NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Characterization and Development of Advanced Heat Transfer Technologies

2010 DOE Vehicle Technologies Program Review Presentation

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Project ID: **APE018**

OVERVIEW

Timeline

- Project Start: FY 2008
- Project End: FY 2010
- Percent Complete: 80%

Budget

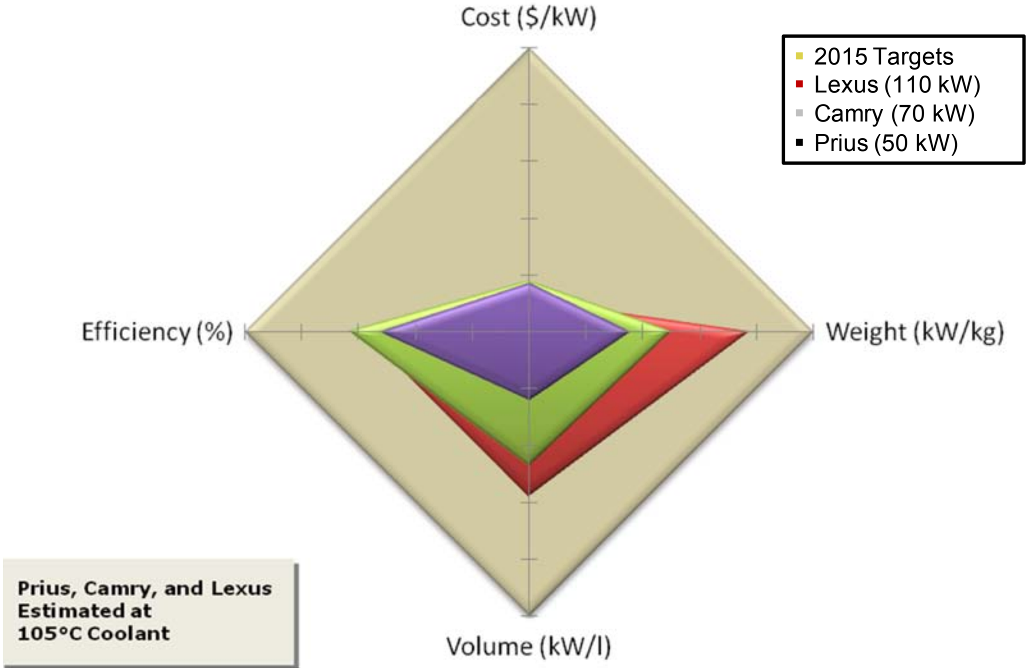
- **Total Funding (FY08-FY10)**
  - DOE: $**1175**K
  - Contract: $110K
- **Annual Funding**
  - FY08: $375K
  - FY09: $450K
  - FY10: $350K

Partners/Collaboration

- 3M Electronics Markets Materials Division
- Wolverine Tube
- Delphi
- FreedomCAR Electrical & Electronics Technical Team
- University of Colorado, Boulder
- Colorado School of Mines

Barriers

- Weight, volume, thermal control
- Performance
- Cost



PROJECT OBJECTIVES / RELEVANCE

OBJECTIVES

Investigate the use of surface enhancement techniques to increase heat transfer in:

1. Single-phase jet impingement cooling (free & submerged)
2. Two-phase heat transfer (spray cooling)

RELEVANCE

Potential application to increasing heat dissipation requirements in automotive power electronics

Efficient heat transfer technologies can enable:

- Increased **power density** & **specific power** by reducing cooling system volume/weight

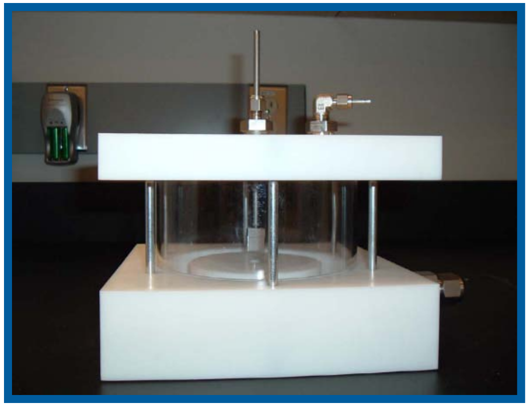
APPROACH

SURFACE ENHANCEMENT: SINGLE-PHASE JET IMPINGEMENT

- Further increase the already high heat transfer rates of jet impingement cooling
- 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 heat transfer

Procedure:

1. Fundamental study on the effect of enhanced surfaces on jet impingement heat transfer
   - Free and submerged jets
2. Conduct tests at various jet velocities



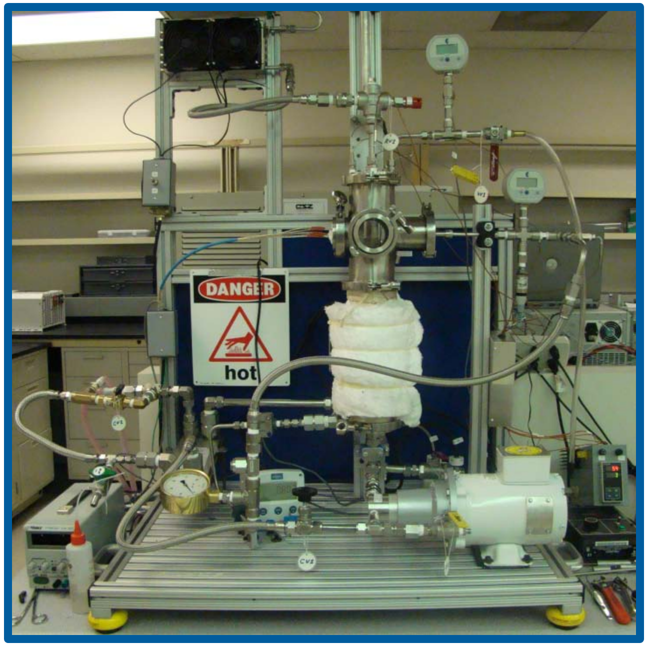
APPROACH

SURFACE ENHANCEMENT: TWO-PHASE HEAT TRANSFER

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

Procedure:

1. Fundamental study on the effect of enhanced surfaces on spray cooling
2. Conduct tests at various fluid flow rates



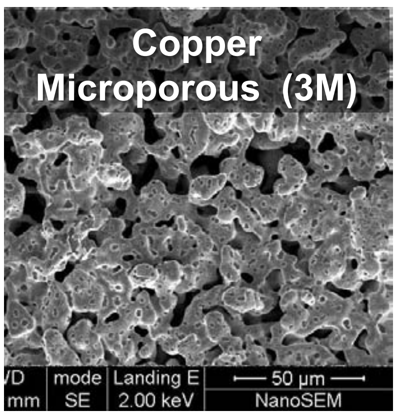
APPROACH

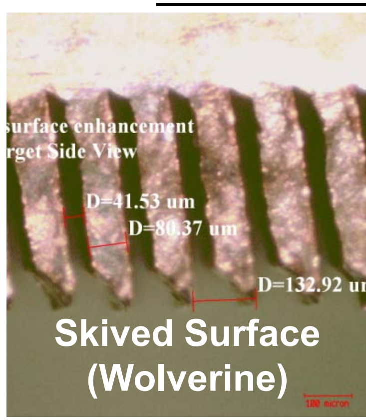
STRATEGY

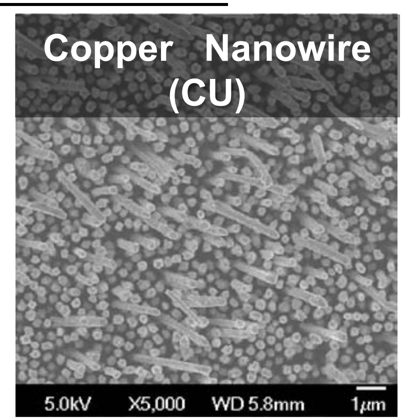
- **Current Work:** Fundamental study to characterize the thermal performance of the enhanced surfaces

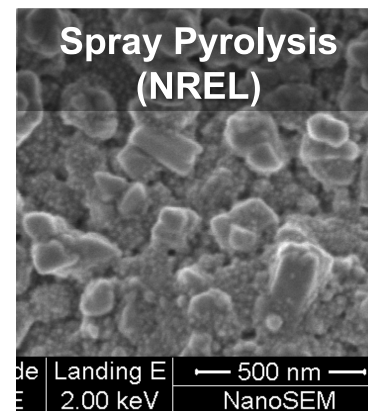
- **Future Work:** Implement technology on an actual power electronics module & evaluate the surface enhancement's reliability

Enhanced Surfaces

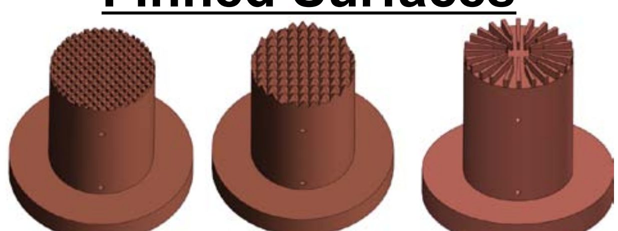








Finned Surfaces



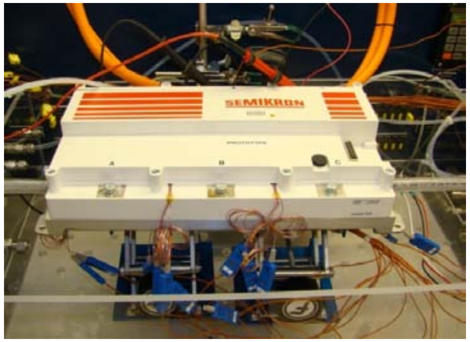
SINGLE-PHASE JET IMPINGEMENT

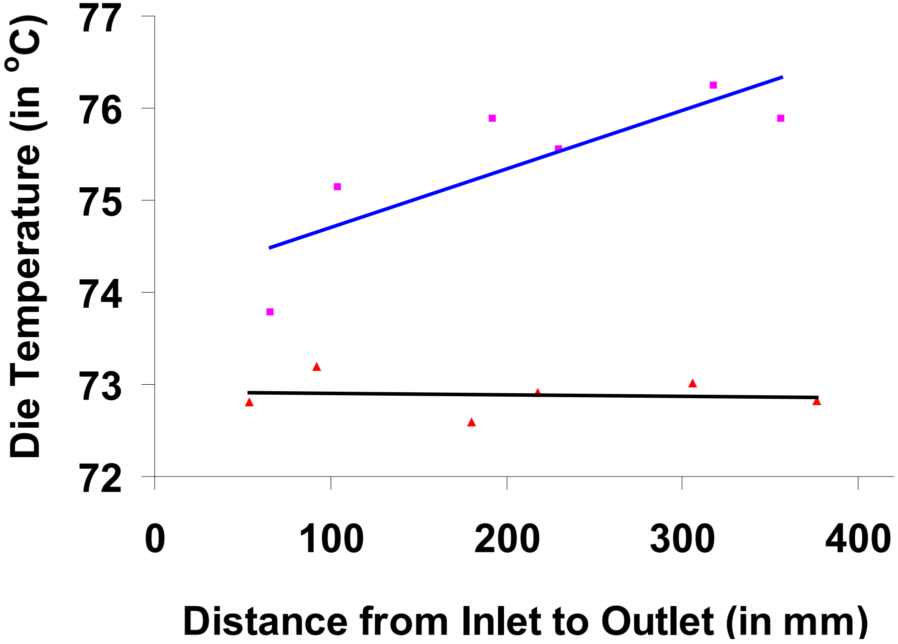
- Water @ 25°C inlet temperature
- Free and submerged jet configurations
- 11 different surfaces tested
- Channel flow tests for reference

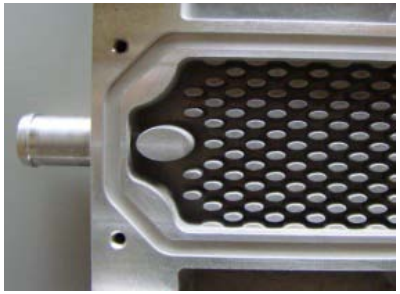
TECHNICAL ACCOMPLISHMENTS

WORK PREVIOUSLY PRESENTED: Low thermal-resistance jet impingement cooling of power electronics

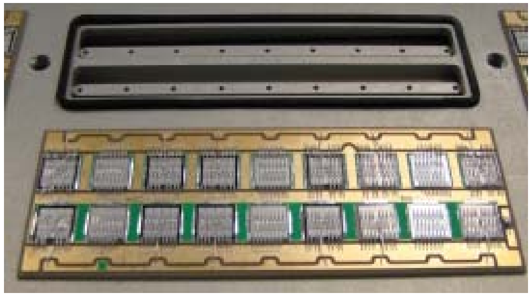
- Tests showed 35% reduction in overall thermal resistance (junction to coolant)
- Achieved thermal performance without increased parasitic power
- Improved temperature uniformity
- Potential for reduced cost, weight and volume







Baseline



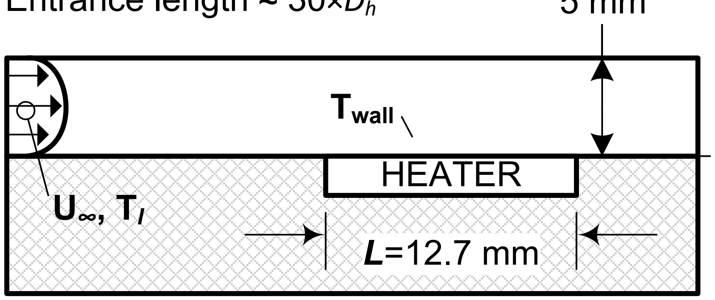
Low R_{th} Design

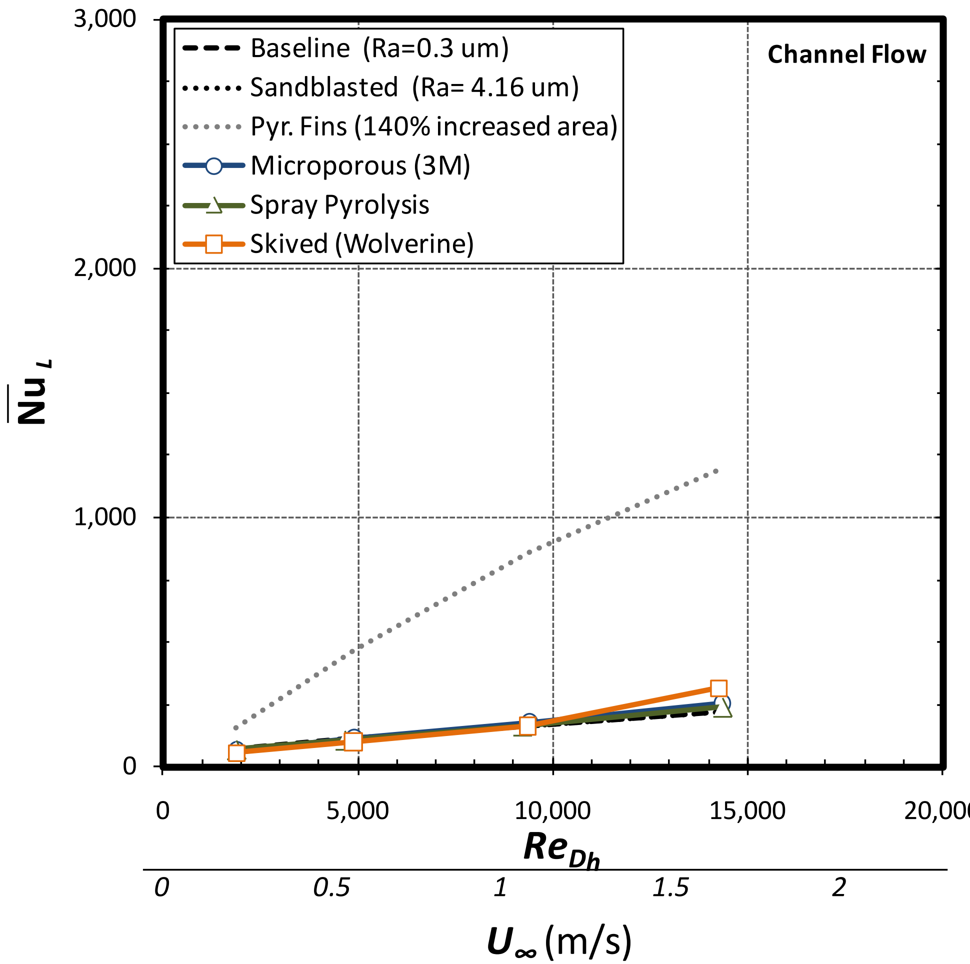
Technical Accomplishments

ENHANCED SURFACES: SINGLE PHASE

- 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×D_h



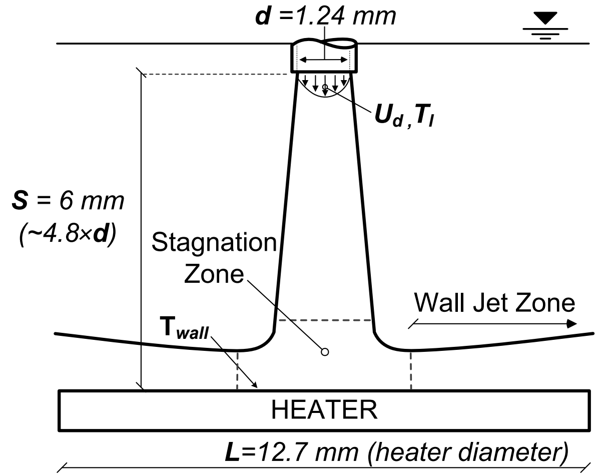


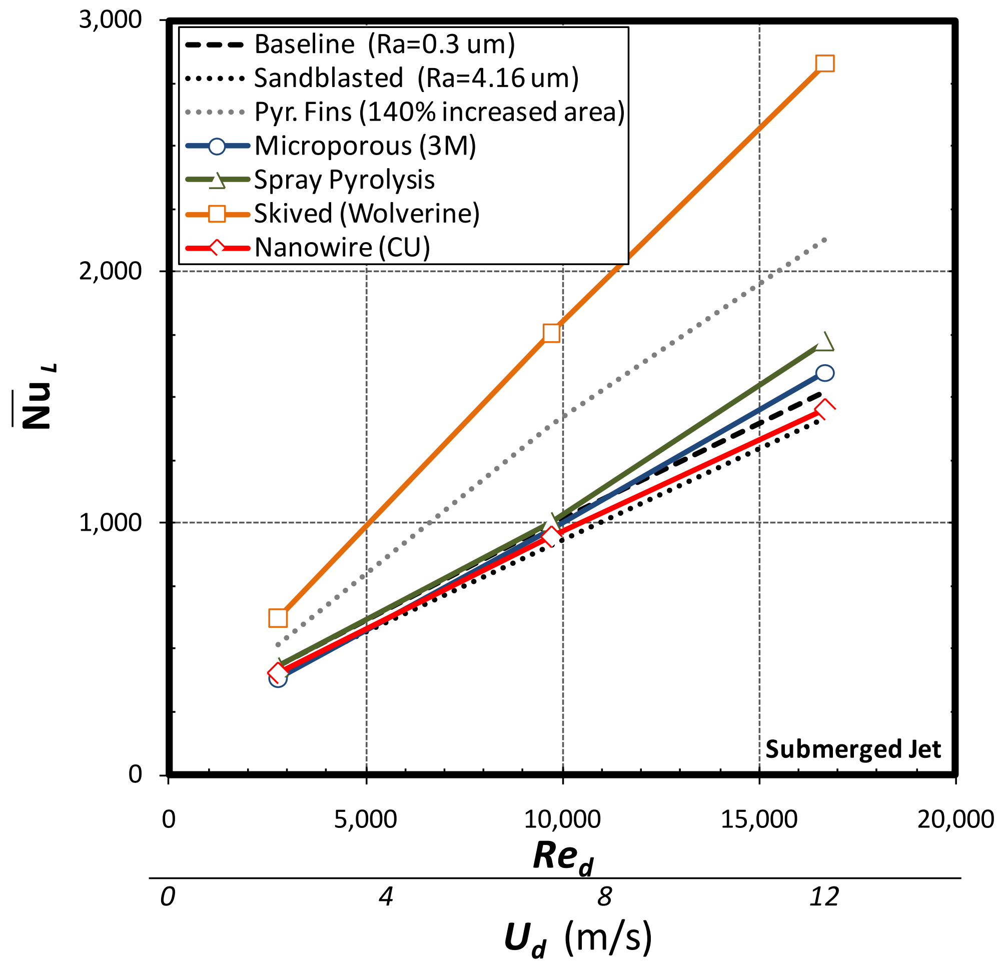
Channel Flow Results

TECHNICAL ACCOMPLISHMENTS

ENHANCED SURFACES: SINGLE PHASE

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



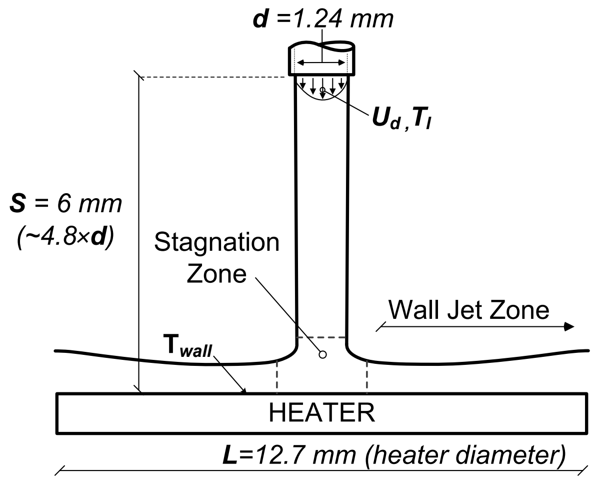


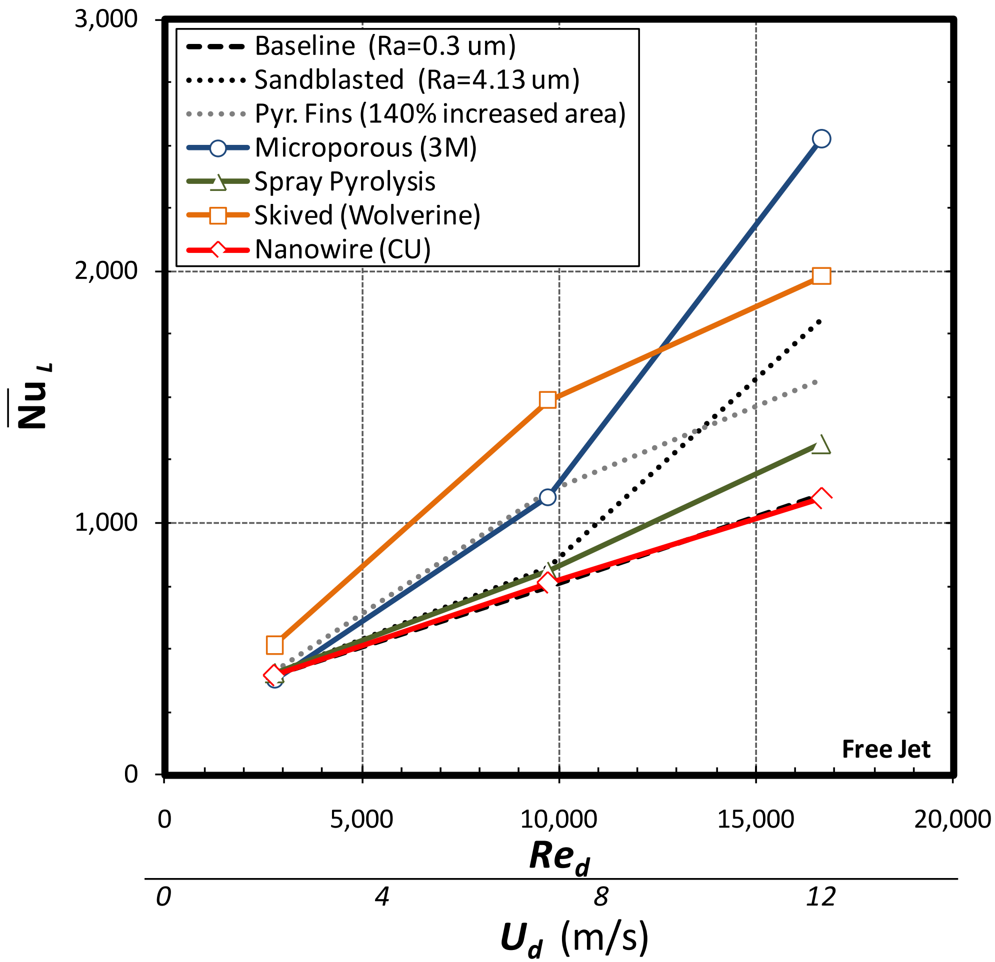
Submerged Jet Results

TECHNICAL ACCOMPLISHMENTS

ENHANCED SURFACES: SINGLE PHASE

- 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





Free Jet Results

TWO-PHASE SPRAY COOLING

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

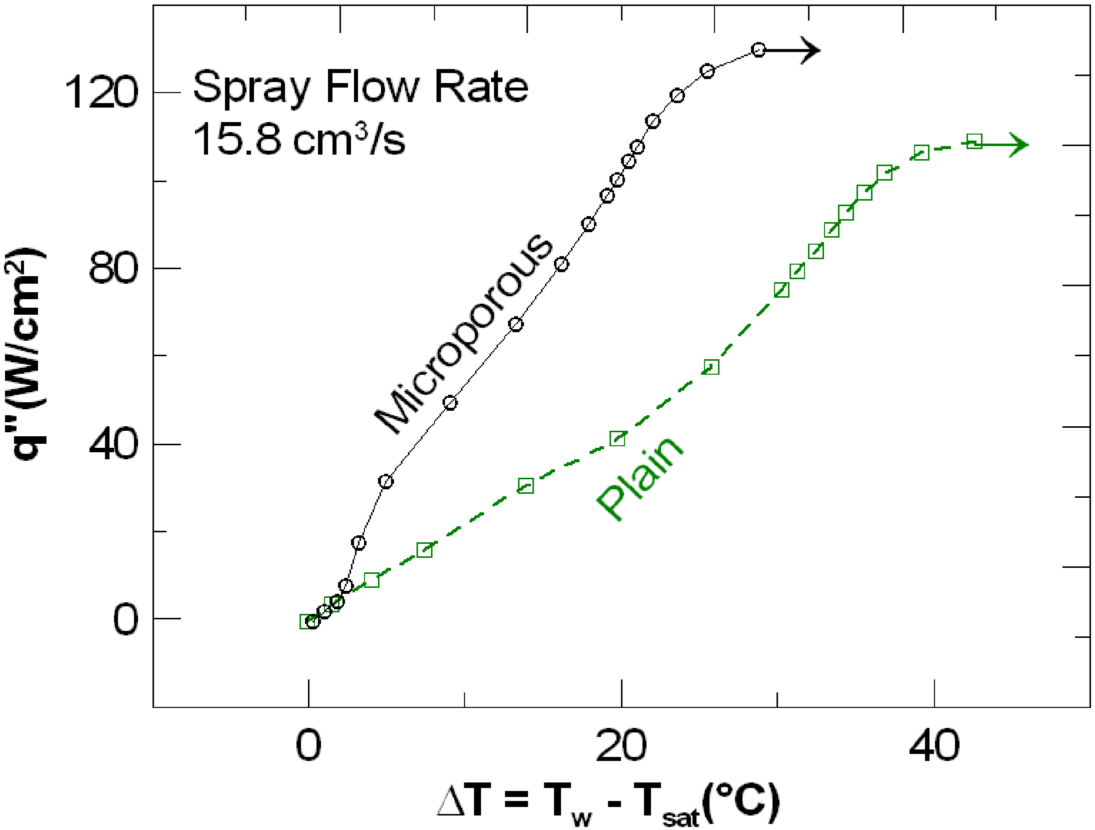
Technical Accomplishments

ENHANCED SURFACES: TWO-PHASE

SPRAY COOLING

Microporous Coating

- 100-300% increase in Nucleate Boiling (N.B.) heat transfer
- 7-20% increase in the critical heat flux (CHF)
- Coating structure (micro cavities of various sizes) enhances boiling heat transfer



HFE-7100 Dielectric Fluid

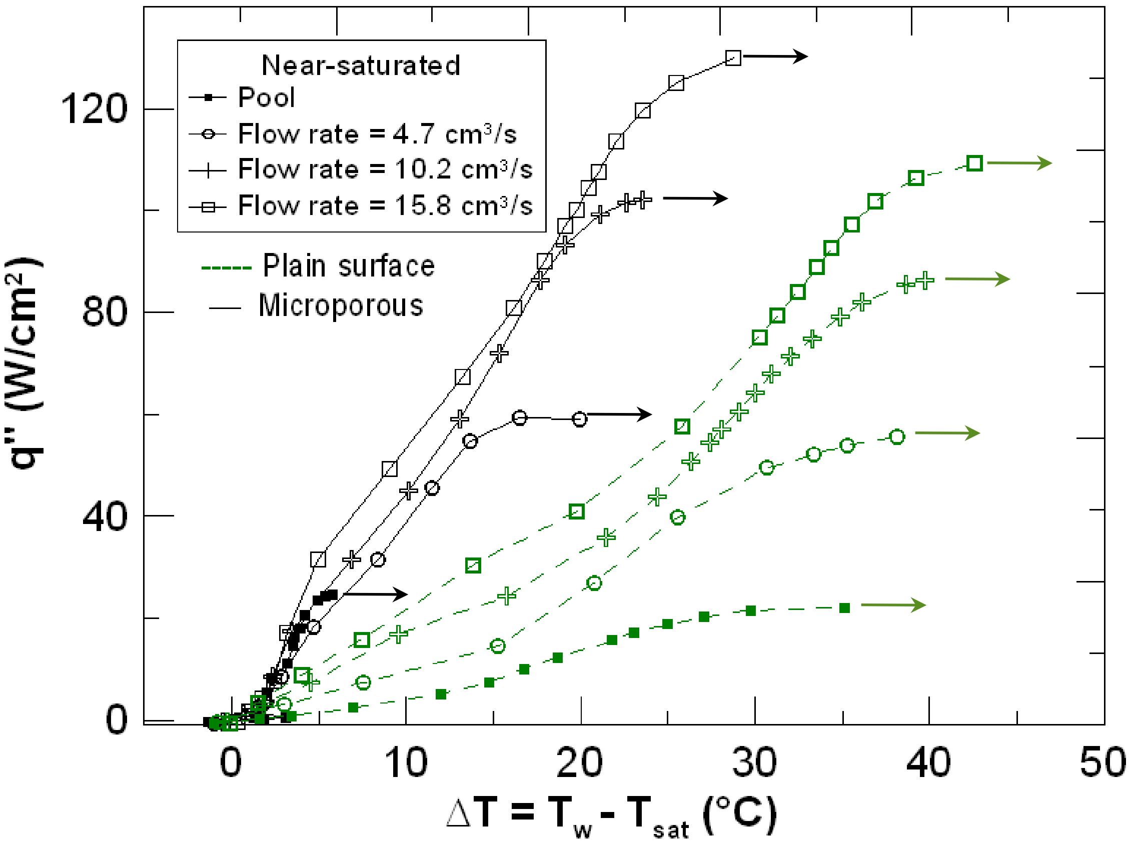
Full cone spray @15.8 cm^3/s

TECHNICAL ACCOMPLISHMENTS

ENHANCED SURFACES: TWO-PHASE

SPRAY COOLING: Flow Rate Effect

- Increasing flow rate has minimal effect on N.B. 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

Technical Accomplishments

SYSTEM LEVEL IMPLICATION

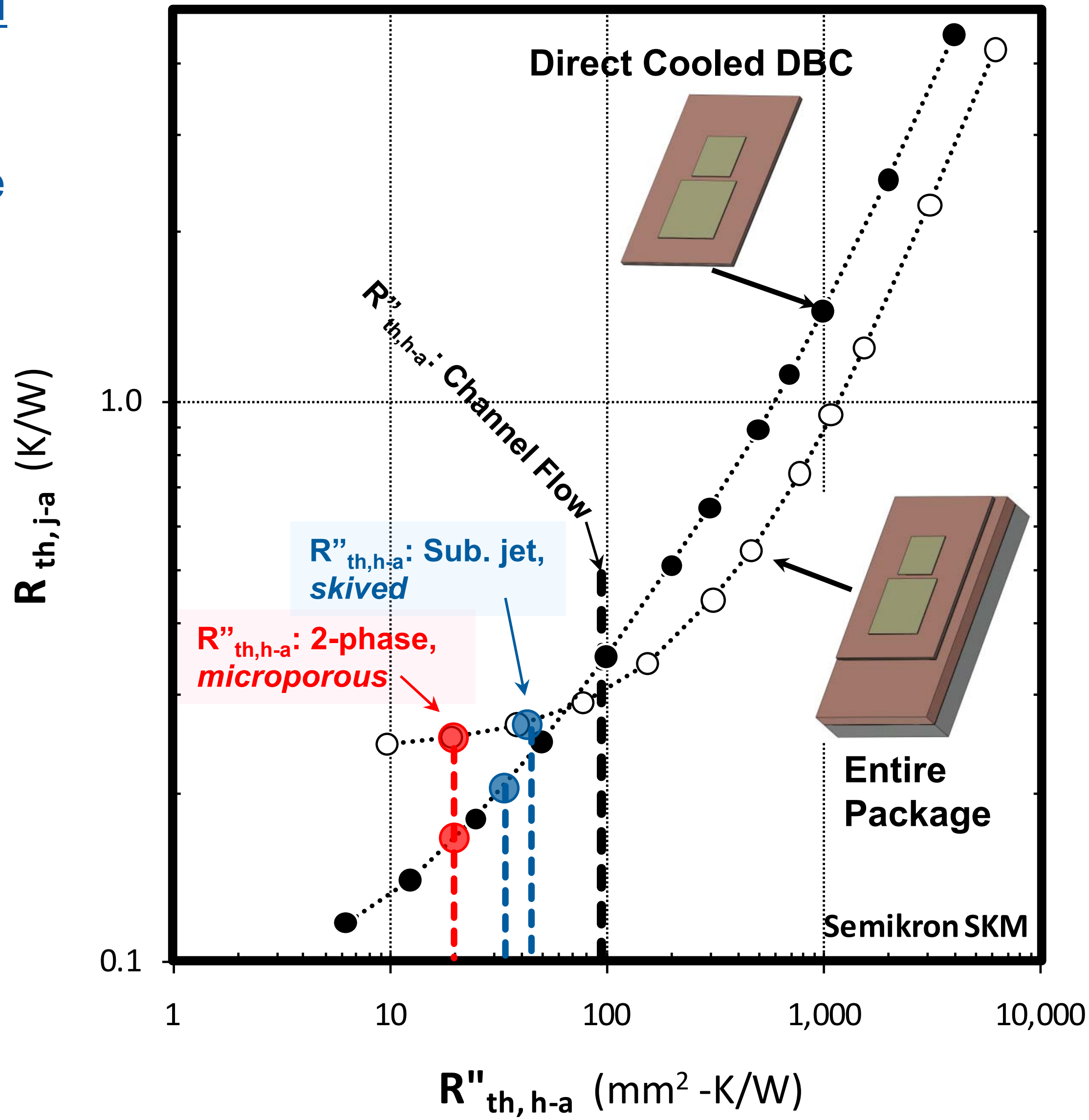
Jet impingement

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

Two-phase

- P. 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



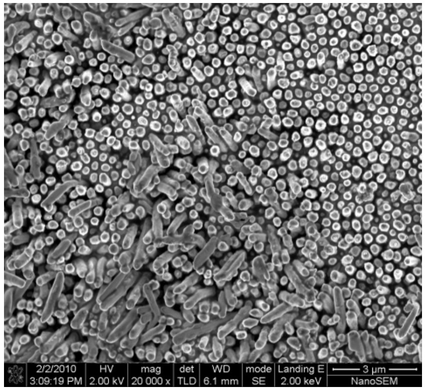
COLLABORATIONS

UNIVERSITY PARTNERS

- University of Colorado, Boulder (*Graduate Student*)
- Colorado School of Mines (*Graduate Student*)

INDUSTRIAL PARTNERS

- 3M Electronics Markets Materials Division
- Wolverine Tube, Inc.
- FreedomCAR Electrical & Electronics Technical Team
- Delphi



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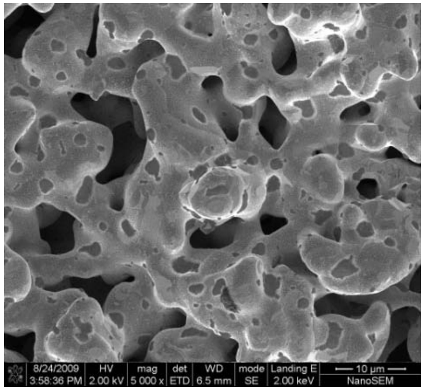
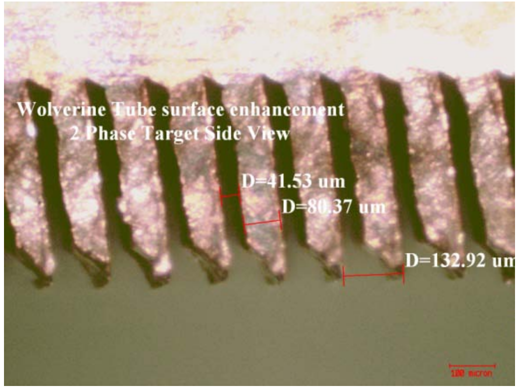


3M



Wolverine

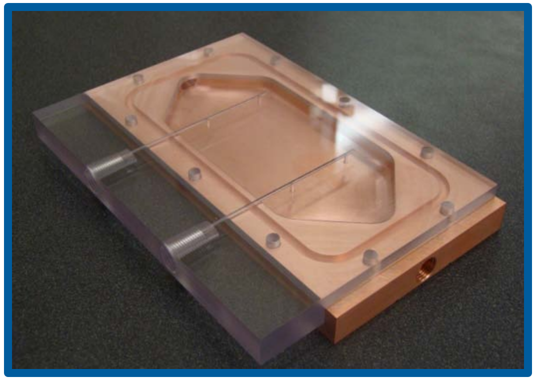
PROPOSED FUTURE WORK

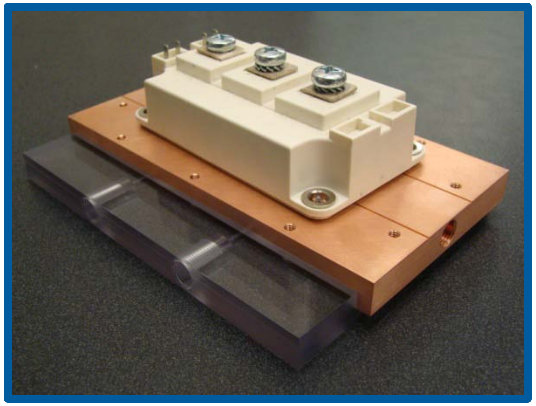
i. **Reliability:** Investigate the coating's bonding to the surface and its ability to remain effective under long term use
   - Coating performance over time
   - Nozzle degradation over time

ii. **Implement** jet impingement with enhanced surfaces on a commercially available power electronics package (Semikron SKM)

iii. **Synthesize/optimize** additional coatings using spray pyrolysis
   - Single & two-phase applications

iv. **Implement** flow visualization to understand underlying physics/mechanisms behind surface enhancements
   - High speed video & Schlieren Shadowgraphs





SUMMARY

OBJECTIVES

- Investigate the use of surface enhancement techniques as a means of increasing heat transfer in both single-phase jet impingement and two-phase spray cooling
- Efficient heat transfer technologies can enable increased **power density** & **specific power** by reducing cooling system volume/weight

APPROACH

- Evaluated the thermal performance of the enhanced surfaces in free and submerged jet configurations at various jet velocities
- Evaluated the thermal performance of the microporous coating on spray cooling at various fluid flow rates

SUMMARY

TECHNICAL ACCOMPLISHMENTS

1. **Demonstrated the jet impingement heat transfer enhancement capabilities of enhanced surfaces**
   - ~130% heat transfer coefficient increase (Microporous, *3M*): free jet configuration
   - ~100% heat transfer coefficient increase (Skived, *Wolverine*): submerged jet configuration
2. **In two-phase spray cooling tests, the microporous coating (*3M*) produced**
   - ~100-300% nucleate boiling heat transfer coefficient increase
   - ~7-20% increase in the critical heat flux (CHF)
3. **Surface enhancement is a simple yet effective means of improving heat transfer efficiency which has the potential to increase the Specific Power and Power Density of automotive power electronics**