



Additive Manufacturing And Experimental Characterization Of Nickel-Titanium Shape-Memory Alloy Wick Structures and Heat Pipes For Spacecraft Thermal Control



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- High power communication and scientific CubeSats & small spacecraft, approaching 100s W to kW thermal loads
- Small spacecraft may soon incorporate emerging sub-kW electric propulsion technologies for increased flexibility
- For SWaP requirements, need deployable high capacity, low areal density radiators
- Conventional deployment mechanisms may add excessive mass to the system

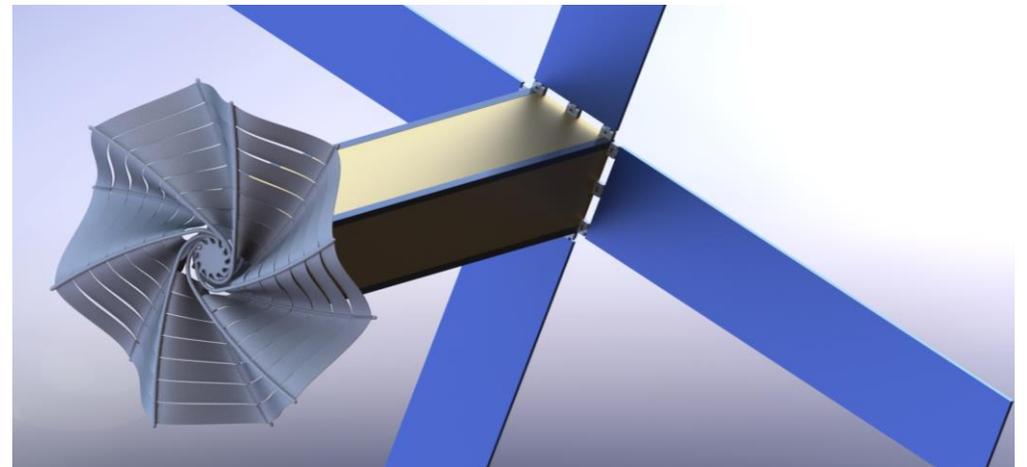
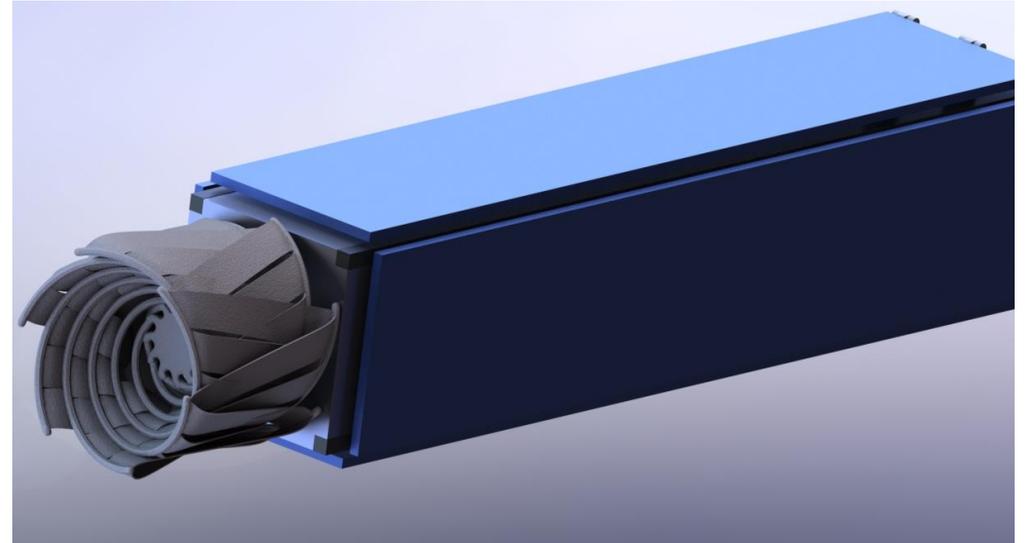


Blue canyon technologies XB3 cubesat



Satrev STORK

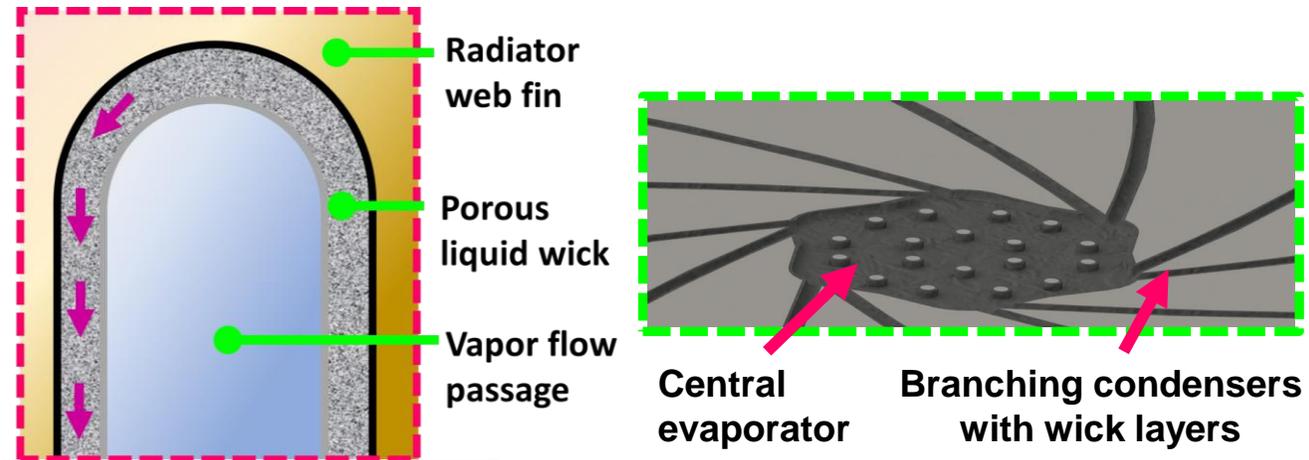
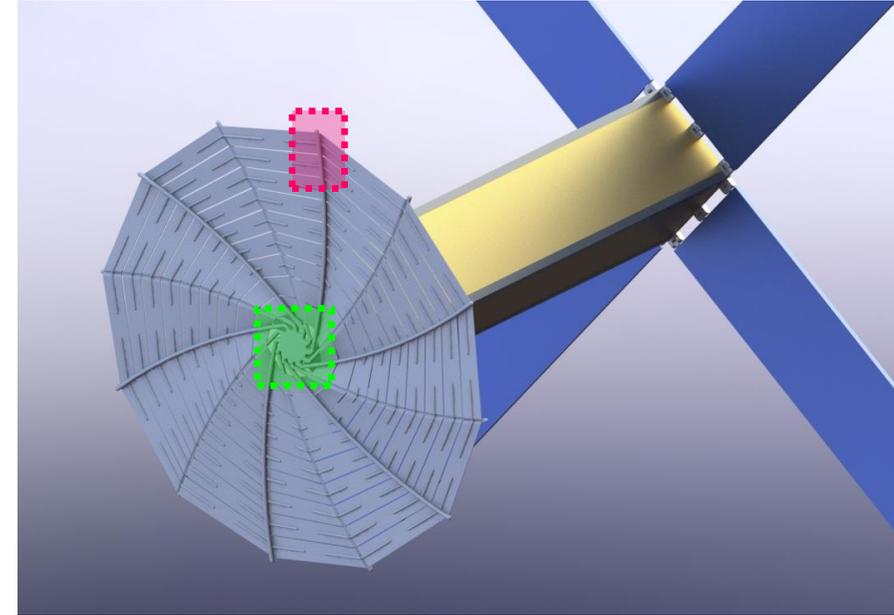
- Passive Thermally Deployed Shape-Memory Alloy Heat-Pipe Radiators for High-Intensity Small Satellites
- Demonstrate AM NiTi radiators with integral wicking heat pipe networks.
- NiTi shape-memory alloy: foldable (origami) geometry that will passively deploy from stowed form
- Goals:
 - High deployed-to-stowed area ratio
 - Lower areal density
 - Low thermal resistance



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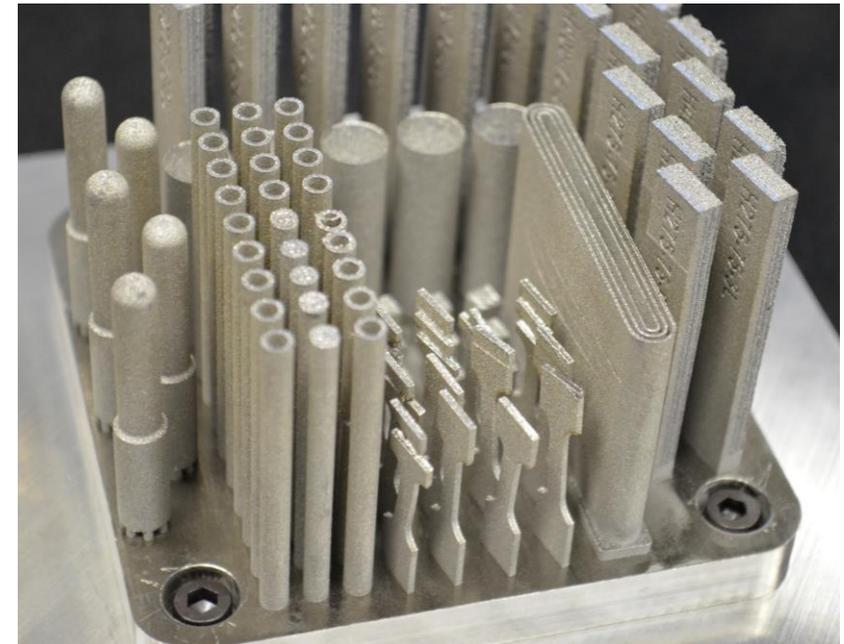
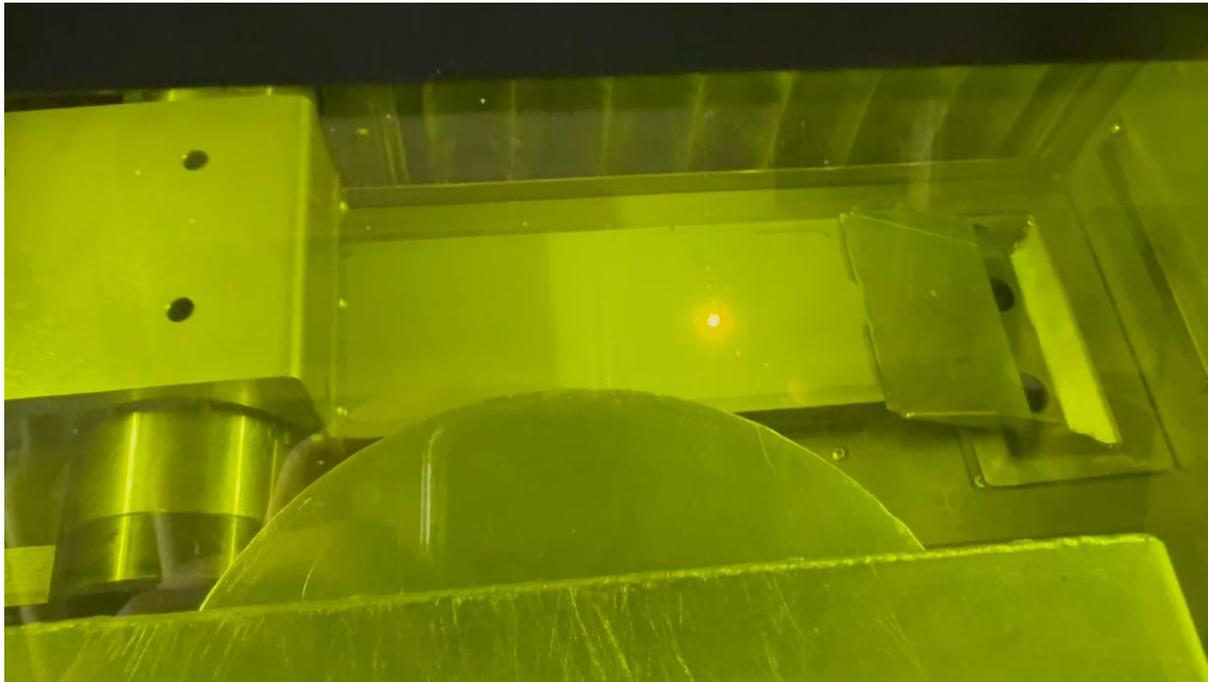
Objectives of Present Study

- Develop AM NiTi porous wick manufacturing strategies for high permeability (K) and (K/r_{pore})
- Rate-of-rise experimental campaign to measure wick capillary properties
- Evaluate surface treatments that yield hydrophilic NiTi surfaces
- Produce and test full AM NiTi wicking heat pipes to verify approach and stable hydrophilic surfaces



- **Laser Powder Bed Fusion (LPBF)**
 - Samples were produced using 3D Systems DMP Flex 100, direct metal printing system equipped with a 100 W laser;
 - Samples built with Fort Wayne Metals NiTi #5 powder (55.1 wt% Ni).

Solid Region Build Parameters	
Laser power (W)	100 (93)
Layer Height (μm)	30
Scan speed (mm/s)	950
Hatch spacing (μm)	80



Wick Coupon Production

- Wick sections produced by laser scanning with wide hatch spacings (275 and 400 μm vs. $\sim 100 \mu\text{m}$ track width) and reduced laser power
- Varying raster spacing, layer count between scan rotations, laser power
- Identified lower power limit to prevent defects

H275-L1-P75 ($\epsilon = 37\%$)



H275-L6-P75 ($\epsilon = 52\%$)



H400-L3-P75 ($\epsilon = 63\%$)



H275-L1-P60 ($\epsilon = 58\%$)



H275-L6-P60 ($\epsilon = 61\%$)



H400-L3-P60



H275-L3-P75 ($\epsilon = 46\%$)



H400-L1-P75 ($\epsilon = 59\%$)



H400-L6-P75 ($\epsilon = 64\%$)



H275-L3-P60



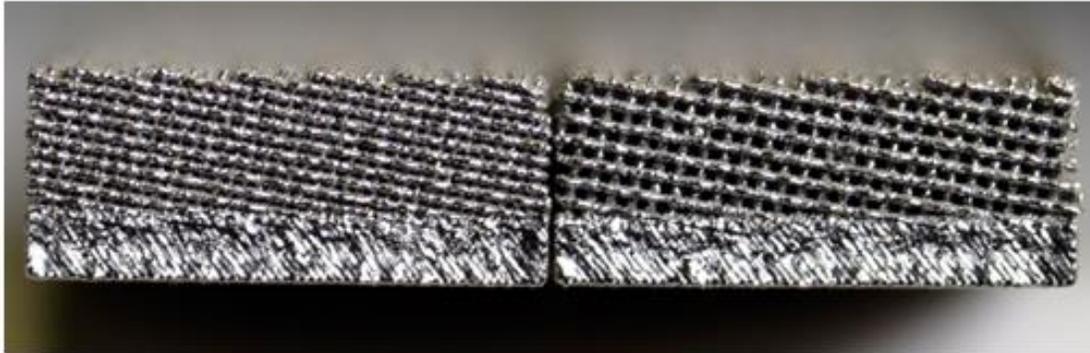
H400-L1-P60



H400-L6-P60



- Low laser power build limit (~60% laser power) resolved with higher power in second batch

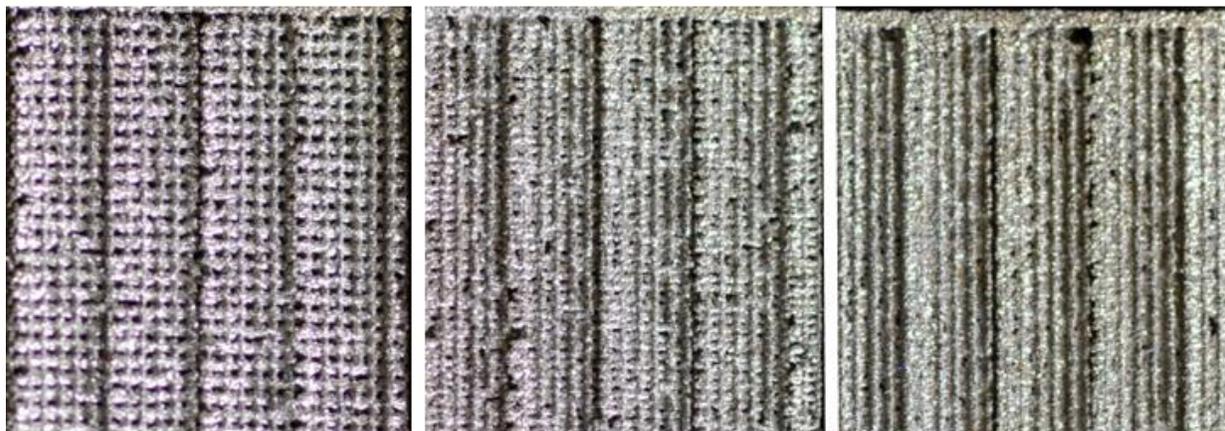


275-L6-P90

400-L6-P100

275-L6-P90

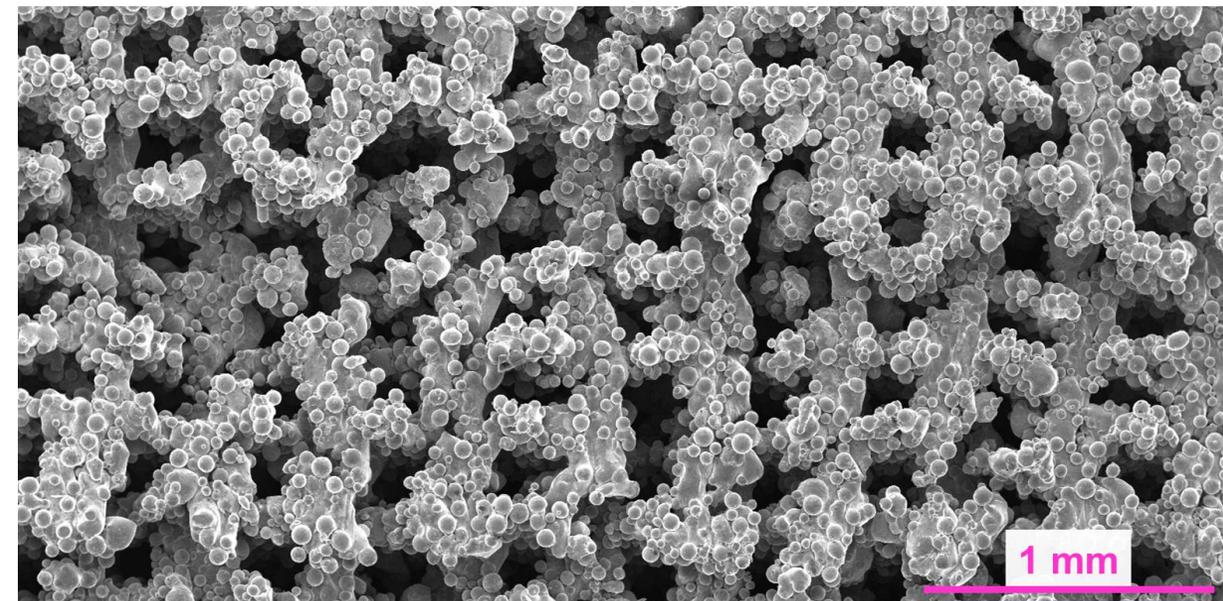
275-L6-P60



400-L6-P90

400-L3-P90

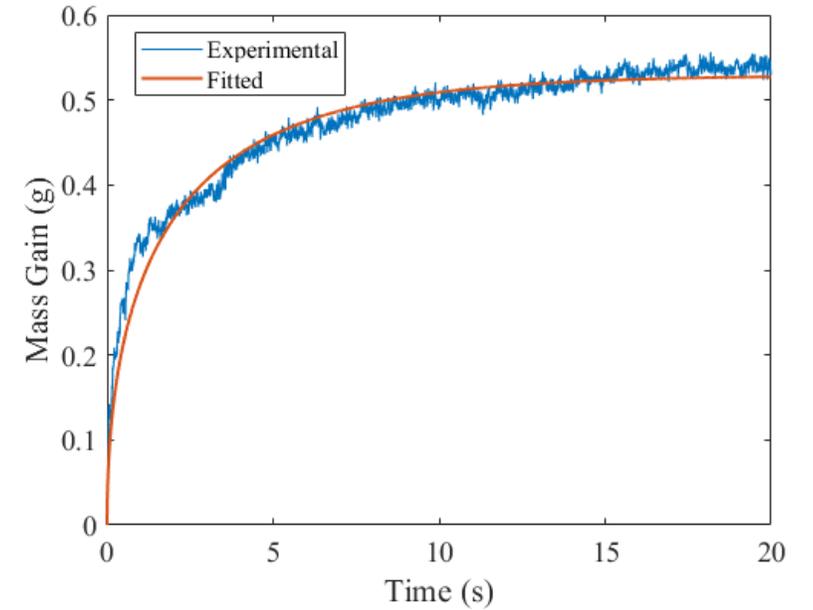
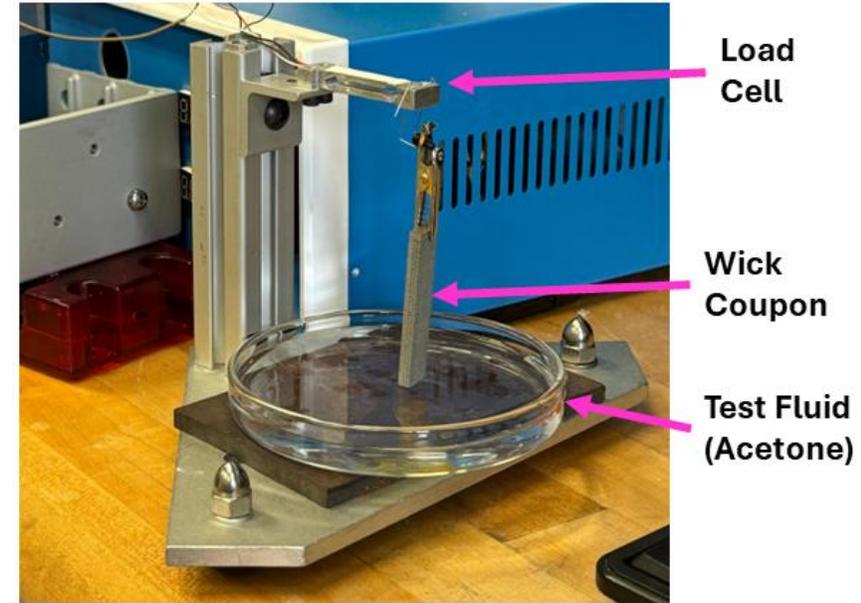
400-L1-P90



1 mm

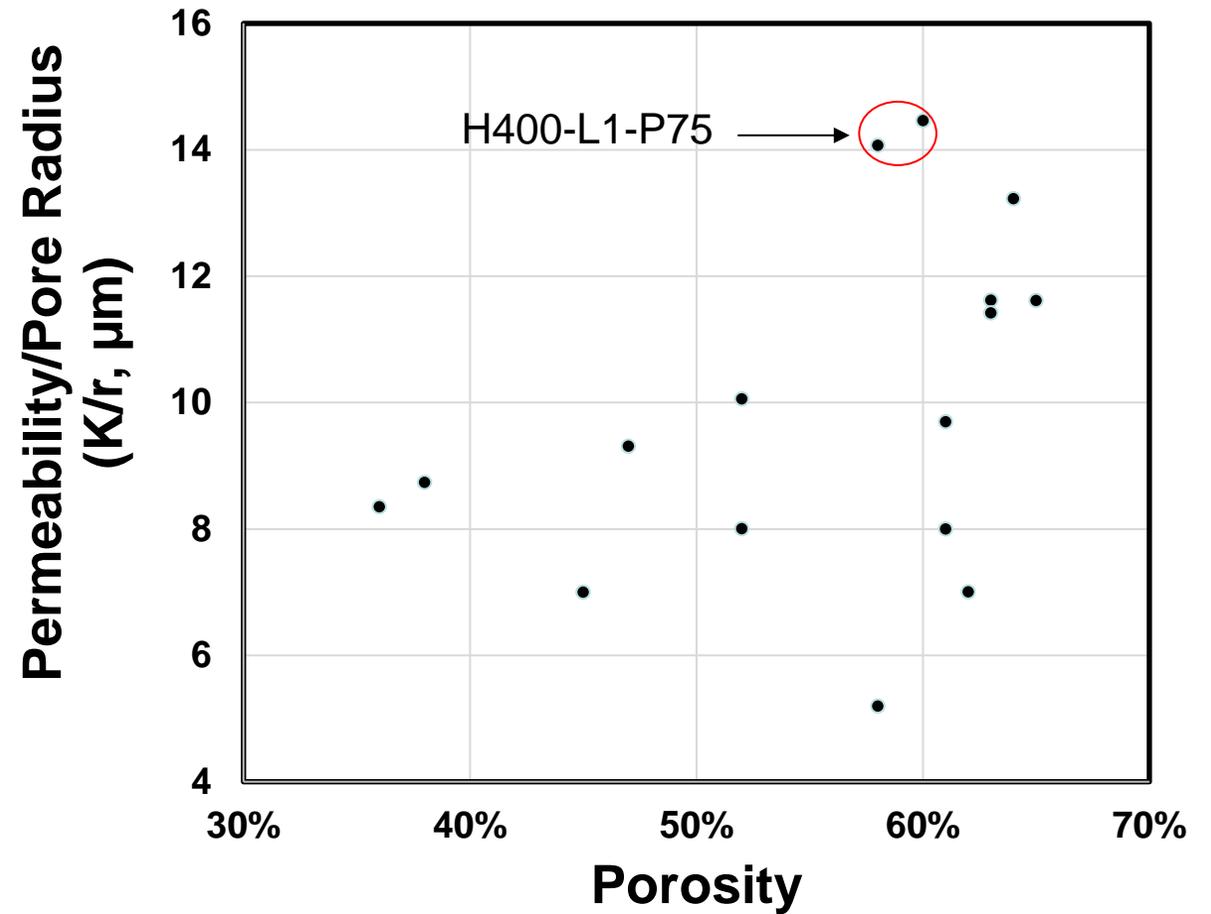
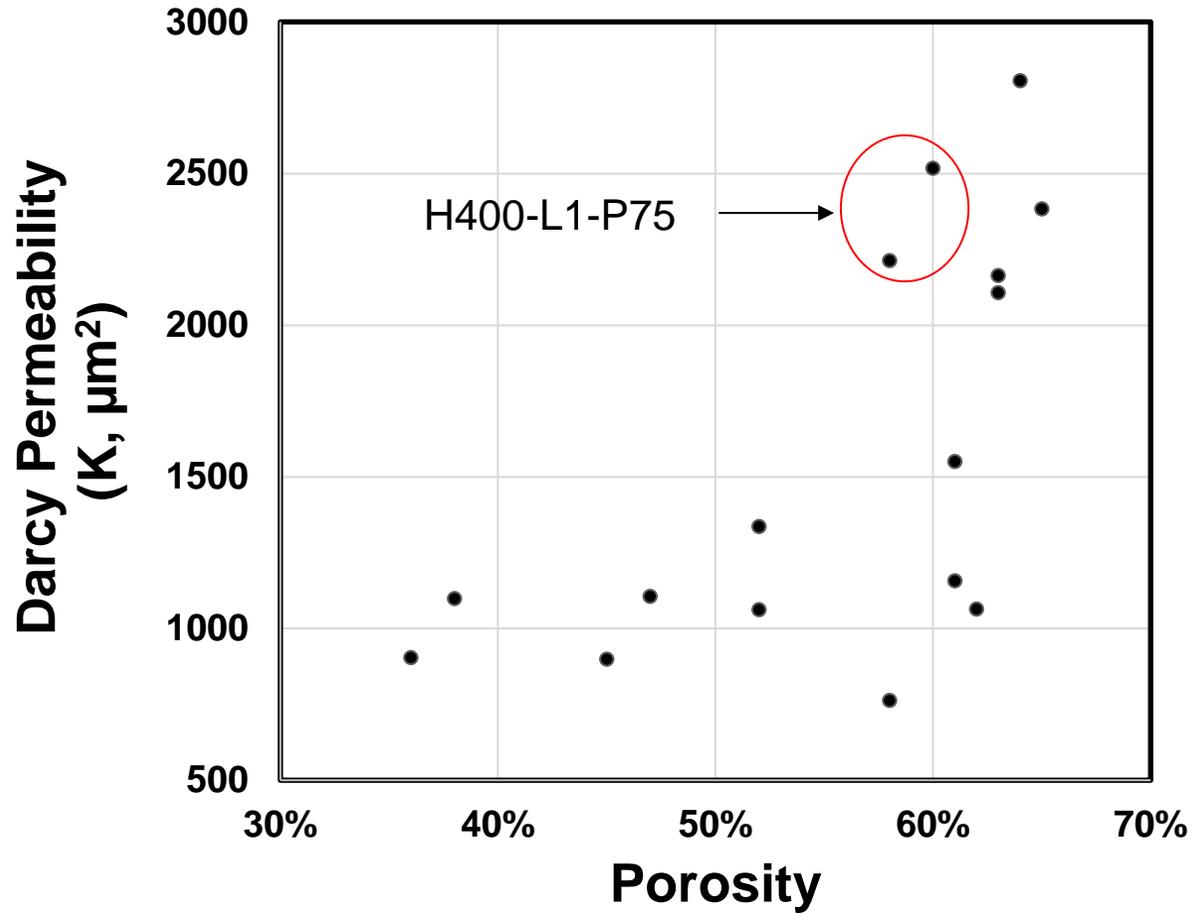
- RoR setup to evaluate the wick effective permeability (K) and average pore radius (r_{pore})
- Suspend wick from load cell over test fluid (acetone), add fluid until contact & measure transient uptake
- Best fit (K) and (r_{pore}) to analytic rate of rise model

$$\underbrace{\frac{\rho_L \epsilon}{2} \frac{d^2 h(t)}{dt^2}}_{\text{Inertial}} = \underbrace{\frac{2 \sigma_L \cos \theta \epsilon}{r_{pore}}}_{\text{Capillary Pressure}} - 2 \frac{\mu}{K} h(t) \frac{dh(t)}{dt} - (\rho_L g \epsilon) h(t)$$



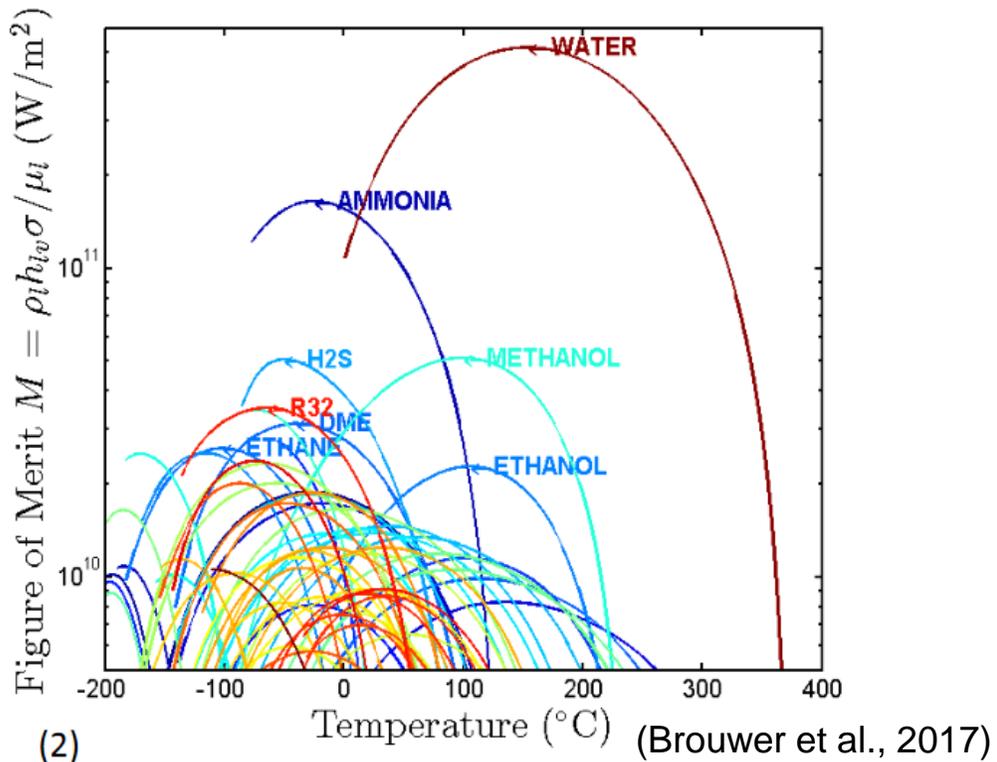
- Multiple tests with coupons (& duplicates) to assess K & r_{pore} uncertainties
- Best capillary performance with more open wick structures ($H = 400 \mu\text{m}$)

Specimen	Porosity (ϵ , %)	Permeability (K , μm^2)	Pore Radius (r_{pore} , μm)	K/r_{pore} (μm)
H275-L1-P75	37%	1170 ± 280	132 ± 25	8.8 ± 0.4
H275-L1-P60	58%	760	147	5.2
H275-L3-P75	46%	960 ± 120	148 ± 40	7.0 ± 2.3
H275-L6-P75	52%	1200 ± 190	133 ± 0	9.0 ± 1.4
H275-L6-P60	61%	1260 ± 240	153 ± 6	8.2 ± 1.3
H400-L1-P75	59%	2390 ± 150	170 ± 11	14.1 ± 0.4
H400-L3-P75	63%	2620 ± 780	187 ± 3	14.0 ± 3.9
H400-L6-P75	64%	2780 ± 360	204 ± 7	13.7 ± 2.1



Surface Treatment to Produce Hydrophilic Wicks

- Native NiTi surfaces are poorly wetting with water: optimal heat pipe fluid for thermal management temperature range
- Post-build: ultrasonic cleaning in organic solvents & DI water to remove contaminants and excess unsintered powder.
- After initial cleaning all coupons were found to be hydrophobic

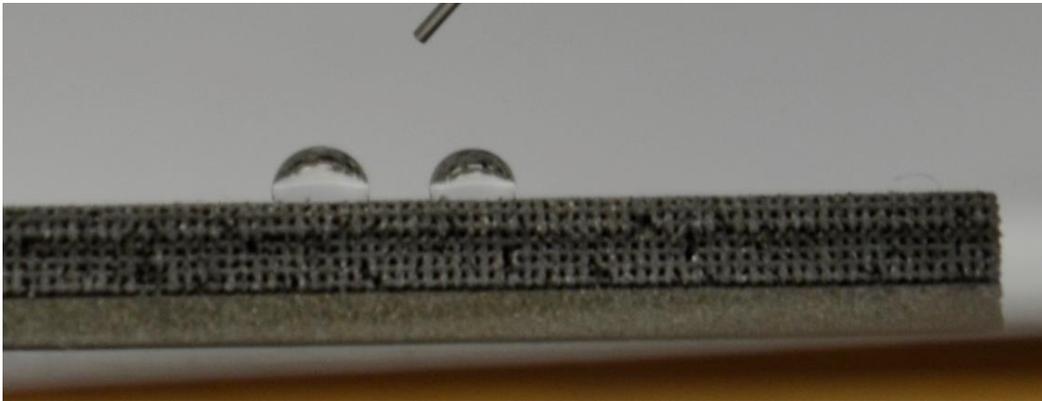


1. Ultrasonic cleaning with neutral pH aqueous detergent (Elma Lab Clean N10)
 2. Ultrasonic cleaning with mildly alkaline aqueous detergent (Elma Tec Clean A4)
 3. H_2O_2 treatment to grow TiO_2
 4. NaOH solution treatment to grow sodium titanates: $\text{Na}_x\text{Ti}_y\text{O}_z$
- Coupons were dried in vacuum (dry-scroll pump) after every treatment

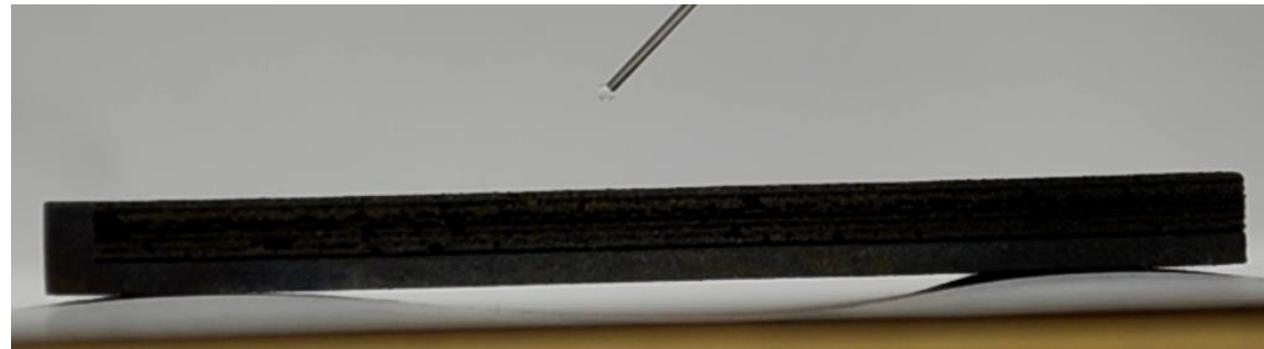
	EDS Surface Composition (wt%)				
	Ni	Ti	O	C	Na
Untreated Uncleaned	43.1	37.6	9.2	10.1	0
Ultrasonic Detergent Cleaned	44.8	39.1	7.7	8.3	0
H_2O_2 Treatment	40.2	33.7	18.4	7.7	0
NaOH Treatment	41.3	33.8	17.7	6.9	0.1

- Sessile droplet tests to assess wettability
- Acetone cleaning, H₂O₂ oxidation ineffective at improving wettability
- Detergent cleaning & NaOH treatment produced hydrophilic surfaces
- Wettability degrades in environment (NaOH treatment more durable)

Treatment	Results
Acetone cleaning	Did not improve wettability
Neutral pH detergent	Improved wettability, degraded after ~48 hrs
Alkaline detergent	
H ₂ O ₂ solution	Unchanged wettability, surface color change
NaOH solution	Improved wettability, persisted for over a week

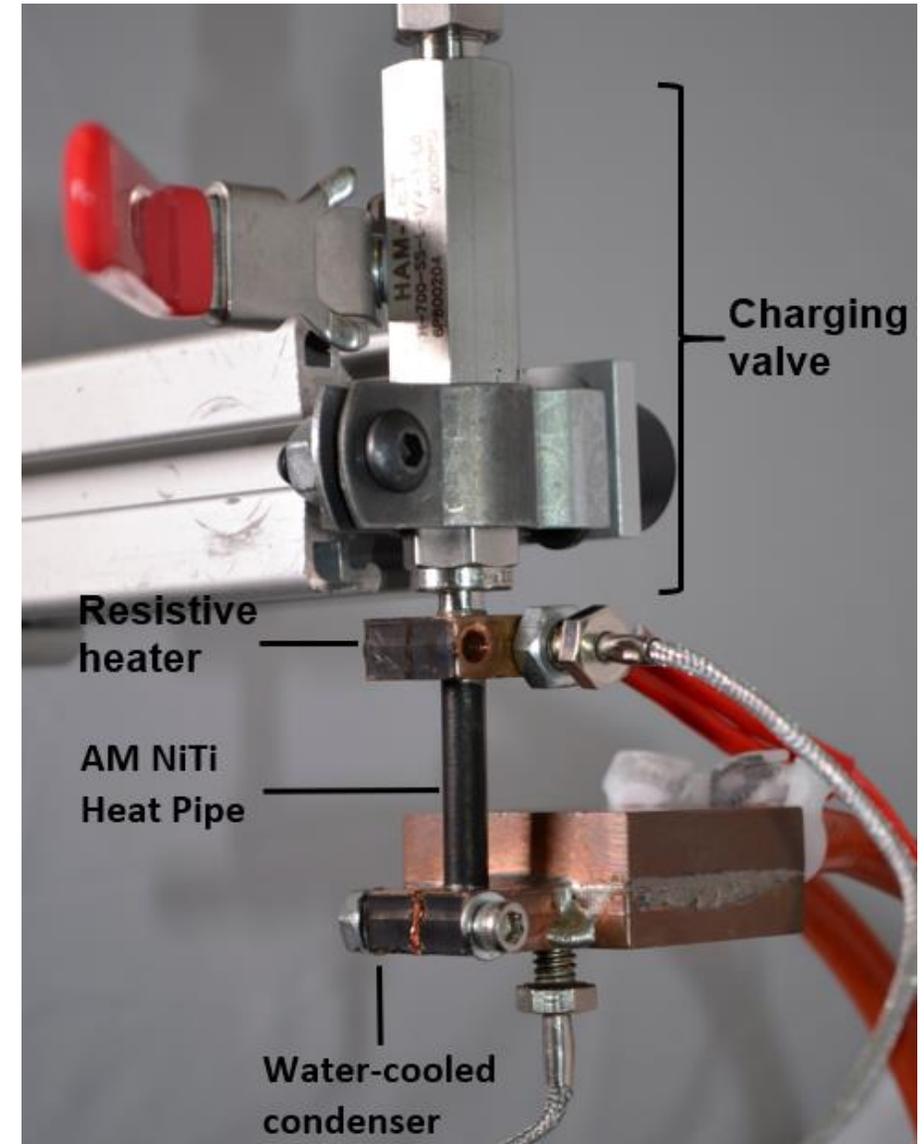


Native surface / acetone cleaning ($\theta \sim 90^\circ$)



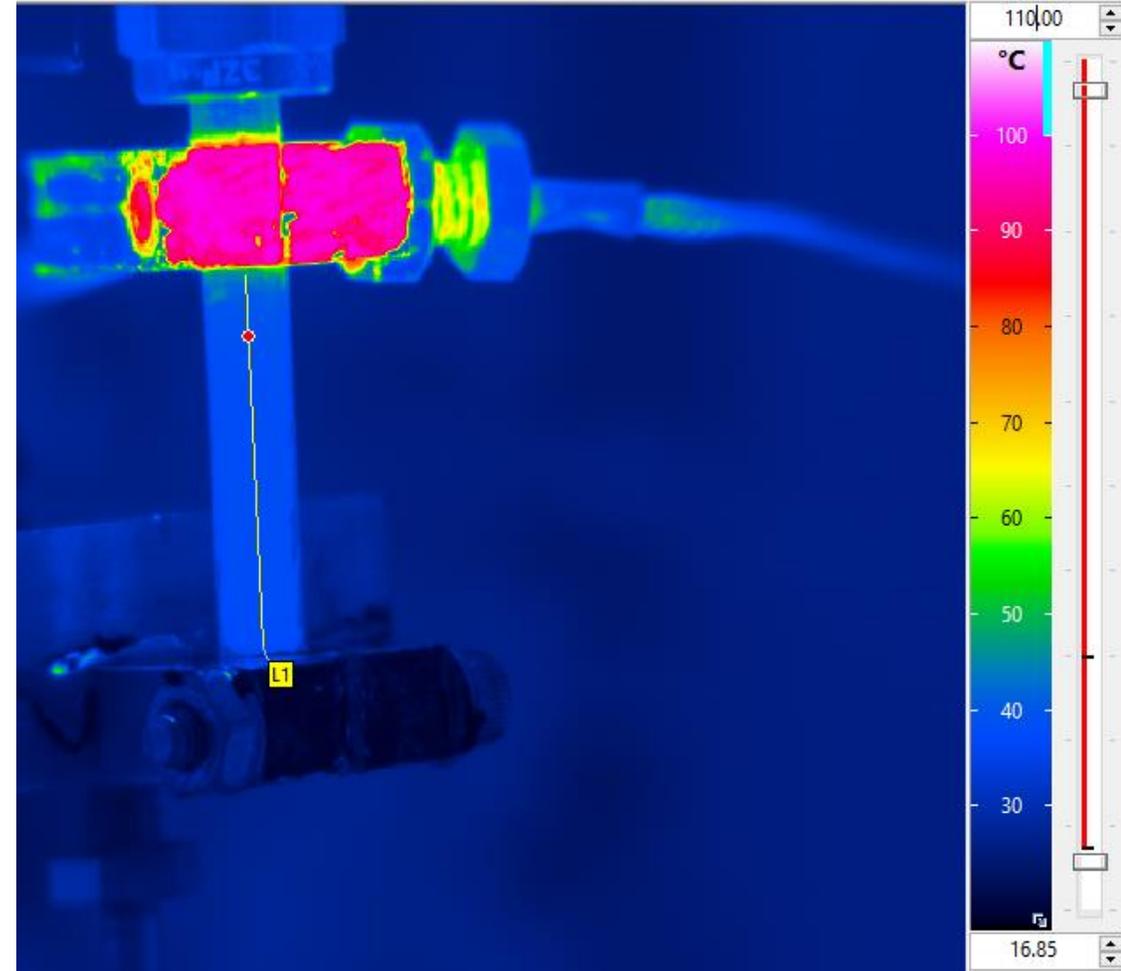
Heat Pipe Design and Thermal Test Setup

- AM NiTi heat pipe ($OD = 6 \text{ mm}$, $L = 60 \text{ mm}$)
- H400-L1-P75 internal wick layer ($900 \text{ }\mu\text{m}$ thick)
- Upper clamped copper heater block ($Q = 3.6 \text{ W}$, $T_H \sim 90^\circ\text{C}$)
- Lower clamped liquid cooled condenser ($T_C \sim 90^\circ\text{C}$)
- Adiabatic length: 26 mm
- Heat pipe cleaned with alkaline detergent, charged with $\sim 2 \text{ ml}$ of water, vacuum applied until nearly isothermal surface during operation



Heat Pipe Test Results

- For initial detergent-cleaned tests, uniform surface temperature degraded after 1 hr
 - (possible loss of surface wettability or minor leaks)
- Heat pipe then treated with NaOH, and testing restarted, sealing verified
- Second test: nearly isothermal heat pipe operation for 150 hr continuous run



Conclusions

- AM NiTi wick production and characterization:
 - Porous NiTi SMA wicks produced through LPBF
 - Build parameters varied to find baseline parameters for low defects
 - Acetone RoR tests to measure K , r_{pore} & downselect AM build parameters
 - Surface cleaning and treatment strategies evaluated to produce hydrophilic wicks
- Full AM NiTi wicking heat pipe produced and post-processed, characterized in thermal test setup with 150 hr continuous operation

Future work

- Improved heat pipe test specimens (additional instrumentation, improved thermal interfaces for characterization)
- Development of compliant shape-memory NiTi heat pipes
- Heat pipe integration into thermally self-deploying radiator panel prototype



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