



Power Electronics Thermal Control

Sreekant Narumanchi

Center for Transportation Technologies and Systems



**Presented at the
*Interagency Advanced
Power Group Meeting***

**Golden, Colorado
May 5, 2010**

NREL/PR-540-48053

NREL's Center for Transportation Technologies and Systems

Cabin Thermal Comfort and Waste Heat Utilization



Utility Interface/ Renewable Energy

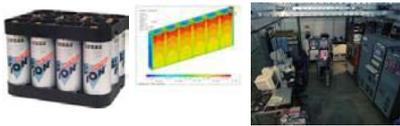
HOMER
WinDs



Biofuels and Engine Optimization



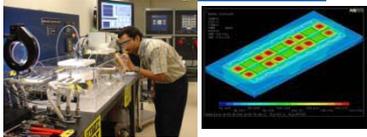
Energy Storage Thermal Control



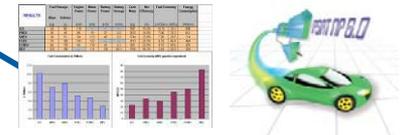
Real World Drive Cycle Analysis



Power Electronics Thermal Control



Powertrain Engine Tradeoffs (Perf., Size, Cost, Life)



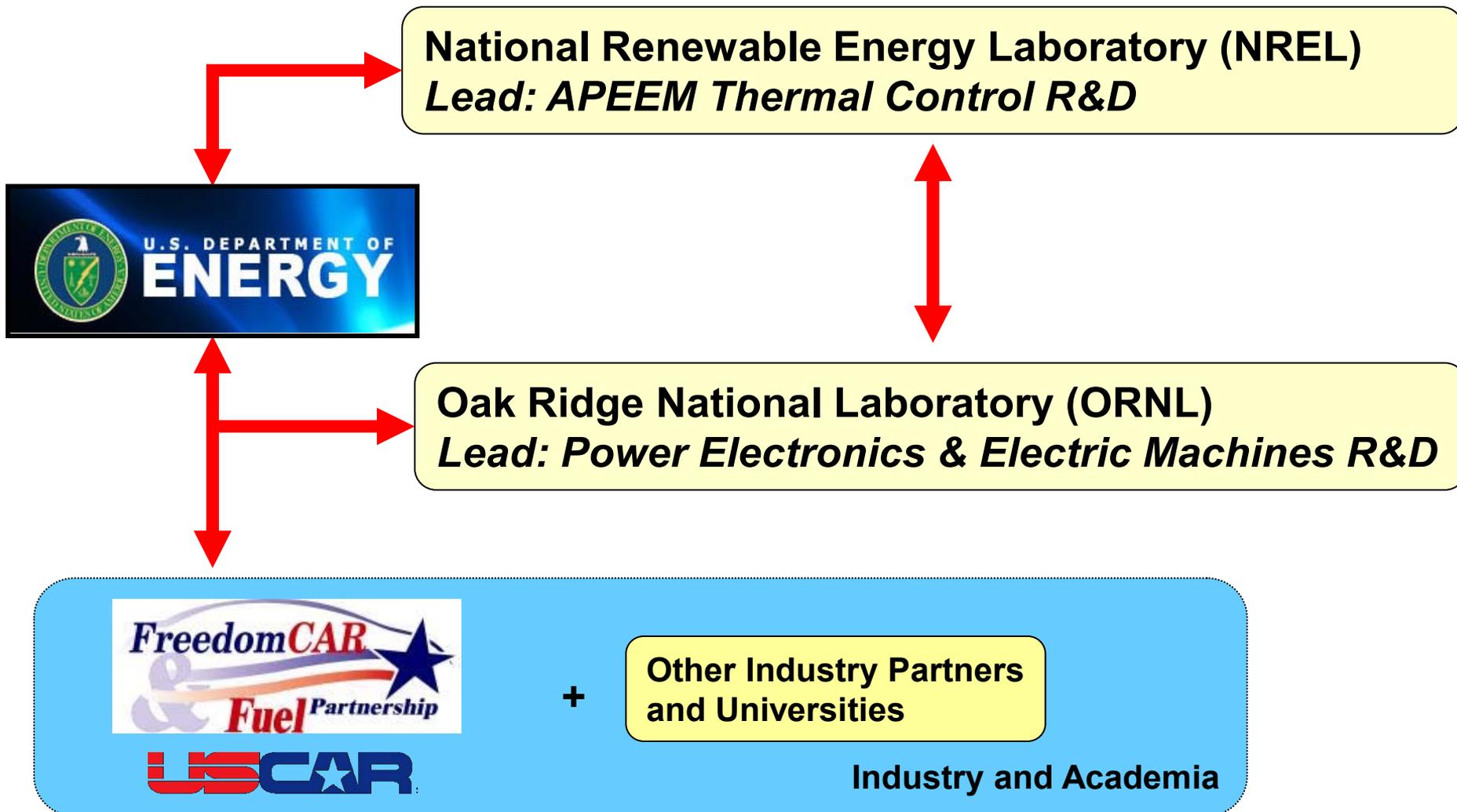
Thermal Impacts on Tailpipe Emissions



Vehicle Thermal and Energy Management Strategies



DOE's Advanced Power Electronics and Electric Machines (APEEM)



DOE's Advanced Power Electronics and Electric Machines (APEEM)



Reduce Dependence on Oil
Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life; coolant (air or 105°C WEG)

Technology Targets

Year	Traction Drive System				Power Electronics			Motors		
	(\$/kW)	(kW/kg)	(kW/l)	Efficiency	(\$/kW)	(kW/kg)	(kW/l)	(\$/kW)	(kW/kg)	(kW/l)
2010	19	1.06	2.6	>90%	7.9	10.8	8.7	11.1	1.2	3.7
2015	12	1.2	3.5	>93%	5	12	12	7	1.3	5
2020	8	1.4	4	>94%	3.3	14.1	13.4	4.7	1.6	5.7

Challenges

size cost weight

Research Focus Areas

Power Electronics

- inverters and converters
- innovative topologies
- packaging
- temperature-tolerant devices
- capacitors

Motors

- permanent magnet (PM) motors
- high performance non-PM motors
- permanent magnets

PEEM Thermal Control

- heat transfer techniques
- materials
- area enhancement
- alternative coolants

Integrated Traction Drive System

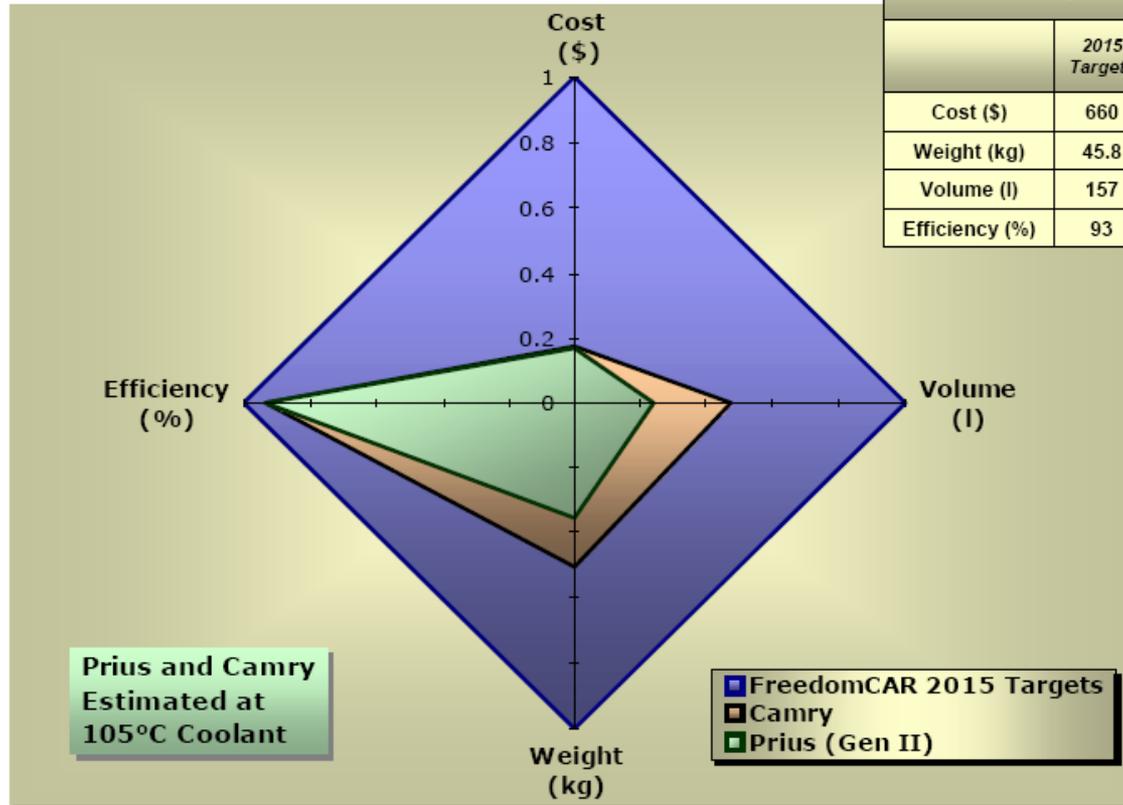
- benchmarking technologies
- innovative system designs

Technical targets

Coolant System Material Selection Number of Devices

55 KW System at 105°C

	2015 Targets	Prius (Gen II)	Camry
Cost (\$)	660	3880	3740
Weight (kg)	45.8	137.5	91.7
Volume (l)	157	68.8	33.3
Efficiency (%)	93	86	88



Prius and Camry
Estimated at
105°C Coolant

FreedomCAR 2015 Targets
Camry
Prius (Gen II)

Heat
Generation

Cooling
Requirements

Heat Flux

Heat
Exchanger
Volume

Heat Exchanger Materials

FY10 – Thermal Management projects

<div style="text-align: center;"> PROJECT / FOCUS AREA </div>	PE Packaging	Thermal Systems Integration	Heat Transfer Technologies	Thermal Stress and Reliability
Thermal System Performance and Integration	★	★		
Electical and Thermal Characterization, Modeling, and Reliability Assessment	★	★		★
Thermal Stress and Reliability	★			★
Thermal performance and reliability of bonded interfaces	★			★
Characterization and Development of Advanced Heat Transfer Technologies	★	★	★	★
Air Cooling Technology	★		★	
Thermal Control of PHEV / EV Charging Systems		★	★	
Electric Motor Thermal Control		★	★	
Thermal Assessment		★	★	

Approach

Improve PE device efficiency (ORNL)

$$Q = h A (T_B - T_C)$$

Maximize base plate temperature

- PE materials selection
- reduce thermal resistance

Coolant temperature

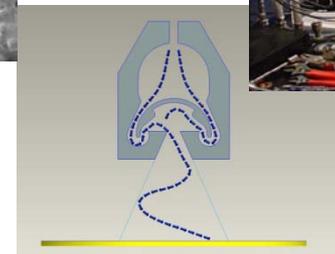
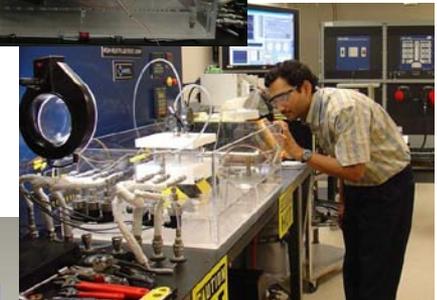
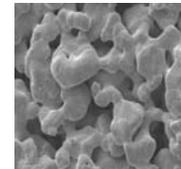
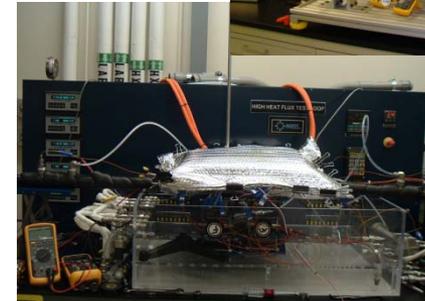
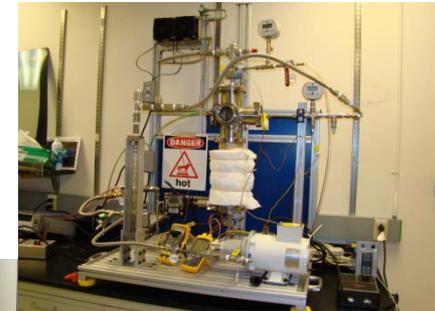
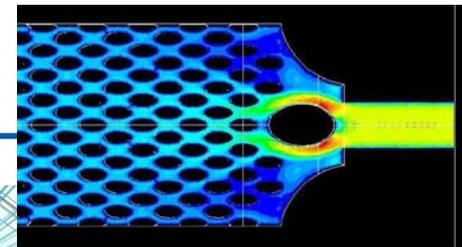
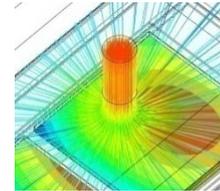
- reduce coolant temperature
- evaluate alternatives

Increase surface area

- fin shape optimization
- double sided cooling
- surface enhancements
- thermal spreading

Enhance heat transfer coefficient

- jet / spray cooling
- self-oscillating jets
- phase change



Integration and Reliability

Enhanced surfaces in conjunction with single-phase and two-phase flows

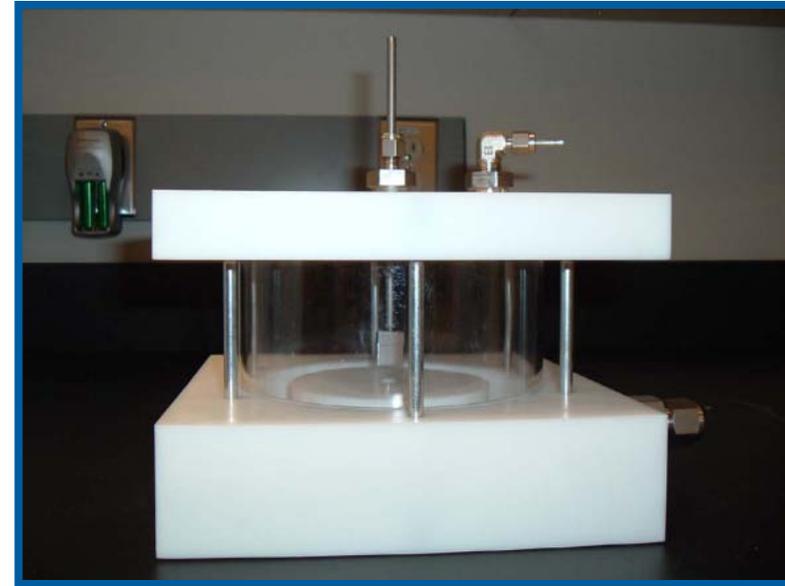
Approach

Surface enhancement: Single-phase channel flow, jet impingement

- Further increase the heat transfer rates in conjunction with single-phase channel flows and jet impingement.
- Prior studies have shown that surface roughening can:
 - Increase h -values by as much as 32% [**Gabour & Lienhard (1994)**],
 - Reduce R_{th} by as much as 60% [**Sullivan et al. (1992)**].
- Limited, if any, studies exist on the use of micro-porous and nano-structures as a means of enhancing jet impingement and channel flow heat transfer.

Procedure:

1. Fundamental study on the effect of enhanced surfaces on channel flow and jet impingement (free and submerged jets) heat transfer.
2. Conduct tests at various channel flow and jet velocities.



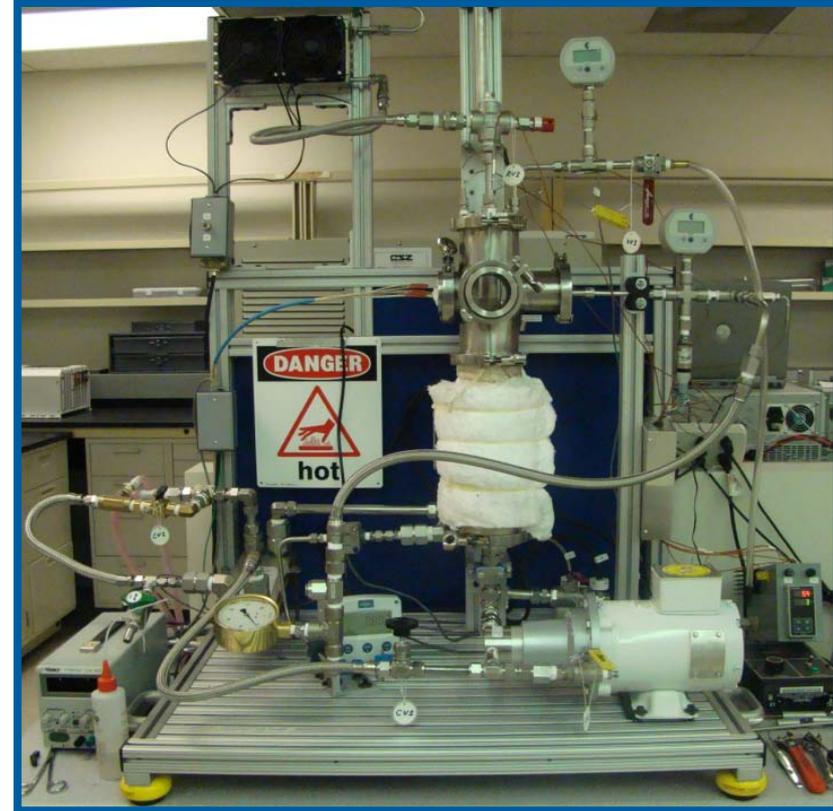
Approach

Surface enhancement: Two-phase heat transfer

- High heat transfer rates.
- Direct cooling using dielectric fluids can eliminate thermal bottlenecks.
- There are very few published studies (if any) investigating the effect of microporous and/or nano-structures on spray impingement boiling performance.

Procedure:

1. Fundamental study on the effect of enhanced surfaces on pool boiling, flow boiling, spray and jet impingement boiling.
2. Conduct tests at various fluid flow rates.

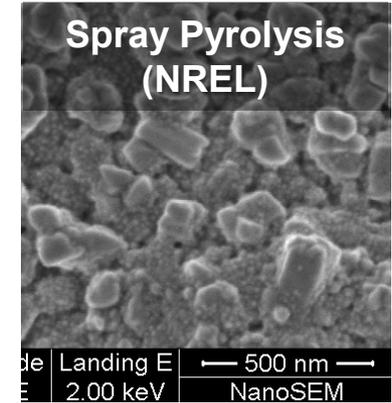
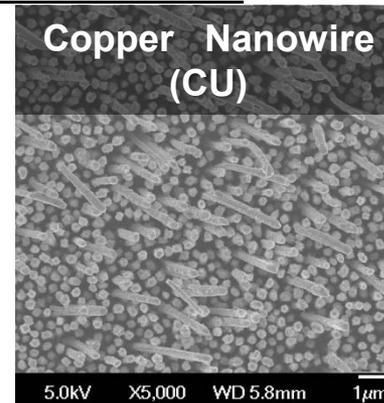
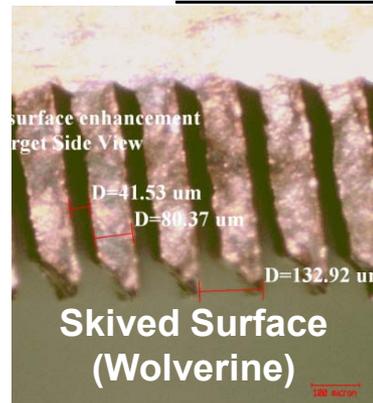
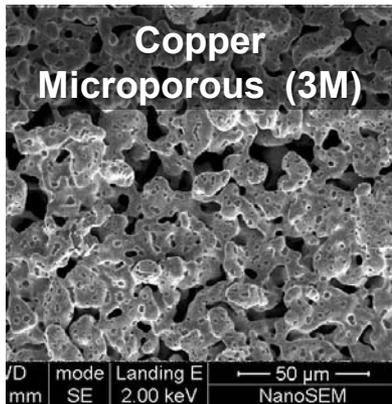


Approach

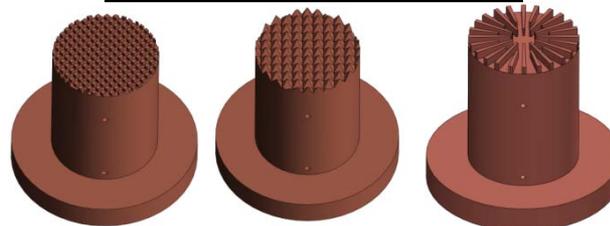
Strategy

- Current Work:** Fundamental study to characterize the thermal performance of the enhanced surfaces.
- Future Work:** Implement technology on an actual power electronics module & evaluate the surface enhancement's reliability.

Enhanced Surfaces



Finned Surfaces

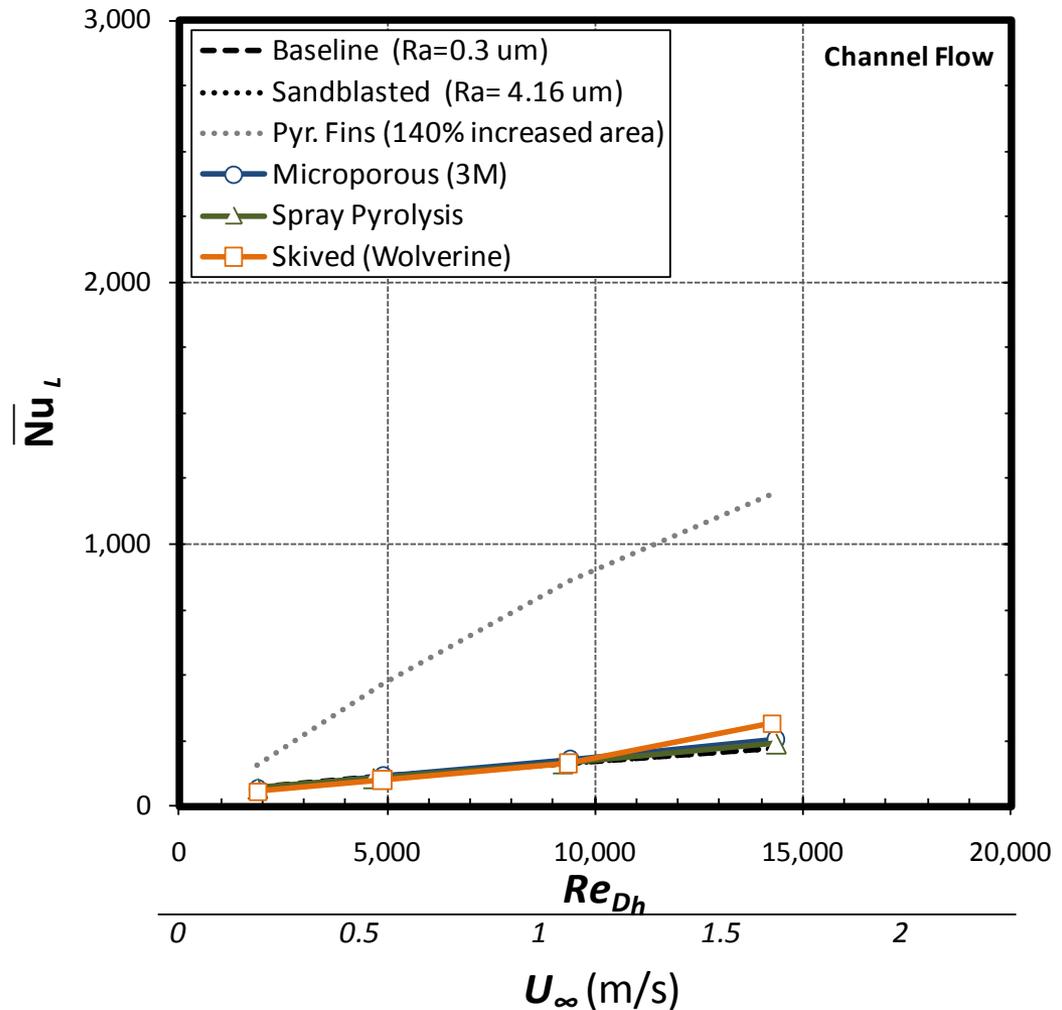
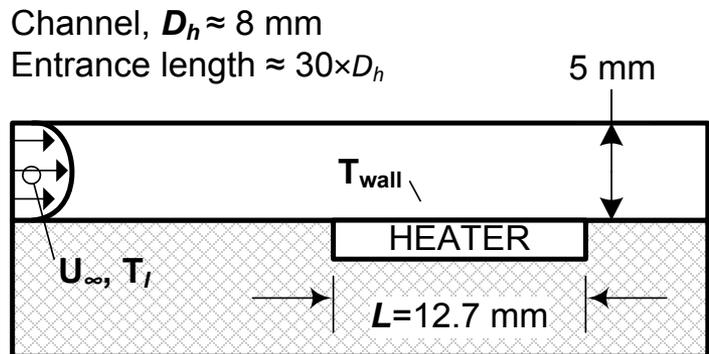


Single-phase channel flow and jet impingement in conjunction with enhanced surfaces

- **Water @ 25°C inlet temperature.**
- **Channel flow, free and submerged jet configurations.**
- **11 different surfaces tested.**
- **Channel flow tests for reference.**

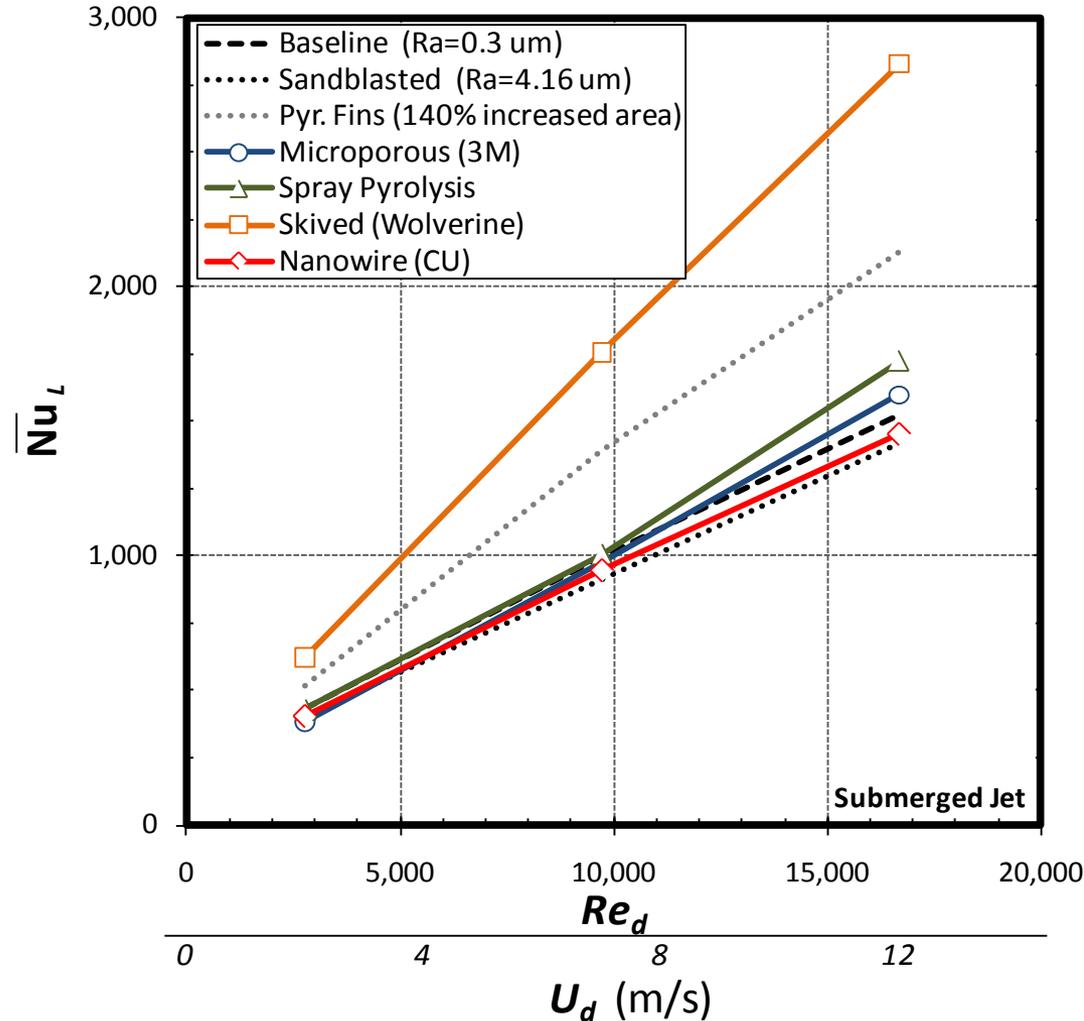
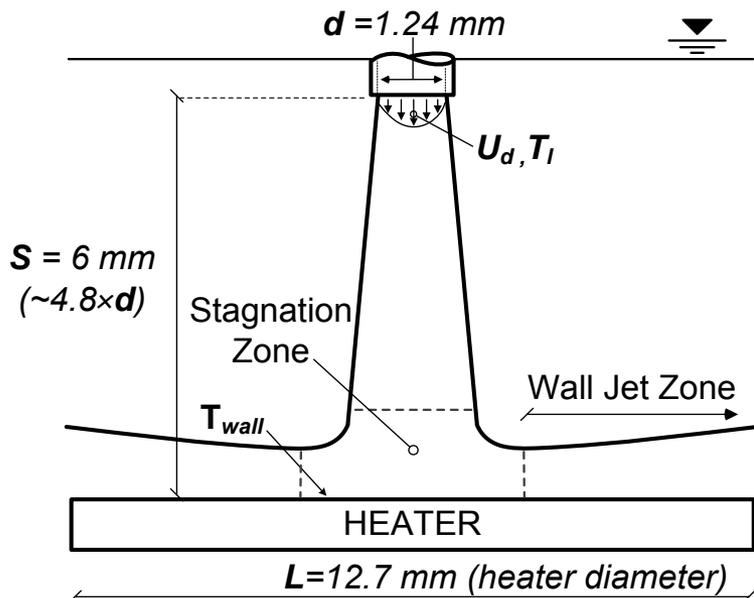
Enhanced surfaces: single-phase channel flow results

- Reference configuration, typical of existing cooling configurations.
- Roughened and microporous surfaces have no effect on performance.



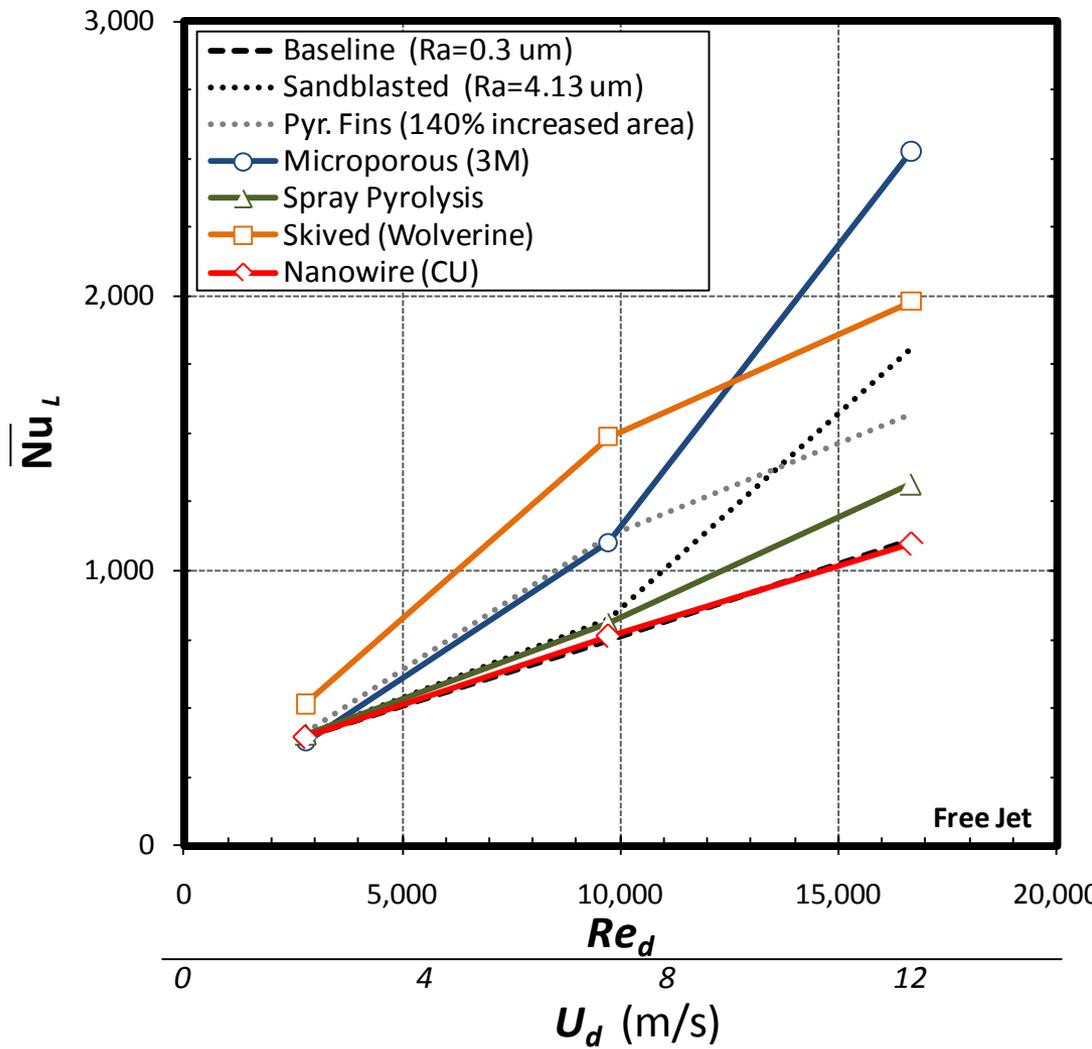
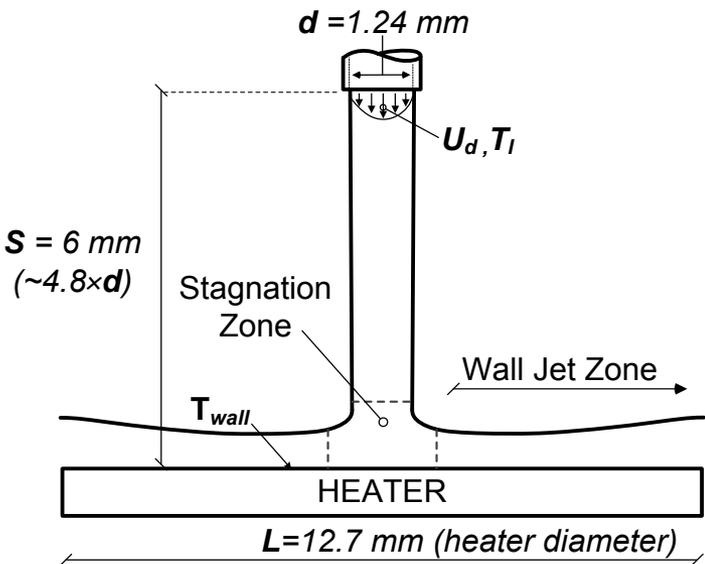
Enhanced surfaces: single-phase submerged jet results

- Microporous/roughened surfaces had minimal effect on performance.
- Skived (Wolverine) produced highest h -value enhancement (~100%).
- Finned structures outperformed microporous/roughened surfaces (increased area effect).



Enhanced surfaces: single-phase free jet results

- Microporous coating (3M) produced highest h -value enhancement (~130%).
- Greater enhancement than that reported in literature.
- Microporous/roughened surfaces outperformed finned surfaces at higher velocities.



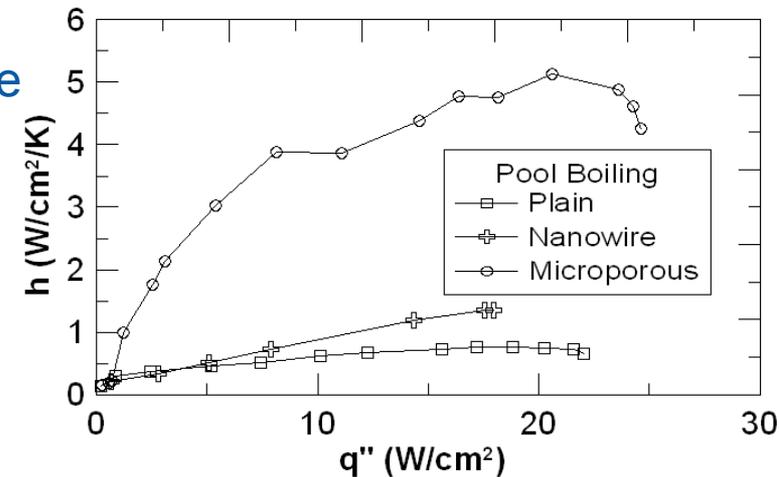
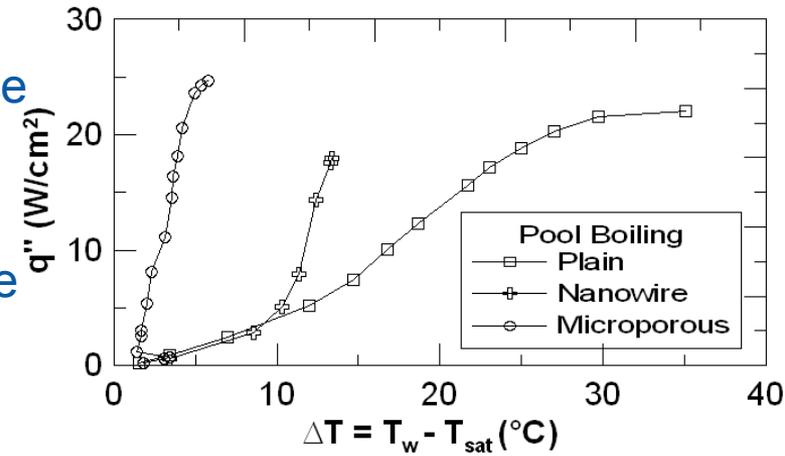
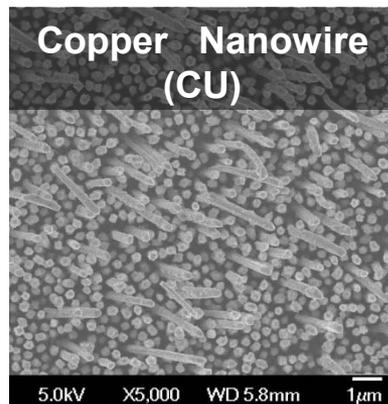
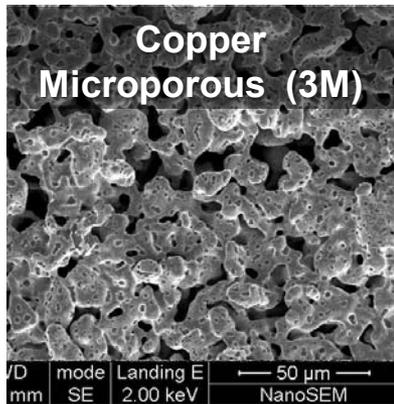
Two-phase cooling (pool boiling and spray impingement boiling) in conjunction with enhanced surfaces

- **HFE-7100 dielectric.**
- **Saturated and subcooled conditions.**
- **Pressurized, full cone spray nozzle.**
- **Three different enhanced surfaces tested.**
- **Pool boiling tests for reference.**

Enhanced surfaces: pool boiling (saturated HFE 7100)

Microporous Coating and Nanowires

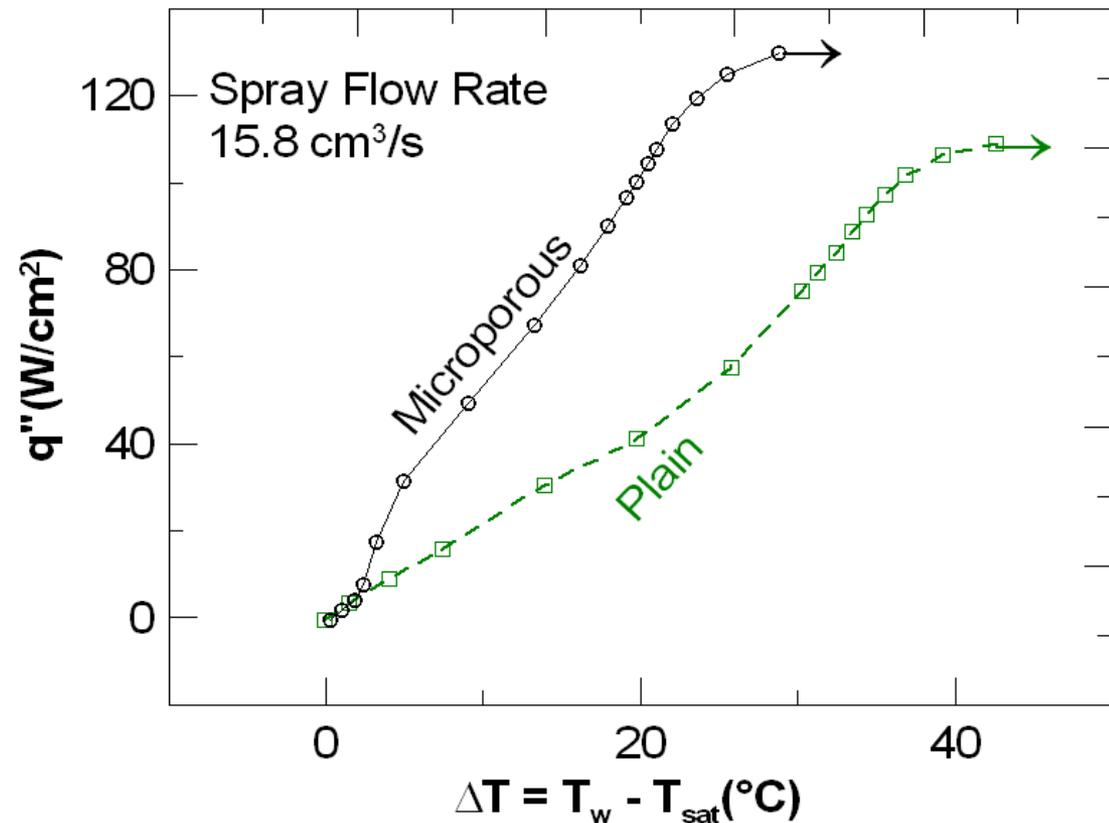
- Both the enhanced surfaces show lower incipience temperatures than the plain surface.
- The microporous surface showed ~500% increase in the heat transfer coefficient at the same heater power, and ~10% increase in the critical heat flux (CHF) in comparison to the plain surface.
- The nanowire surface showed about 60% increase in the h near the CHF, while the CHF itself was considerably lower.



Enhanced surfaces: spray impingement boiling (saturated HFE 7100)

Microporous Coating

- 100-300% increase in nucleate boiling (N.B.) heat transfer with respect to plain surface.
- 7-20% increase in the CHF with respect to plain surface.
- Coating structure (micro cavities of various sizes) enhances boiling heat transfer.

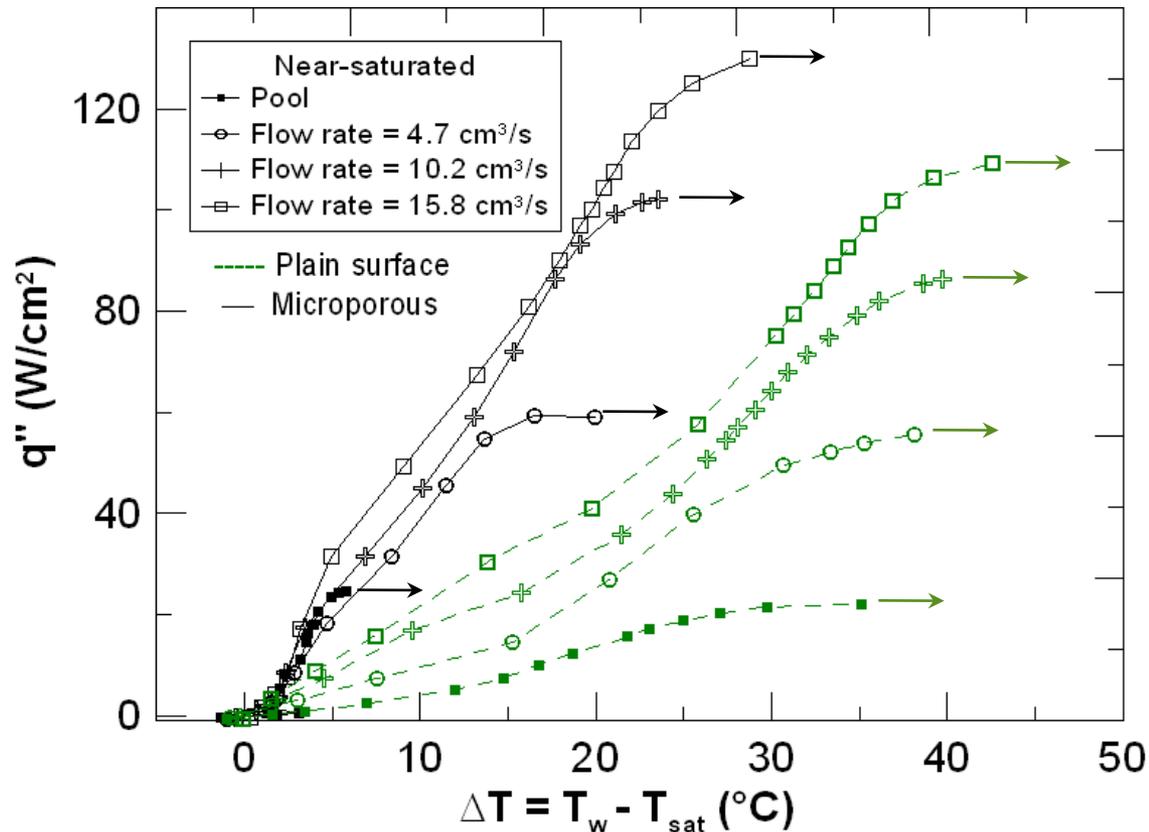


HFE-7100 dielectric Fluid
Full cone spray @15.8 cm³/s
(corresponds to 7 m/s velocity)

Enhanced surfaces: spray impingement boiling (saturated HFE 7100)

Flow Rate Effect

- Increasing flow rate has minimal effect on nucleate boiling heat transfer for the microporous surface.
- Boiling is the dominant heat transfer mechanism on coated surface, less sensitive to convective effects.



HFE-7100 dielectric fluid
Saturated conditions

System level implication

Jet impingement

• Submerged jet w/ skived surface decreases R_{th-j-a} by:

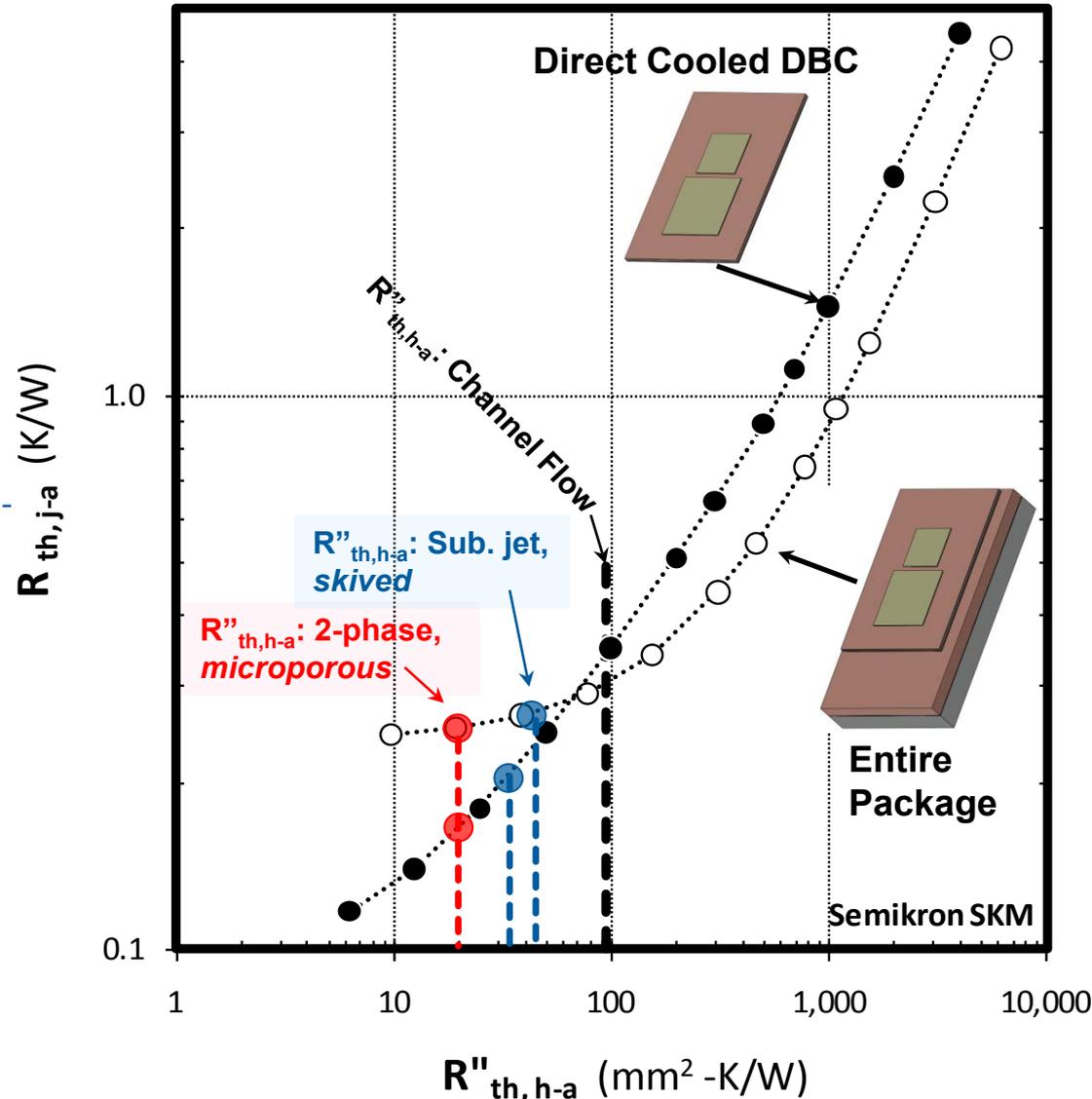
- 11% (Entire Package),
- 39% (DCD).

Two-phase

• Pool boiling or spray cooling w/ microporous coating decreases R_{th-j-a} by:

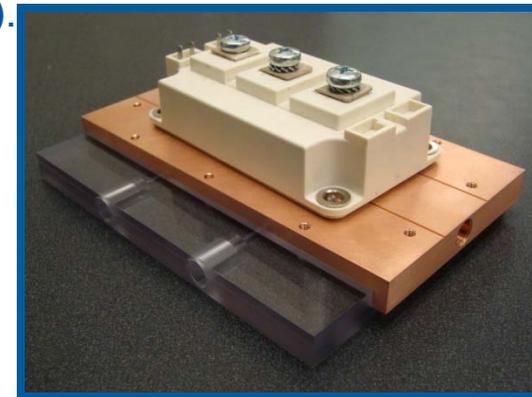
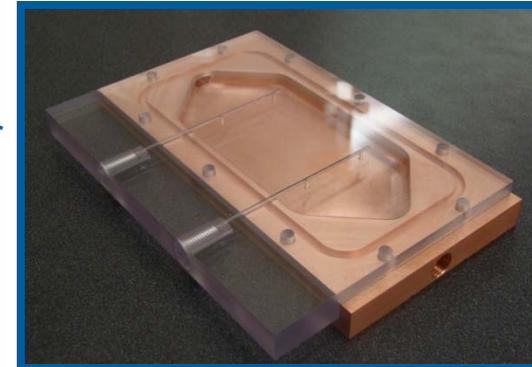
- 16% (Entire Package),
- 61% (DCD).

Decrease in R_{th-j-a} will vary with different package configuration.



Future Work

- i. **Reliability:**
 - Investigate degradation of plain surface when subject to jet impingement including nozzle degradation over time,
 - Investigate ability of enhanced surface to remain effective under long term use.
- ii. **Synthesize/optimize** additional coatings (e.g., using spray pyrolysis)
 - Single-phase & two-phase applications (HFE7100, HFO-1234yf).
- iii. **Implement** single-phase jet impingement with enhanced surfaces on a commercially available power electronics package (Semikron SKM).
- iv. **Implement** two-phase cooling with enhanced surface in a package.
- v. **Implement** flow visualization/characterization to understand underlying physics/mechanisms behind surface enhancements
 - PIV/micro-PIV, High speed video & Schlieren shadowgraphs.



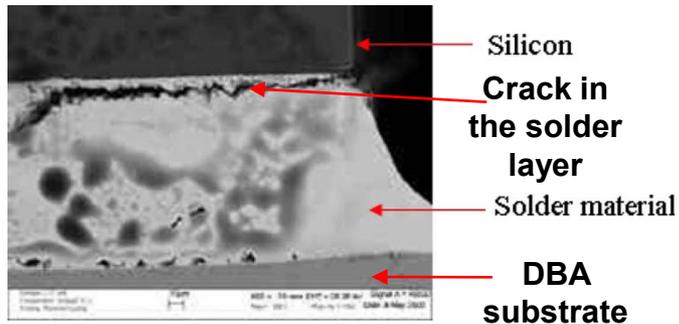
Thermal interface materials for power electronics applications

Thermal interface materials - project relevance

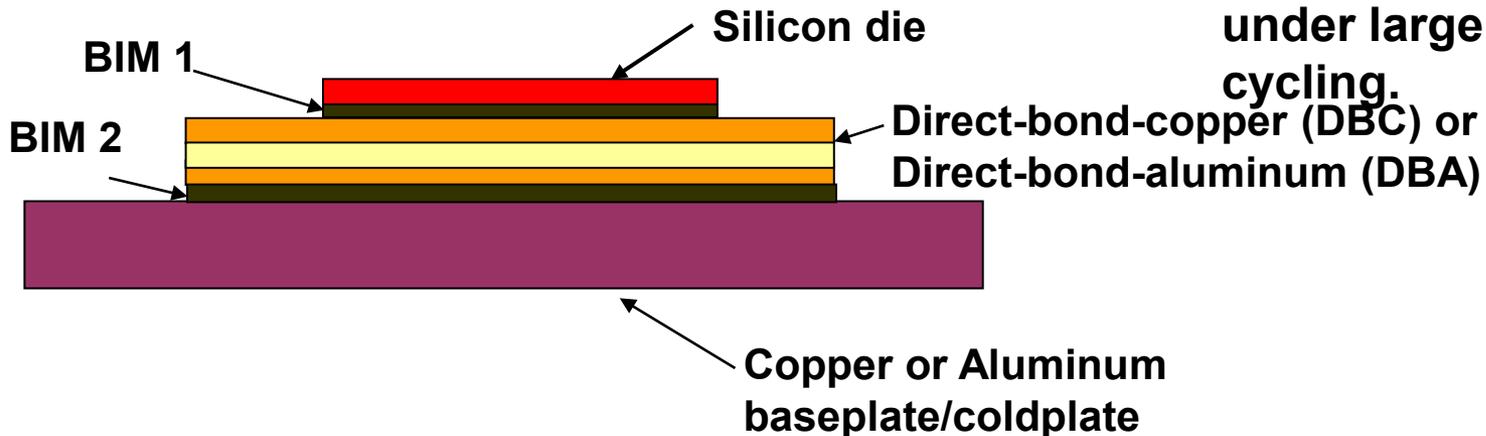
- Excessive temperature can degrade the performance, life, and reliability of power electronic components.
- Advanced thermal control technologies are critical to enabling higher power densities and lower system cost.
- Interfaces pose a major bottleneck to heat removal.
- Bonded interface materials (BIMs) based on solder are associated with thermomechanical reliability concerns under temperature cycling, as well as degradation at higher temperatures ($>120^{\circ}\text{C}$).

The Problem

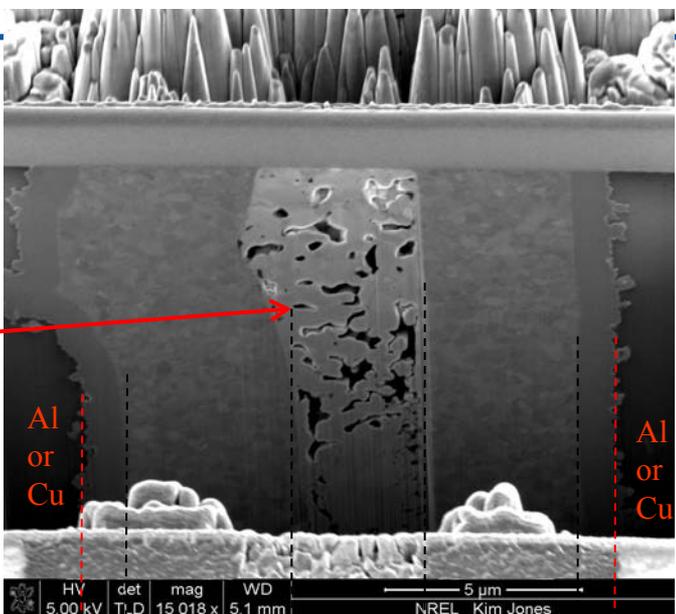
K. Stinson-Bagby, M.S. Thesis,
Virginia Tech, 2002.



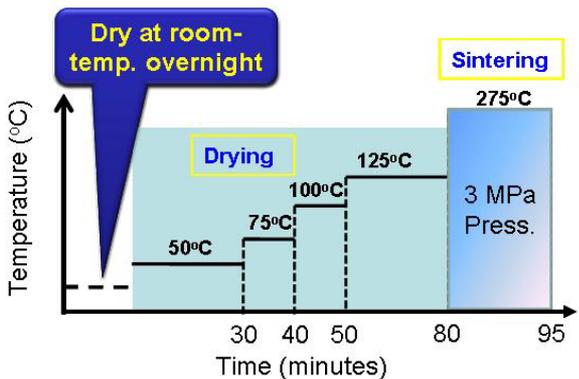
- Conventional TIMs do not meet thermal performance and reliability targets.
- Due to advantages from a packaging viewpoint, industry is trending toward bonded interfaces.
- Bonded interfaces such as solder degrade at higher temperatures, and are prone to thermomechanical failure under large temperature cycling.



Sintered interfaces – based on silver nanoparticles



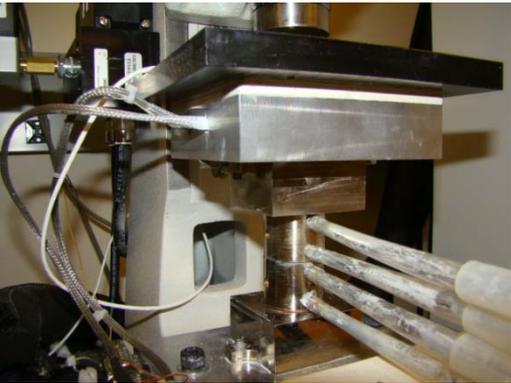
Fixture



Sintering cycle

- Sintered interfaces synthesized between silvered Cu-Cu and Al-Al disks (31.8 mm diameter) at Virginia Tech.
- A nickel coating (~2 μm) followed by silver coating (~2 μm) is applied on the copper and aluminum disks.
- For comparison, lead-free solder (SN100C) interface synthesized between Cu-Cu disks (31.8 mm diameter).
- Different thicknesses fabricated (20 ~ 200 microns).

Sintered interfaces – preliminary experimental results

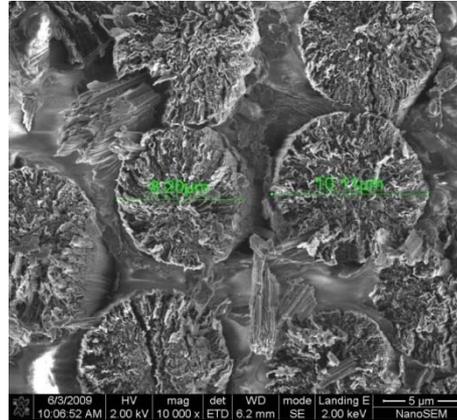
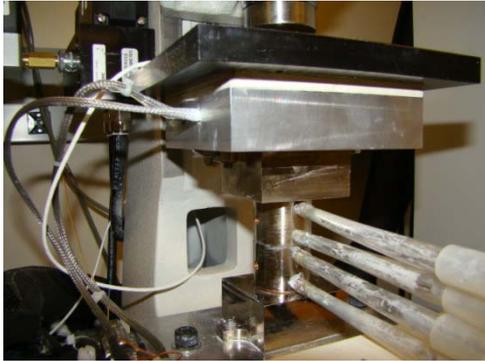


ASTM test fixture

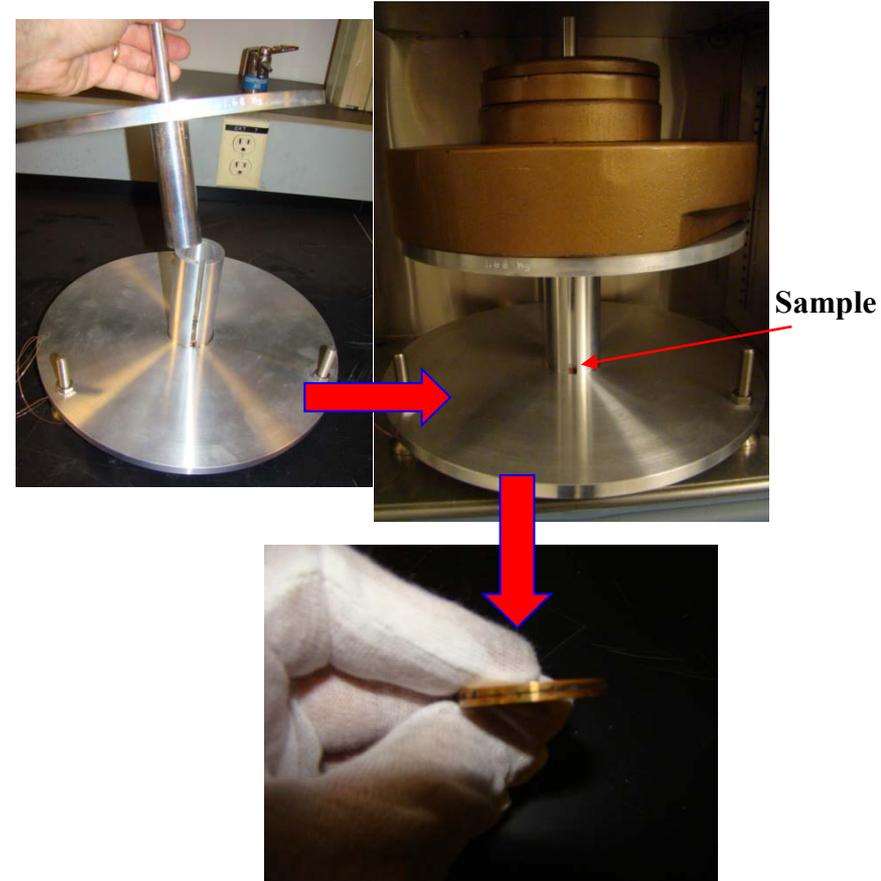
Samples	Thickness (μm)	Resistance ($\text{mm}^2\text{K}/\text{W}$)
Silvered Cu-Cu sintered interface	20	5.8
	27	8.0
	64	5.4
Silvered Al-Al sintered interface	28	14.9
	103	25.2
	144	5.0
Cu-Cu soldered interface (SN100C)	80	1.0
	150	4.8
	200	3.7

- The thermal resistance tests were performed using the NREL ASTM TIM apparatus
 - Average sample temperature $\sim 65^\circ\text{C}$, pressure is 276 kPa (40 psi).
- The silvered Cu-Cu sintered interface shows promising thermal performance.
- Results hint at some problems with the bonding of the silvered Al-Al interface.
- The lead-free solder (SN100C) interface initial thermal results are very promising.

Thermoplastics with embedded carbon fibers



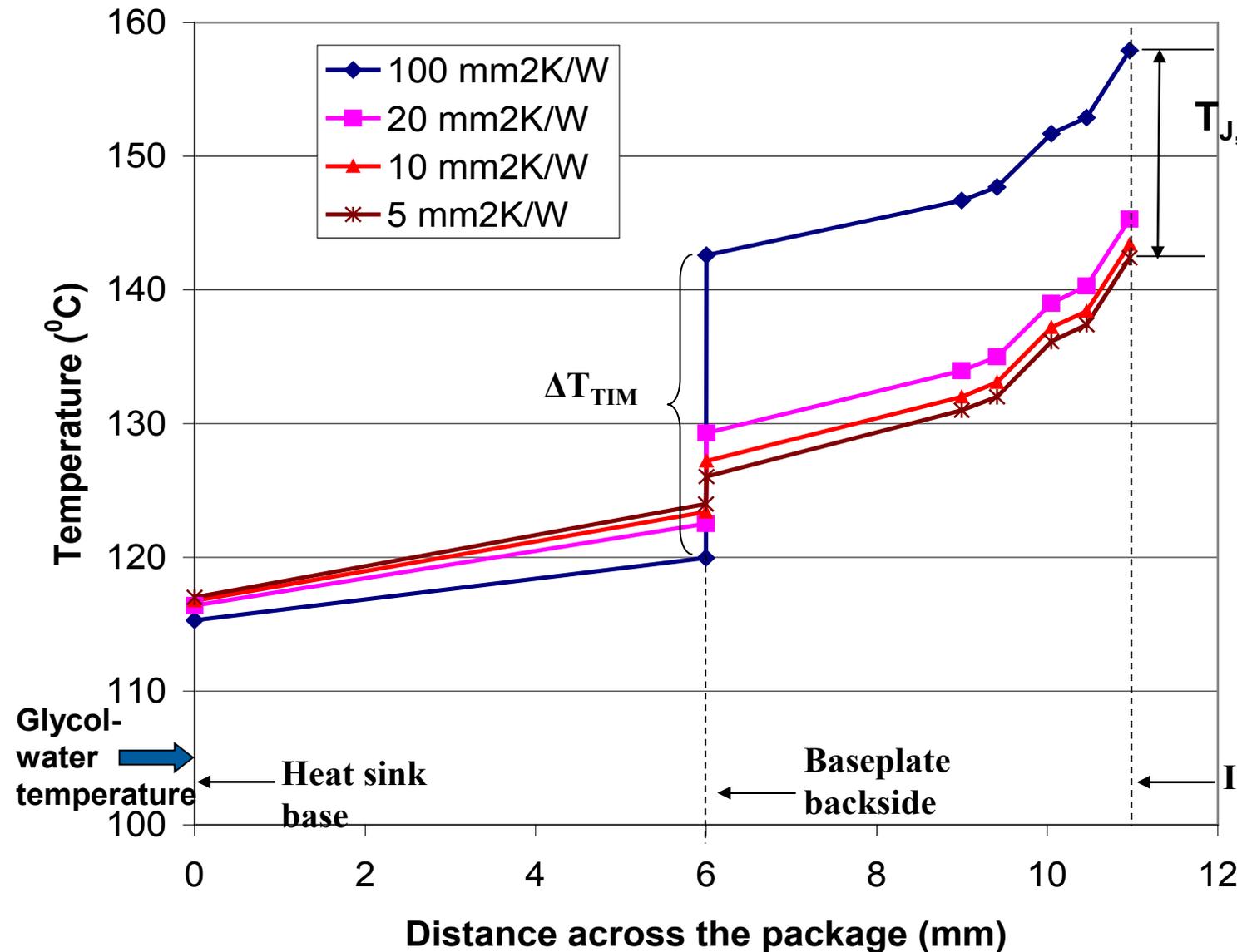
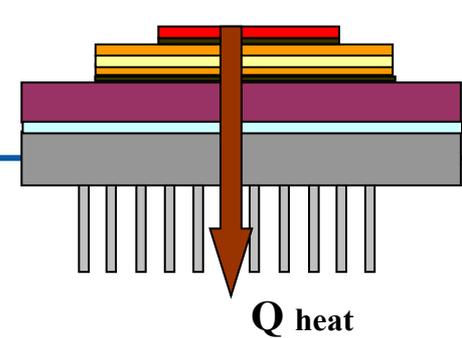
Sequence of bonding steps



- Thermoplastic films (provided by Btech) bonded between 31.8 mm diameter copper disks.
- Promising thermal results (**8 mm²K/W for 100 microns bondline thickness**).
- Continuing work at NREL to further decrease contact resistance to approach target thermal performance, as well as characterize reliability.

Temperature Across a Package

- FEA analysis using Toyota package



At 100 W/cm² heat dissipation in the die, the maximum junction temperature ($T_{J,max}$) decreases by 16°C when TIM resistance decreases from 100 to 8 mm²K/W.

IGBT location

Baseplate backside

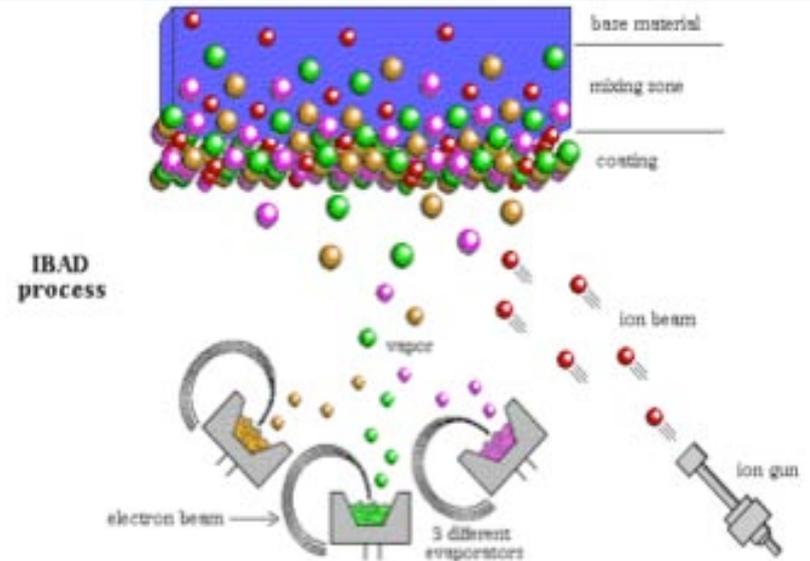
Heat sink base

Glycol-water temperature

Future Work

Remainder of FY10

- Work with Btech to develop and test (via ASTM steady-state approach) improved and reliable thermoplastics with embedded carbon fibers meeting target thermal performance
 - Reduce contact resistance via ion-implantation and metal evaporation/sputtering techniques.
- In collaboration with Virginia Tech and Btech, synthesize and characterize various joints between DBA/DBC and aluminum/copper baseplate
 - Synthesis of soldered, sintered, brazed and thermoplastic joints,
 - Subject joints to thermal shock,
 - Thermal resistance measurement after select cycles,
 - CSAM after select cycles,
 - High-potential test after select cycles,
 - Modeling of the joint thermomechanical behavior (physics-of-failure) – end-of-life predictive model.



Tom Gennett, NREL

Future Work

FY11, FY12

- Detailed synthesis and characterization of thermal performance and reliability of joints based on the matrix given below
 - Synthesis of bond/joint,
 - Subject joint/bond to thermal shock,
 - Thermal resistance measurements after select cycles,
 - Joint quality characterization (CSAM) after select cycles,
 - High-potential test after select cycles,
 - Modeling of thermo-mechanical behavior of the joints,
 - Degradation/end-of-life model of the joints and the package.



Joint Material	Substrate	Metallization	Coating	Baseplate
Solder Joints (Pb free & Pb)	AlN	Al	Ag	Al
Brazed Joints	Al ₂ O ₃	Cu	Au	Cu
Sintered Joints	Si ₃ N ₄			AlSiC
Thermoplastics				

+
PROCESS
+
REPETITIONS



Summary

- Thermal management plays an important part in the cost of electric drives in terms of power electronics packaging.
- Very promising results from microporous coatings and skived surfaces in conjunction with single and two-phase flows.
- Sintered materials and thermoplastics with embedded fibers show significant promise as TIMs.
- Appropriate cooling technology depends on:
 - Package application,
 - Reliability.

Acknowledgments

- Susan Rogers, U.S. Department of Energy
- Kevin Bennion, Charles King, Mark Mihalic, Gilbert Moreno, Michael O'Keefe, Suraj Thiagarajan, Travis Venson, Tom Gennett, Kim Jones, Bobby To (NREL)
- Wei Wang and Ronggui Yang (CU Boulder)
- Jay Browne (Btech)
- Gary Eesley (Delphi)
- Greg Smith (GM)
- Sy-Jenq Loong (Wolverine Tube Inc.)
- Phil Tuma (3M)
- G.Q. Lu (Virginia Tech)