Advanced Liquid Cooling R&D



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National Renewable Energy Laboratory
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Overview

Timeline

Project Start Date: FY11

Project End Date: FY13

Percent Complete: 80%

Budget

Total Project Funding: $1.6M

DOE Share: $1.6M

Funding Received in FY11 and FY12: $1.2M

Funding for FY13: $400K

Barriers and Targets

- Cost
- Weight
- Specific power
- Power density

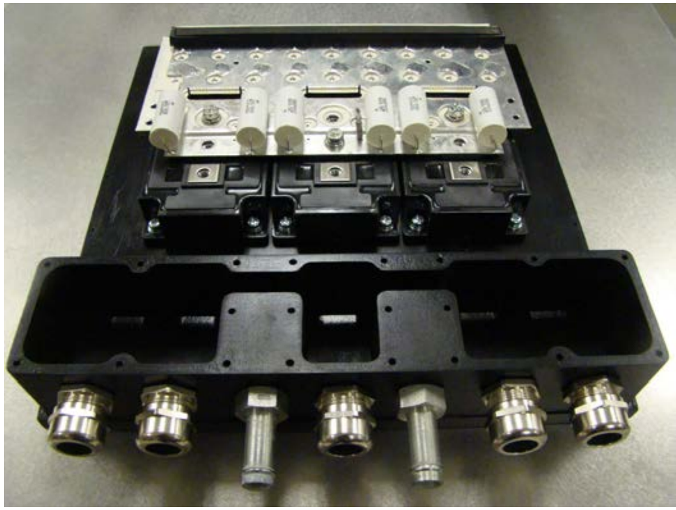
Partners

- Interactions/ collaborations
  - UQM Technologies, Inc., Delphi and Wolverine Tube, Inc.
- Project lead: National Renewable Energy Laboratory (NREL)

Relevance/Objective(s)

- Advanced thermal management technologies are critical to enabling higher power densities
  - Resulting in lower weight, size and cost

- **Objectives**
  - Design and develop light-weight, single-phase liquid-cooled, automotive inverter-scale heat exchanger based on impinging jets and enhanced surfaces.
  - Through thermal management, directly contribute towards the 2015 power electronics targets.
  - Enable use of high-temperature water-ethylene glycol (WEG) coolant for power electronics cooling.



Credit: Mark Mihalic, NREL

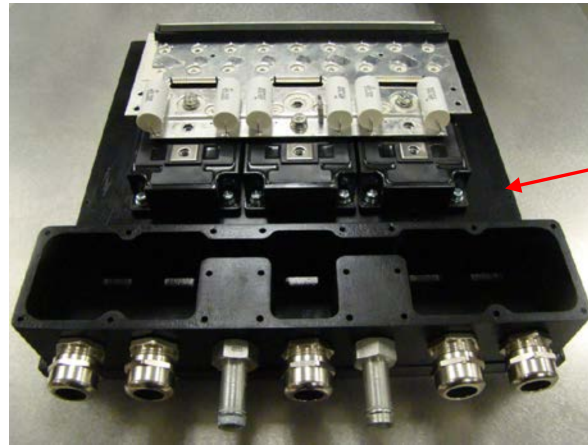
Milestones

Date	Milestone or Go/No-Go Decision
September 2011	Completed finite element analysis (FEA) and computational fluid dynamics (CFD) modeling to design the first prototype heat exchanger. **Go/No-Go Decision**: Modeling results showed significant promise for the new design as compared to the baseline channel-flow case; decision was made to proceed with hardware fabrication.
February 2012	Fabricated first jet-based plastic heat exchanger prototype (impingement on plain surface); initiated experimental testing for pressure drop and thermal performance.
September 2012	Completed first study on reliability of the impinging jet configuration on unplated microfinned surfaces.
March 2013	Completed experimental characterization and CFD analysis on the first prototype. Performance benefits with respect to baseline channel-flow case demonstrated; second prototype designed to enable lower pressure drop and easier fabrication/manufacturing. Second round of reliability characterization of jet impingement initiated with impingement on metalized substrates and metal-plated microfinned surfaces. **Go/No-Go Decision:** Proceed with fabrication of second prototype (impingement on plain surface) and third prototype (impingement on microfinned surface) heat exchangers.
June 2013	Complete CFD analysis and fabrication of second and third prototype heat exchangers.
September 2013	Complete experimental thermal performance and pressure drop characterization on second and third prototype heat exchangers. Complete second round of reliability characterization of the impinging jet configuration.

Approach/Strategy

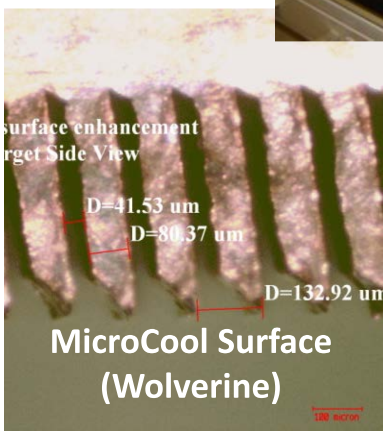
Baseline heat exchanger

Credit: Sreekant Narumanchi, NREL

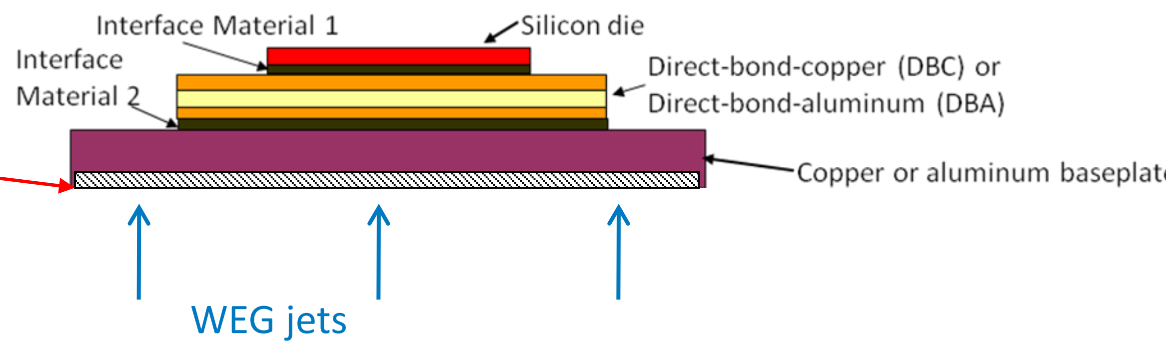


First prototype new heat exchanger

Credit: Mark Mihalic, NREL



Credit: Mark Mihalic, NREL

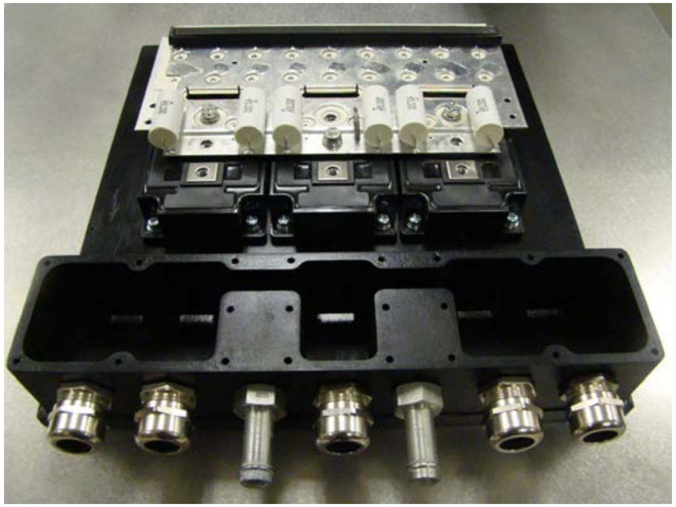


- Reduce thermal resistance, increase heat transfer rates through WEG jet impingement on enhanced surfaces, and use light-weight material.
- Characterize thermal performance based on steady-state and transient/realistic loading conditions.

Validation of CFD Modeling for Baseline and Jet-Based Heat Exchanger

	Flow Rate ($x10^{-4}$ m^3/s)	ΔP (Pa)		$T_{avg,4diodes}$ (°C)		$R_{th,ja}$ (°C/W)		
		Experiment (Exp.)	CFD	Exp.	CFD	Exp.	CFD	
Baseline	0.83	5102	5125	84.6	84.2	0.139	0.137	
	1.33	12548	12325	84.1	84.0	0.134	0.133	
	1.67	19374	17897	83.9	83.9	**0.132**	0.132	
Jet	1.33	--	14214	--	82.6	--	0.120	**12.1% reduction**
	1.67	24407	20803	82.2	82.2	**0.116**	0.116	

- 105.3 W dissipated in four diodes in the center power module
- WEG mixture (50–50% by volume of water and ethylene glycol) at 70°C used as coolant
- Junction temperature in the four diodes measured using the transient thermal tester during the steady-state heating
- Solder (jet case) and grease (baseline case) layer resistances adjusted in the model to match with experiments at $1.67x10^{-4}$ m^3/s (10 liters/min) and 105.3 W



Credit: Mark Mihalic, NREL

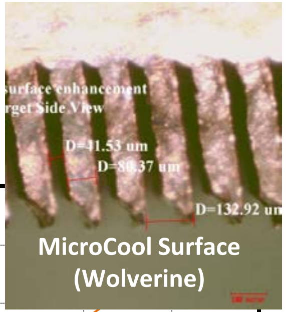
CFD Modeling for Performance at 2.5kW Heat Dissipation

	Flow Rate ($\times 10^{-4}$ m^3/s)	ΔP (Pa)	$T_{avg, devices}$ (ºC)	$R_{th,ja}$ (ºC/W)	$T_{max, devices}$ (ºC)	$R_{th,ja}$ (ºC/W)
Baseline	1.67	17905	117.4	0.0188	121.7	0.0205
Jet (plain surface)	1.67	20801	111.4	0.0164	114.9	0.0178
Jet (enhanced surface)	3.34*		101.3	0.0124	104.5	0.0137

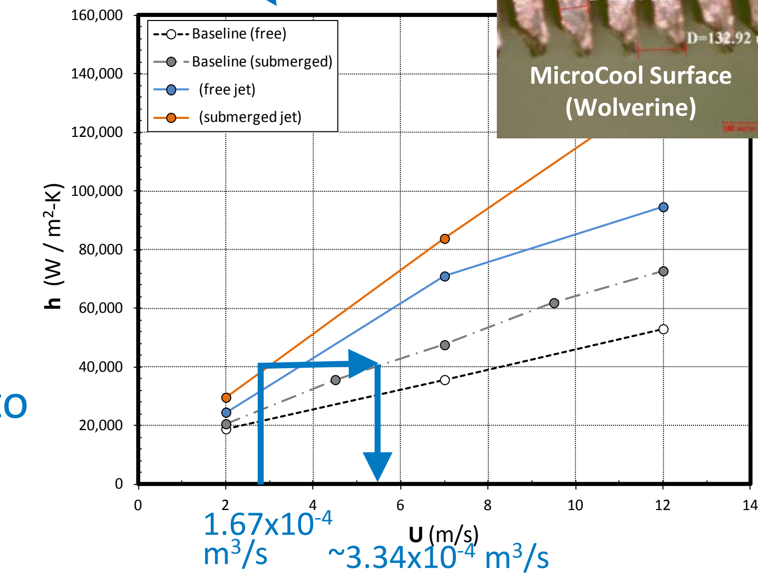
*Twice the jet velocity (flow rate) yields nearly equivalent heat transfer as enhanced surfaces

- 2520 W dissipated in 24 IGBTs and 24 Diodes
- WEG mixture at 70°C used as coolant
- 1156 W and 3456 W power levels and heat dissipation ratios of Q_{IGBT}/Q_{Diode} = 1:1, 2:1, 3:1 investigated, yielded same thermal resistance
- Jet impingement on plain surface yielded 12.6% reduction in thermal resistance
- Jet impingement on microfinned surface projected to reduce thermal resistance by 33%

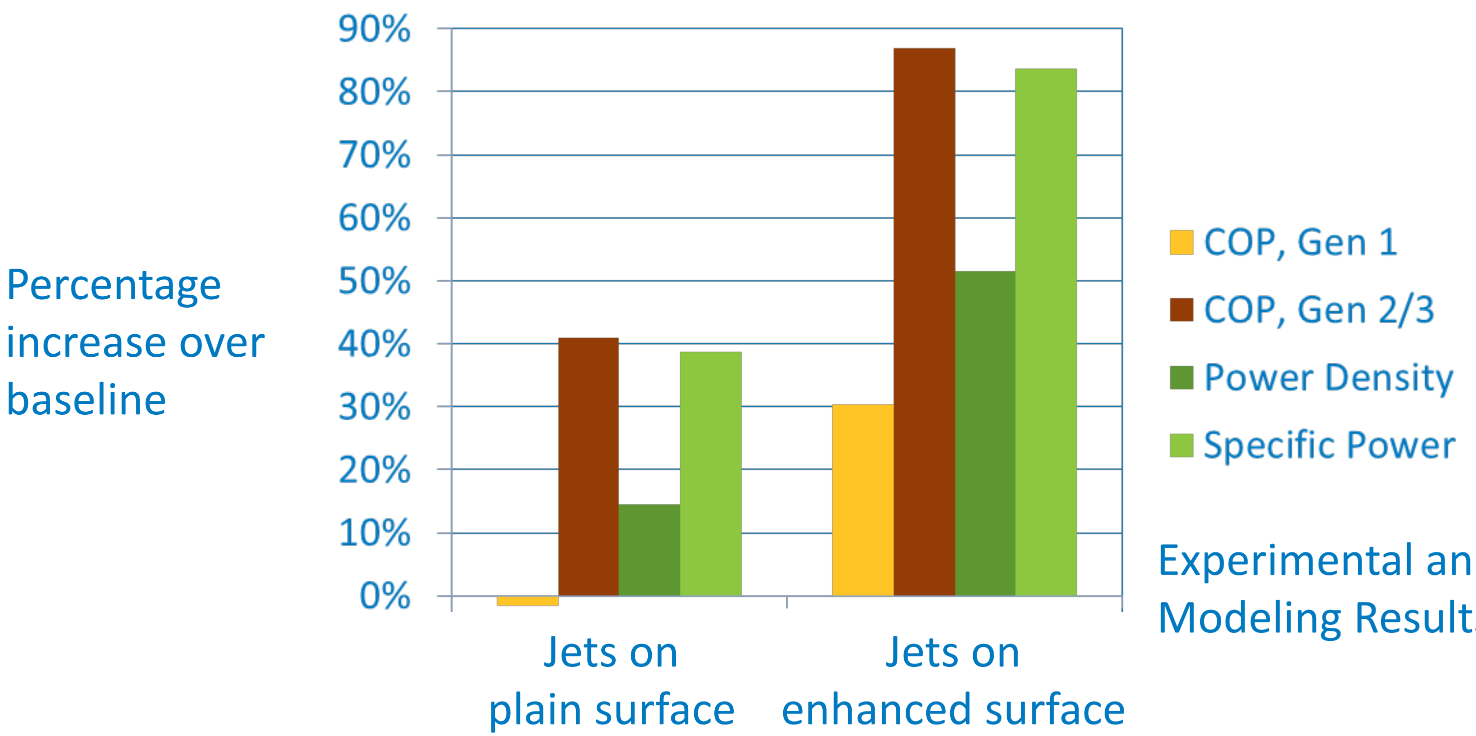
Credit: Mark Mihalic, NREL



MicroCool Surface (Wolverine)



Impacts on Coefficient of Performance (COP), Power Density, Specific Power and Cost



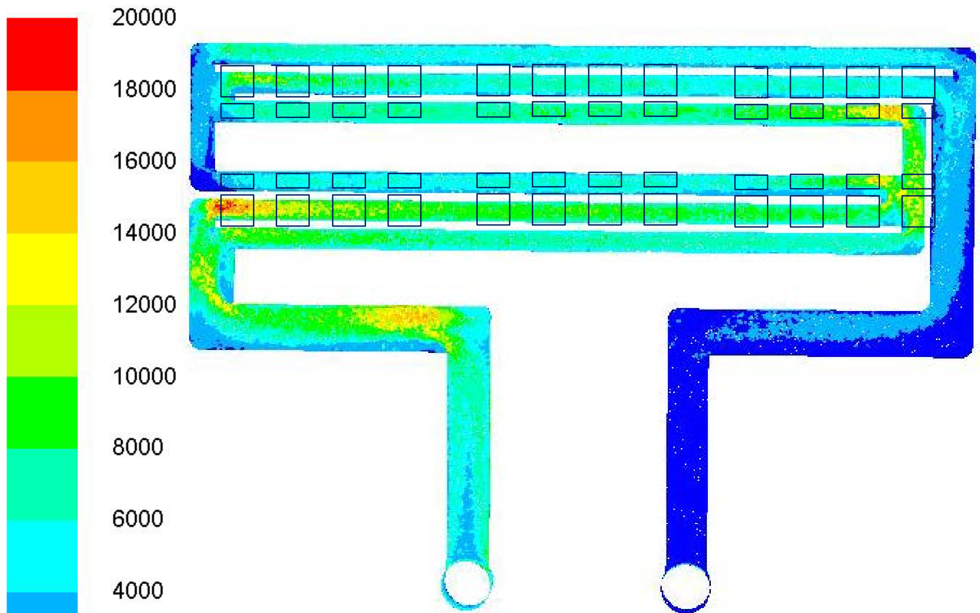
Experimental and Numerical Modeling Results

- Up to 30% increase in COP for 1st generation prototype
- Due to lower pressure drop (fluid power), 2nd generation (plain surface) COP increase projected at >40% and 3rd generation (enhanced surface) increase of >85%
- Up to 51% increase in power density
- Using plastic results in approximately 2.9 kg (6.3 lb) or 50% weight reduction of the heat exchanger - results in up to 84% increase in specific power
- Cost will be competitive/lower with respect to aluminum baseline heat exchanger

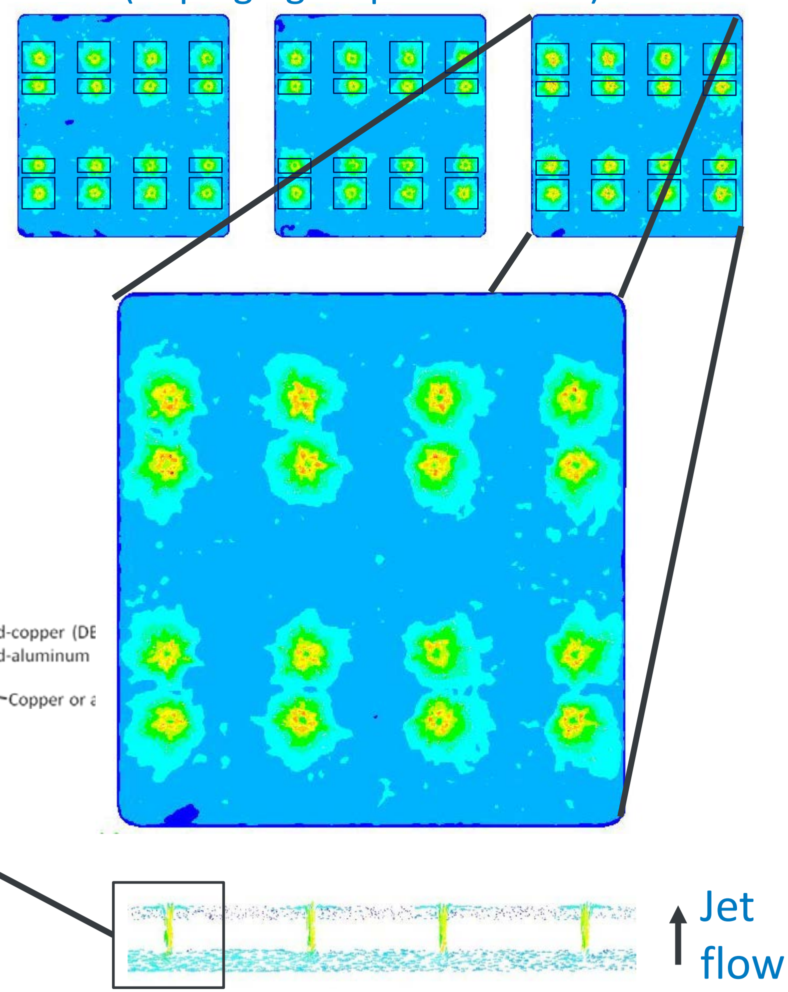
Heat Transfer in the Baseline and Jet Configurations

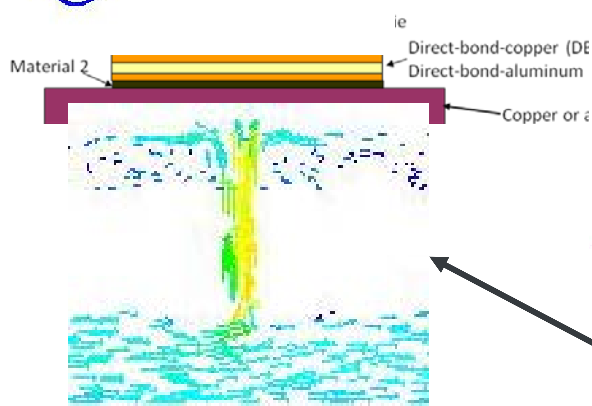
Heat Transfer Coefficient
(W/m^2-K)

Baseline



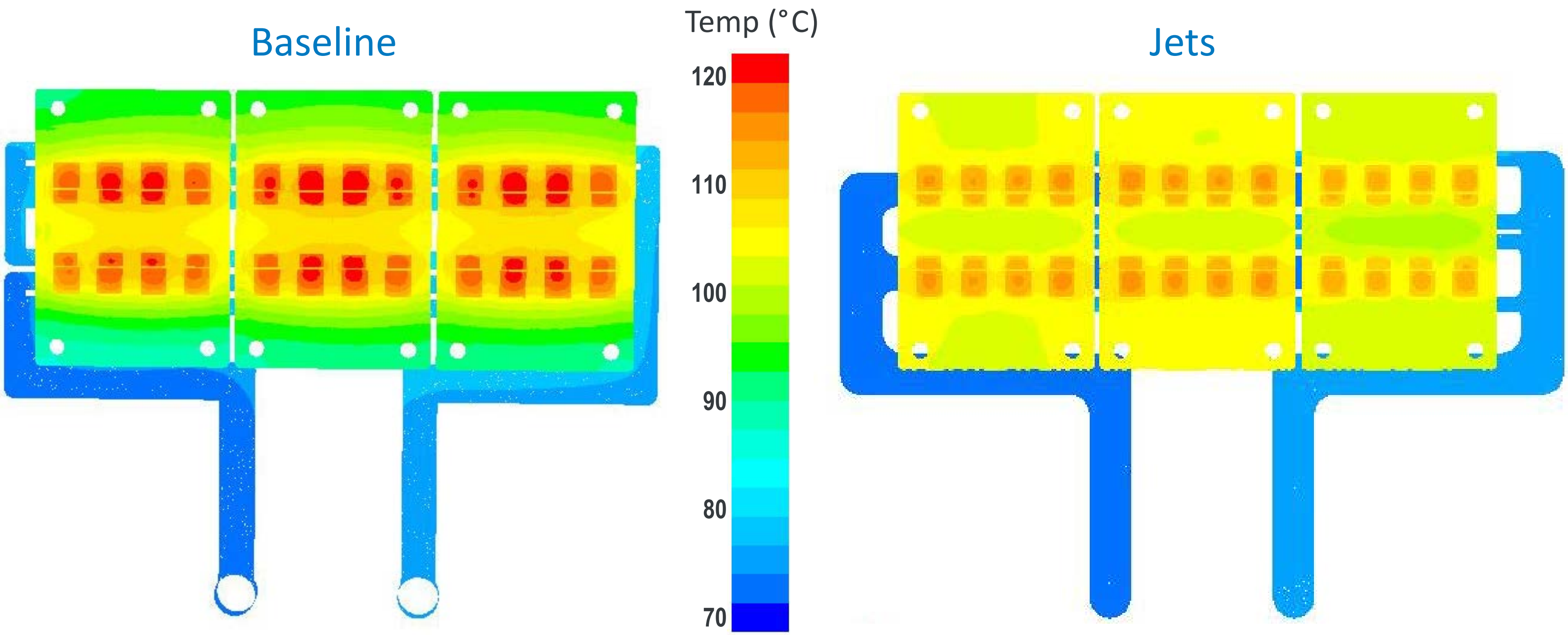
Jets
(impinging on plain surface)





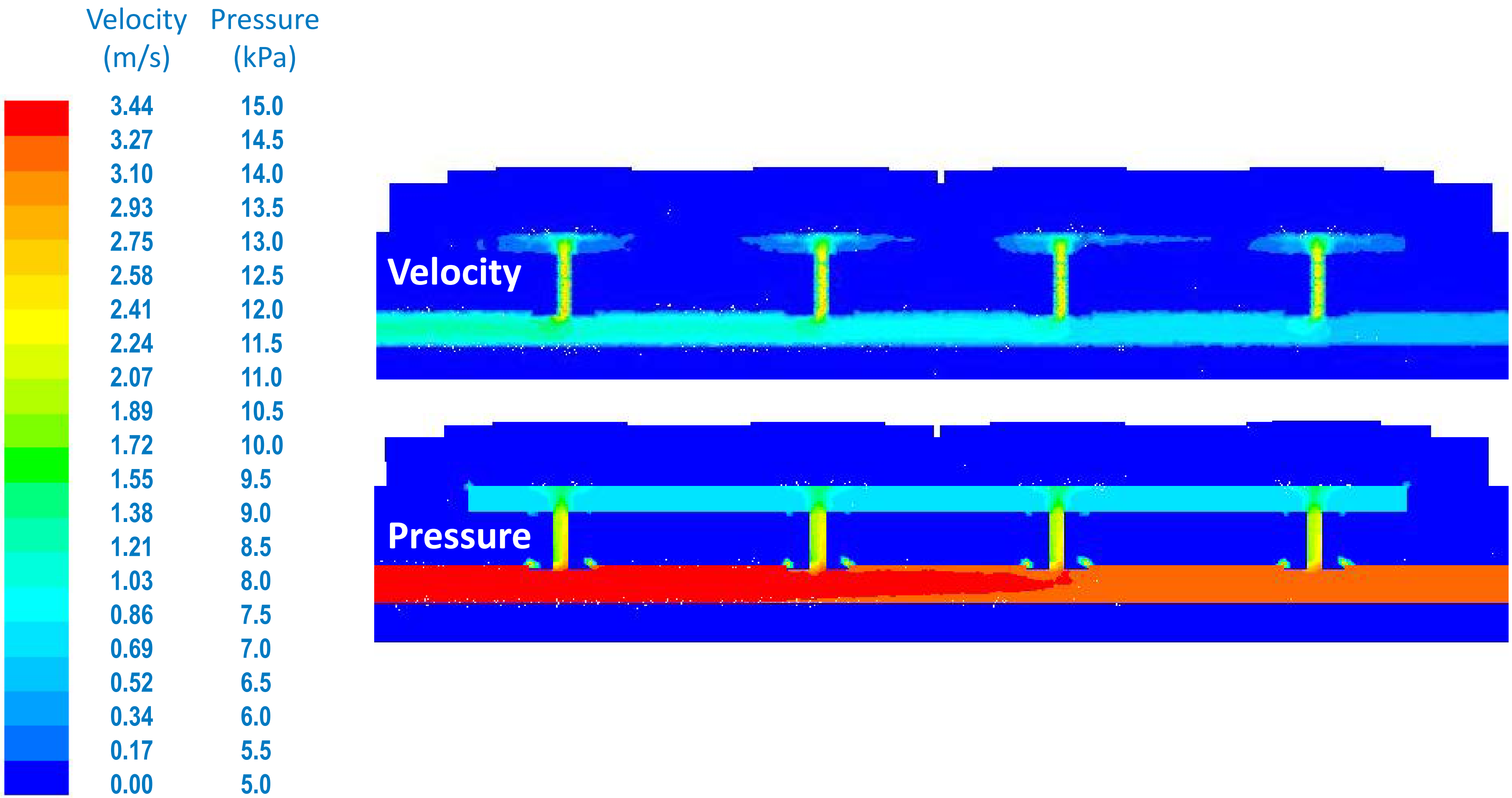
- Jets provide localized cooling on devices

Temperatures in the Baseline and Jet Cases



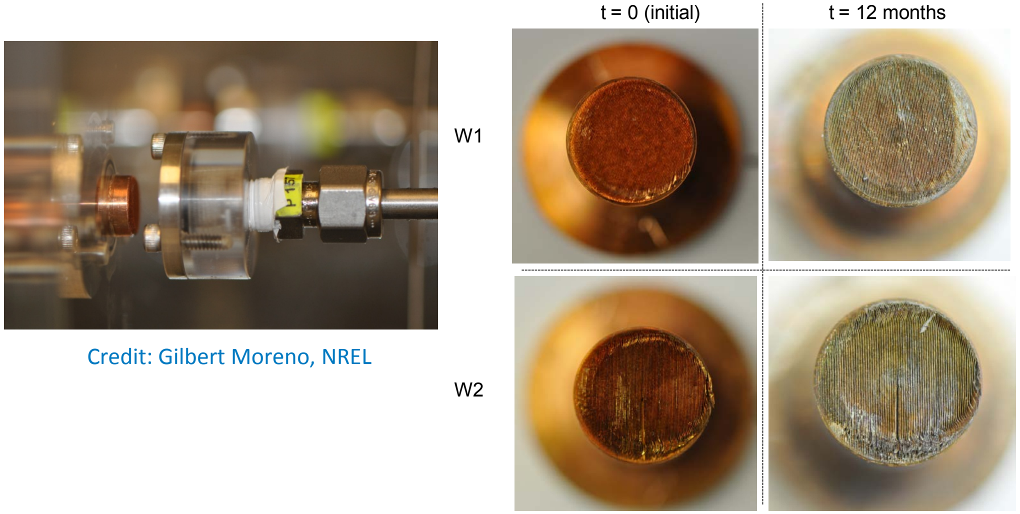
- 2520 W (24 IGBT @ 70 W, 24 Diodes @ 35 W)
- WEG mixture at 70°C used as coolant
- For same flow rate, average and maximum device temperature reduced by ~6 to 7°C for the case of jets versus the baseline

Jet Velocity and Pressure

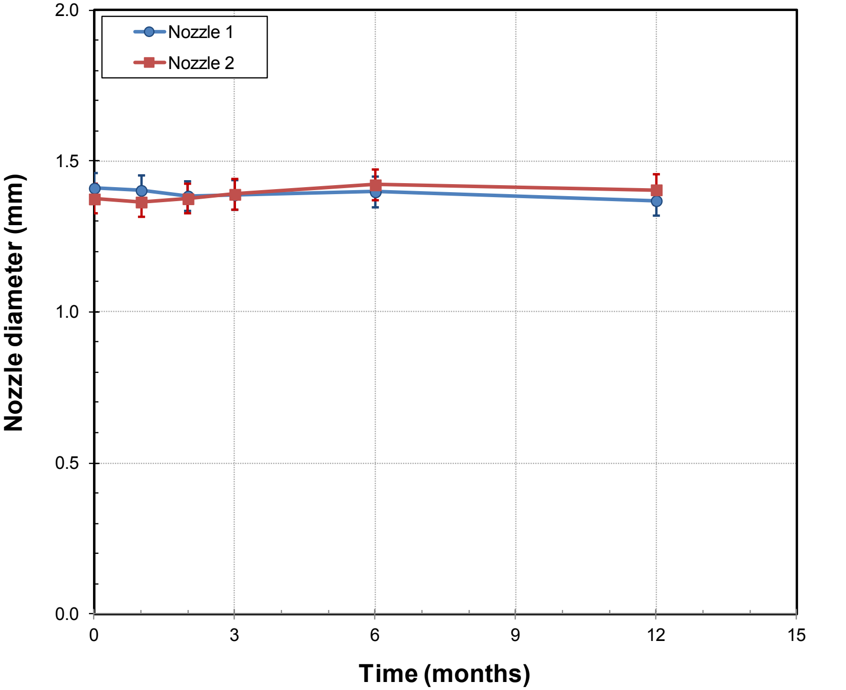


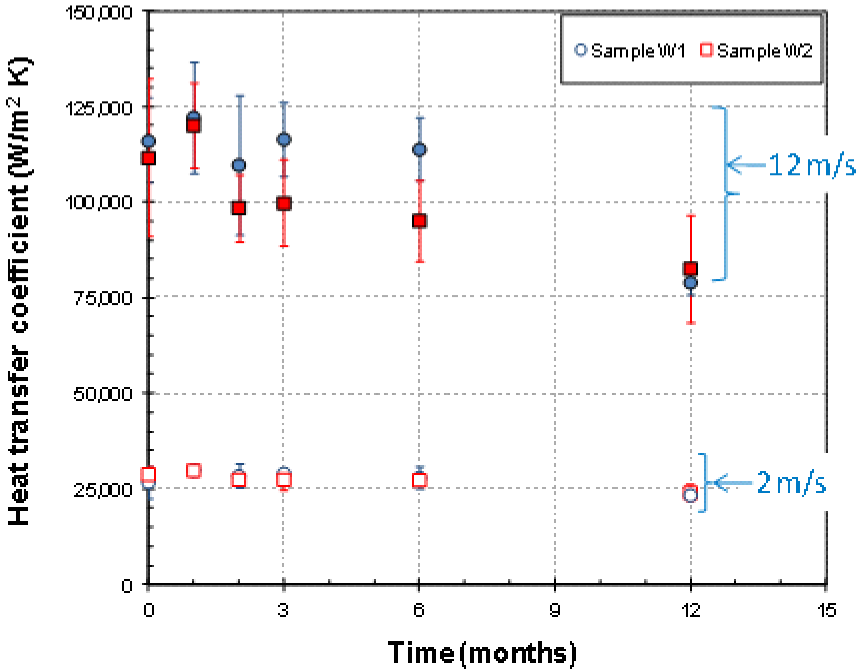
- Jets relatively uniform, with slightly higher velocities on downstream side, reducing thermal resistance

Jet Impingement Reliability Characterization



Credit: Gilbert Moreno, NREL





- Tests with WEG jet impinging on microfinned surface (on 12.5-mm-diameter copper target surface)
- Negligible change in jet nozzle diameter after 12 months of nearly continuous impingement
- Degradation in thermal performance due to oxidation

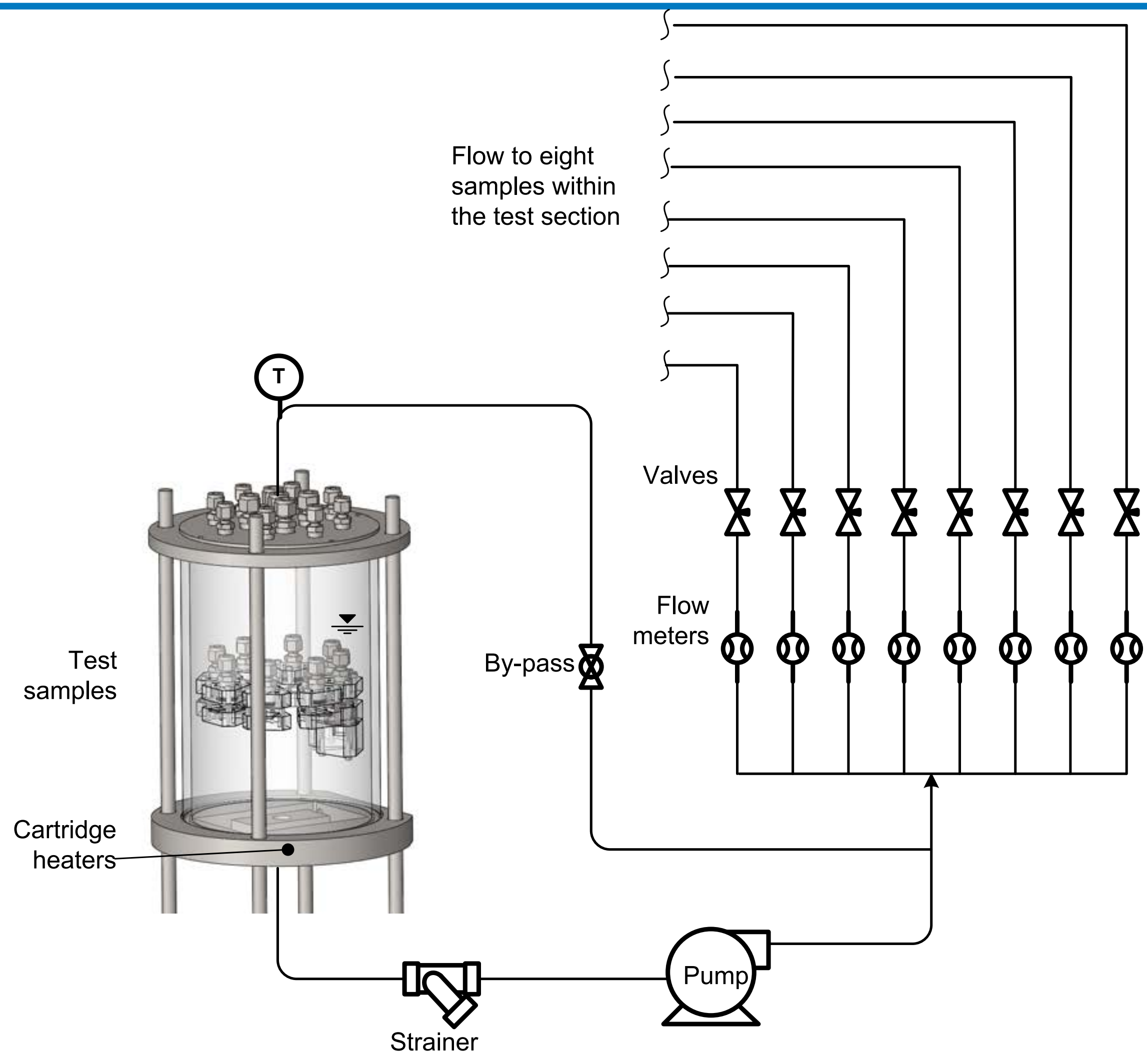
Jet Impingement Reliability Characterization – Second Round

8 samples being tested simultaneously

- 3 DBC substrates
- 3 DBA substrates
- 2 microfinned surfaces (nickel-plated)

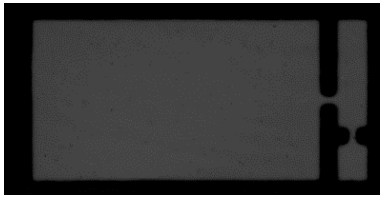
Test Conditions

- Long-term impingement tests have begun in February, 2013
- Automotive-grade WEG
- 65°C operating temperature
- Submerged jets
  - 5 m/s at the nozzle exit
  - Average nozzle diameter ~1.3 mm
  - ~3 mm distance between nozzle and sample surfaces



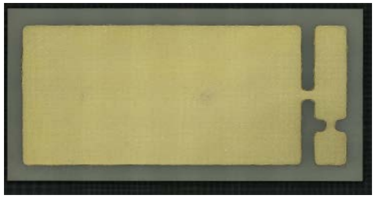
Jet Impingement Reliability Characterization – Second Round

- 6 Delphi DBA/DBC samples
  - Periodic testing metrics
    - Scanning Acoustic Microscopy (C-SAM) imaging
    - Thermal Diffusivity
    - Laser profilometry
    - Digital microscope images

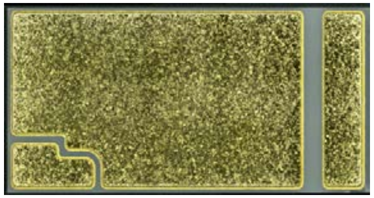


C-SAM image of Delphi DBA substrate interface

C-SAM image of Delphi DBC substrate interface

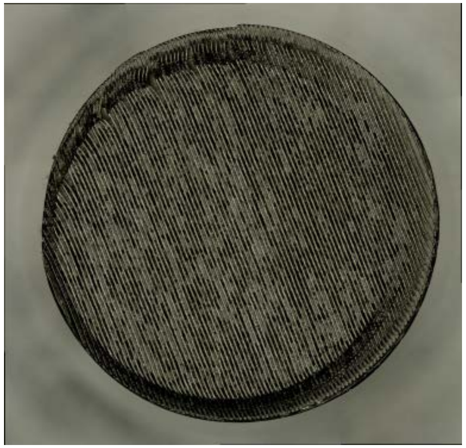


Digital microscope image of Delphi DBA surface



Digital microscope image of Delphi DBC surface

- 2 Wolverine microfinned samples (nickel-plated)
  - Periodic testing metrics
    - Digital microscope images
    - Heat transfer coefficients



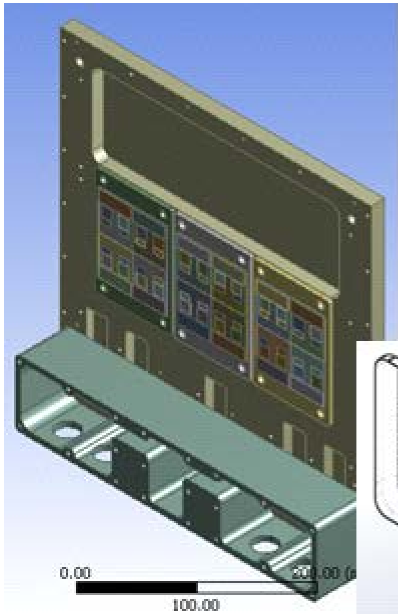
Digital microscope image of microfinned surface

Credit (all images): Jana Jeffers, NREL

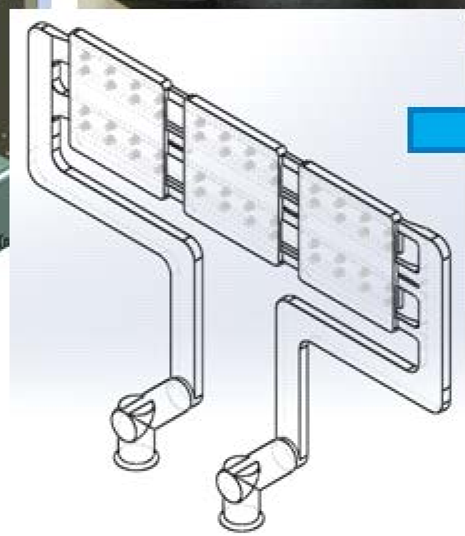
Collaboration and Coordination

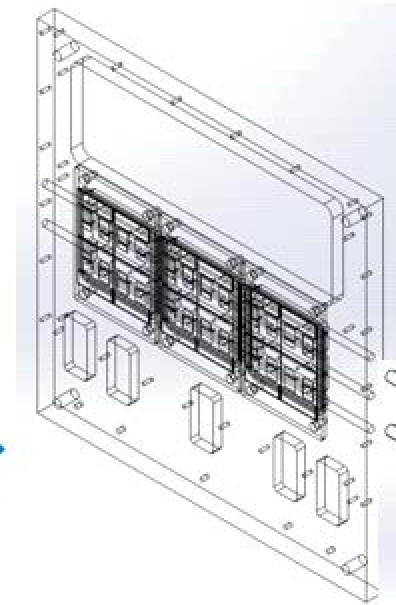
Collaborator	Type of Interaction/Collaboration
UQM Technologies Inc. (Industry)	• Source for inverter and power modules • Source for dynamometer testing of the inverter
Wolverine Tube, Inc. (Industry)	• Provided microfinned enhanced surface on copper base plate and blocks
Delphi Electronics & Safety (Industry)	• Provided DBC and DBA substrates for reliability characterization of jets

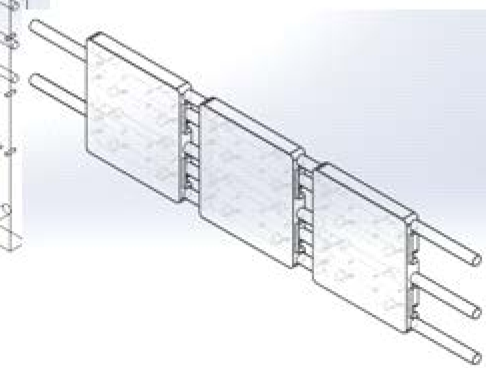
Proposed Future Work (Remainder of FY13)



Credit: Mark Mihalic, NREL







- Fabrication and characterization of new jet-impingement heat exchanger (second prototype) out of plastic:
    - Will be easier to manufacture using traditional processes,
    - Maintain thermal performance similar to the first prototype,
    - Have less pressure drop, decreasing fluid power, and increasing COP,
    - Potentially reduce volume due to different manifold connections.

Proposed Future Work (Remainder of FY13)

- Characterization of prototype (third) performance based on jet impingement on microfinned surfaces.
- Complete characterization of reliability of jet impingement on DBC/DBA, as well as on nickel-plated microfinned surface.
- Address aspects related to mass-manufacturing as well as cost comparisons of the new heat exchanger with respect to the baseline aluminum heat exchanger.

Summary

DOE Mission Support

- Through thermal management, help make progress towards 2015 power electronics targets
- Enable use of high-temperature WEG coolant

Approach

- Jet impingement on base plate with and without microfinned surface
- Light-weight, low-cost plastic for rest of the heat exchanger
- Demonstration of reliability

Accomplishments

- First experimental prototype of plastic heat exchanger incorporating jet impinging on plain surface shows 12.6% reduction in thermal resistance compared to the baseline case.
- Analysis shows potential for up to 33% reduction in thermal resistance for the case of jets impinging on microfinned surfaces as compared to the baseline
  - Up to 85% increase in COP
  - 51% increase in power density
  - 84% increase in specific power

Summary

Accomplishments

- First round of reliability characterization shows nozzle diameter unaffected by long-term (12 months) near-continuous jet impingement.
    - Some degradation in heat transfer of un-plated microfinned surface due to oxidation of the surface.

Future work

- Complete fabrication and demonstration of performance of simpler prototype heat exchangers incorporating impingement on both plain and microfinned surface.
- Complete comprehensive reliability assessment of the impinging jet configuration.

Collaborations

- UQM Technologies Inc.
- Wolverine Tube Inc.
- Delphi Electronics & Safety

NATIONAL RENEWABLE ENERGY LABORATORY

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