NATIONAL RENEWABLE ENERGY LABORATORY

Power Electronics Thermal Control

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Center for Transportation Technologies and Systems

Presented at the
Interagency Advanced
Power Group Meeting

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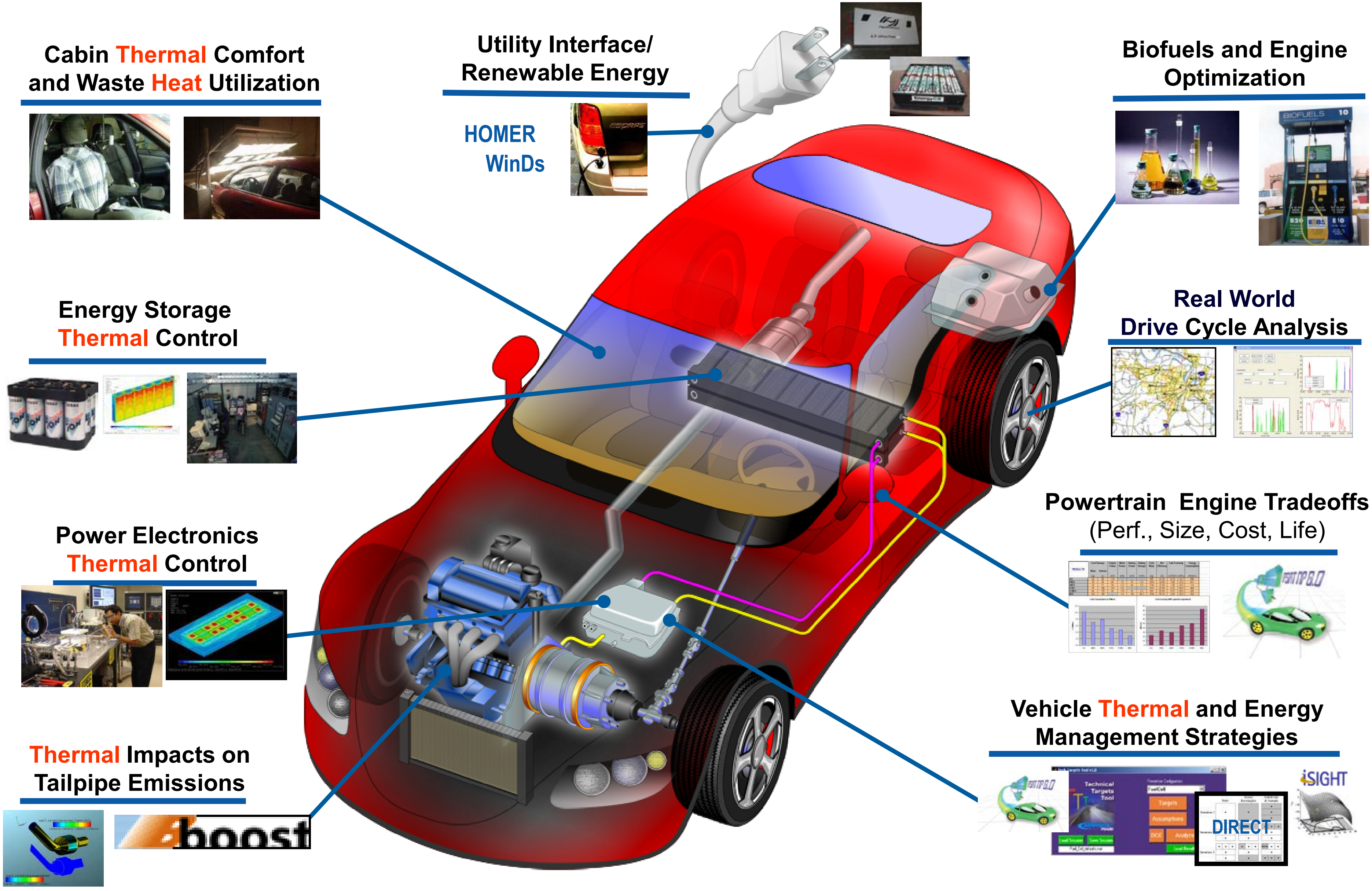
NREL/PR-540-48053

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

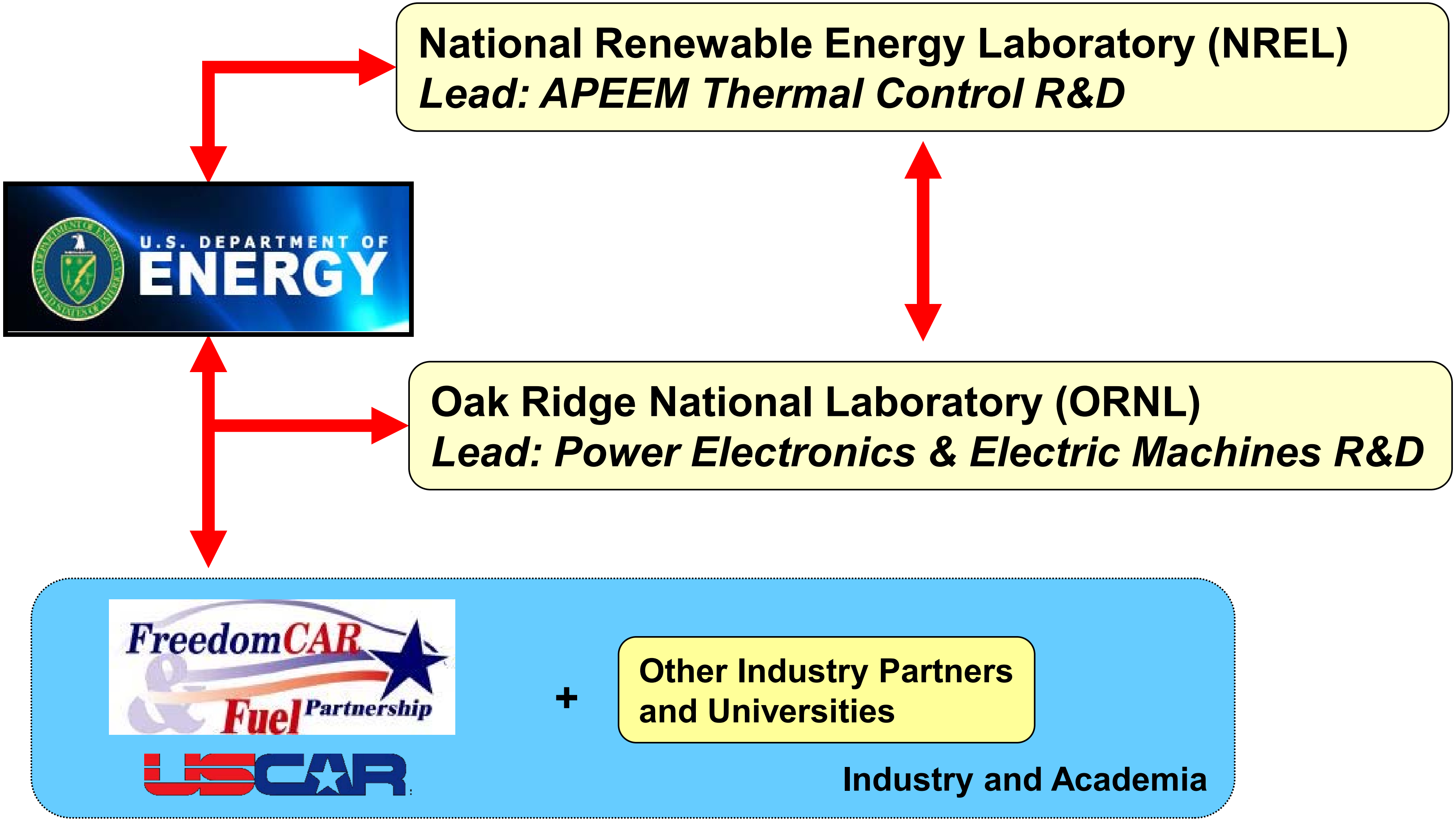
Power Electronics Thermal Control

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)



U.S. DEPARTMENT OF ENERGY

National Renewable Energy Laboratory (NREL)
Lead: APEEM Thermal Control R&D

Oak Ridge National Laboratory (ORNL)
Lead: Power Electronics & Electric Machines R&D

FreedomCAR & Fuel Partnership

USCAR

\+

Other Industry Partners and Universities

Industry and Academia

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

	Traction Drive System				Power Electronics			Motors		
Year	($/kW)	(kW/kg)	(kW/l)	Efficiency	($/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

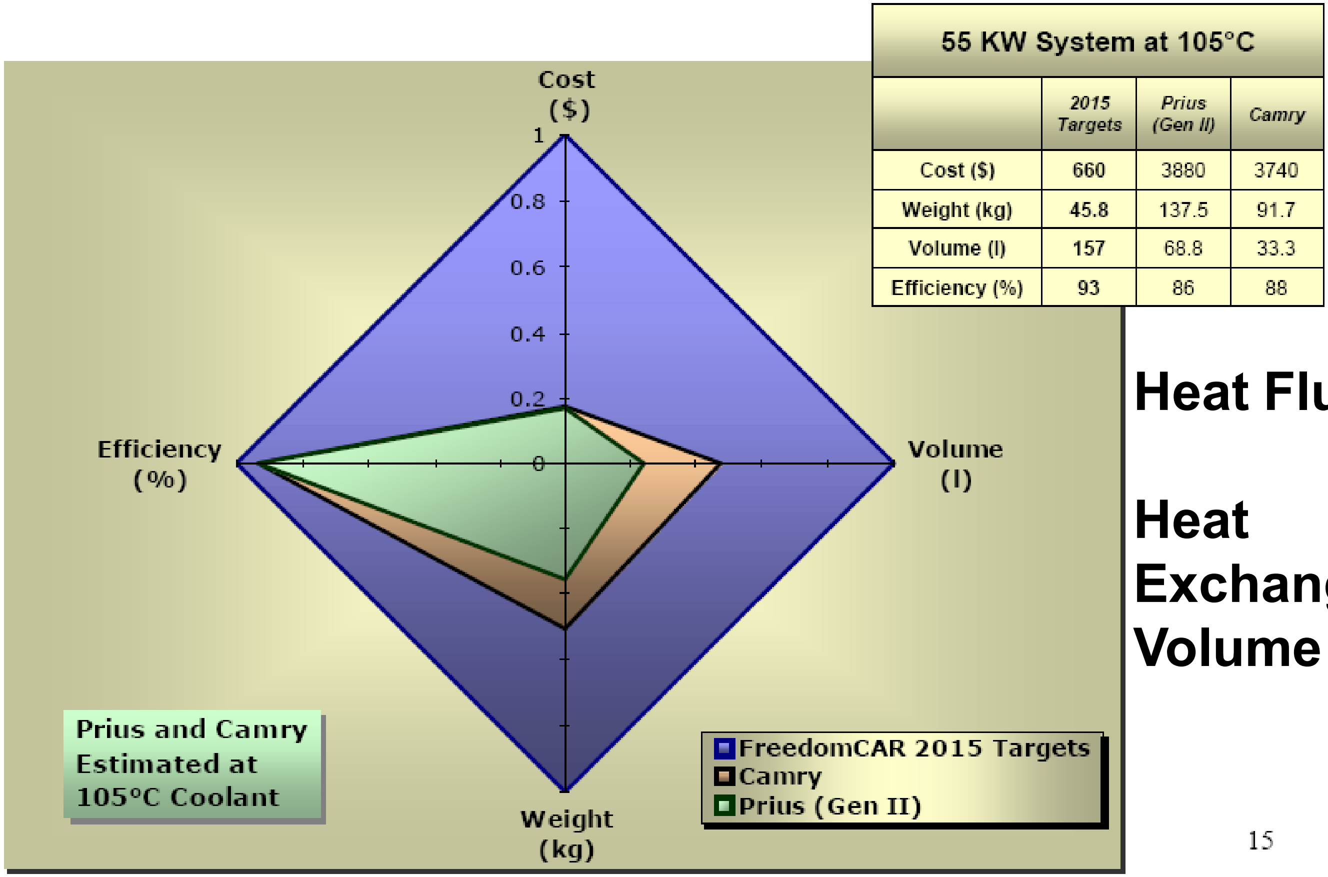
- benchmarking technologies
- innovative system designs

Technical targets

Coolant System
Material Selection
Number of Devices

Heat Generation

Cooling Requirements



Prius and Camry Estimated at 105°C Coolant

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

Heat Flux

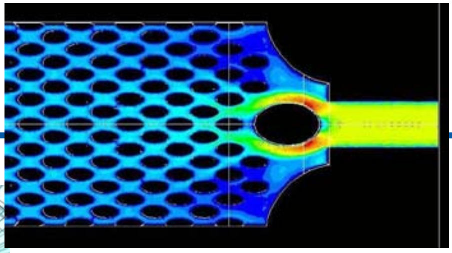
Heat Exchanger Volume

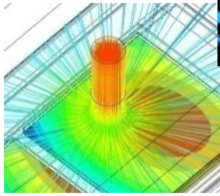
Heat Exchanger Materials

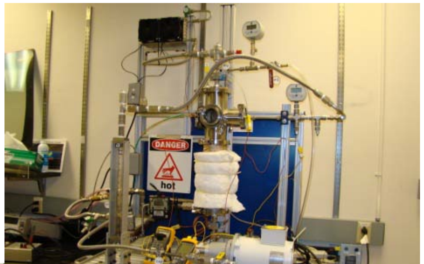
FY10 – Thermal Management projects

FOCUS AREA PROJECT	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





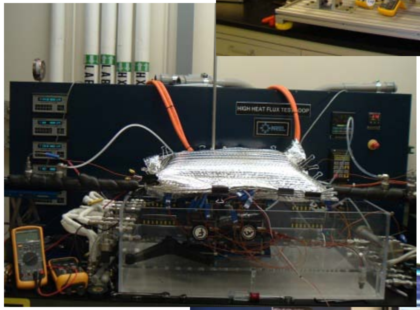


Improve PE device efficiency (ORNL)

Maximize base plate temperature
- PE materials selection
- reduce thermal resistance

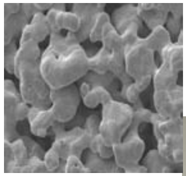
$$Q = h\ A\,(T_B - T_C\ )$$

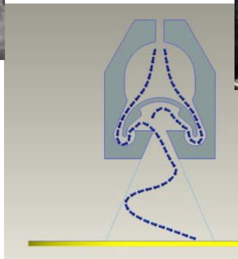
Coolant temperature
- reduce coolant temperature
- evaluate alternatives

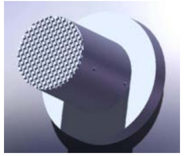


Increase surface area
- fin shape optimization
- double sided cooling
- surface enhancements
- thermal spreading

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.

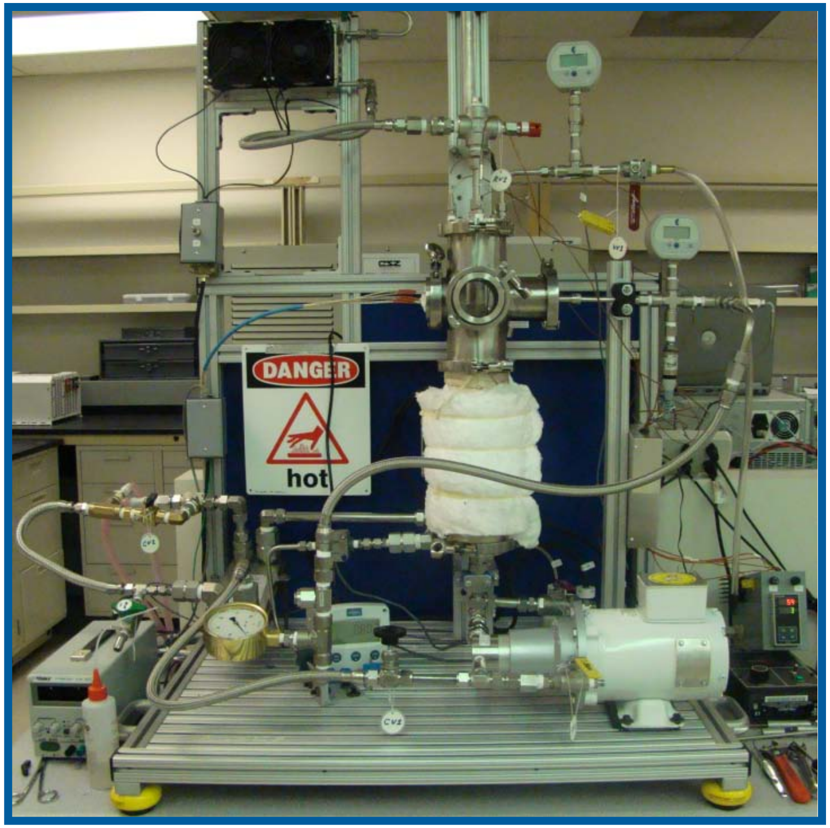
Procedure:

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.

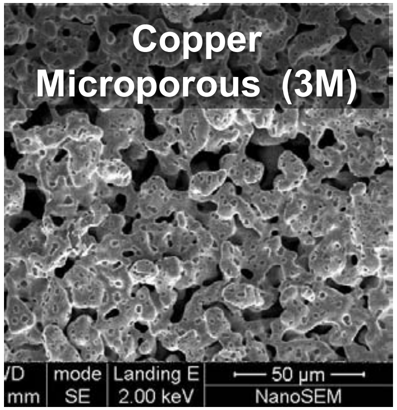
Approach

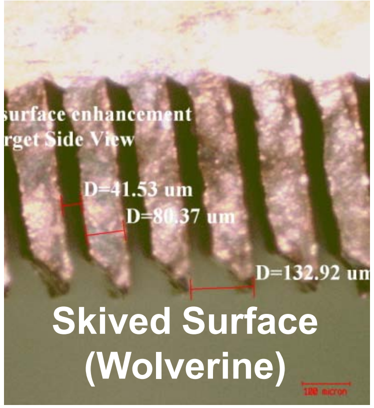
Strategy

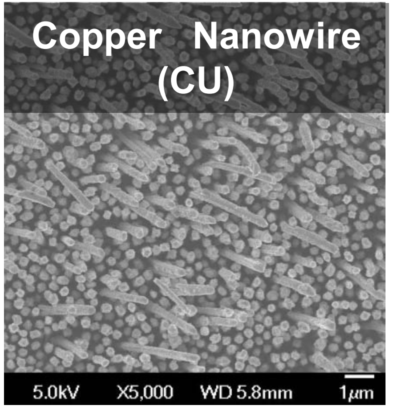
•**Current Work:** Fundamental study to characterize the thermal performance of the enhanced surfaces.

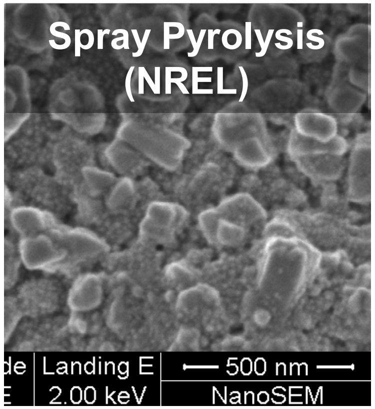
•**Future Work:** Implement technology on an actual power electronics module & evaluate the surface enhancement's reliability.

Enhanced Surfaces

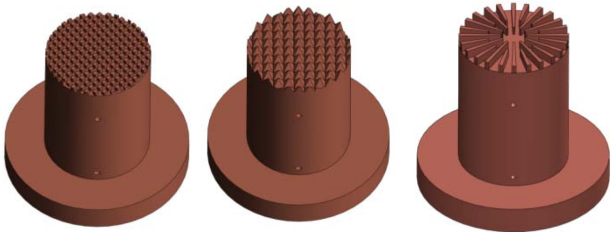








Finned Surfaces



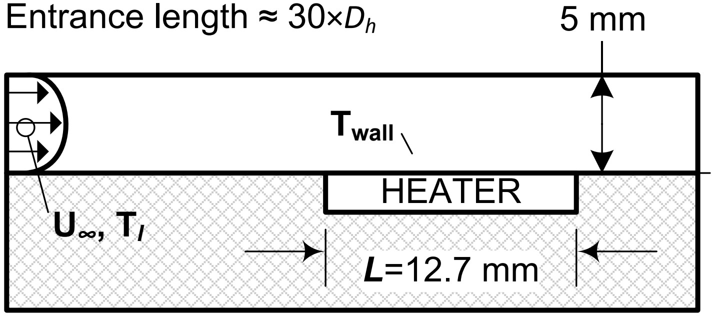
Single-phase channel flow and jet impingement in conjunction with enhanced surfaces

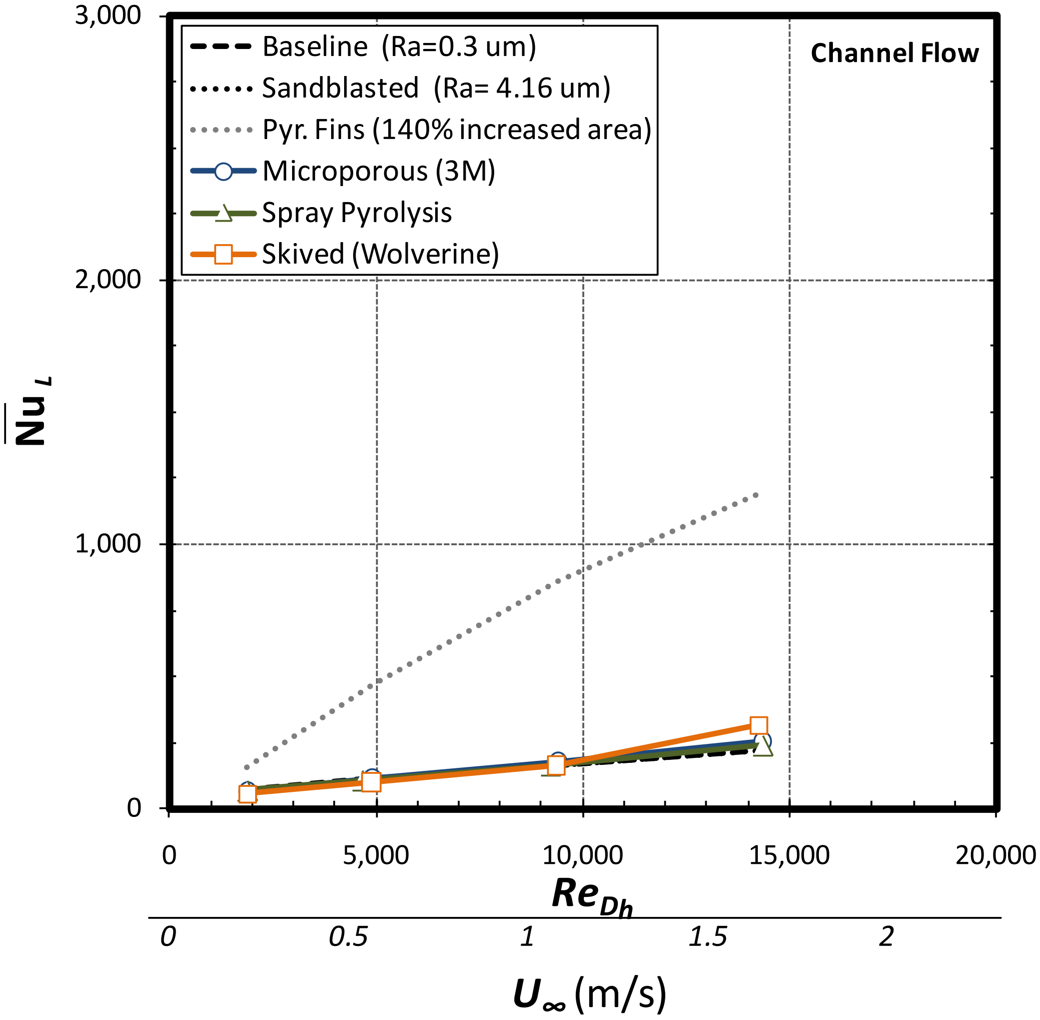
- **Water @ 25°C inlet temperature.**
- **Channel flow, free and submerged jet configurations.**
- **11 different surfaces tested.**
- **Channel flow tests for reference.**

Enhanced surfaces: single-phase channel flow results

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

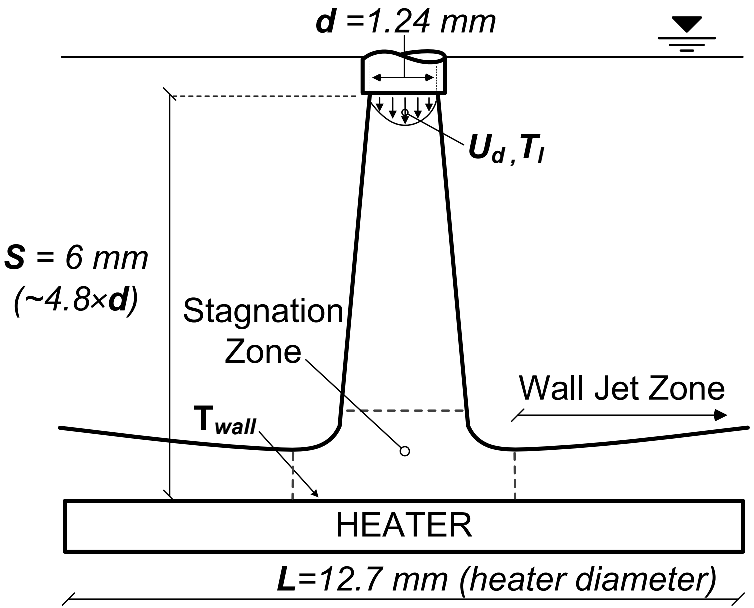
Channel, $D_h \approx 8$ mm
Entrance length ≈ $30 \times D_h$

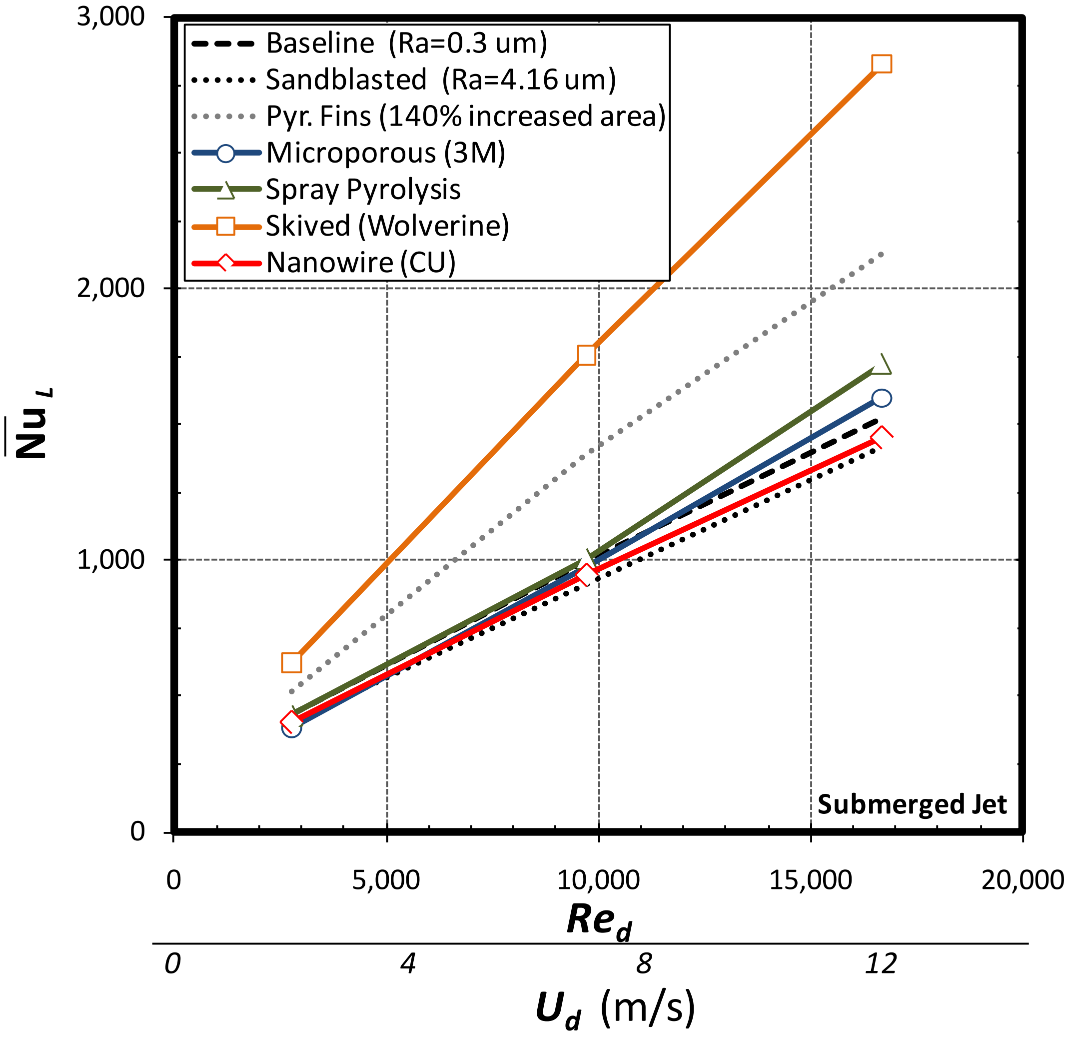




Enhanced surfaces: single-phase submerged jet results

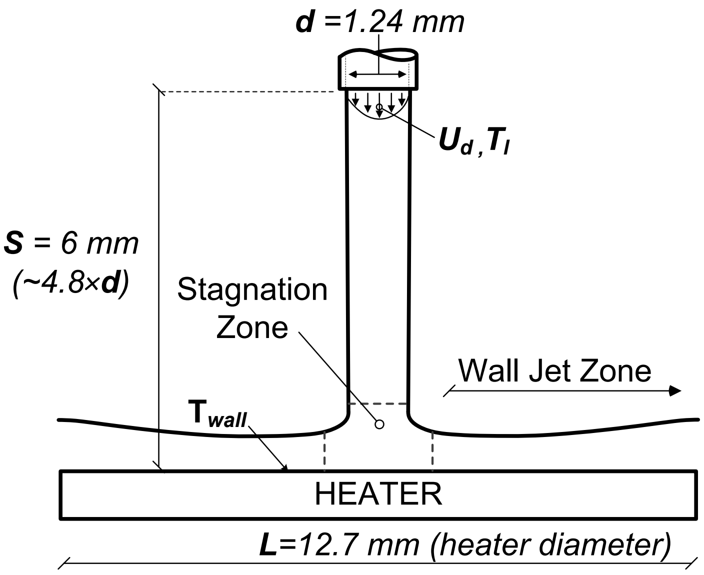
- Microporous/roughened surfaces had minimal effect on performance.
- Skived (Wolverine) produced highest *h*-value enhancement (~100%).
- Finned structures outperformed microporous/roughened surfaces (increased area effect).

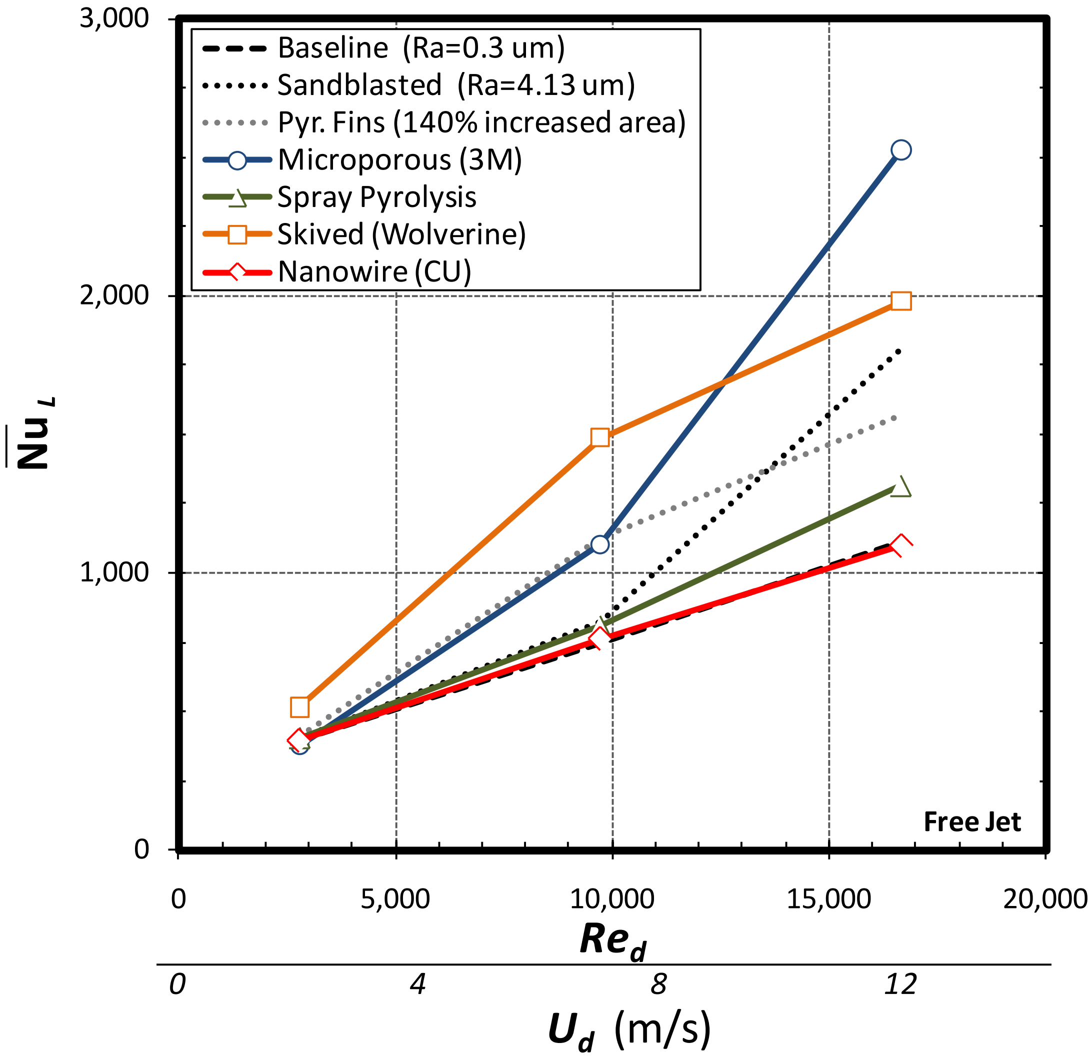




Enhanced surfaces: single-phase free jet results

- 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.

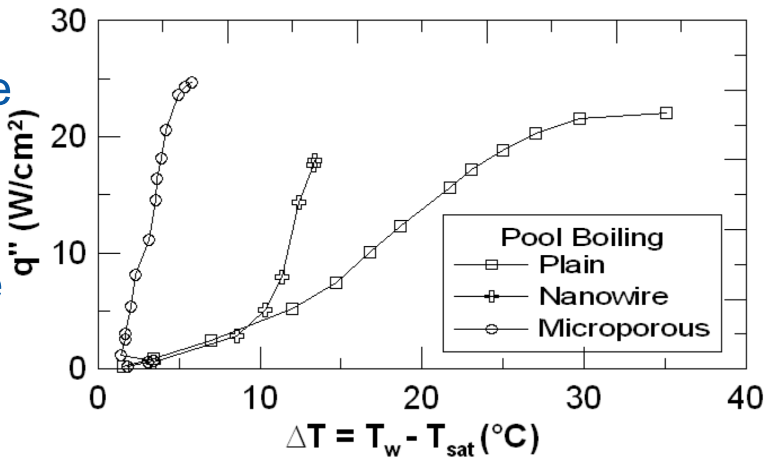
Enhanced surfaces: pool boiling (saturated HFE 7100)

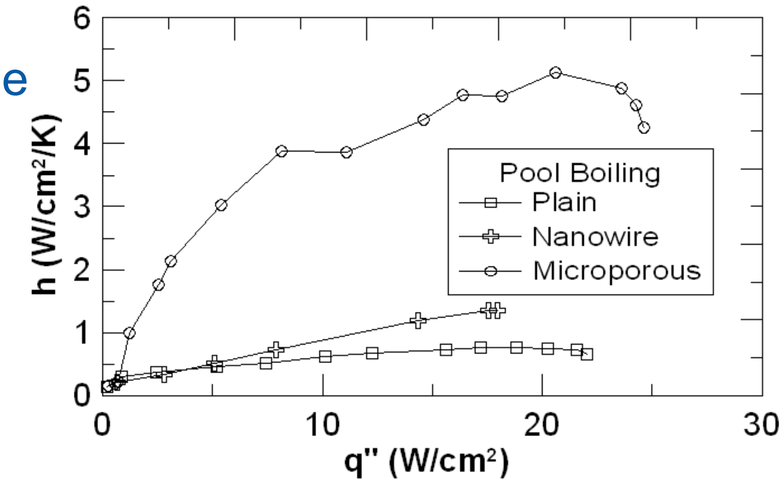
Microporous Coating and Nanowires

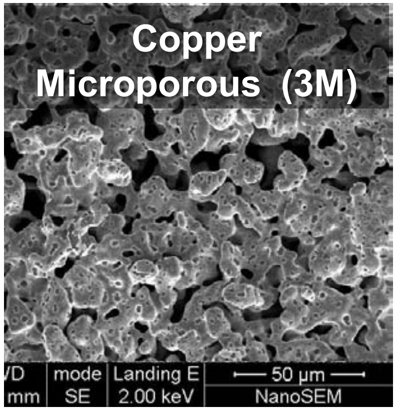
- Both the enhanced surfaces show lower incipience temperatures than the plain surface.

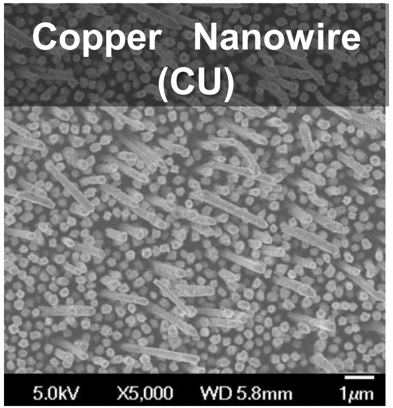
- The microporous surface showed ~500% increase in the heat transfer coefficient at the same heater power, and ~10% increase in the critical heat flux (CHF) in comparison to the plain surface.

- The nanowire surface showed about 60% increase in the *h* near the CHF, while the CHF itself was considerably lower.





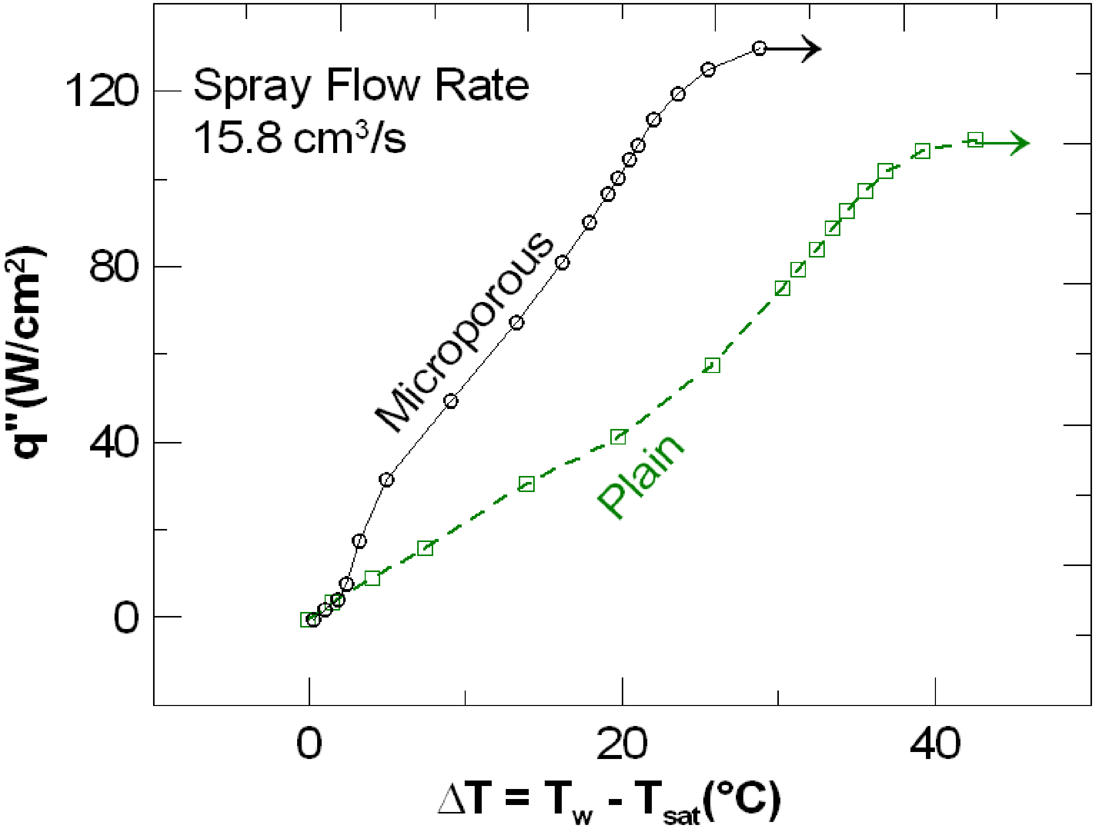

Copper Microporous (3M)


Copper Nanowire (CU)

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

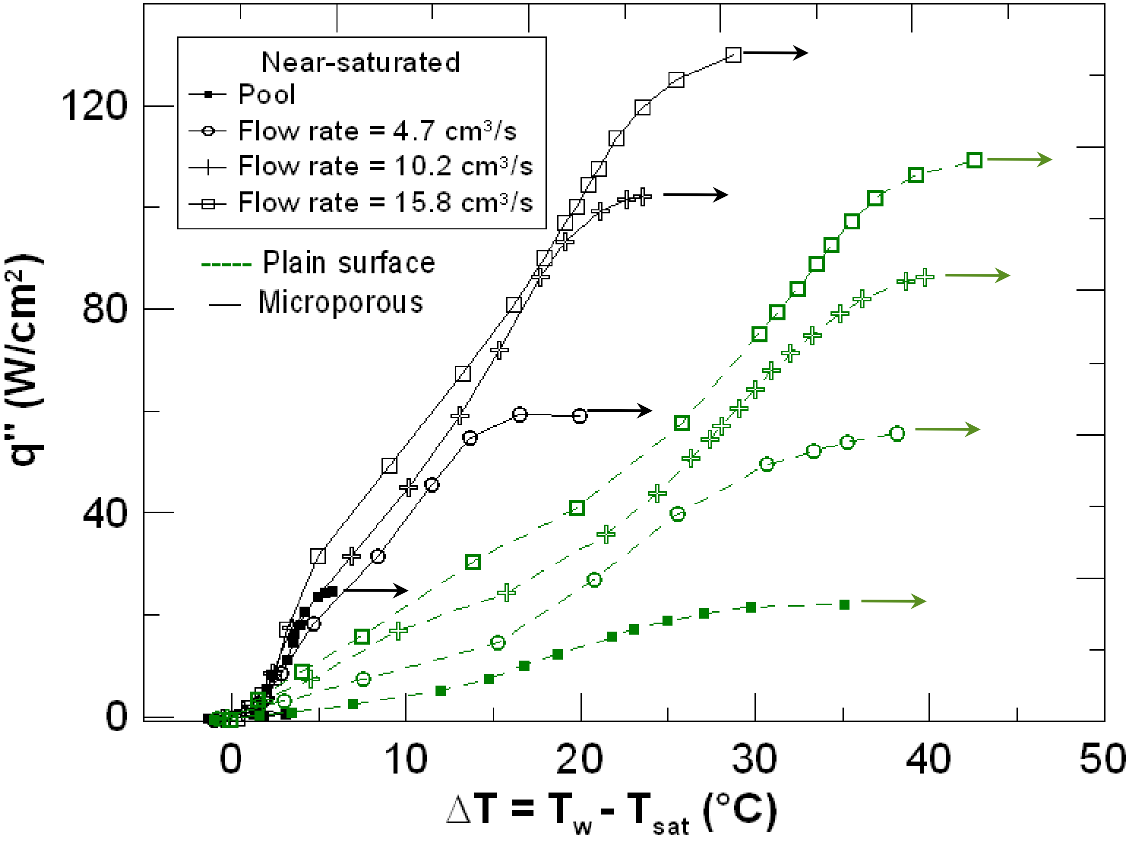
Full cone spray @15.8 cm^3/s (corresponds to 7 m/s velocity)

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

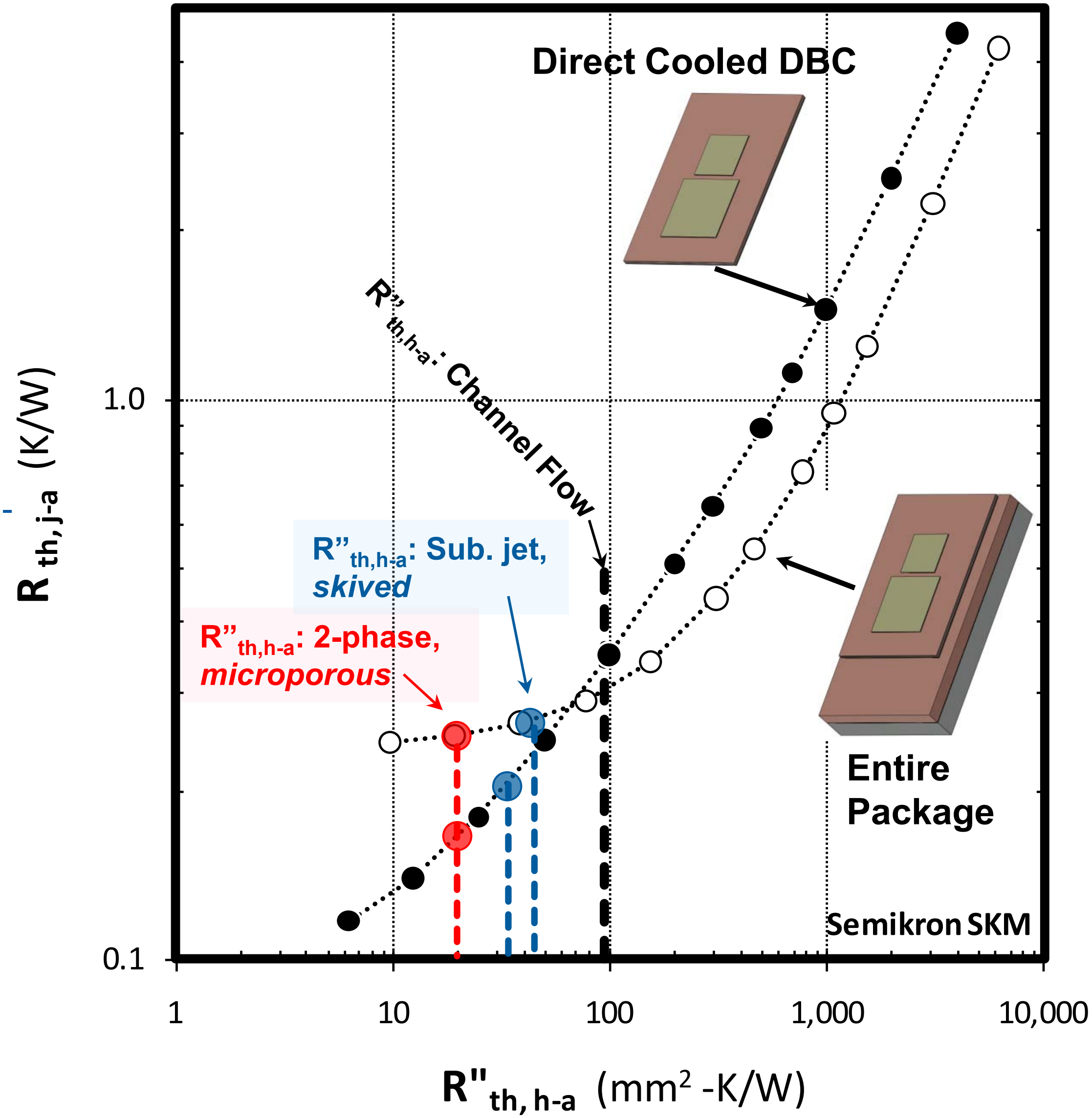
Jet impingement

- Submerged jet w/ skived surface decreases $R_{th\text{-}j\text{-}a}$ by:
  - **11% (Entire Package),**
  - **39% (DCD).**

Two-phase

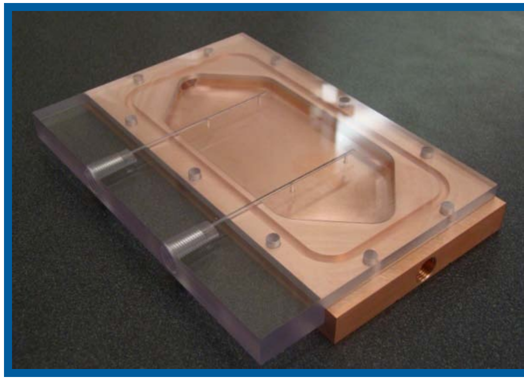
- Pool boiling or spray cooling w/ microporous coating decreases $R_{th\text{-}j\text{-}a}$ by:
  - **16% (Entire Package),**
  - **61% (DCD).**

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

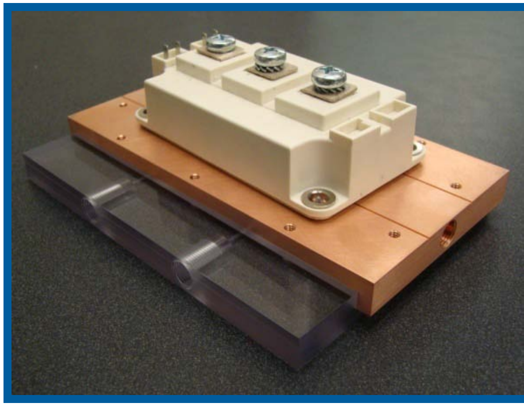


Future Work

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.

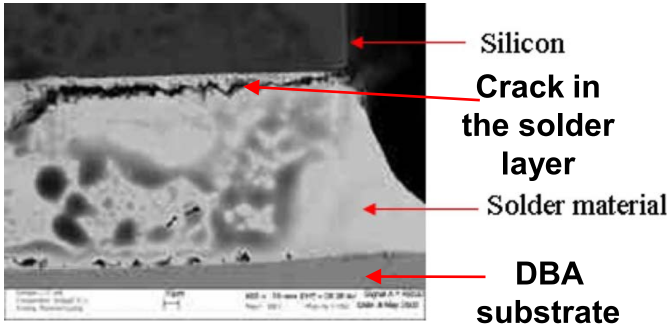
- Advanced thermal control technologies are critical to enabling higher power densities and lower system cost.

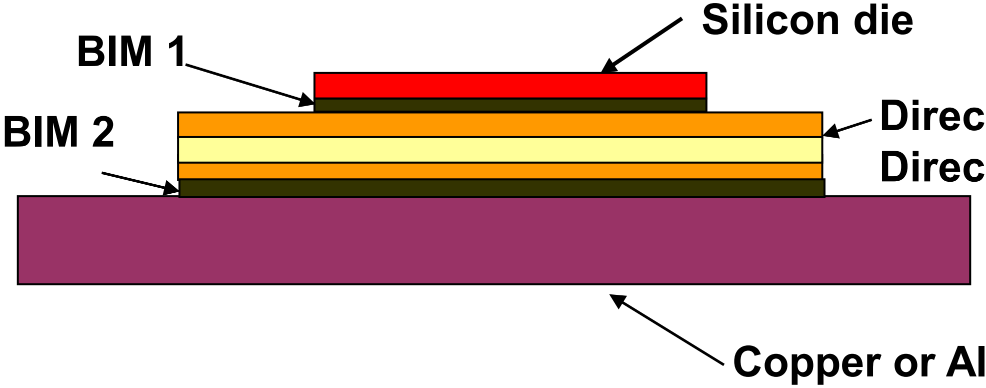
- Interfaces pose a major bottleneck to heat removal.

- Bonded interface materials (BIMs) based on solder are associated with thermomechanical reliability concerns under temperature cycling, as well as degradation at higher temperatures (>120°C).

The Problem

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





BIM 1

BIM 2

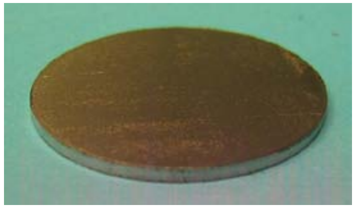
Silicon die

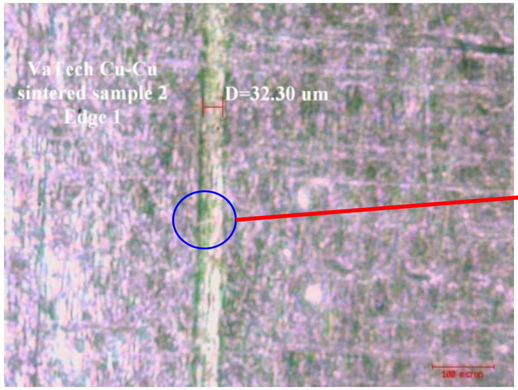
Direct-bond-copper (DBC) or Direct-bond-aluminum (DBA)

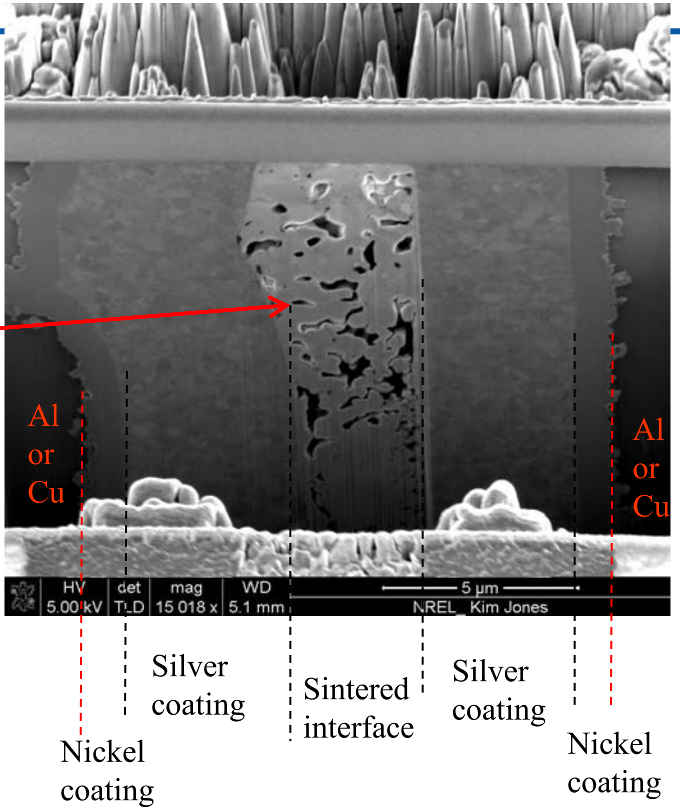
Copper or Aluminum baseplate/coldplate

- 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.

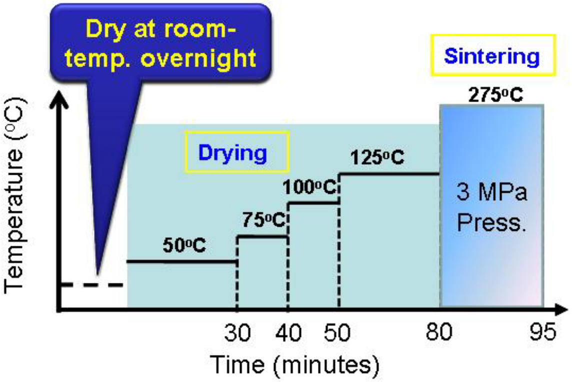
Sintered interfaces – based on silver nanoparticles







Fixture

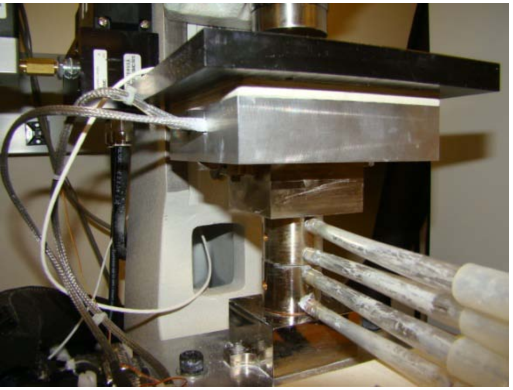


Sintering cycle

- 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).

G.-Q. Lu, Virginia Tech
Synthesis of sintered interface

Sintered interfaces – preliminary experimental results

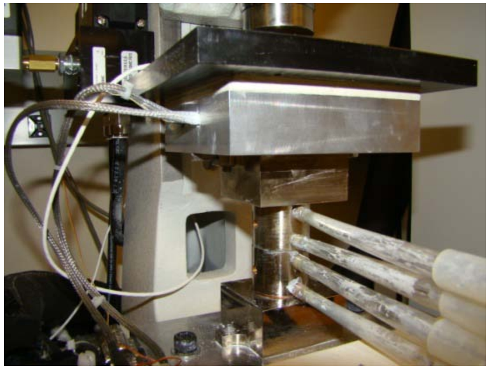


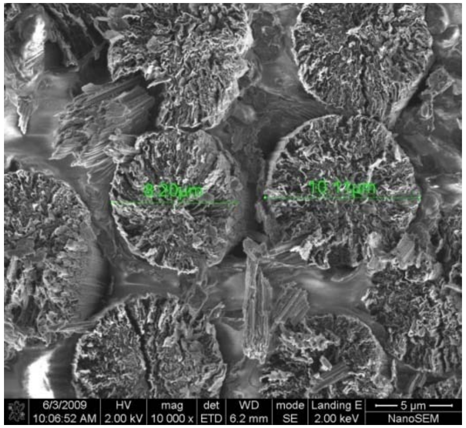
ASTM test fixture

Samples	Thickness (µm)	Resistance (mm^{2}K/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**

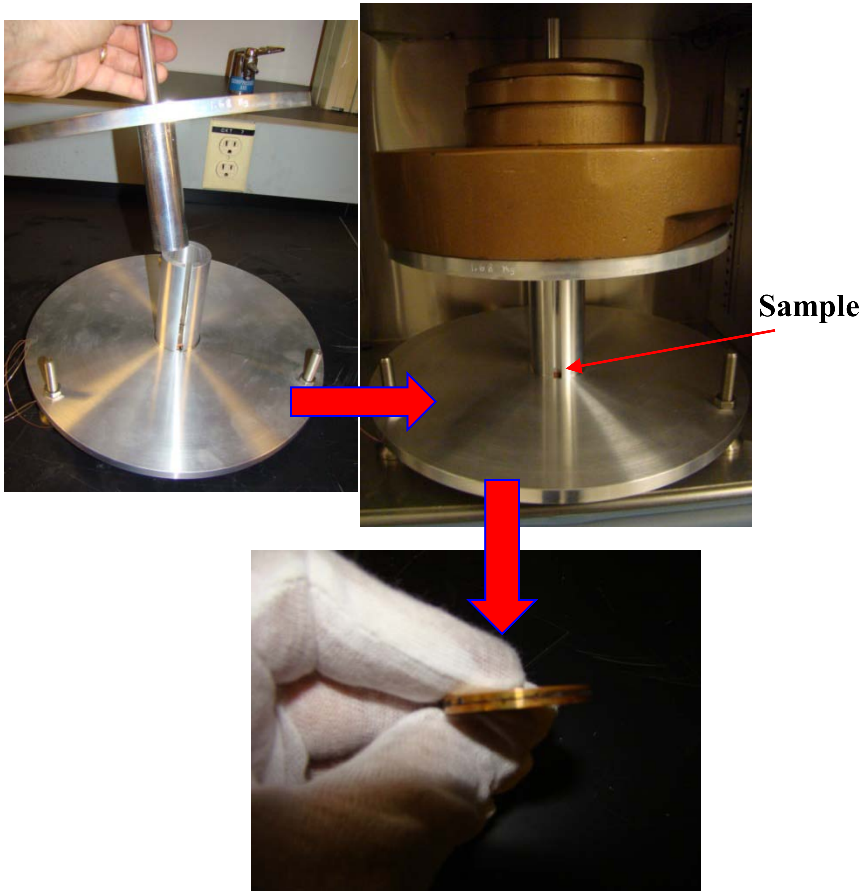
- The thermal resistance tests were performed using the NREL ASTM TIM apparatus
  - Average sample temperature ~ 65°C, pressure is 276 kPa (40 psi).
- The silvered Cu-Cu sintered interface shows promising thermal performance.
- Results hint at some problems with the bonding of the silvered Al-Al interface.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

Thermoplastics with embedded carbon fibers





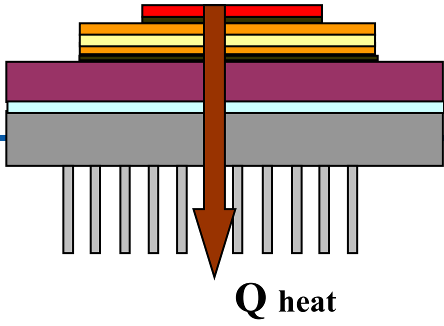
Sequence of bonding steps

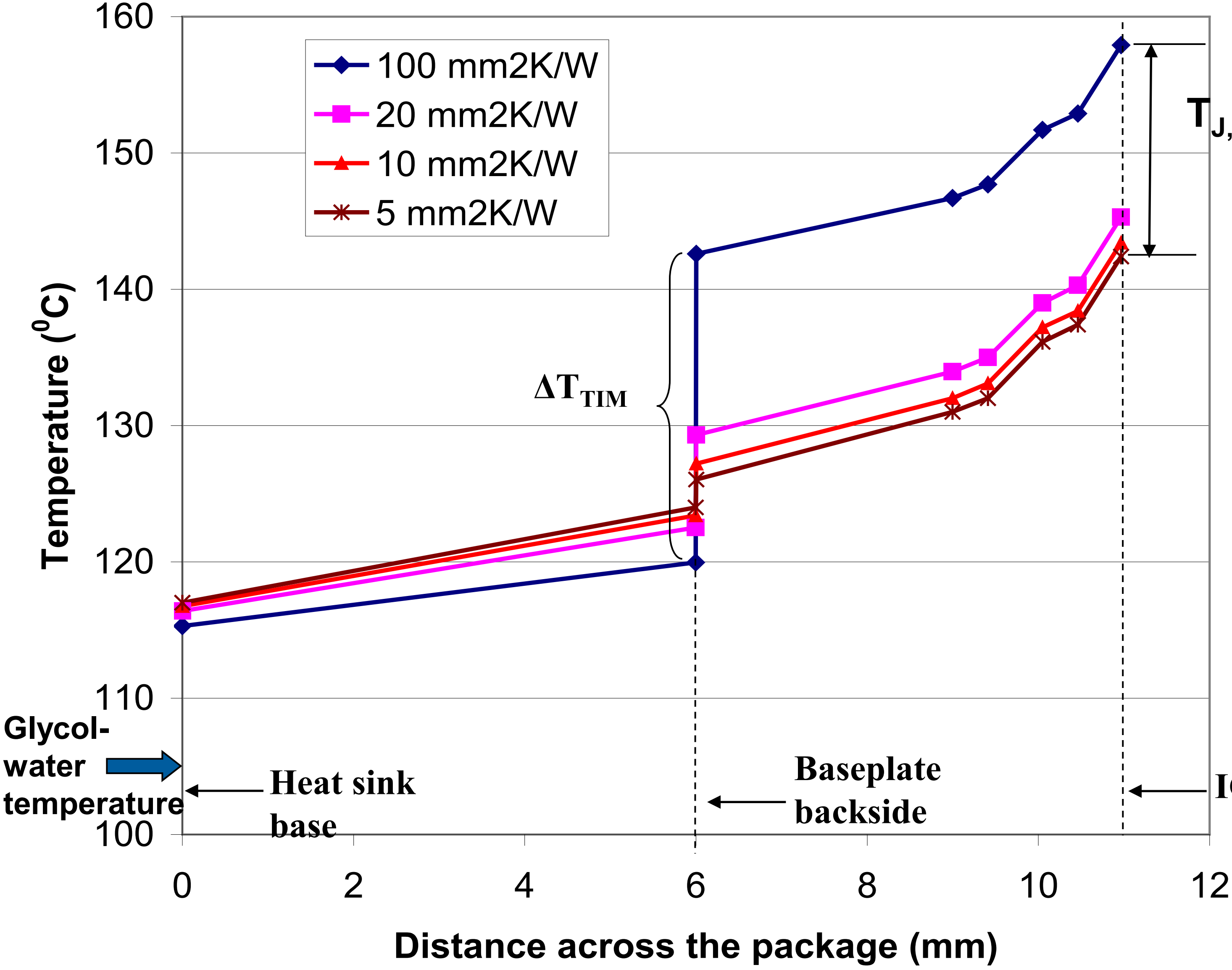


- Thermoplastic films (provided by Btech) bonded between 31.8 mm diameter copper disks.
- Promising thermal results (8 mm^{2}K/W for 100 microns bondline thickness).
- Continuing work at NREL to further decrease contact resistance to approach target thermal performance, as well as characterize reliability.

Temperature Across a Package

- FEA analysis using Toyota package





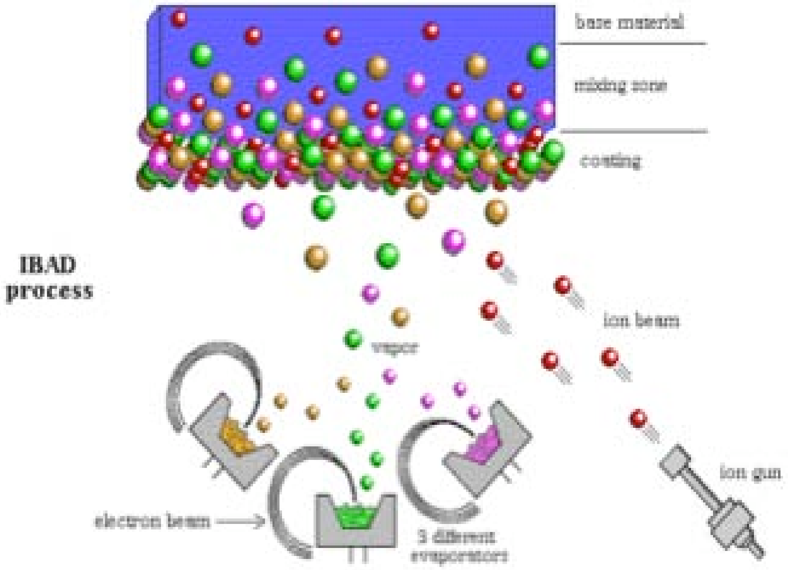
At 100 W/cm^2 heat dissipation in the die, the maximum junction temperature ($T_{J,max}$) decreases by 16°C when TIM resistance decreases from 100 to 8 mm^{2}K/W.

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_2O_3	Cu	Au	Cu
Sintered Joints	Si_3N_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.

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