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

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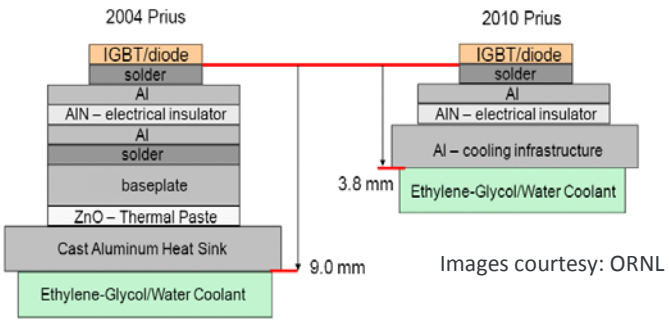
# Thermal Management of Power Electronics

Prius 2004

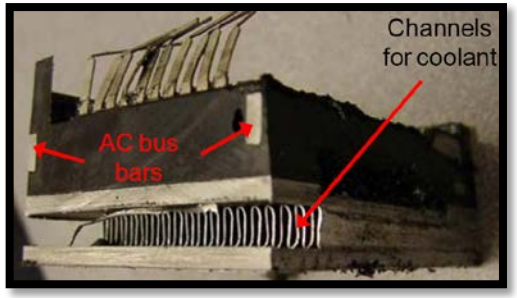
## State of the Art




Images courtesy: ORNL

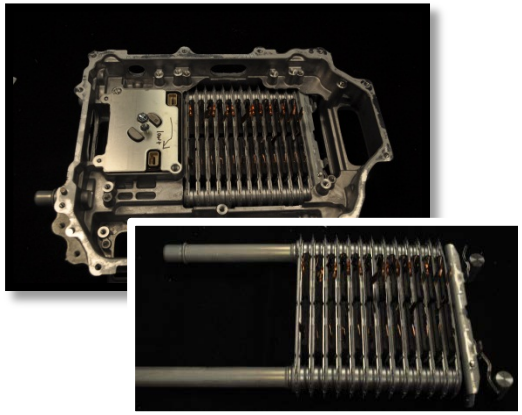
Camry 2007

Prius 2010




Leaf 2011

Camry 2012



**Impacts: Lower cost, volume, and weight**

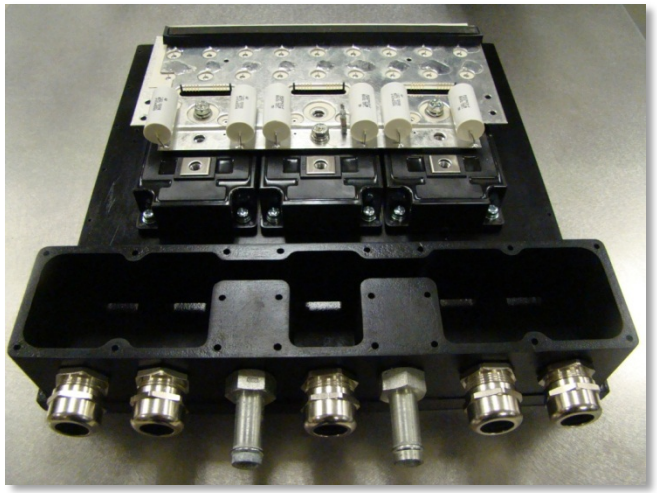
**Enabling technology : Enhanced heat transfer/thermal management**

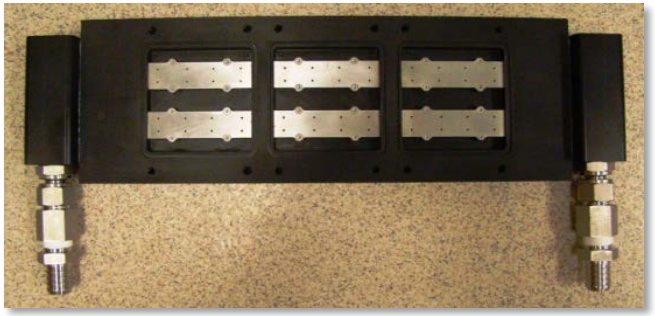
# Research Objectives

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

## Objectives

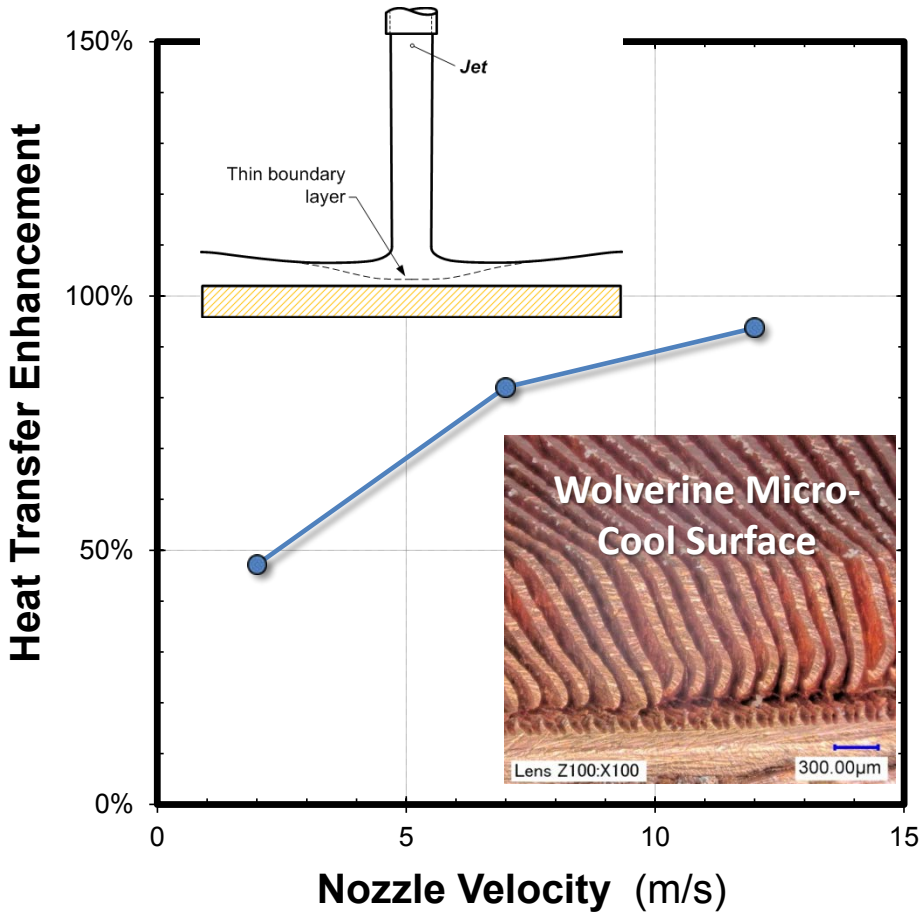
- Design and develop a light-weight, single-phase, liquid-cooled, automotive inverter-scale heat exchanger based on impinging jets and enhanced surfaces
- Enable use of high-temperature water-ethylene glycol (WEG) coolant for power electronics cooling

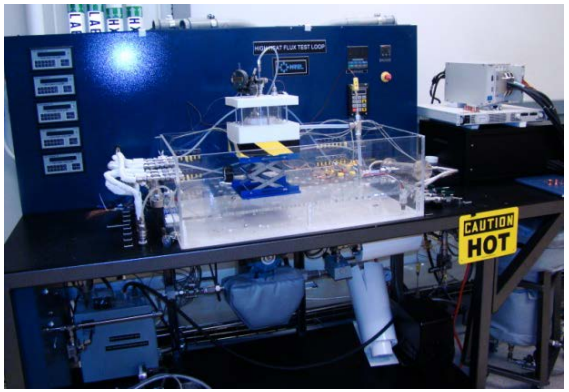


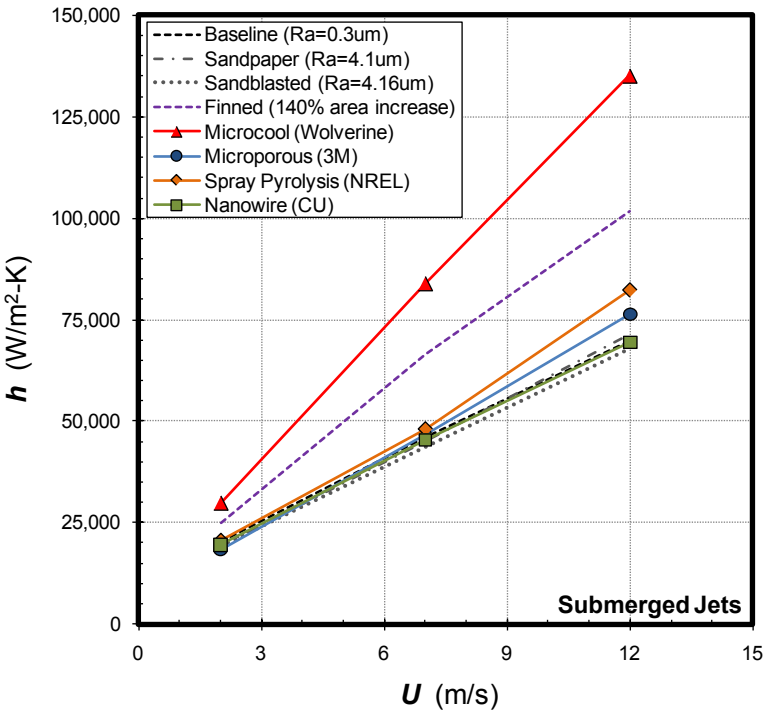


# Jets on Enhanced Surfaces

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



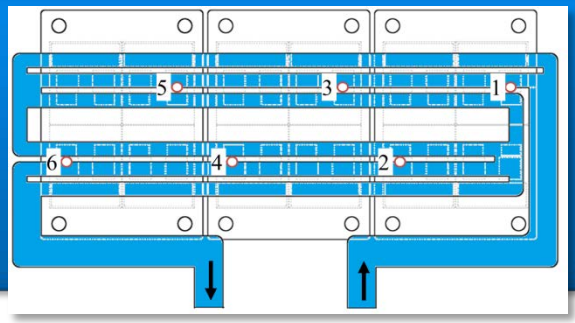



# Three Configurations Were Tested

## Baseline heat exchanger

Aluminum channel flow cold plate



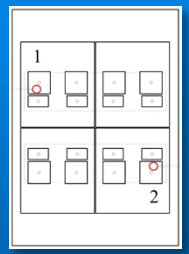
## First version heat exchanger prototype

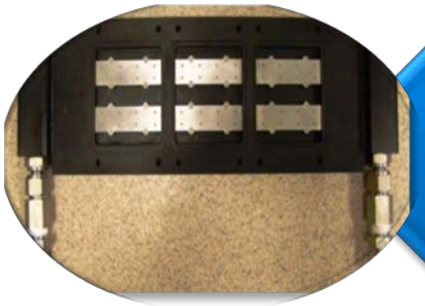
**Plastic manifold (lower weight)**

Same flow path as baseline

**Submerged jet impingement on plain surfaces**

**Submerged jet impingement on microfinned enhanced surfaces**



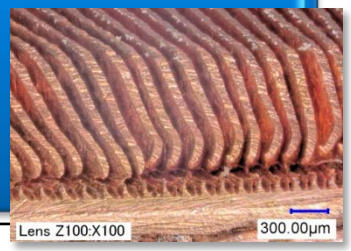
## Second version heat exchanger prototype

Plastic manifold (lower weight)

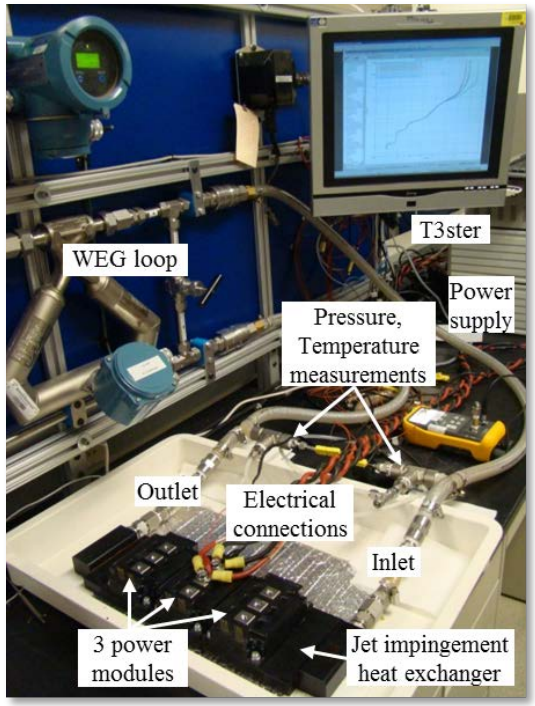
**Simplified flow path to reduce pressure loss**

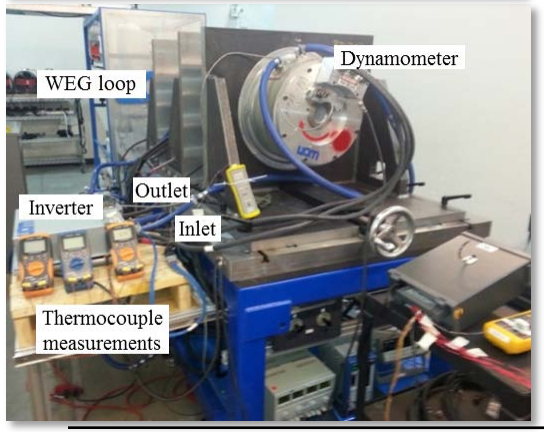
Submerged jet impingement on plain surfaces

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, $\Delta P$

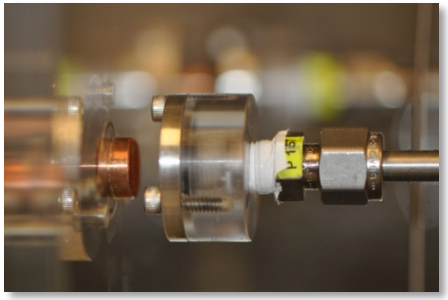
**Modeling (CFD)**

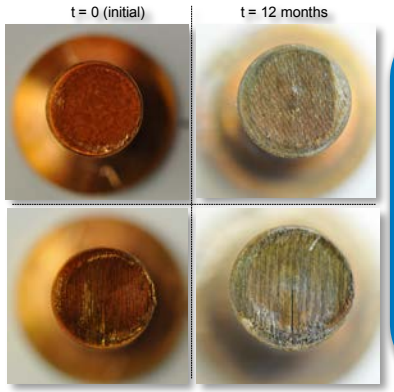
- Validate models at 105-W heat (50%–50% WEG at 70°C; 5, 8, 10 L/min)
- Model 2.5 kW heat (24 IGBTs, 24 diodes)
- Metrics: $R_{th,j\text{-}l}$, $\Delta P$

**Experiments (inverter level)**

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

# Reliability Characterization

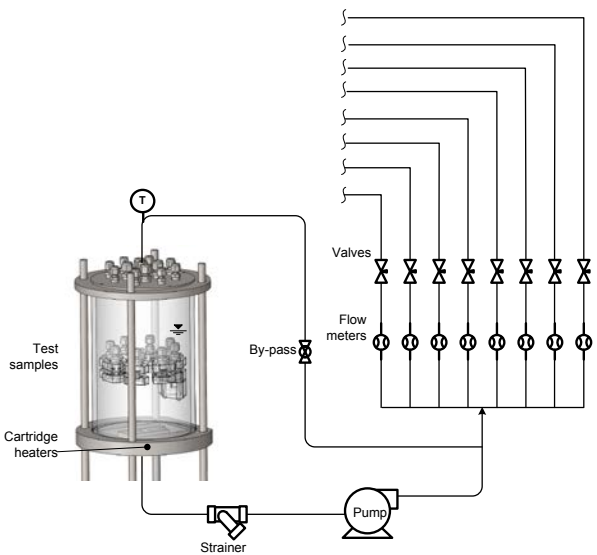


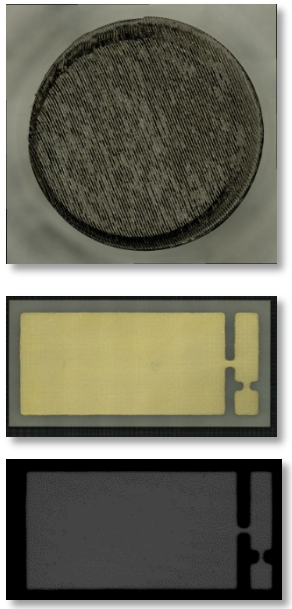



12-month testing of free WEG jet impinging on microfinned surface

- 35°C WEG
- 2 m/s jet, 12 m/s jet

previous work



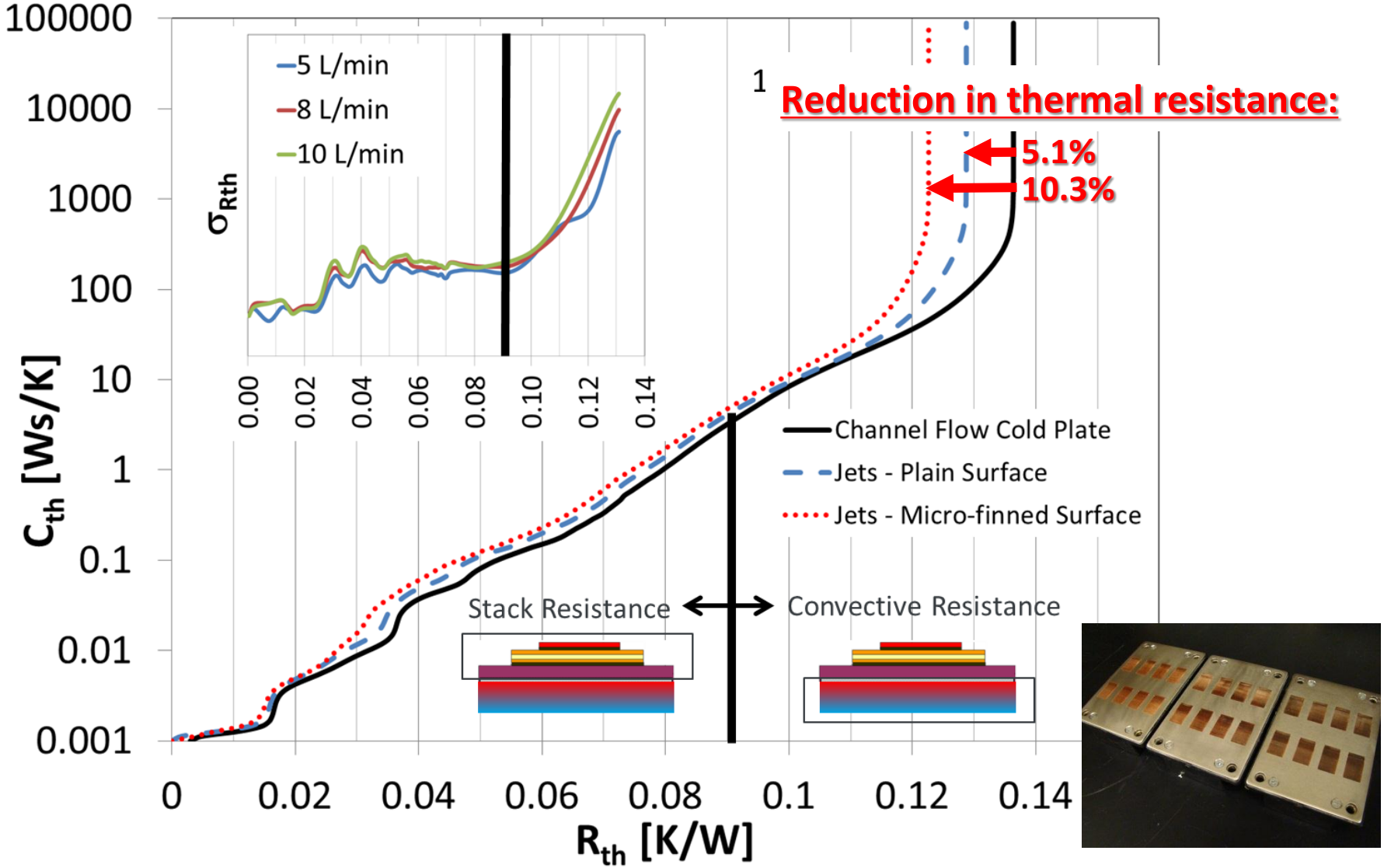



DBA = direct-bond-aluminum
DBC = direct-bond-copper

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

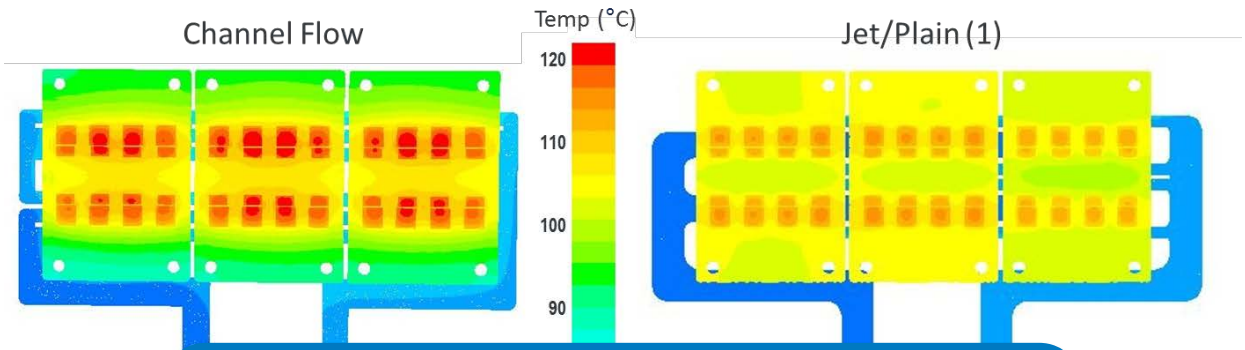
- **65°C automotive-grade** WEG
- **5 m/s** jet (1.3-mm nozzle, 3-mm jet distance)

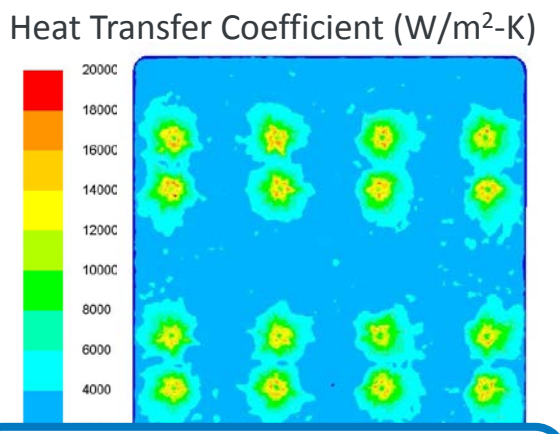
# Thermal Resistance Map from T3ster (105-W experiment)



# 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



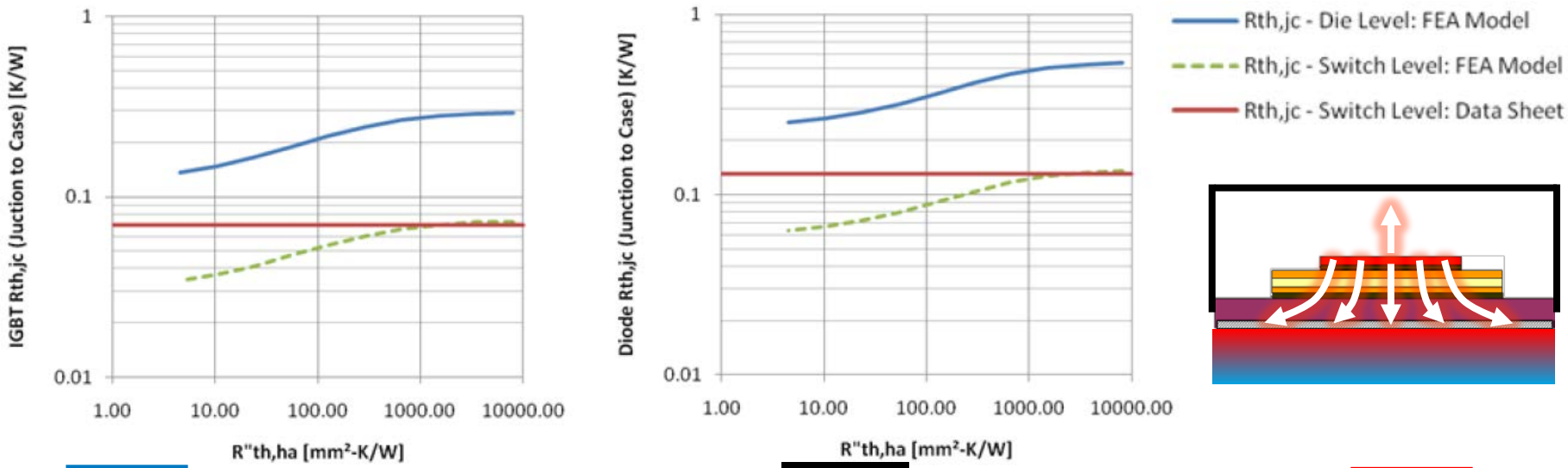




Temperature reduction (jets to baseline):

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

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

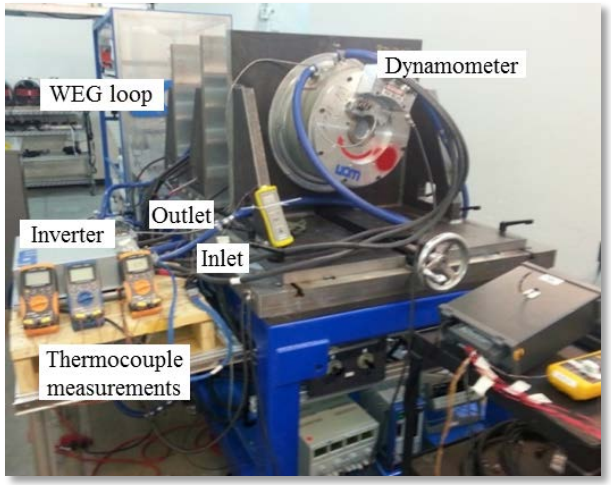
Decreased $R_{th,j\text{-}l}$

4 diodes (105 W)

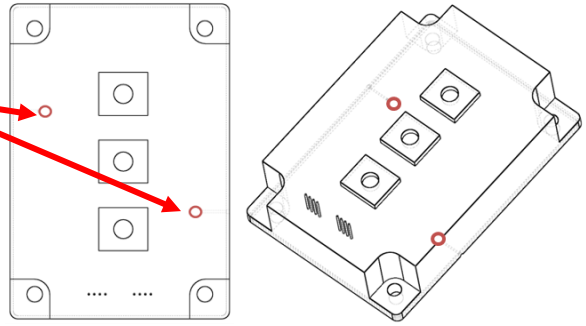
24 IGBTs / 24 diodes (2520 W)

Increased Heat Flux and Distribution

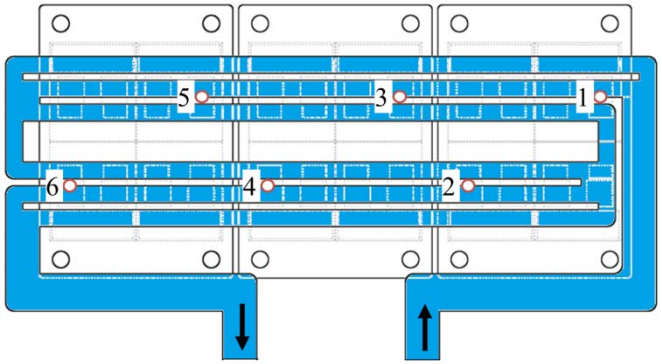
# Inverter Testing on Dynamometer



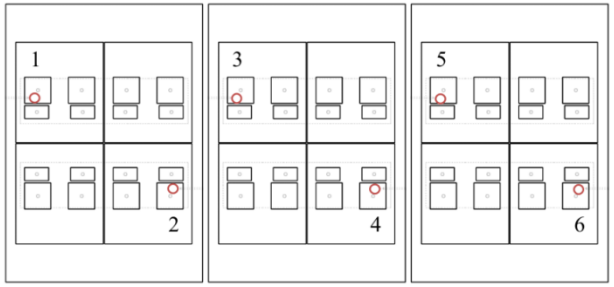
Thermocouple locations (middle of copper baseplate)



Channel Flow




Jet Impingement




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

40, 60, 80, 100 kW Electrical Power

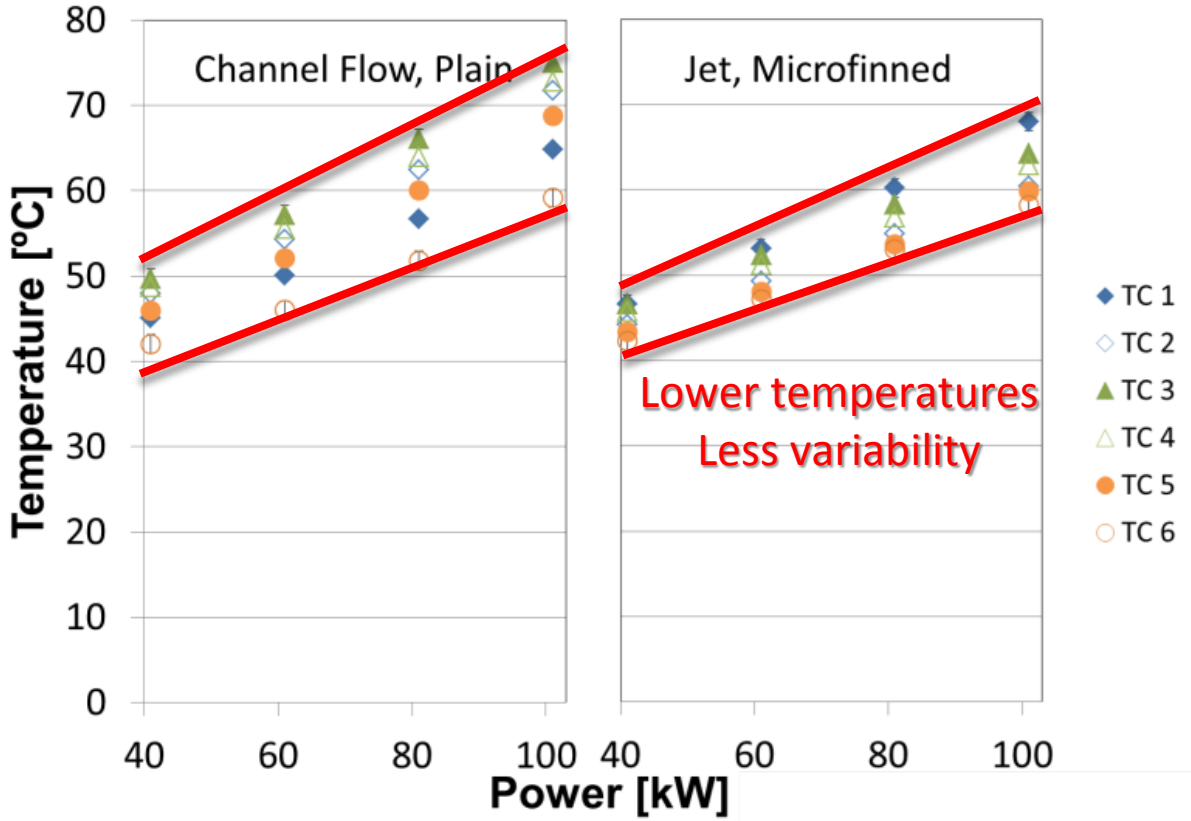
0.9, 1.3, 1.6, 2.2 kW heat dissipation (model estimate)

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

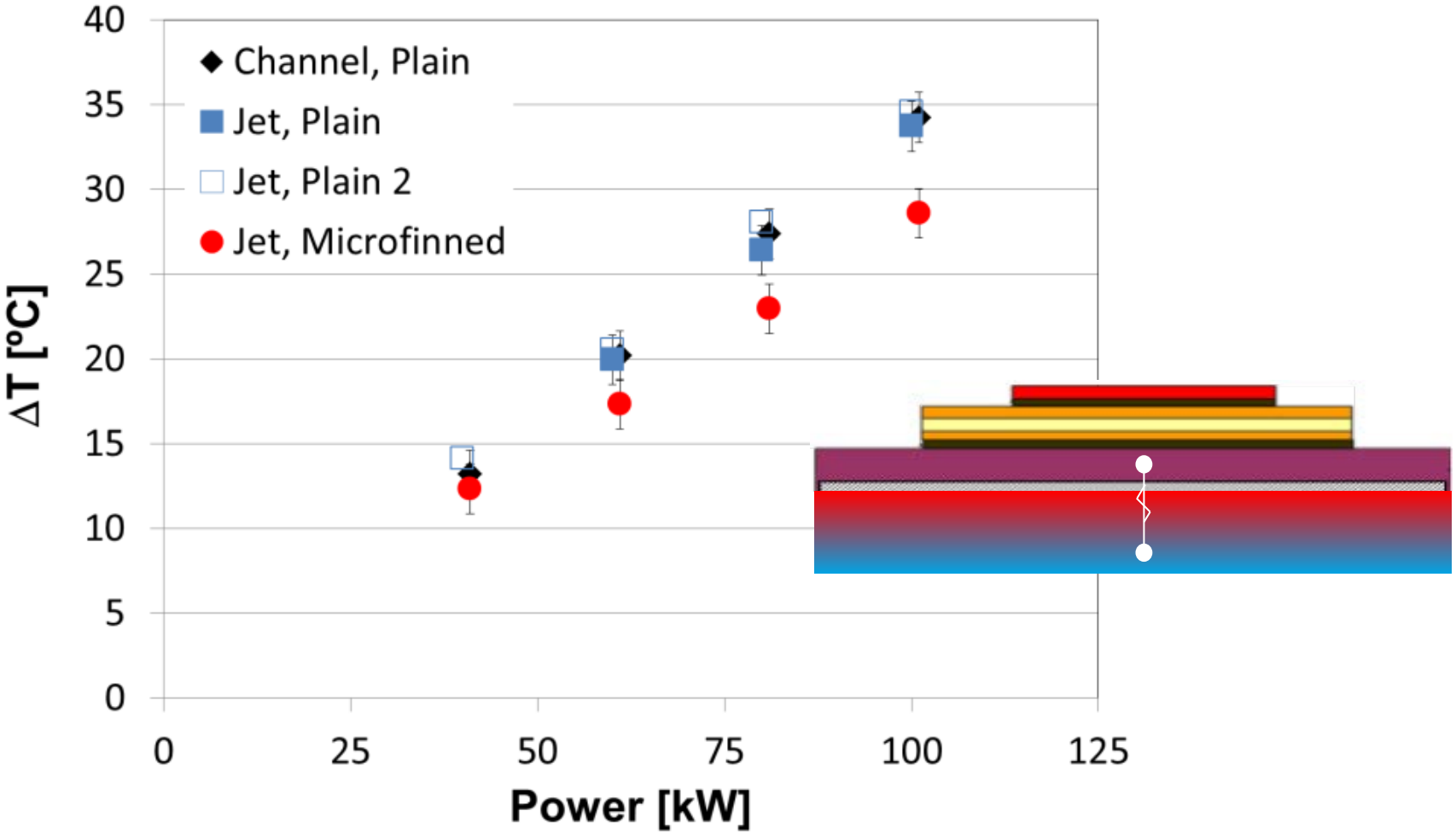
# Thermocouple Temperatures

## 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 |

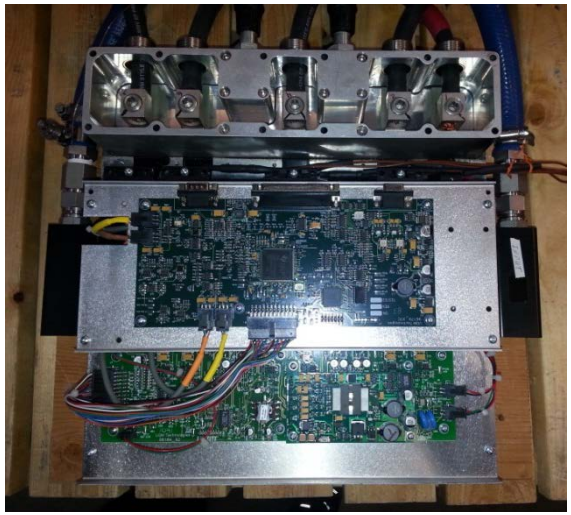


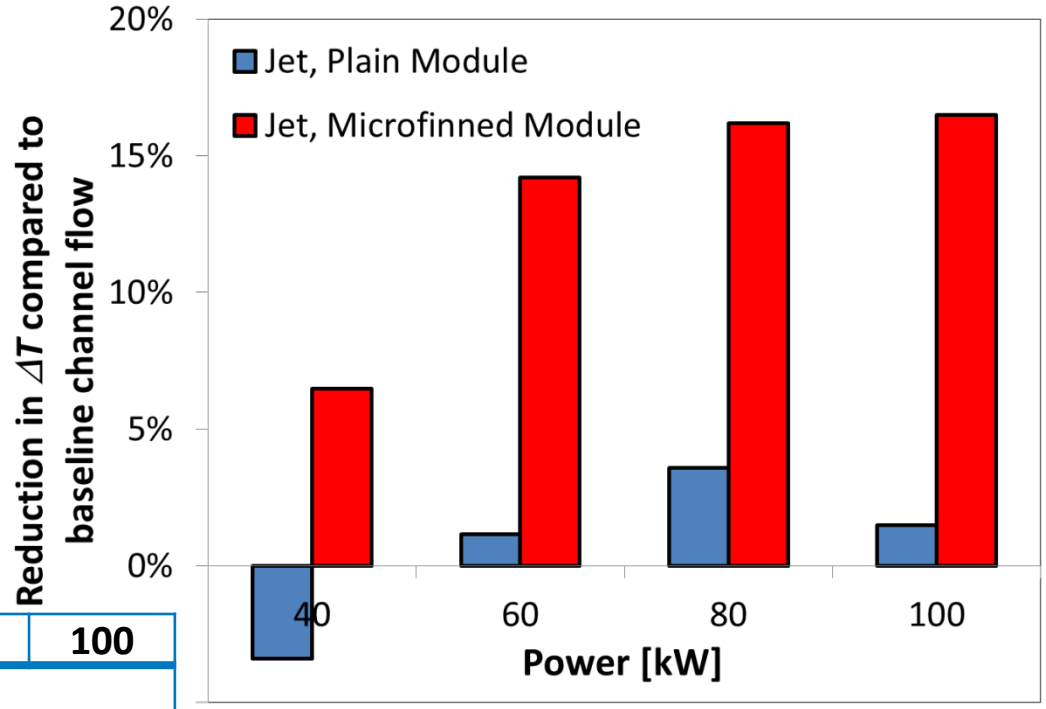
# Temperature Difference (Baseplate to Coolant)




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**

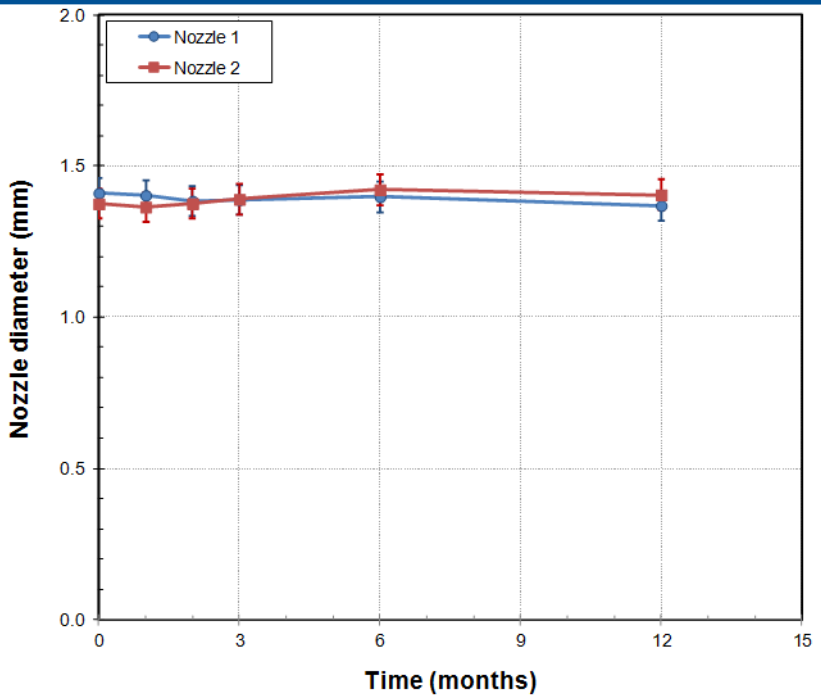
17% **Increase in Coefficient of Performance**

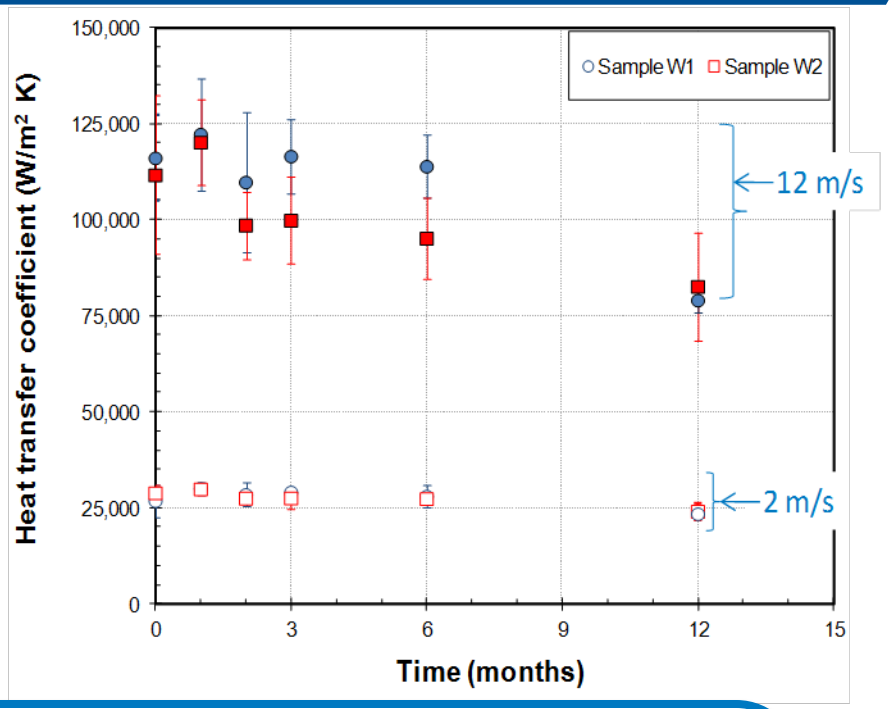
12% **Increase in power density**

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** ($5^0$C less spread) than channel flow case
- Jet reliability is good

# Jet and Surface Reliability (First Round Testing)

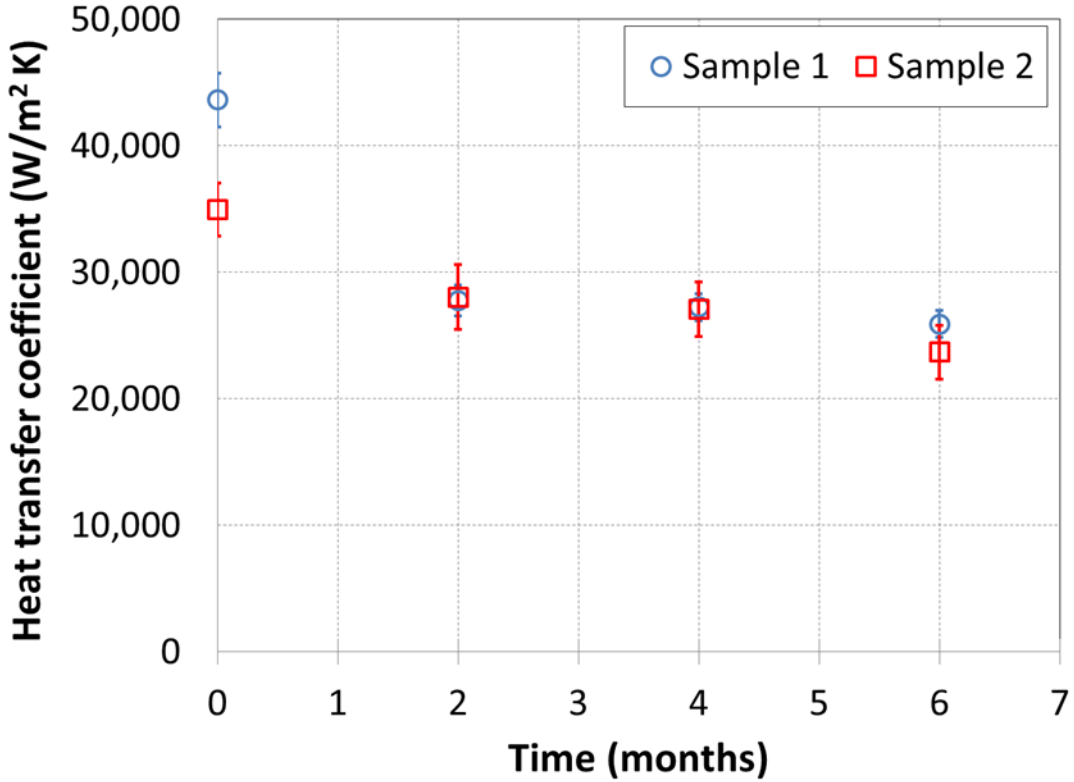


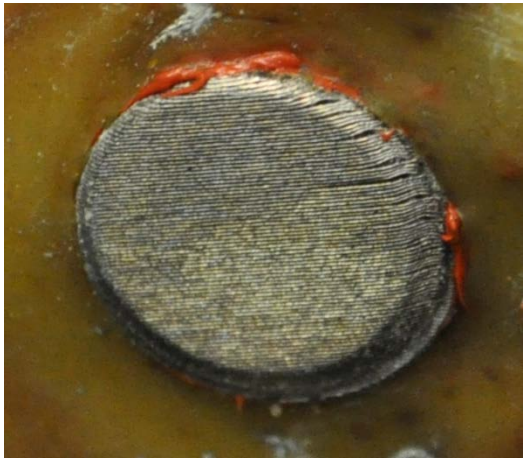



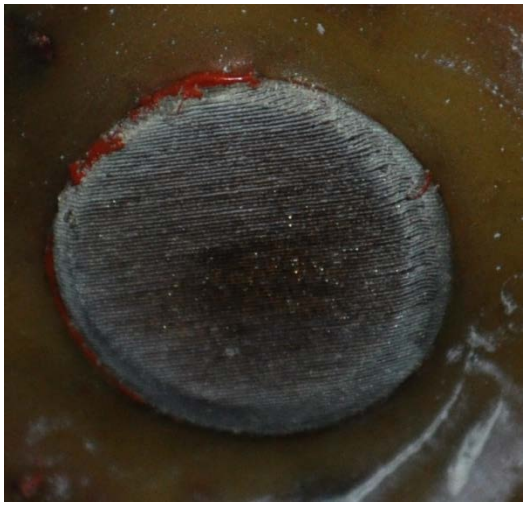

- Negligible change in jet nozzle diameter after 12 months of nearly continuous impingement
- Degradation in thermal performance of surfaces due to oxidation (no coating, no corrosion inhibitors)

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

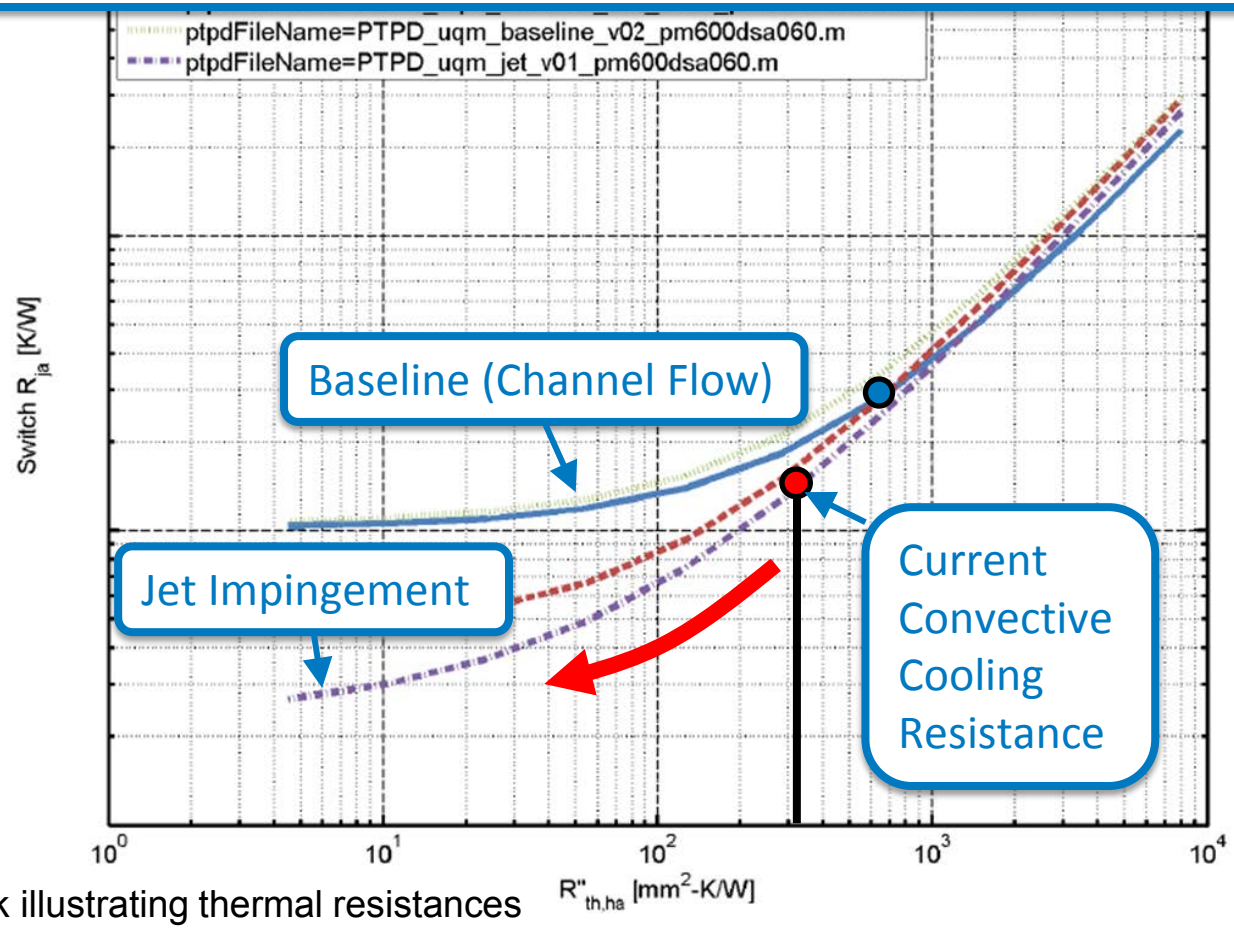
# Thermal Performance Summary (Compared to Baseline Channel Flow)

| 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** | | | | |
| **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% |

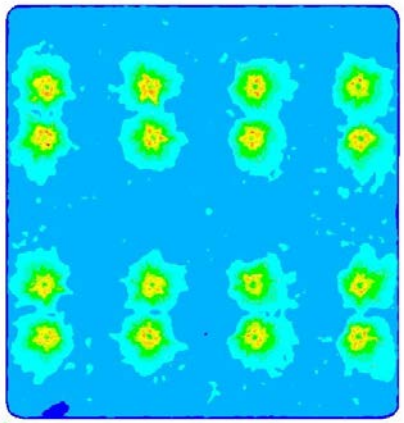
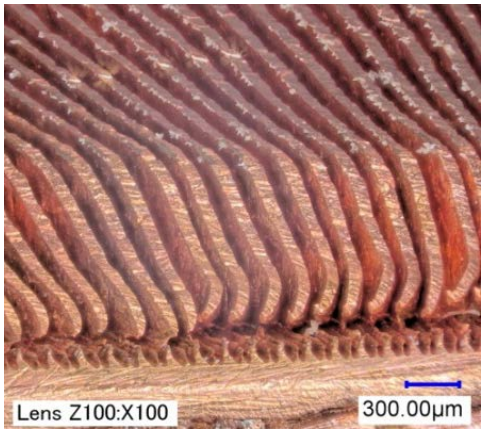
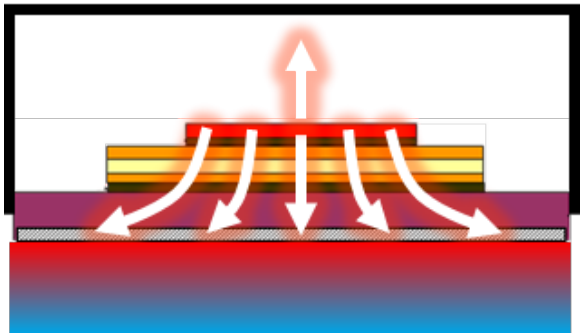
- Jets provide localized cooling on devices
- Enhanced surfaces increase jet effectiveness

# 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)