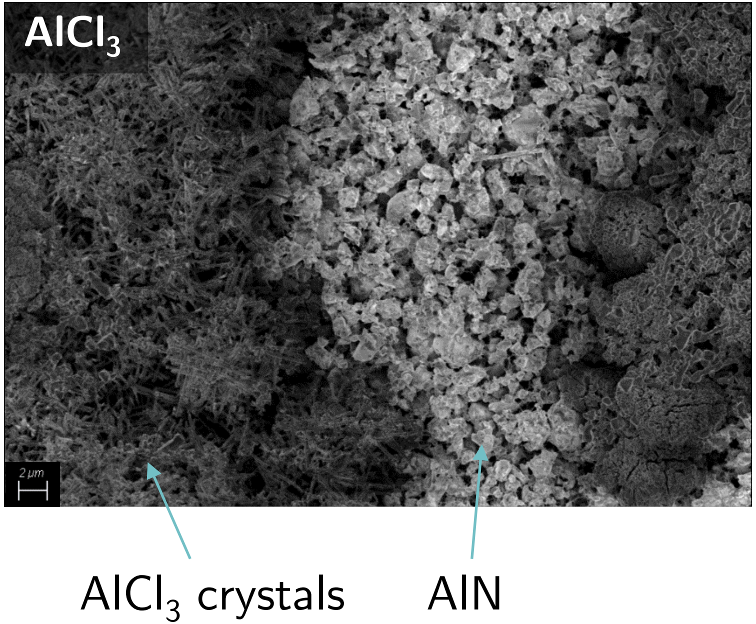
- No difference from control with $AlBr_3$, I_2, or Dowtherm A

- Residual crystalline structures with chloride working fluids



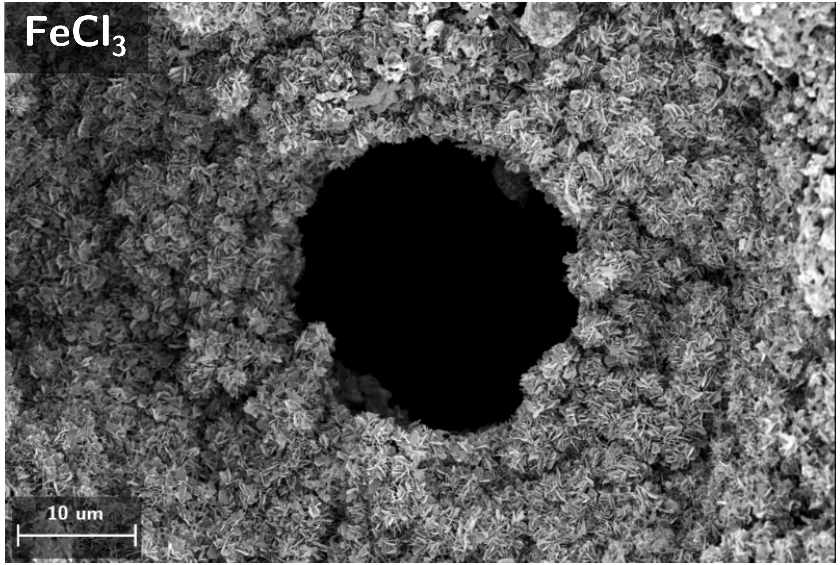
$AlCl_3$ – SEM Results

- No difference from control with $AlBr_3$, I_2, or Dowtherm A
- Residual crystalline structures with chloride working fluids

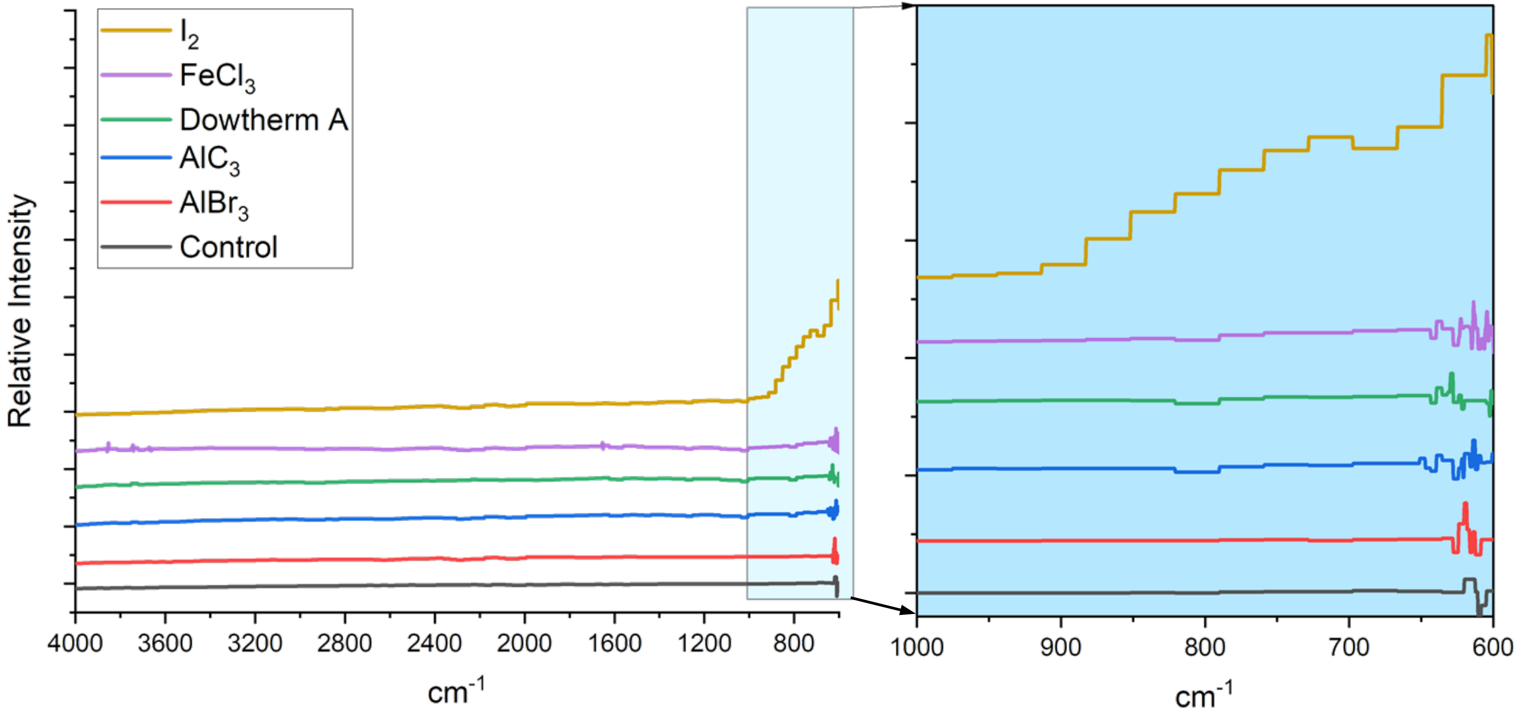


$FeCl_3$ – SEM Results

- No difference from control with $AlBr_3$, I_2, or Dowtherm A
- Residual crystalline structures with chloride working fluids



Iodine Appears Reactive with AlN



Fourier transform infrared spectroscopy (FTIR)

Conclusions

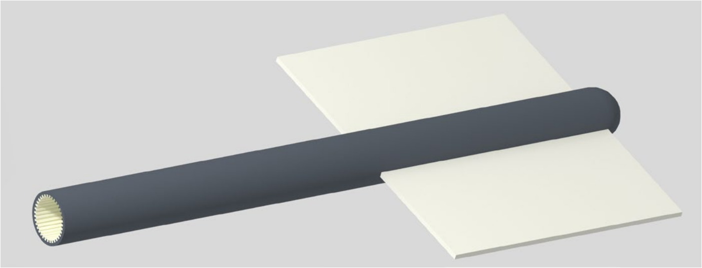
- Novel aluminum nitride formulation applied to AM process

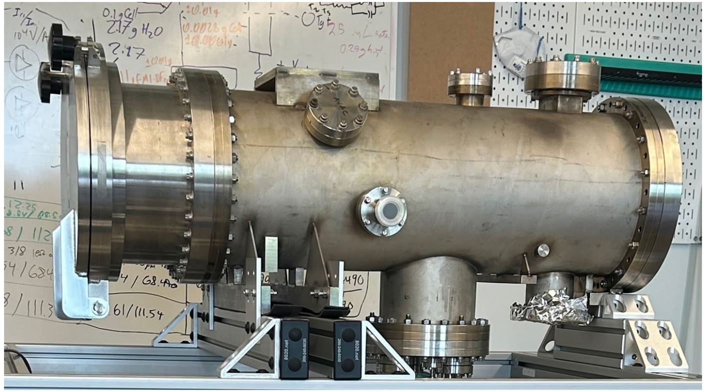
- Lower sintering temperature successfully trialed

- Working fluid compatibility tested with AM AlN
  - $AlBr_3$, $AlCl_3$, $FeCl_3$ and Dowtherm A nonreactive
  - FTIR revealed reactivity with I_2
  - Additional diagnostics planned (X-ray photoelectron spectroscopy)

Future Work

- Scale heat pipe testing
  - Conventional and Dowtherm A working fluids
- Vacuum testing of working fluids and heat pipe





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