NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Characterization and Development of Advanced Heat Transfer Technologies

Kenneth Kelly

National Renewable Energy Laboratory

2009 DOE Vehicle Technologies Annual Merit Review

May 22, 2009

Presented at the 2009 U.S.DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review & Peer Evaluation Meeting held 18-22 May 2009 in Arlington, Virginia

NREL/PR-540-45792

APE-11

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Project Start: FY 2008
- Project End: FY 2010
- Percent Complete: 66%

Budget

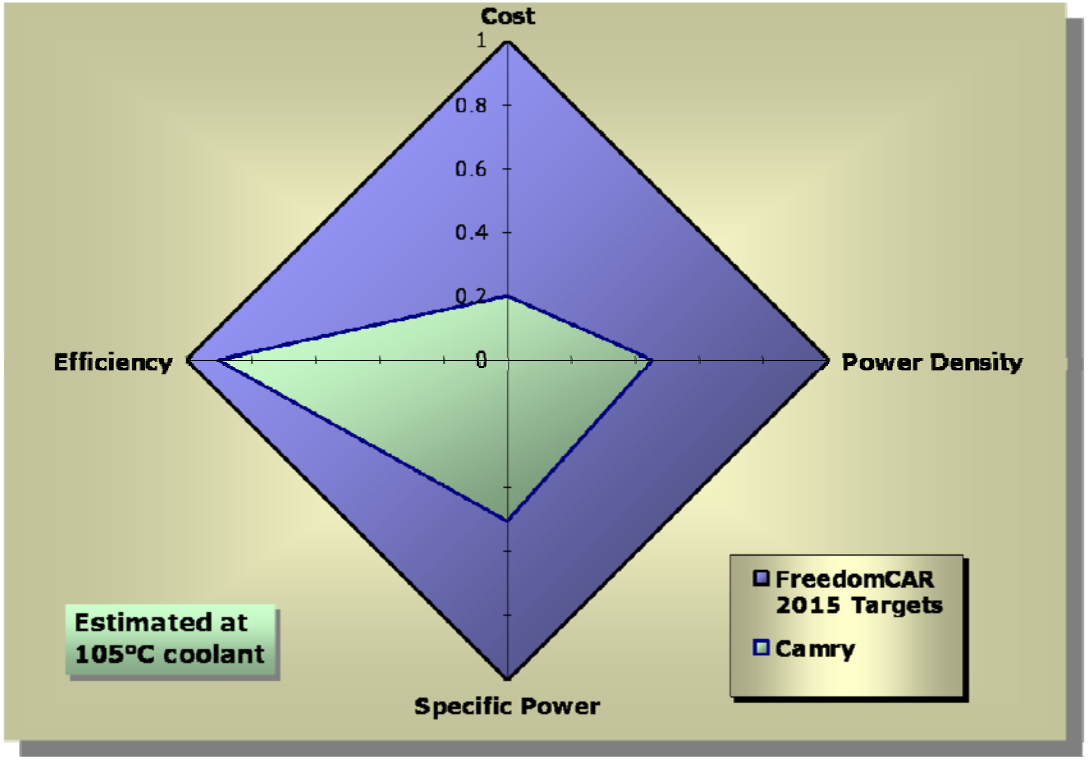
- Total Funding (FY07-FY10)
  - DOE: $**825**K
  - Contract: $0K
- Annual Funding
  - FY08: $375K
  - FY09: $450K

Partners/Collaboration

- Electrical and Electronics Technical Team (EETT)
- Semikron, Delphi
- Purdue University, University of Colorado, Wisconsin University
- NASA, ONR, IAPG

Barriers

- Cost ($/kW)
- Specific Power (kW/kg)
- Power Density (kW/L)
- Efficiency

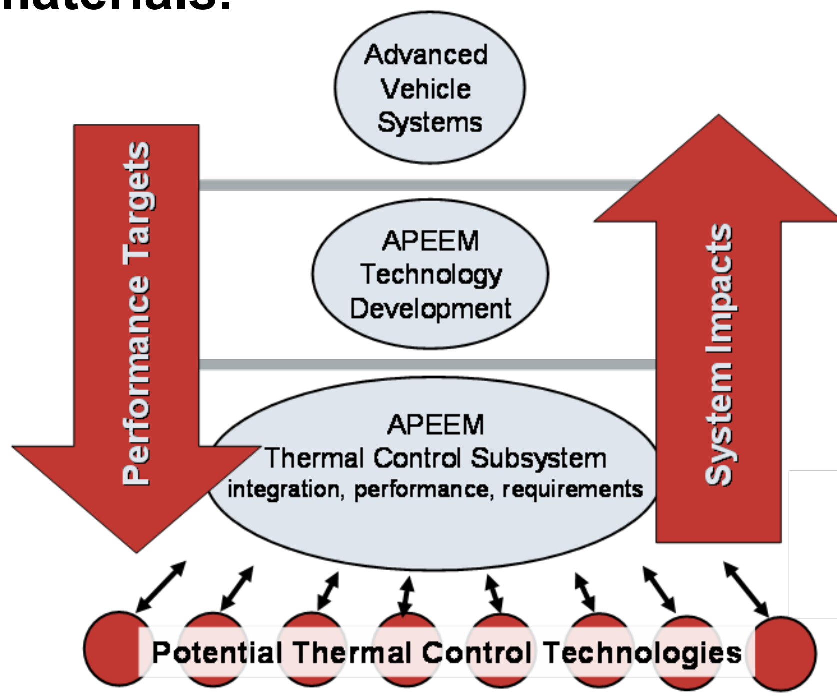


Problem Statement

- **Low-cost / high-performance thermal solutions are critical to achieving program targets – increased power density, specific power, and lower cost.**
- **Many advanced heat transfer technologies focus on high performance but tend to add system complexity and cost.**
- **Automotive PE systems may be over-designed or de-rated to compensate for thermal limitations.**

Objectives

- Characterization and development of candidate heat transfer technologies which have the potential in enabling low-cost thermal solution for Automotive Power Electronics.
- Enable improved power density and system cost reductions through effective heat transfer performance in conjunction with lower cost materials.



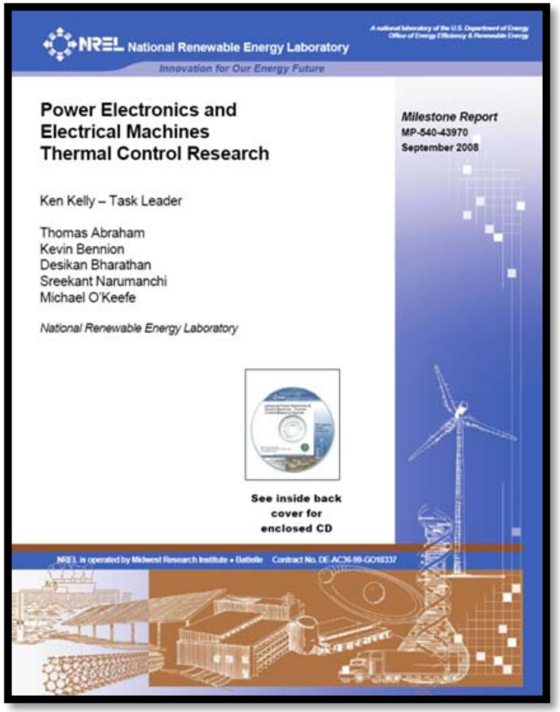
Characterize Performance
Develop Promising Technologies

Milestones (FY08 & FY09)

FY08

Report on status and results of the thermal control technology R&D (September 2008):

- Completed testing and evaluation of baseline elliptical pin-fin and low thermal resistance heat exchangers with Semikron inverter.
- Demonstrated testing showed over 35% decrease in thermal resistance and improved temperature uniformity.
- Presented integrated modeling process to evaluate tradeoffs between thermal performance and low-cost material selection.



FY09

Evaluate potential for implementing low-cost materials with aggressive heat transfer (July 2009).

Report on status and results of the thermal control technology R&D (September 2009).

Approach

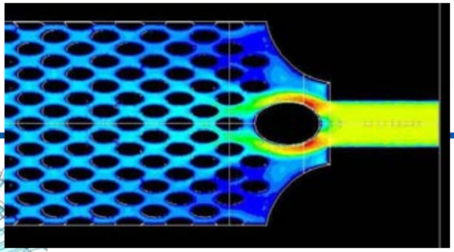
- Indentify potential heat transfer technologies through interactions with industry and research partners.
  - Literature search
  - Industry and research partner interactions

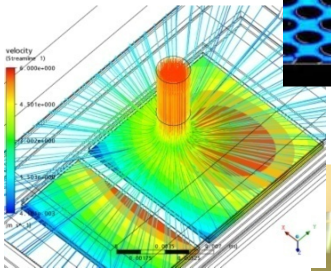
- Objective and consistent characterization of thermal performance of promising technologies relative to automotive requirements.
  - Move from fundamental to practical based solutions

- Development of most promising technologies based on automotive packaging and performance constraints with focus on enabling increased power density with lower system cost.
  - Design optimization with regard to industry partner requirements
  - Experimental characterization of final packaged prototype

- Transfer knowledge to industry partners.

Approach



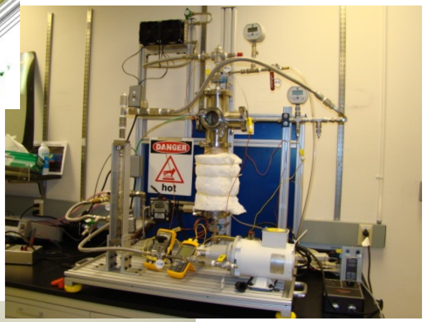


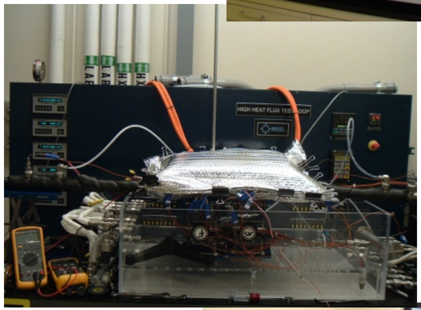
Improve PE device efficiency (ORNL)

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

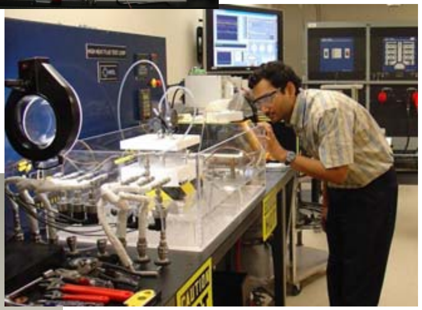
coolant temperature

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

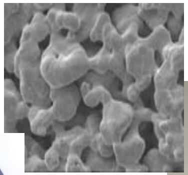


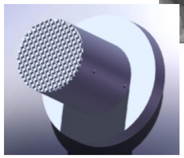


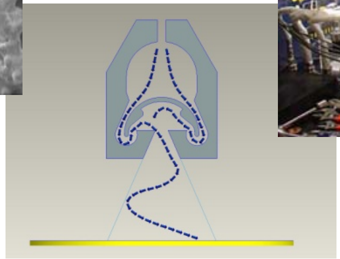
Increase surface area
-fin shape optimization
-double-sided cooling
-surface enhancements
-thermal spreading



Enhance heat transfer coefficient
- jet / spray cooling
- self-oscillating jets
- phase change







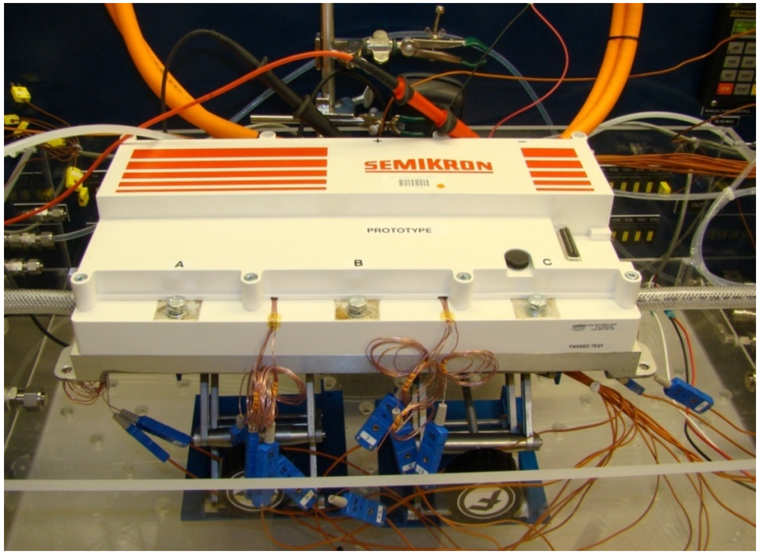
Technical Accomplishments

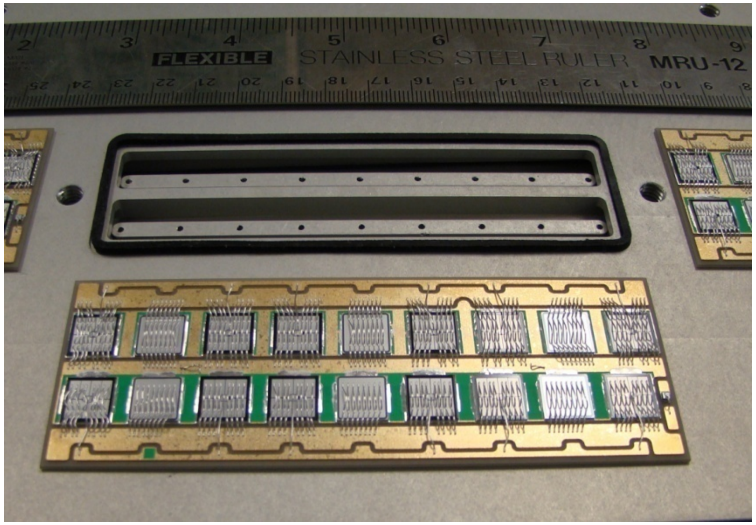
Low thermal-resistance structure for jet impingement cooling of power electronics

Completed testing of "Low Thermal-Resistance Power Module Assembly" demonstrated with Semikron inverter.

- Tests showed 35% reduction in overall thermal resistance (junction to coolant)
- Enables high temperature coolants
  - 200 W/cm^2 heat dissipation
  - 105 ^oC inlet coolant, Tmax = 150 ^oC
- Achieved thermal performance without increased pressure drop / parasitic power
- Improved temperature uniformity
- Elimination of TIM layer
- Potential for reduced cost, weight, and volume

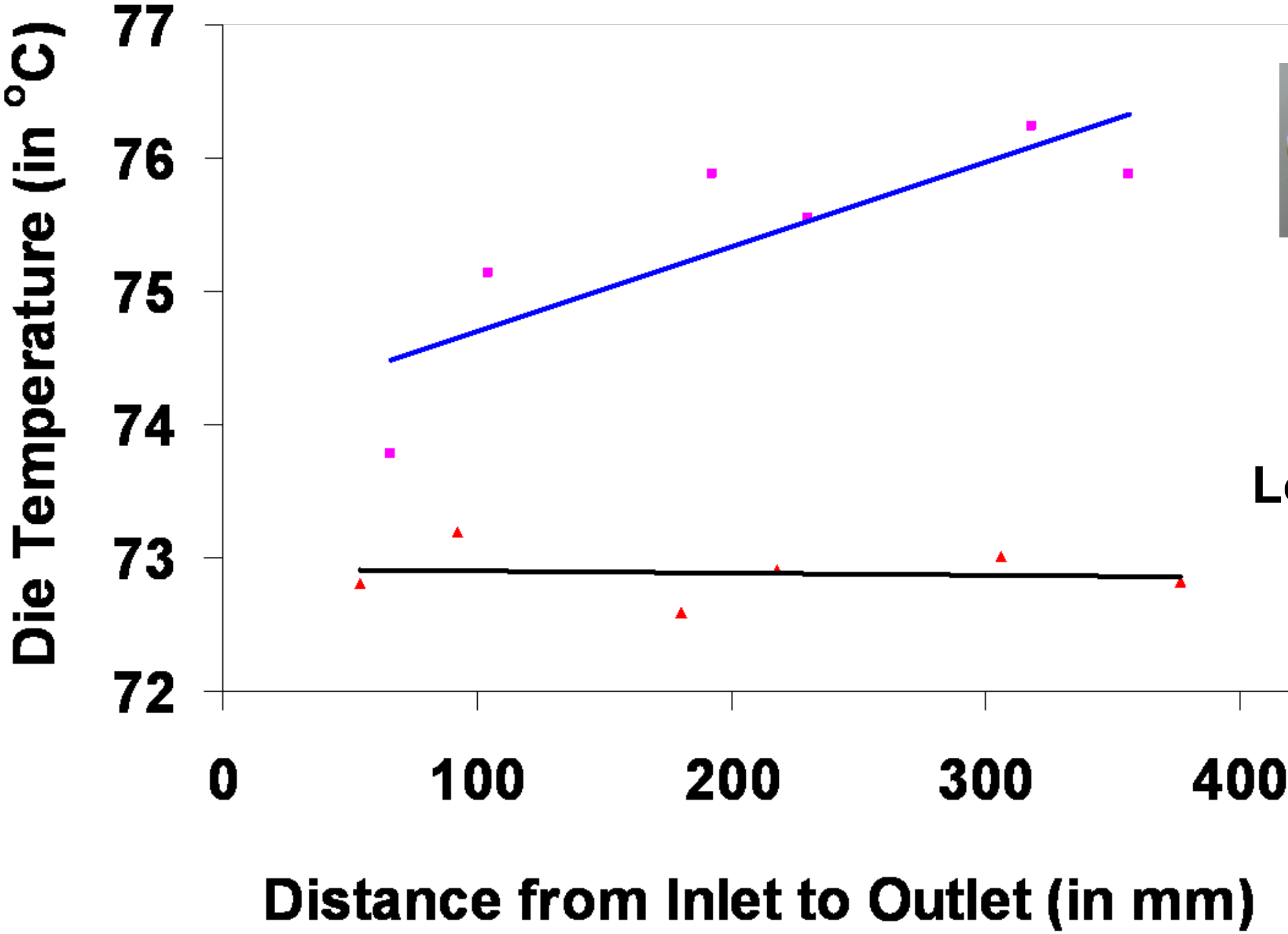
The technology is adaptable to other package configurations.



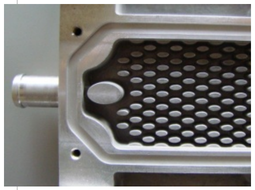


Technical Accomplishments

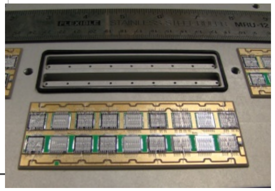
IGBT Test, 1000 W, 10 lpm, 35 W/cm^2



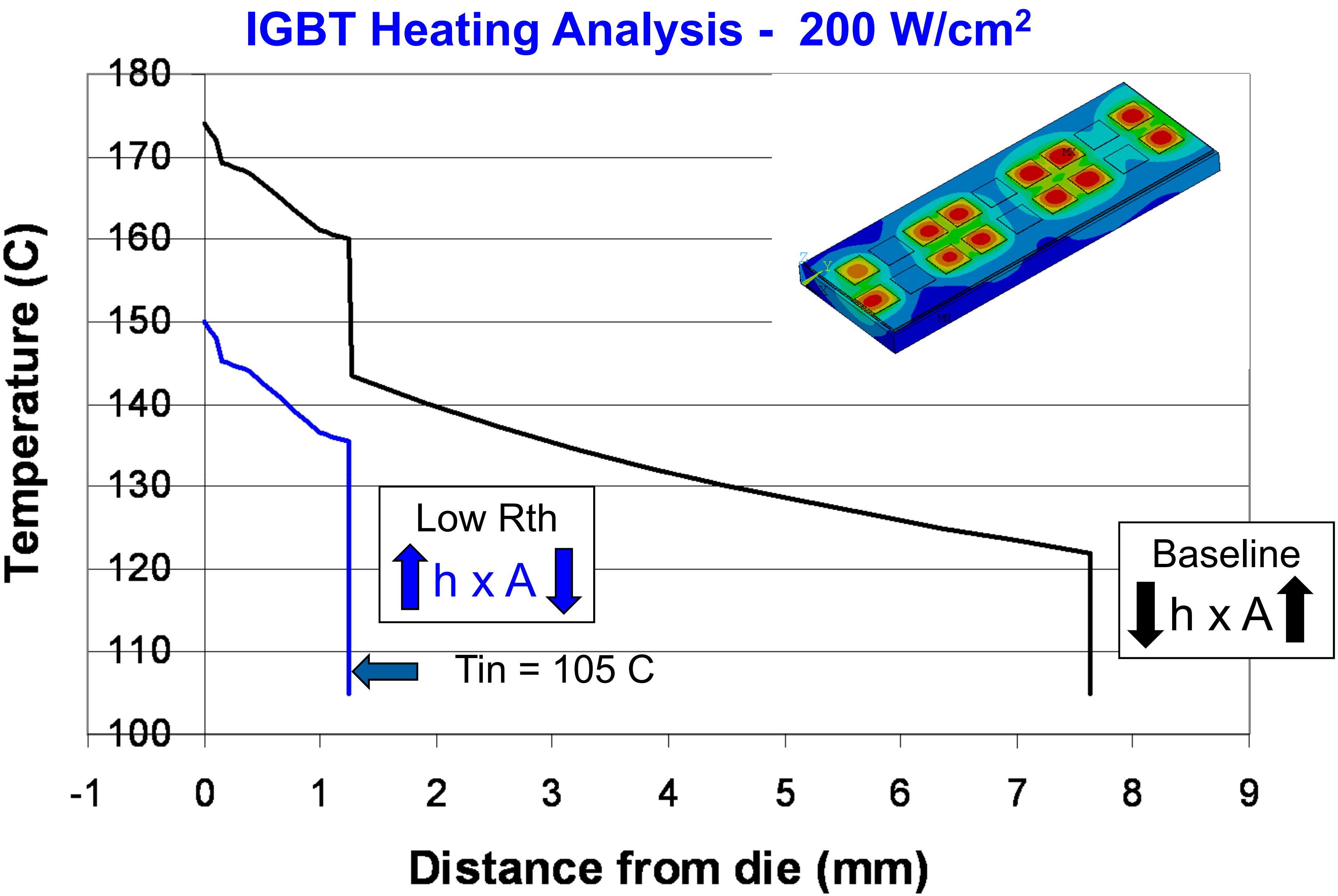
Baseline



Low R_{th} Design



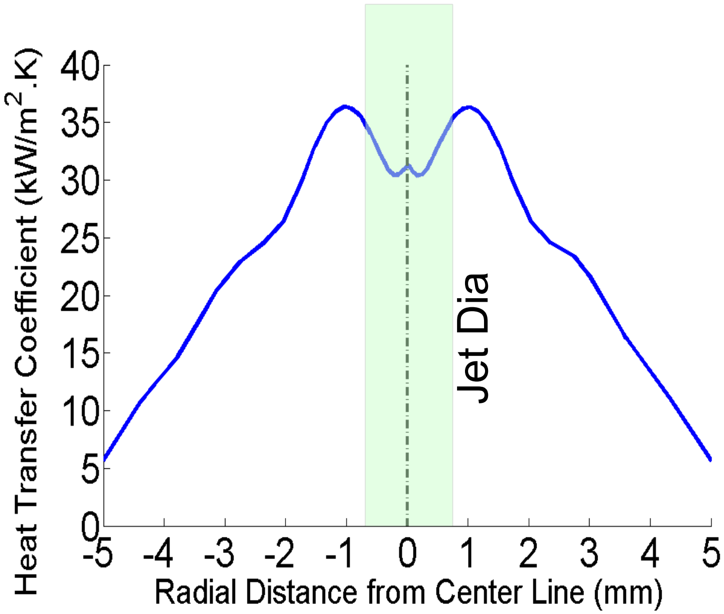
Technical Accomplishments



Technical Accomplishments

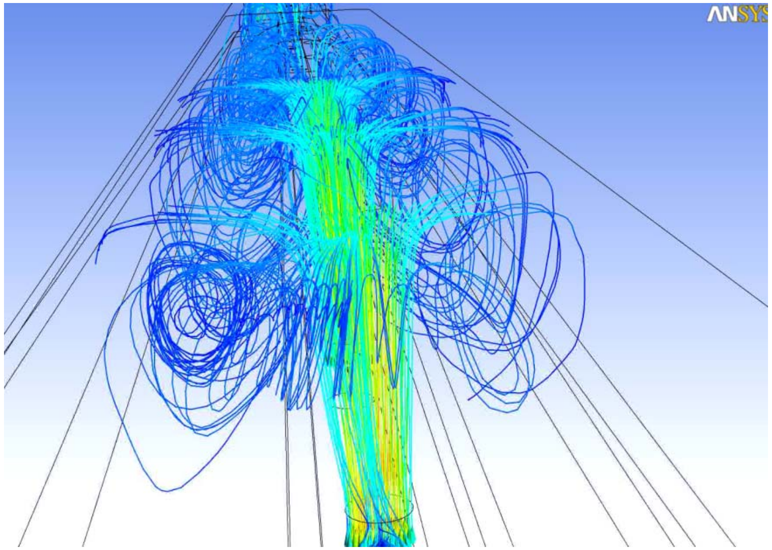
Parametric Jet Simulation Studies

- Conducted initial parametric investigations of packaging effects.
- Excellent correlation with experimental results.
- Peak heat transfer coefficient **(h)** confined to small target area.



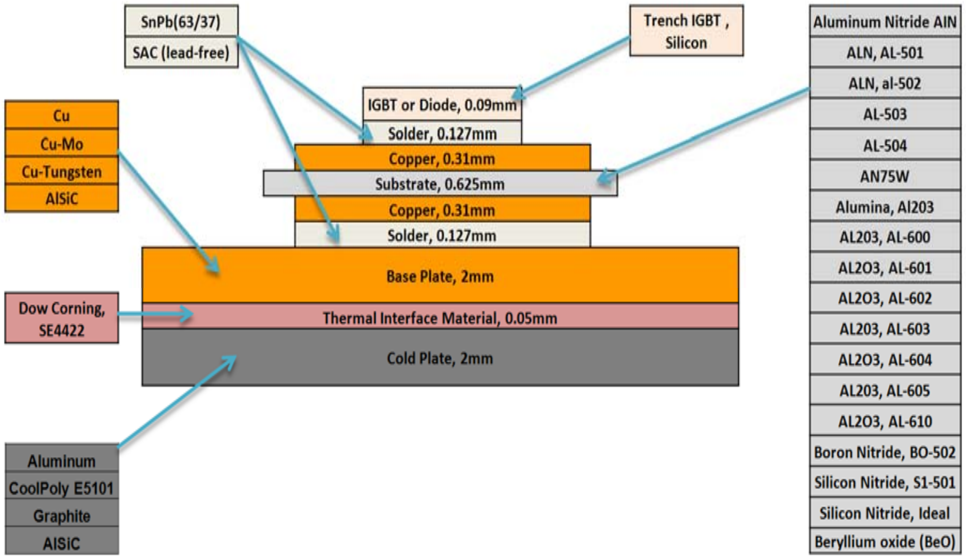
Conclusions

- Jet cooling system must be optimized for a specific package.
- Combining jet impingement with surface enhancement **(h x A)** to maximize overall performance.

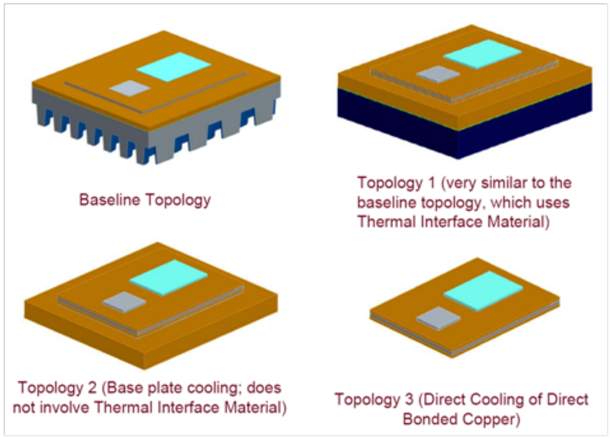


Technical Accomplishments

Materials exploration studies: Trade-off between Cost and Performance



Thermal Packaging Topologies

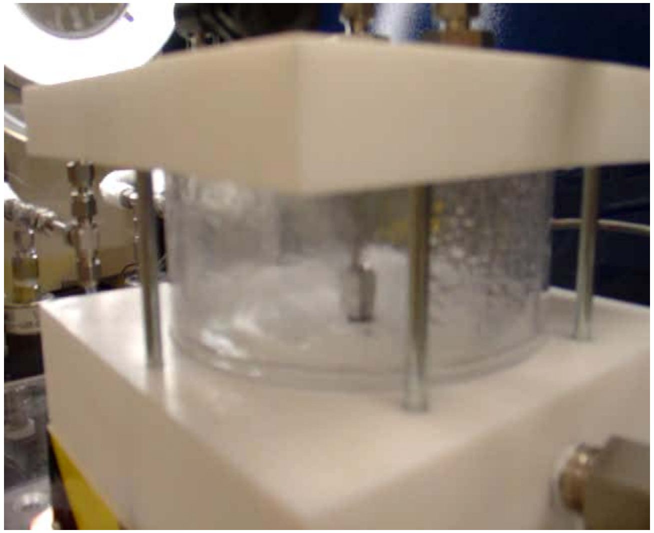


Developed basic framework for rapid assessment of interactions between thermal packaging topologies, materials, and thermal performance.

Low-cost alternate materials are enabled by advanced thermal control (advanced cooling technologies in conjunction with novel thermal packaging topologies).

Technical Accomplishments

Initiated Surface Enhancement Study –
Objective: Low-Cost, High Performance Area Enhancement

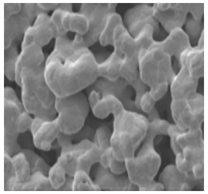


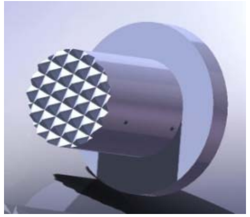
Surface coatings

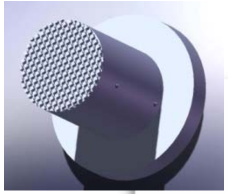
Protrusions

Etching

Roughing







- **Identified candidate surface enhancement geometries through literature search**
- **Initiated testing with NREL's jet impingement test fixture**
- **Completed testing of several candidate geometries**

Key Accomplishments during prior FYs

- Optimized pin-fin design transferred to Semikron.
- Awarded patent for “Low Thermal Resistance Power Module Assembly”.
- Published detailed experimental characterization of self-oscillating jet technology.
- Published experimental and modeling characterization of two-phase with R134A for both jets and spray cooling.

Future Work: FY2009 & FY2010

- Complete experimental evaluation of surface enhancement structures.
- Transfer most promising surface enhancement approaches that combine high performance with low cost manufacturing.
- Evaluate thermal performance of future refrigerant fluid(s) for two-phase cooling of electronics (HFO1234xy).
- Evaluate the potential of electrically activated heat transfer enhancements.

Summary

DOE Mission Support

- Characterization and development of candidate heat transfer technologies which have the potential to enable low-cost thermal solutions for Automotive Power Electronics.

- Enable improved power density and system cost reductions through effective heat transfer performance in conjunction with lower cost materials.

Approach

- Indentify potential heat transfer technologies.

- Objective and consistent characterization relative to automotive requirements.

- Development of most promising technologies.
- Transfer knowledge to industry partners.

Summary

Technical Accomplishments

- Completed testing of “Low Thermal-Resistance Power Module Assembly” integrated with Semikron inverter.
- Testing showed over 35% decrease in thermal resistance and improved temperature uniformity.
- Parametric investigation of package-specific jet impingement design parameters.
- Integrated modeling approach to evaluate tradeoffs between thermal performance and material selection.

Collaborations

- Semikron – collaborative development and demonstration of jet impingement in Semikron inverter.
- Delphi – performance data fed into parametric technology investigation.
- Universities – migration of fundamental research to practical solutions / correlation of test results.
- NASA / ONR / IAPG – two-way sharing of program information, concepts and results.

Publications and Presentations

FY08

- DOE Milestone: “Report on status and results of the thermal control technology R&D.” September, 2008.
- T. Abraham, K. Kelly, K. Bennion, and A. Vlahinos, “Advanced Thermal Control Enabling Cost Reduction for Automotive Power Electronics,” ANSYS Automotive Conference, Dearborn, MI, 2008.

FY09 (Planned)

- DOE Milestone: “Report on status and results of the thermal control technology R&D.” September, 2009.
- Conference Paper: “Design, Development, Analysis and Testing of Low Thermal Resistance IGBT Structure Concept for Automotive Power Electronics .” 5th IEEE Vehicle Power and Propulsion Conference, 2009. (Paper in Progress).

Critical Assumptions and Issues

- Advanced powertrains such as electric, hybrid electric, plug-in hybrid electric, and fuel-cell can enable reduced national fuel consumption goals without sacrifice in consumer mobility. One key barrier to the wide-spread usage of these advanced powertrain technologies is cost. Power electronics and electric machines are a major portion of that cost as evidenced by technical targets set for the FreedomCAR program. In order to achieve the specific FreedomCar goals for 2010, significant advancements in the thermal management of both the power electronics and motors for the electric propulsion system must be achieved.

- Heat dissipation from electronics and electronic systems represents a major technical barrier to achieving all of the FreedomCAR goals in 2010. Advanced thermal control technologies can enable higher power densities and lower system cost. Increased heat dissipation may enable lower-cost and lighter-weight package configurations and materials. As the thermal resistance from junction of the die to the heat sink is reduced, higher power densities can be achieved for the same temperature rise. It is important to reduce thermal cycling and maintain low ambient temperature to improve the life and reliability of the devices.