TRACTION DRIVE INVERTER COOLING WITH SUBMERGED LIQUID JET IMPINGEMENT ON MICROFINNED ENHANCED SURFACES

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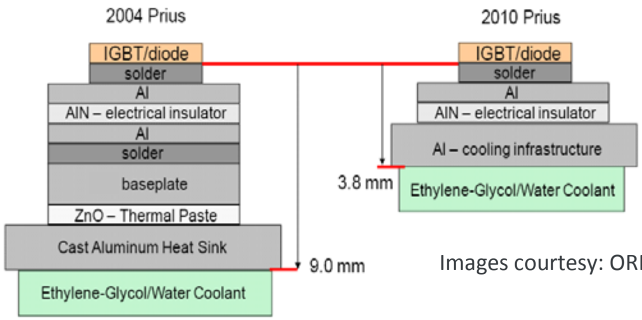
Thermal Management of Power Electronics

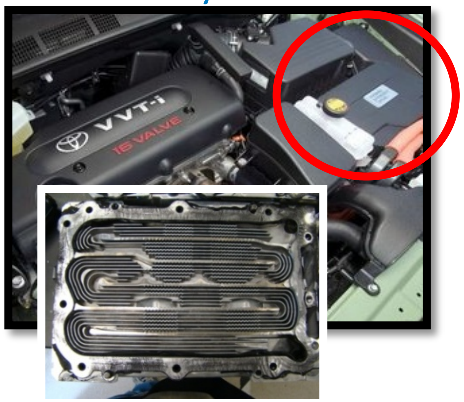
State of the Art

Prius 2004

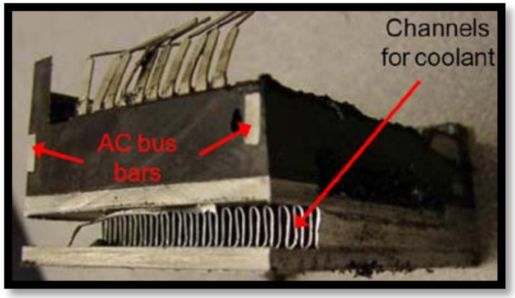


Images courtesy: ORNL

Camry 2007

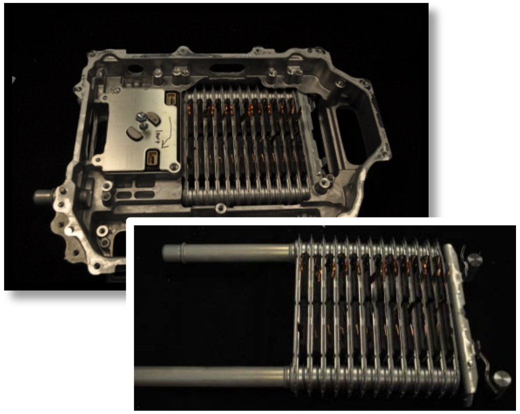


Prius 2010



Leaf 2011

Camry 2012



Impacts: Lower cost, volume, and weight

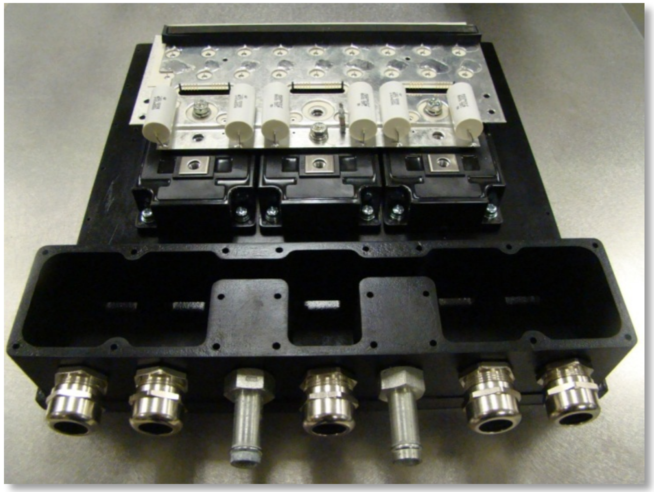
Enabling technology : Enhanced heat transfer/thermal management

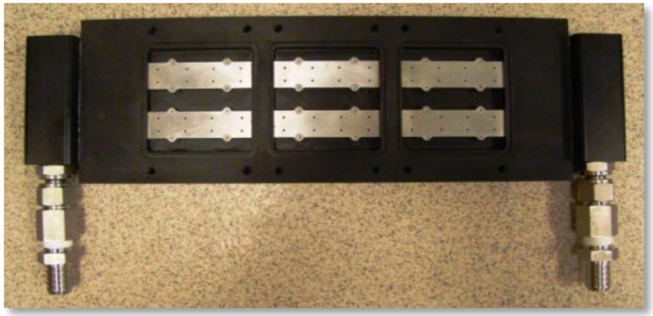
Research Objectives

Advanced thermal management technologies are critical to enabling higher power densities and meeting DOE targets for specific power, power density, and cost

Objectives

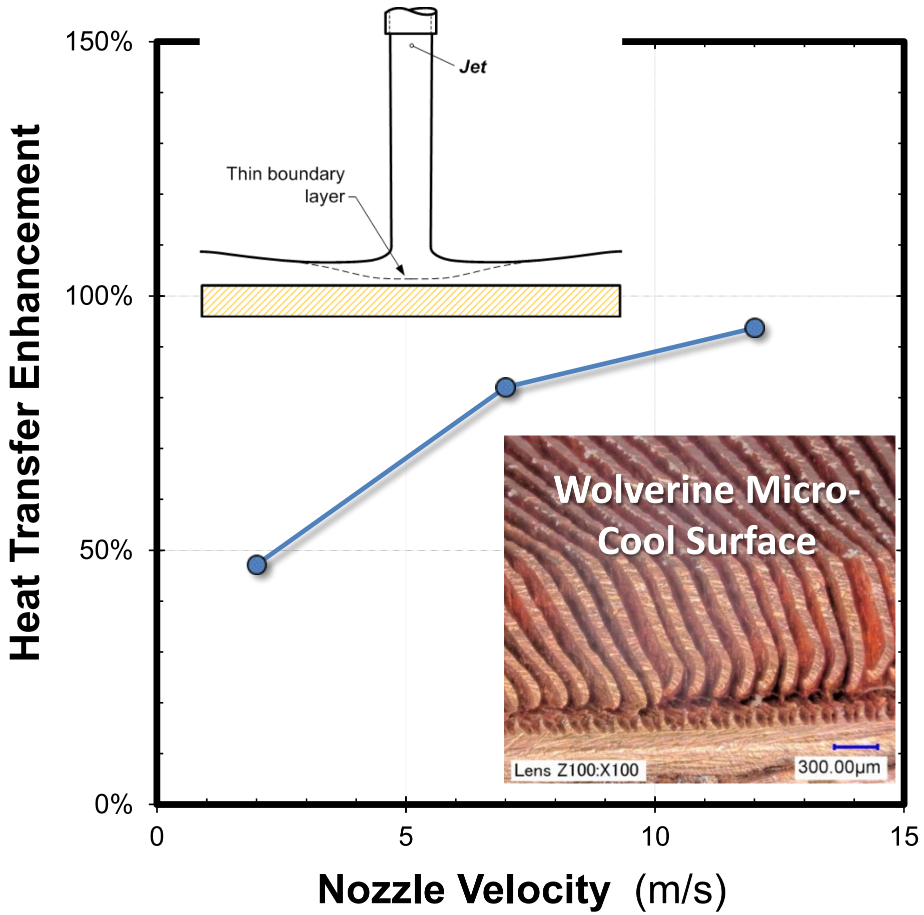
- Design and develop a light-weight, single-phase, liquid-cooled, automotive inverter-scale heat exchanger based on impinging jets and enhanced surfaces
- Enable use of high-temperature water-ethylene glycol (WEG) coolant for power electronics cooling

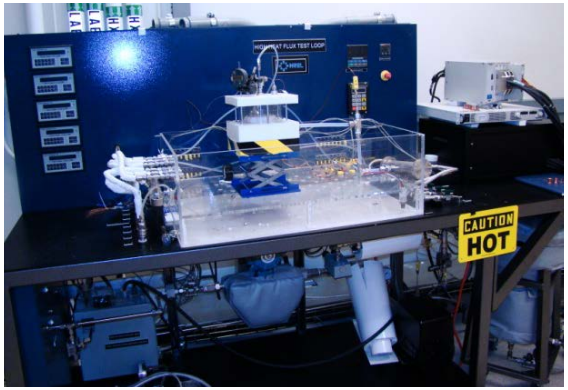


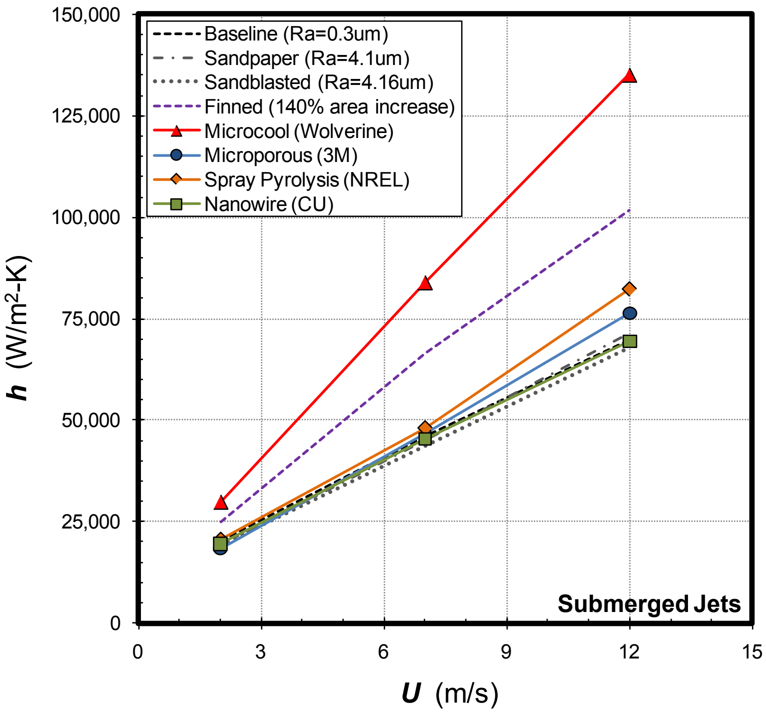


Jets on Enhanced Surfaces

Why use a microfinned enhanced surface?
Large increase in heat transfer coefficient



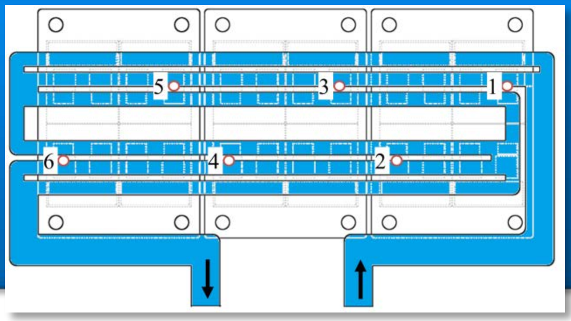




Three Configurations Were Tested

Baseline heat exchanger

Aluminum channel flow cold plate



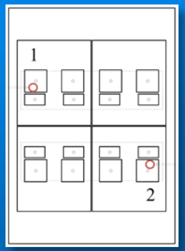
First version heat exchanger prototype

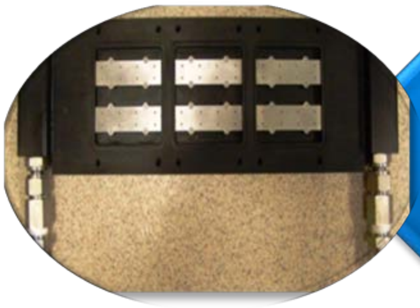
Plastic manifold (lower weight)

Same flow path as baseline

Submerged jet impingement on plain surfaces

Submerged jet impingement on microfinned enhanced surfaces





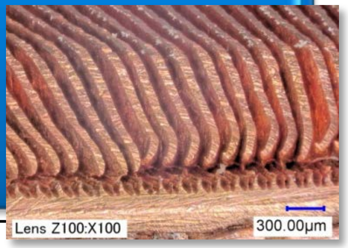
Second version heat exchanger prototype

Plastic manifold (lower weight)

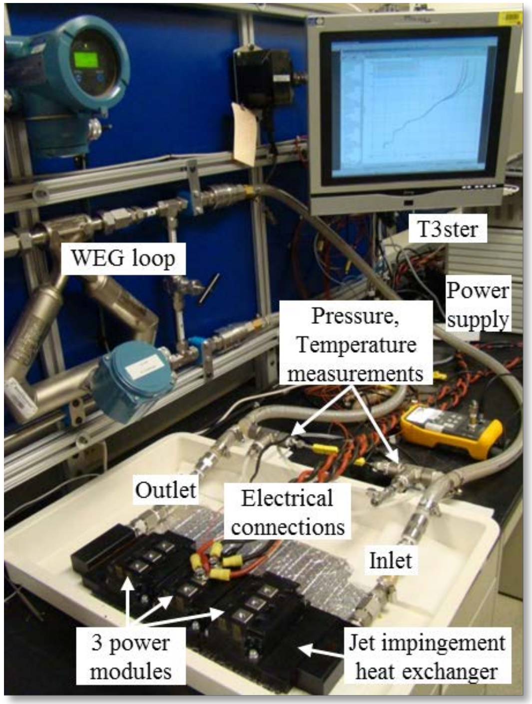
Simplified flow path to reduce pressure loss

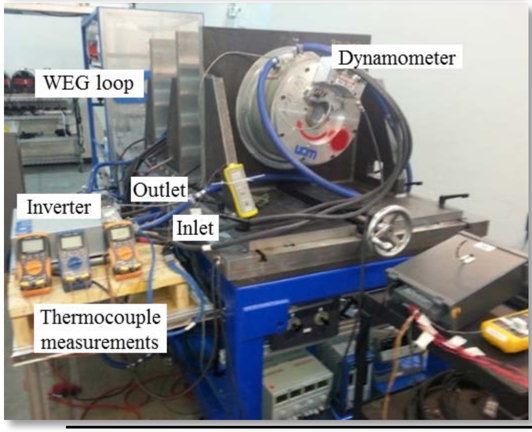
Submerged jet impingement on plain surfaces

Submerged jet impingement on microfinned enhanced surfaces



Experimentation and Modeling Approach





Experiments (low power)

- 50%–50% WEG at 70°C; 5, 8, 10 L/min
- Power 4 diodes (105 W heat)
- Metrics: $R_{th,j\text{-}l}$ using T3ster, ΔP

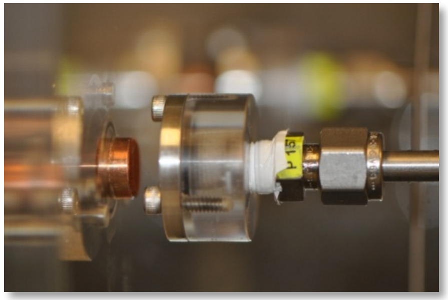
Modeling (CFD)

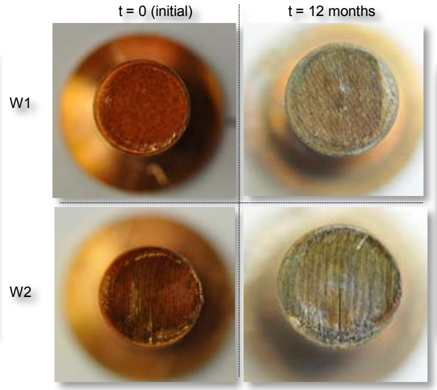
- Validate models at 105-W heat (50%–50% WEG at 70°C; 5, 8, 10 L/min)
- Model 2.5 kW heat (24 IGBTs, 24 diodes)
- Metrics: $R_{th,j\text{-}l}$, ΔP

Experiments (inverter level)

- 40%–60% WEG at 30°C, 10 L/min
- 40, 60, 80, 100 kW Electrical Power
- Metrics: ΔT between probes and coolant

Reliability Characterization

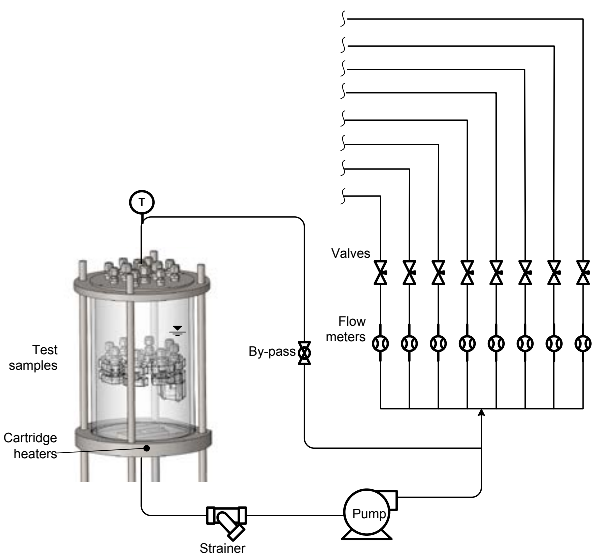


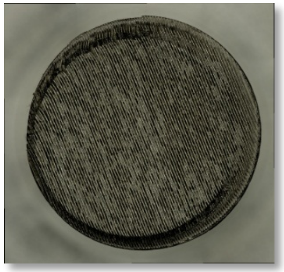


12-month testing of free WEG jet impinging on microfinned surface

- 35^{o}C WEG
- 2 m/s jet, 12 m/s jet

previous work



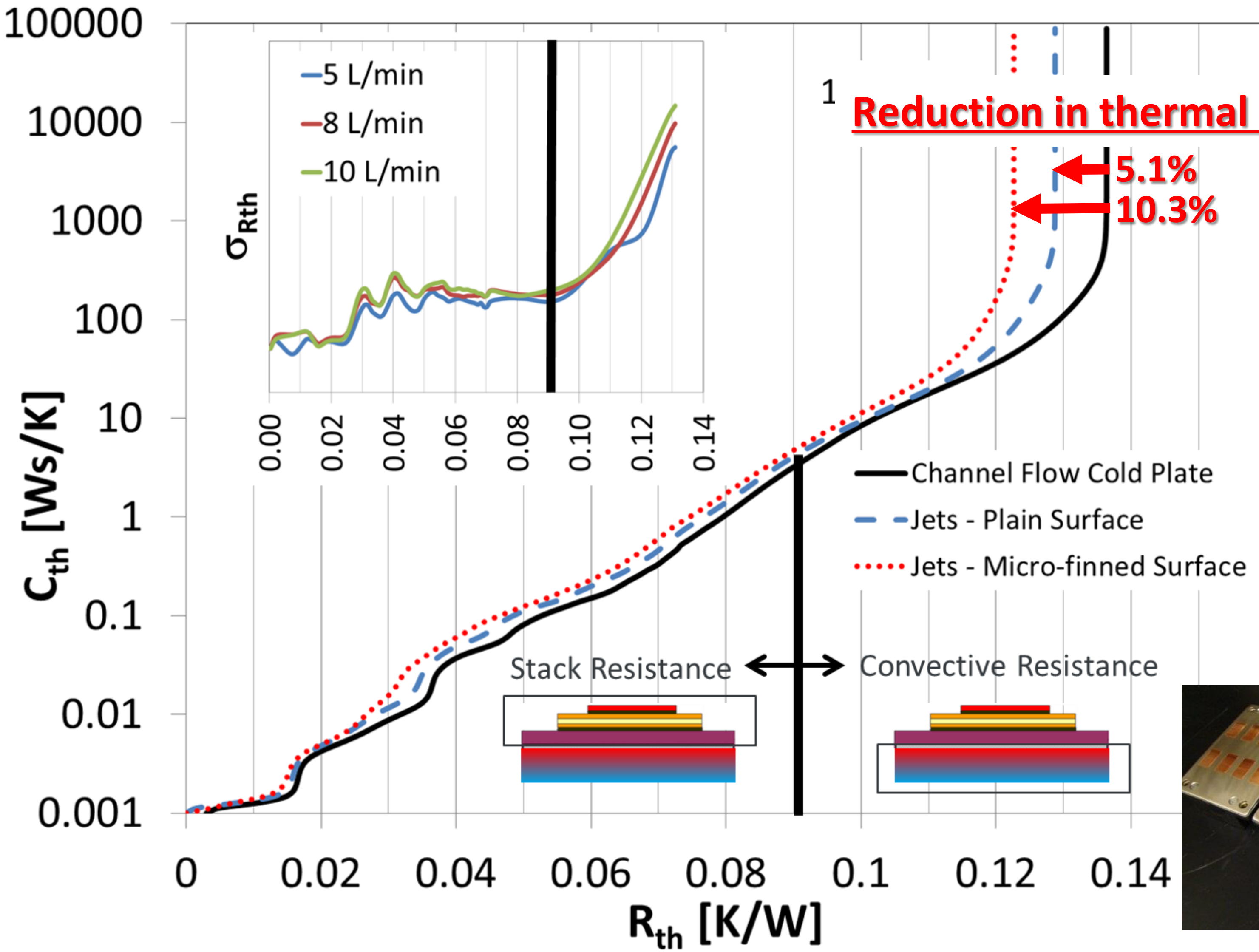


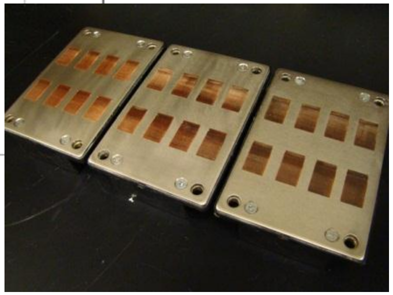
Long-term testing of **submerged** WEG jet on 2 microfinned surfaces (**nickel-plated**), 3 DBC substrates, and 3 DBA substrates

- **65^{o}C automotive-grade** WEG
- **5 m/s** jet (1.3-mm nozzle, 3-mm jet distance)

DBA = direct-bond-aluminum
DBC = direct-bond-copper

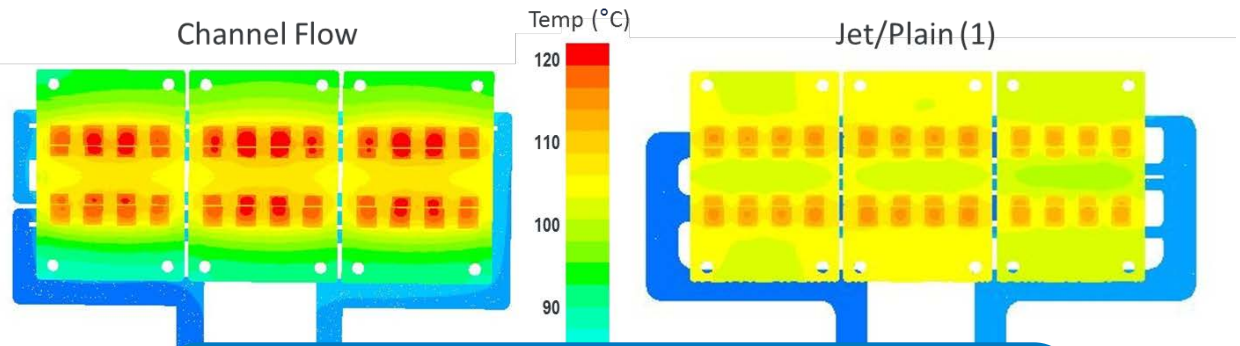
Thermal Resistance Map from T3ster (105-W experiment)





Performance at 2.5 kW Heat Dissipation (model)

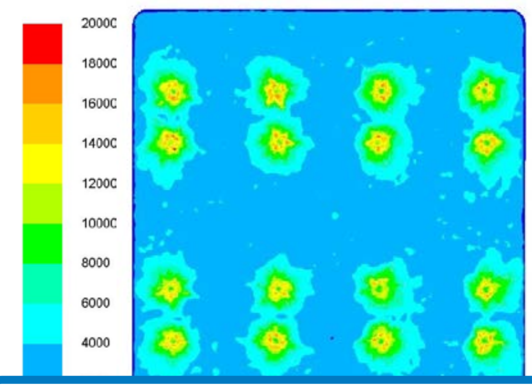
- **9%** (plain) to **32%** (microfinned) reduction in **thermal resistance**
- **5%** (plain) to **40%** (microfinned) increase in **COP** ($1/R_{th}[\Delta P \cdot V]$)
- **29%** (plain) to **55%** (microfinned) increase in **specific power** (kW/kg)
- **6%** (plain) to **28%** (microfinned) increase in **power density** (kW/L)
- Values from modeling represent idealized limit due to external adiabatic boundaries driving heat into the coolant



Temperature reduction (jets to baseline):

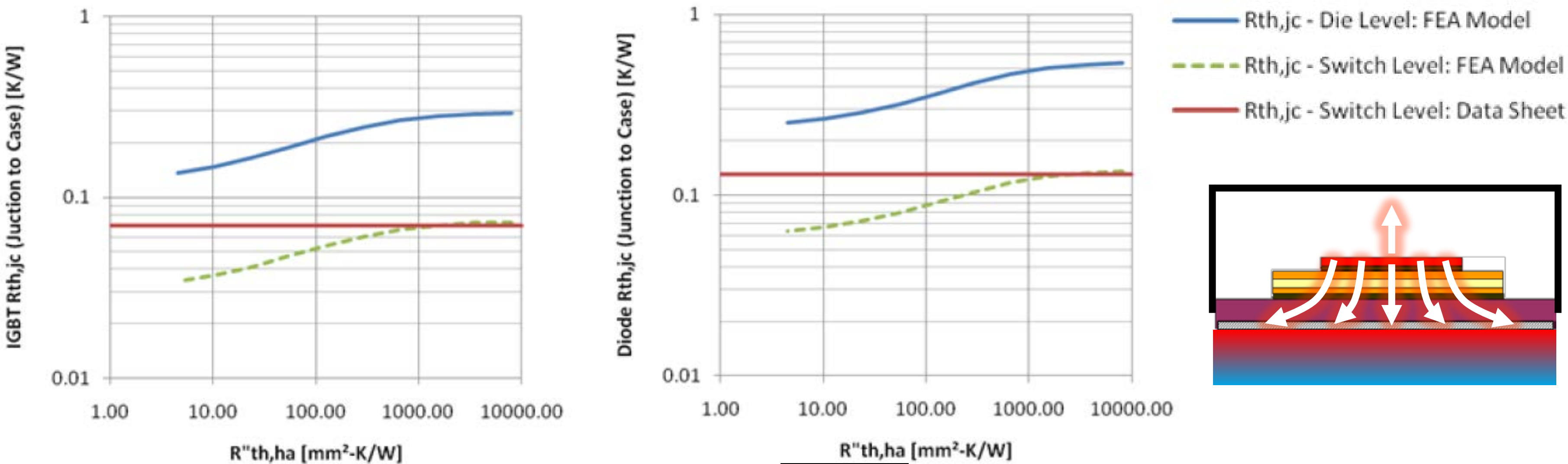
- **5°C – 6°C** (plain)
- **15°C – 16°C** (microfinned)

Heat Transfer Coefficient (W/m²-K)



Jets provide **localized cooling** on devices

Passive Stack Resistance Dependence



Decreased Convective Cooling Resistance

Channel Flow Cold Plate

Jets on Plain Surface

Jets on Enhanced Surface

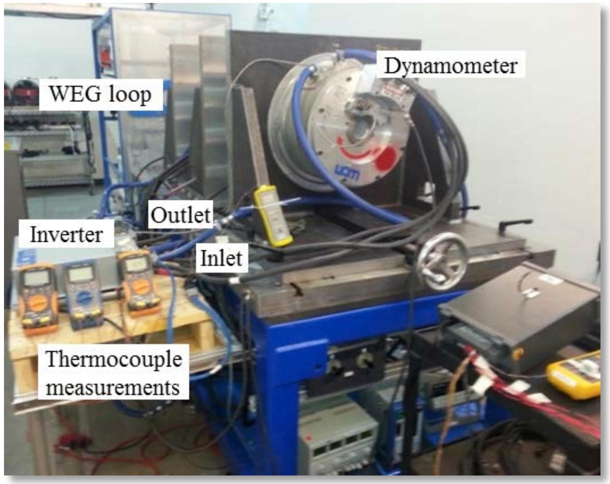
Decreased $R_{th,j\text{-}l}$

4 diodes (105 W)

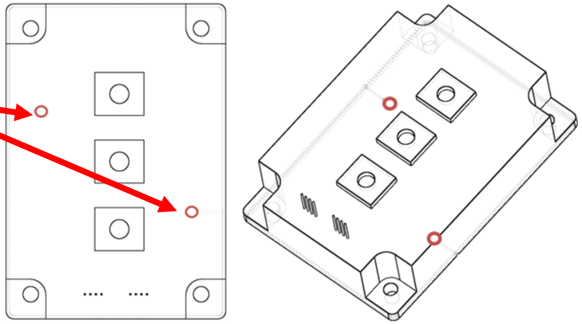
24 IGBTs / 24 diodes (2520 W)

Increased Heat Flux and Distribution

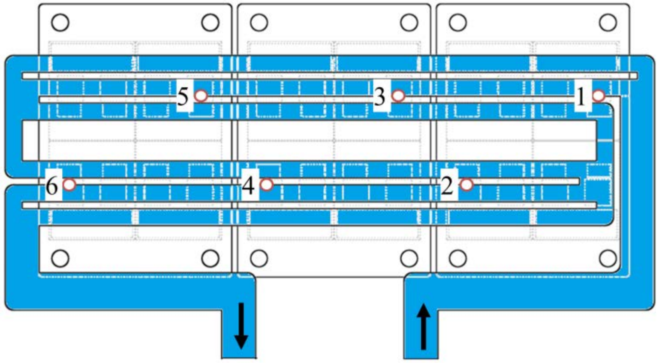
Inverter Testing on Dynamometer



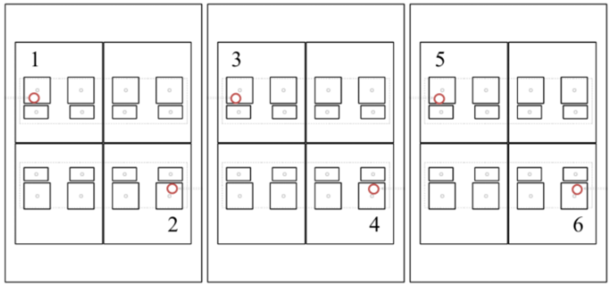
Thermocouple locations
(middle of copper baseplate)



Channel Flow



Jet Impingement



$\Delta T = T_{TC,avg} - T_{coolant,\ avg}$

40, 60, 80, 100 kW Electrical Power

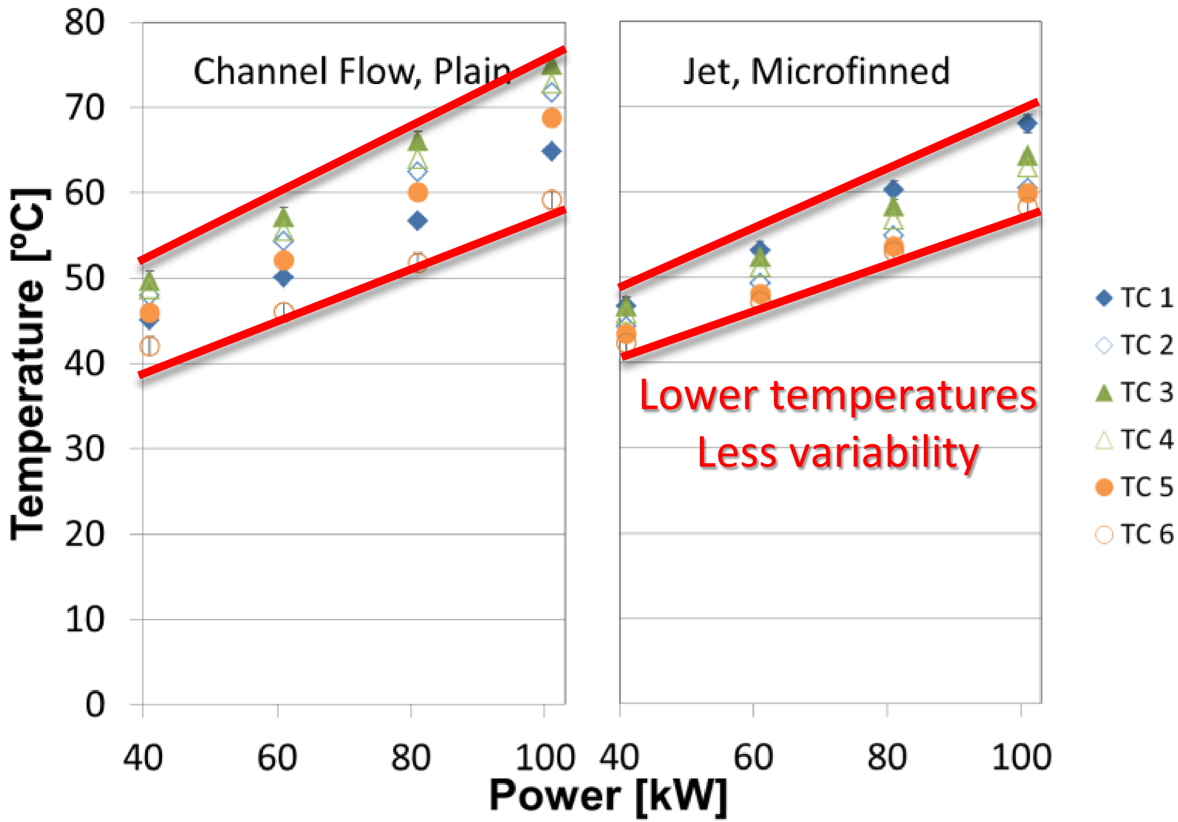
0.9, 1.3, 1.6, 2.2 kW heat dissipation (model estimate)

0.9, 1.1, 1.6, 1.9 kW heat dissipation (simple energy balance)

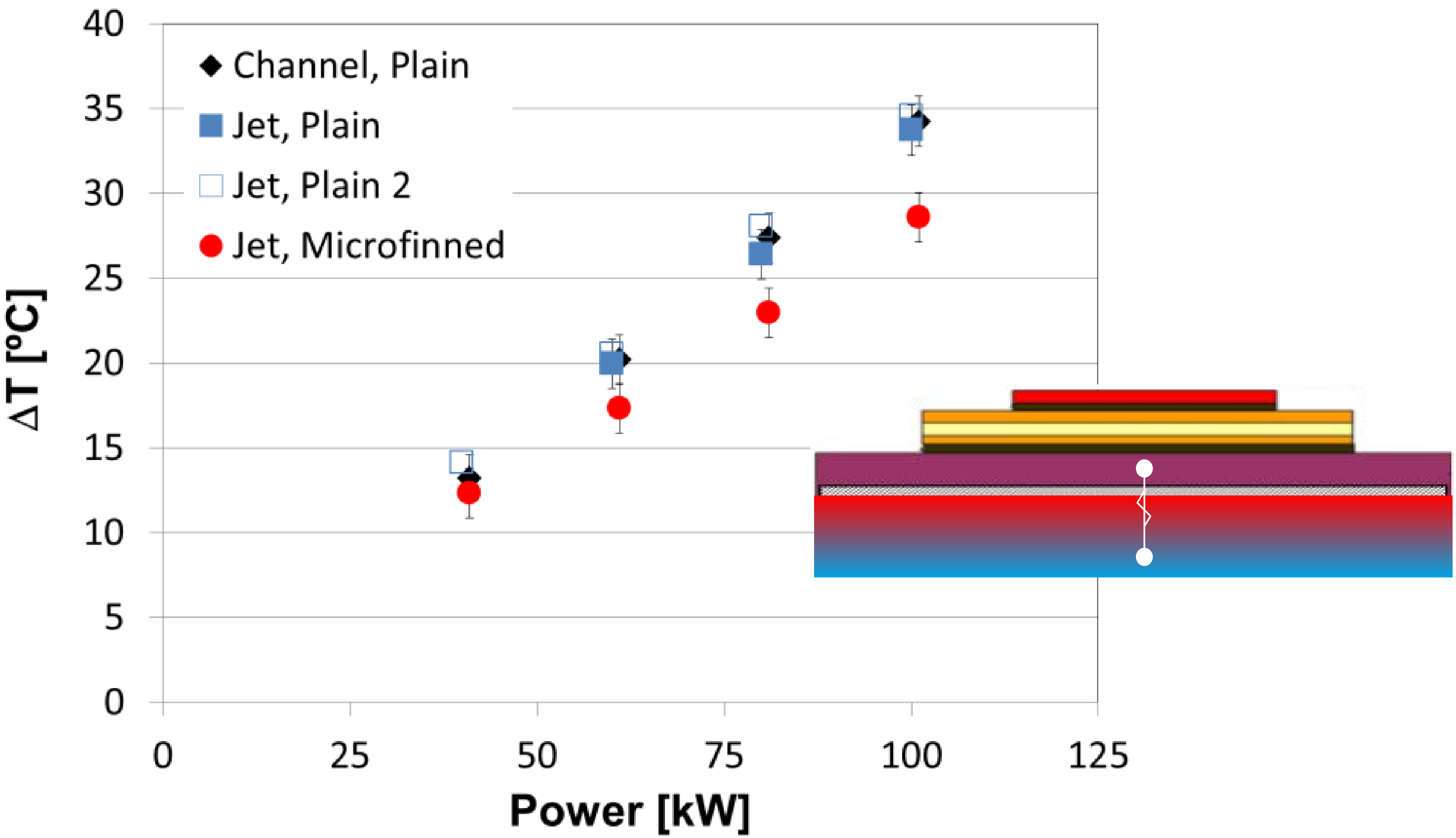
Thermocouple Temperatures

Average thermocouple temperature [°C]

Power [kW]	40	60	80	100
Channel, Plain	46.6	52.5	60.2	68.7
Jet, Plain	N/A	53.5	60.0	67.6
Jet, Microfinned	44.8	50.2	56.1	62.3

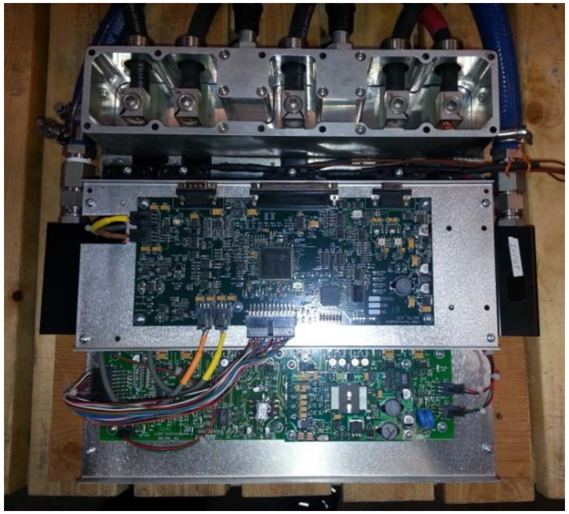


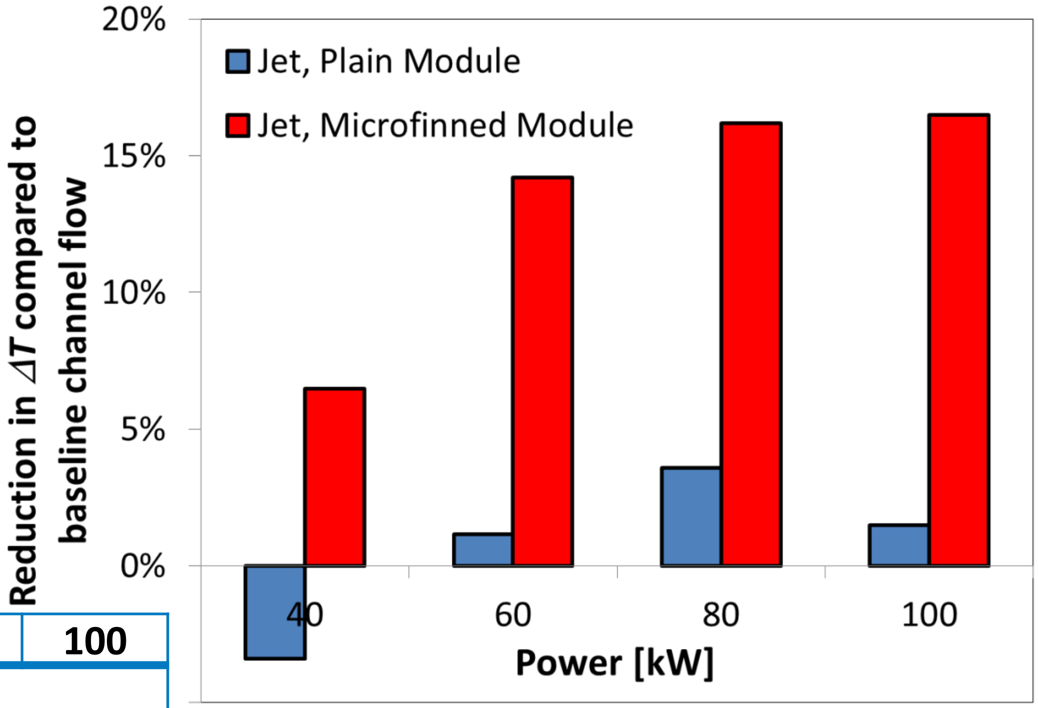
Temperature Difference (Baseplate to Coolant)



ΔT proportional to thermal resistance ($R_{th} = \Delta T/Q$)

Full Inverter Thermal Performance





Improvement over baseline

Power [kW]	40	60	80	100
Coefficient of Performance				
Jet, Plain	-28.5%	-0.8%	1.7%	-0.5%
Jet, Microfinned	4.8%	14.2%	17.0%	**17.4%**
Specific Power				
Jet, Plain	15.8%	20.1%	22.5%	21.1%
Jet, Microfinned	26.4%	33.6%	35.6%	**35.9%**
Power Density				
Jet, Plain	-4.5%	-0.9%	1.1%	-0.1%
Jet, Microfinned	4.3%	10.2%	11.9%	**12.1%**

- **Jets with plain surfaces**: little improvement
- **Jets with microfinned enhanced surfaces**: considerable improvement

Inverter-Scale Experimental Thermal Performance Summary

- Full inverter testing (40 – 100 kW) with jets and microfinned surfaces:

17% **Reduction in thermal resistance**

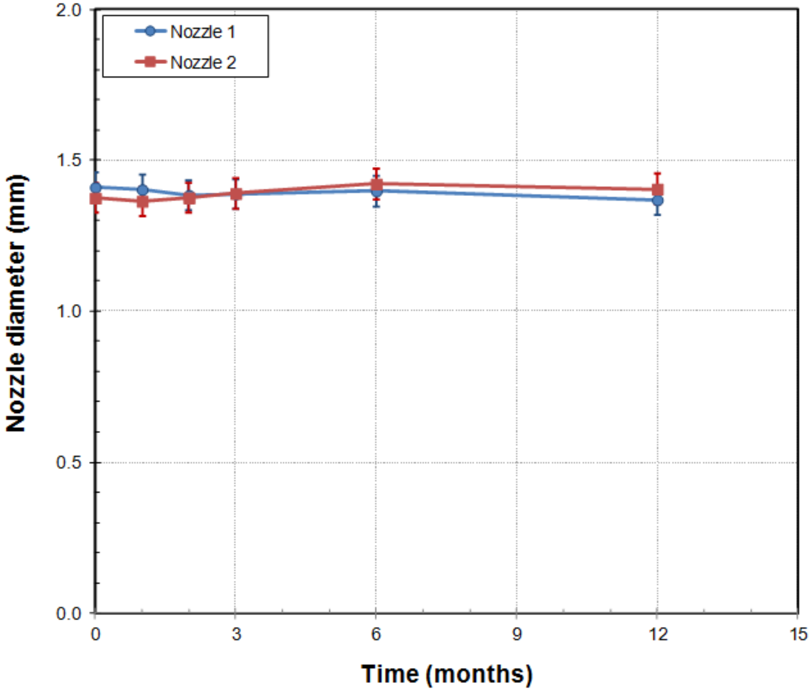
17% **Increase in Coefficient of Performance**

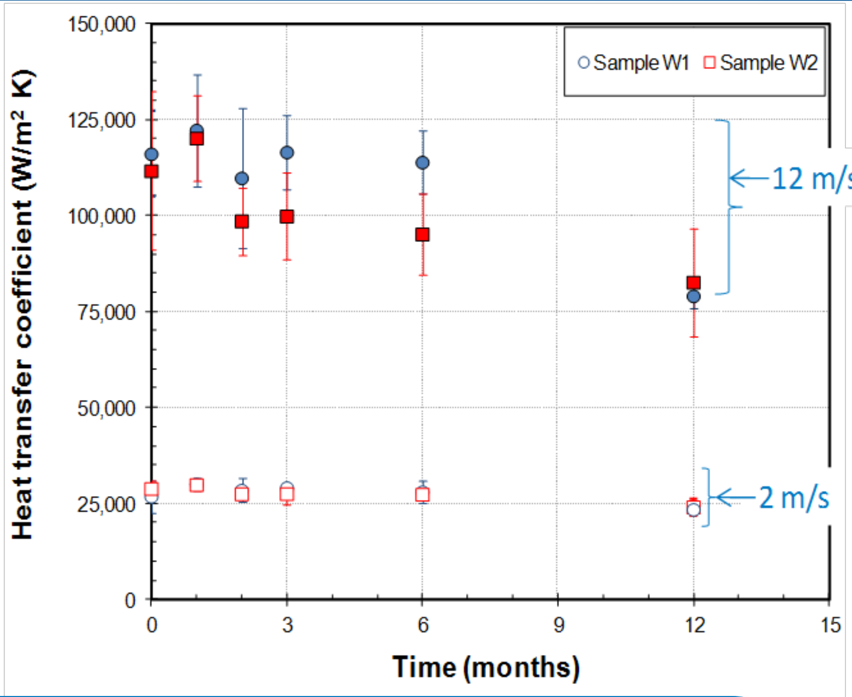
12% **Increase in power density**

36% **Increase in specific power** (reduction in heat exchanger weight by ~ 3 kg) compared to channel flow

- Jets with microfinned surfaces provide **localized cooling** and **improved temperature uniformity** (5^0C less spread) than channel flow case
- Jet reliability is good

Jet and Surface Reliability (First Round Testing)

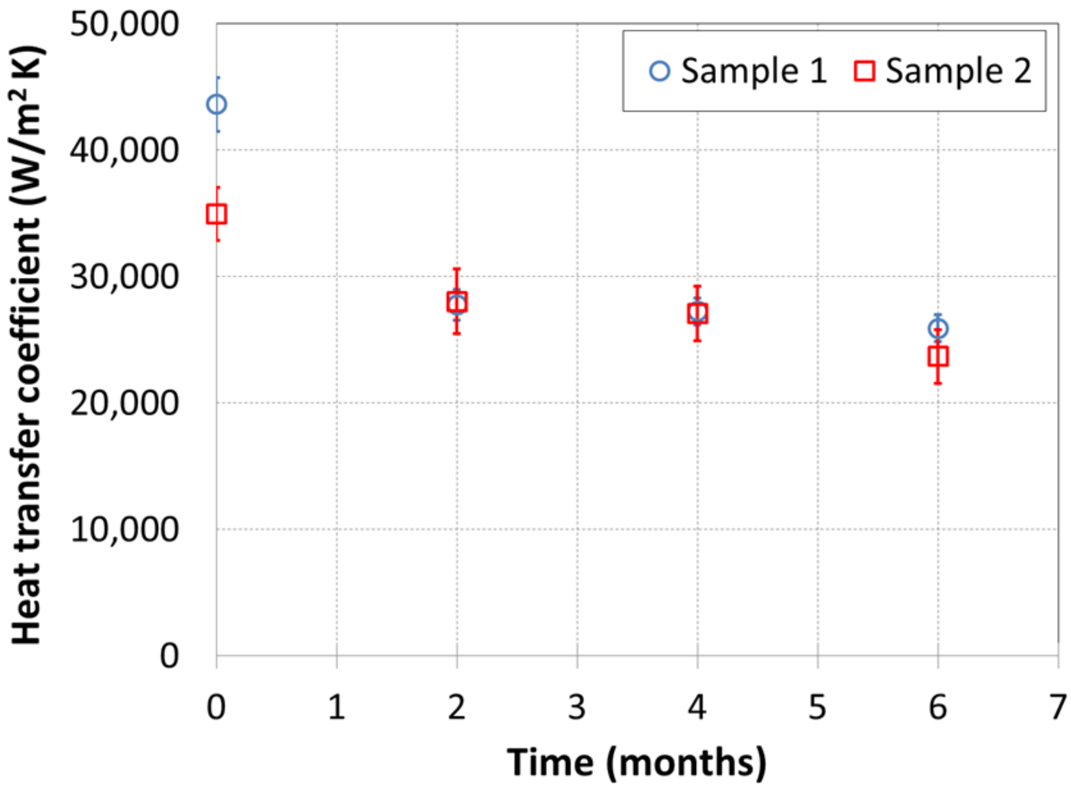


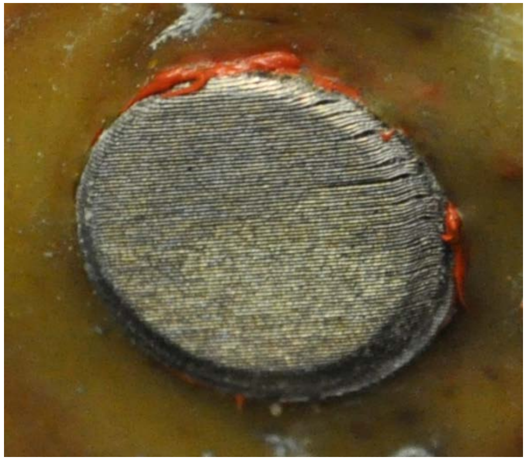


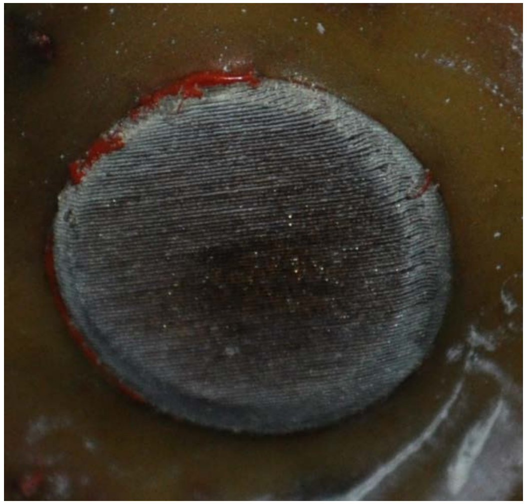
- Negligible change in jet nozzle diameter after 12 months of nearly continuous impingement
- Degradation in thermal performance of surfaces due to oxidation (no coating, no corrosion inhibitors)

G. Moreno, S. Narumanchi and T. Venson, "Micro-structured surfaces for single-phase jet impingement heat transfer enhancement," *ASME Journal of Thermal Science and Engineering Applications,* vol. 5, pp. 1-9, 2013.

Surface Reliability (Second Round Testing)







- Initial break-in period
- Some degradation on surfaces
- Corrosion inhibitors appear to coat surfaces

Thermal Performance Summary (Compared to Baseline Channel Flow)

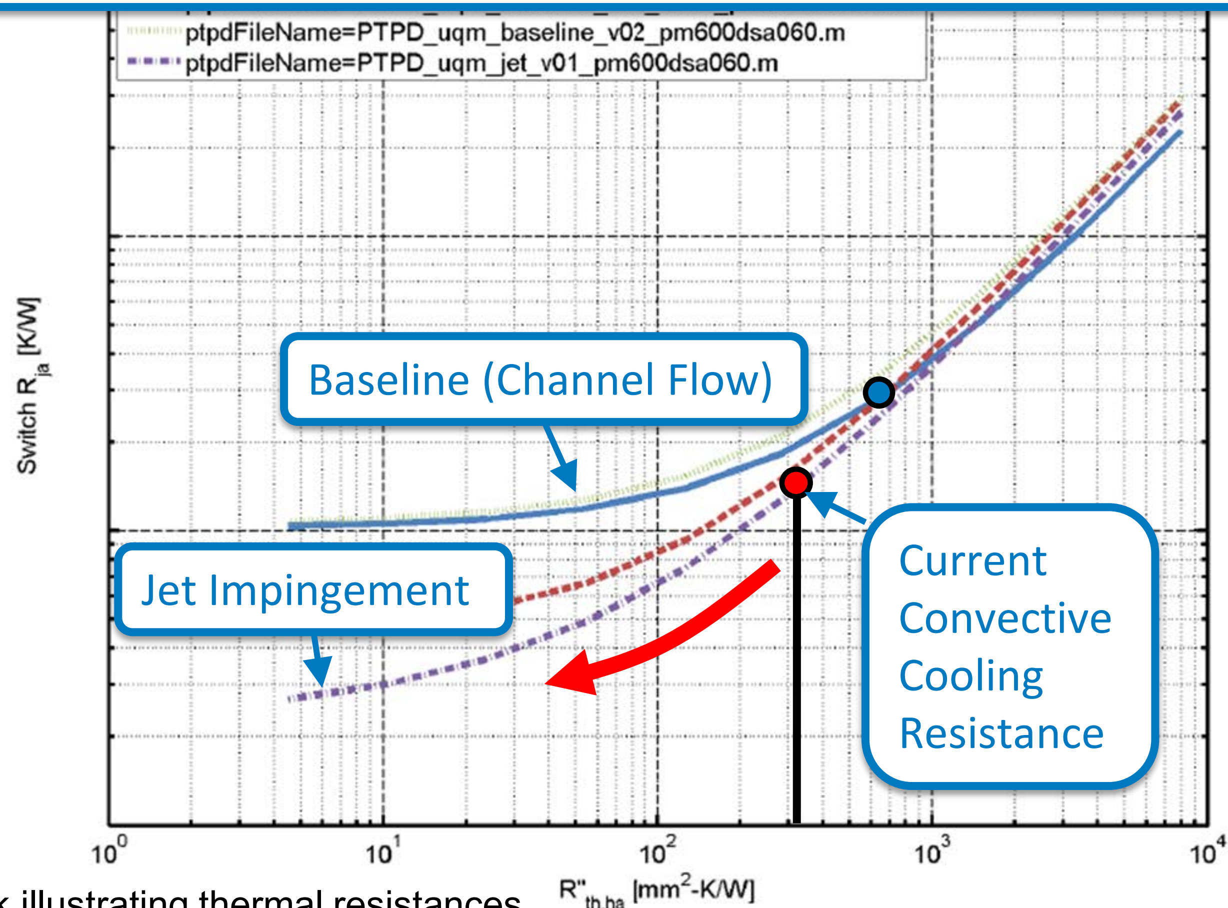
Jet, Plain	Thermal Resistance	COP	Specific Power	Power Density
105 W Experiment (70°C 50%-50% WEG)	5%	0%		
2.5 kW Model (70°C 50%-50% WEG)	9%	5%	29%	6%
~2 kW Experiment (30°C 40%-60% WEG)	2%	0%	21%	0%

Jet, Microfinned	Thermal Resistance	COP	Specific Power	Power Density
105 W Experiment (70°C 50%-50% WEG)	10%	9%		
2.5 kW Model (70°C 50%-50% WEG)	32%	40%	55%	28%
~2 kW Experiment (30°C 40%-60% WEG)	17%	17%	36%	12%

- Jets provide localized cooling on devices
- Enhanced surfaces increase jet effectiveness

Potential for Further Jet Optimization

More aggressive jet cooling strategies can further lower resistance (need to be balanced to not overly increase pressure drop/fluid power)



Previous work illustrating thermal resistances

Conclusions

- Light-weighting with plastics possible with jet impingement because thermal path does not require high conductivity
- Jets provide localized increase in heat transfer (where you need it)
- Enhanced surfaces increase jet heat transfer effectiveness (greater surface area and flow dynamics)