National Renewable Energy Laboratory
Innovation for Our Energy Future

Power Electronic Thermal System Performance and Integration

U.S. Department of Energy Annual Merit Review

P.I. Kevin Bennion

presented by
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National Renewable Energy Laboratory

Thursday June 10, 2010

APE016

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Overview

Timeline

- Project Start: FY 2007
- Project End: FY 2010
- Percent Complete: 75%

Budget

- Total Funding (FY07-FY10)
  - DOE: $1,505K
  - Contract: $0K
- Annual Funding
  - FY09: $375K
  - FY10: $500K

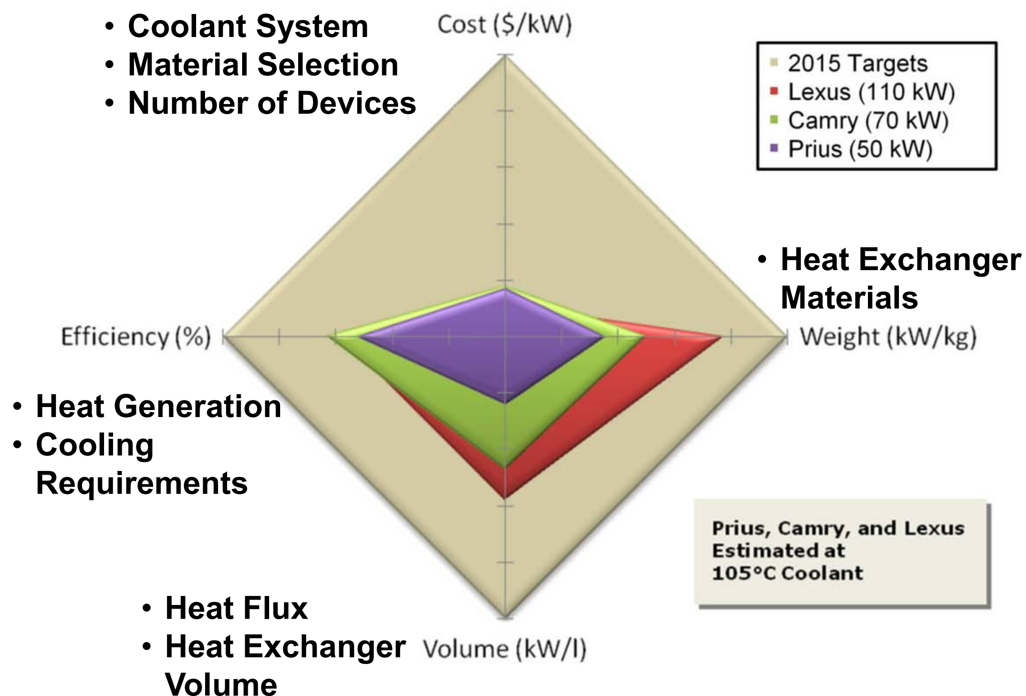
Partners/Collaboration

- Electrical and Electronics Technical Team (EETT)
- USCAR Partners
- Delphi
- Oak Ridge National Laboratory

Barriers

- Cost & Performance
- Weight & Volume
- Life & Thermal Management

Targets



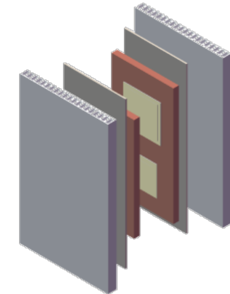
Objectives: Relevance (1/3)

Thermal management directly relates to improvements in cost, power density, and specific power.

Prius PE MY 2004

Camry PE MY 2007

LS 600h PE MY 2008



Double-sided Cooling

Impacts: Lower cost, volume, and weight

"Easy ways to increase output power are paralleling more silicon chips and/or step-up the die size to increase current capacity. But this strategy is unaffordable in terms of both increased chip cost and packaging space."

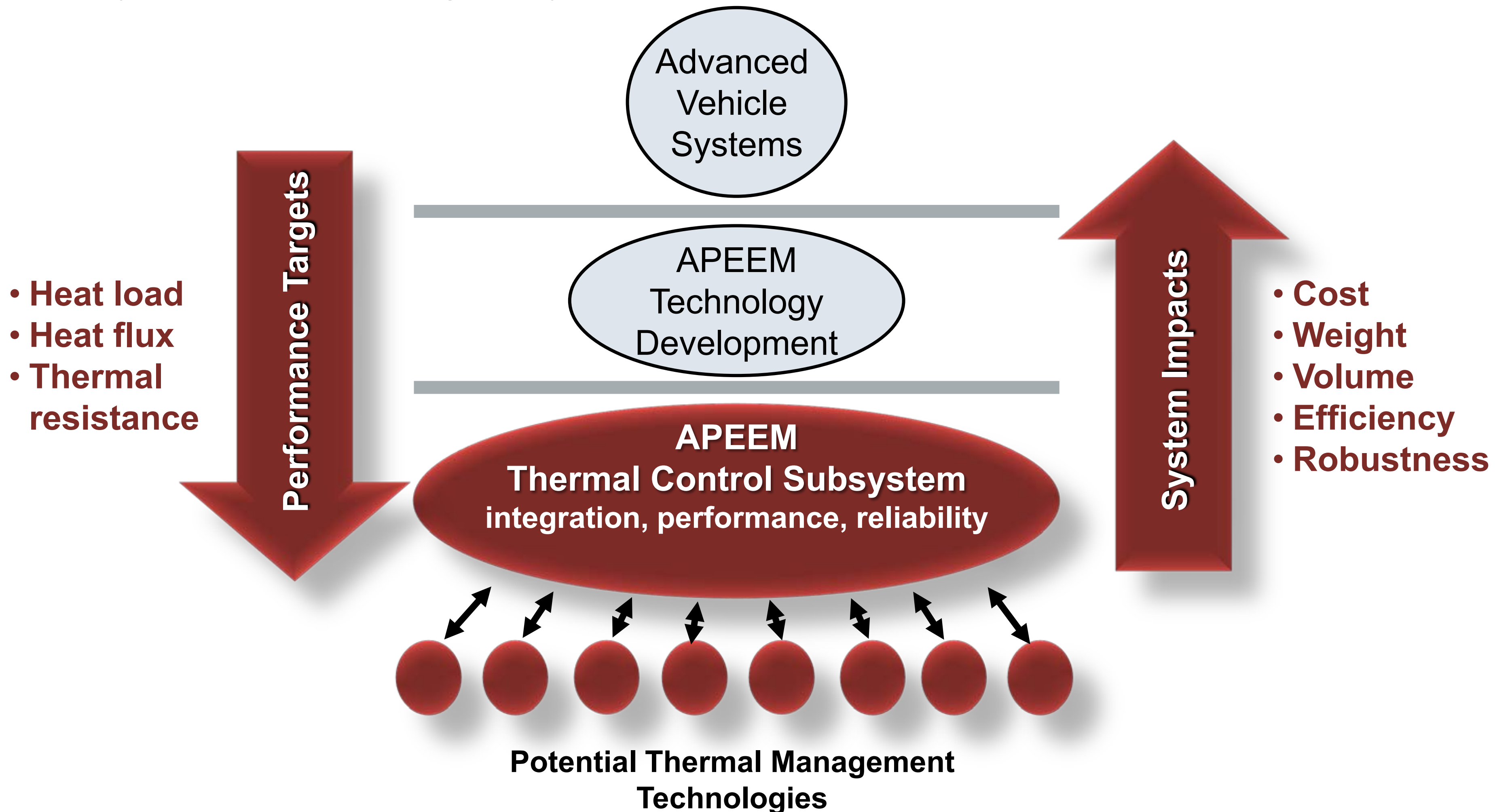
Enabling technology : double-sided cooling package

"The most significant concern for increasing current is intensified heat dissipation."

Source: Yasui, H., et al, "Power Control Unit of High Power Hybrid System" – Denso and Toyota, EVS23

Objectives: Relevance (2/3)

- Facilitate the integration of APEEM thermal management technologies into commercially viable advanced automotive systems including hybrid electric, plug-in hybrid electric, and fuel cell vehicles.

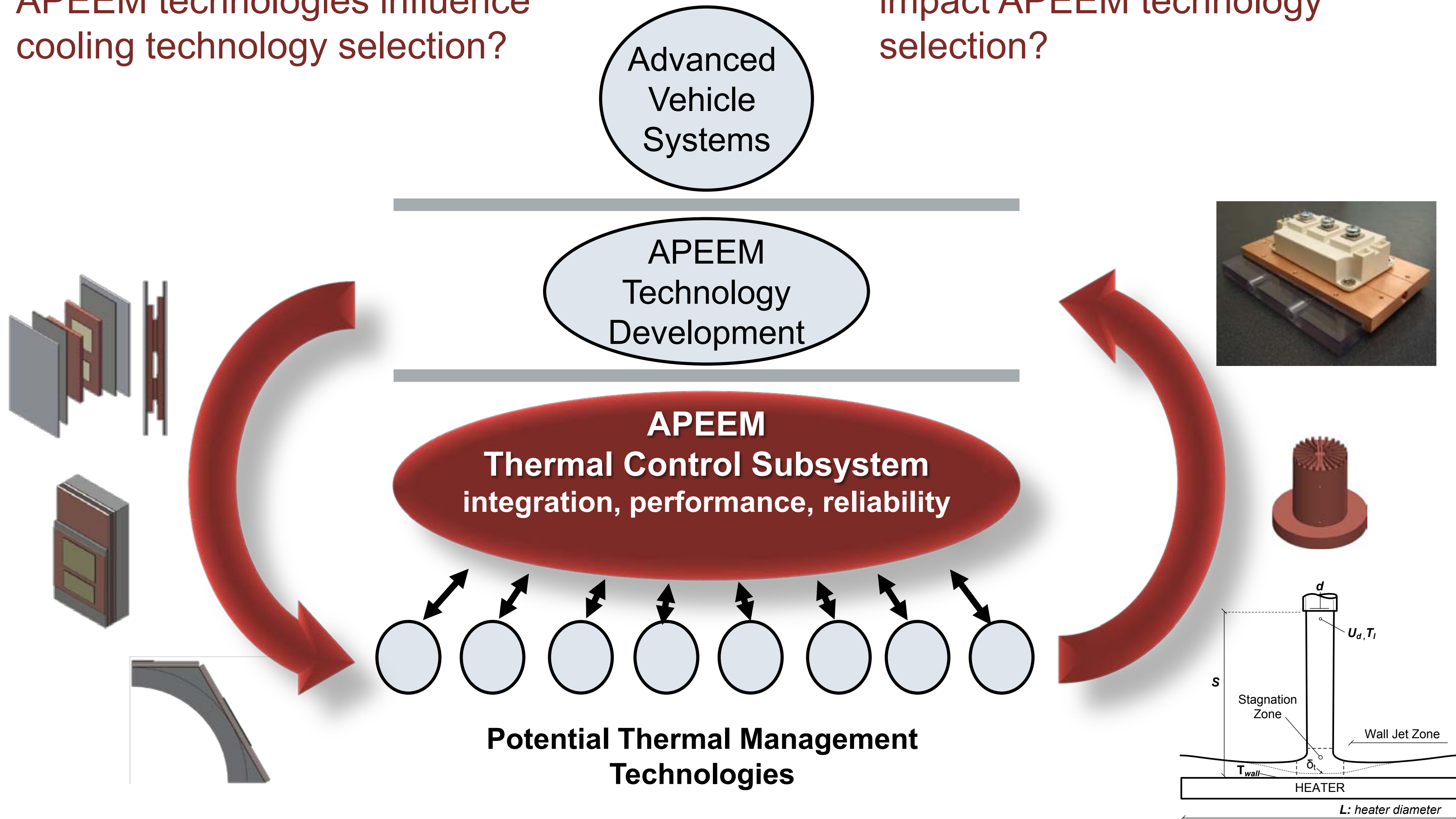


Objectives: Relevance (3/3)

Past Year's Emphasis

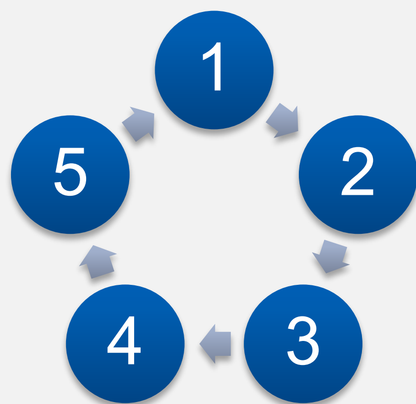
How do developments in APEEM technologies influence cooling technology selection?

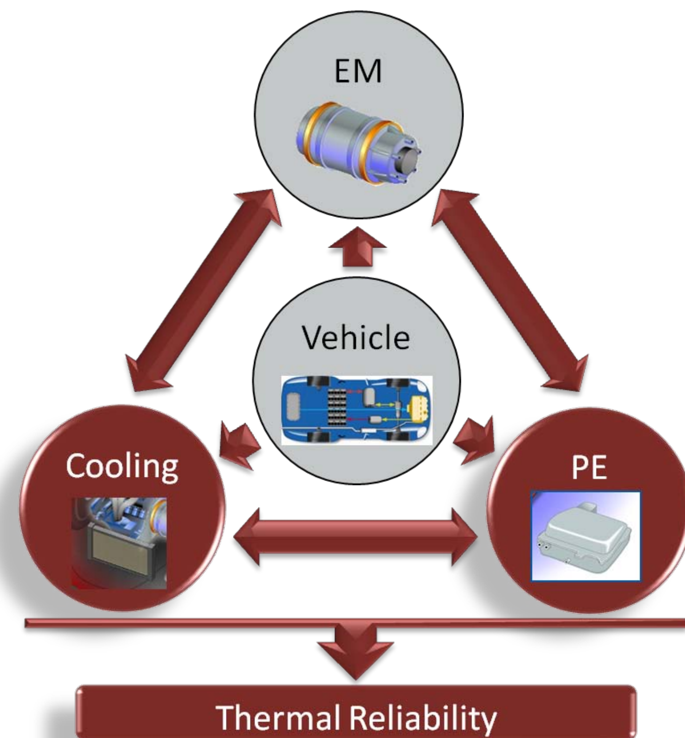
How do developments in cooling impact APEEM technology selection?



Approach/Strategy (1/3)

1. Identify system knowledge gaps
2. Develop process
   - (e.g. model, experiment, or data analysis)
3. Demonstrate process
4. Improve process with industry/partner input
5. Implement process





Approach/Strategy (2/3)

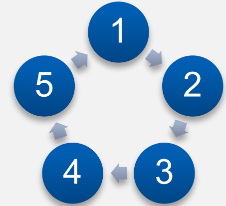
Examples Prior Years

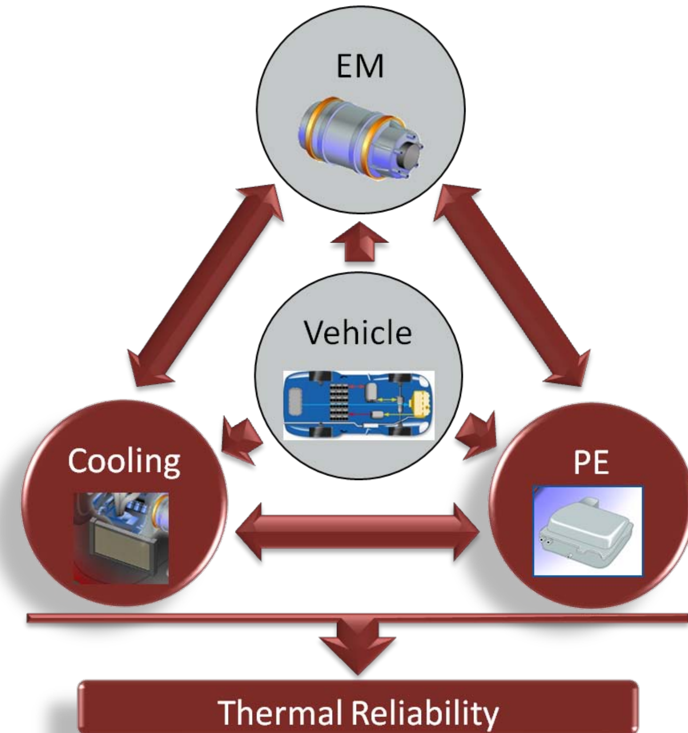
- Thermal duty cycle characterization of in-use power electronics
  PE ↔ Vehicle ↔ Cooling
- Impact of PHEV operation on APEEM systems
  PE ↔ Vehicle ↔ EM ↔ Cooling
- Parametric FEA thermal models for power semiconductor packaging sensitivity analysis
  PE ↔ Cooling ↔Thermal Reliability
- Power semiconductor transient thermal characterization from lumped parameter models
  PE ↔Thermal Reliability

Current Year

- Integrated thermal trade-off analysis process for semiconductor packaging and cooling technologies
  PE ↔Cooling
- Capacitor thermal model development
  PE ↔ Cooling

1. Identify
2. Develop
3. Demonstrate
4. Improve
5. Implement





Approach/Strategy (3/3) - Milestones

FY07

- PHEV Inverter Thermal Duty Cycles (June)
- Annual milestone report - status update (September)
- PHEV Impacts on Power Electronics and Electric Machines (September)

FY08

- Annual milestone report - status update (September)

FY09

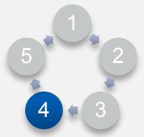
- Rapid Modeling of Power Electronics Thermal Management Technologies (June).
- Annual milestone report - status update (October)

FY10 (Scheduled)

- Conduct Thermal Analysis of APEEM Power Device Packaging Concepts using NREL's Rapid Parametric Thermal Systems Modeling Techniques (September).
- Annual milestone report - status update (October)

Technical Accomplishments & Progress (1/7)

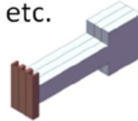
1. Identify
2. Develop
3. Demonstrate
4. **Improve**
5. Implement



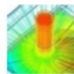
Worked with industry partner to improve integrated thermal analysis of heat exchanger and packaging technology.

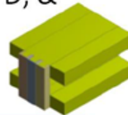
Heat Transfer & Fluid Flow Characterization

Defined Cooling Technologies — Fins, Jets, Microchannels, etc. Air, Liquid Alternate Materials



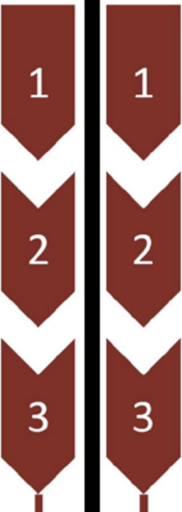
Identified Cooling Performance — Experimental Correlations, CFD, & Analytical h, ΔP, UA





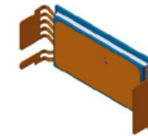
Characterized Heat Exchanger — Effectiveness – NTU Method

$$R_{NTU} = \frac{1}{\varepsilon \dot{m} c_p}$$

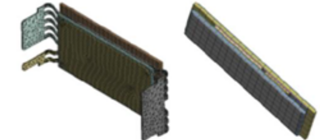


PE Package Thermal Characterization

Defined 3D Package Configuration



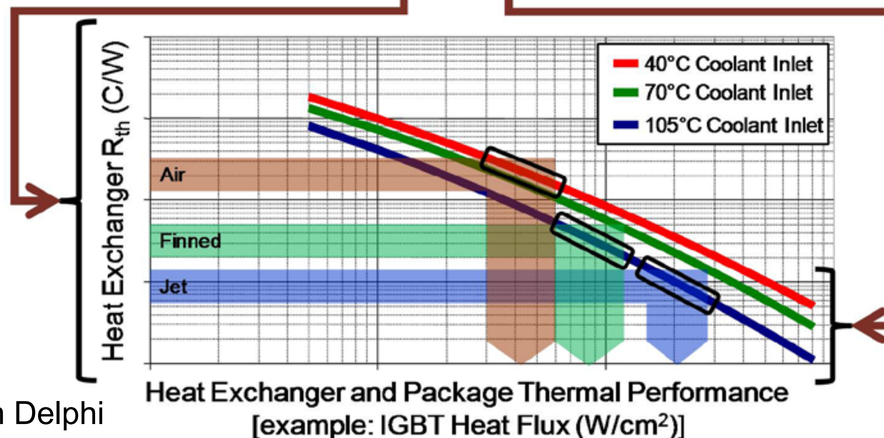
Developed 3D Parametric FEA Models



Characterized Thermal Package — Heat Flux vs. Heat Exchanger Thermal Resistance

System Performance

Determined impact and trade-offs of alternative cooling technologies.



Determined impact and trade-offs of alternative PE packaging technologies and temperature specifications.

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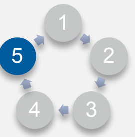
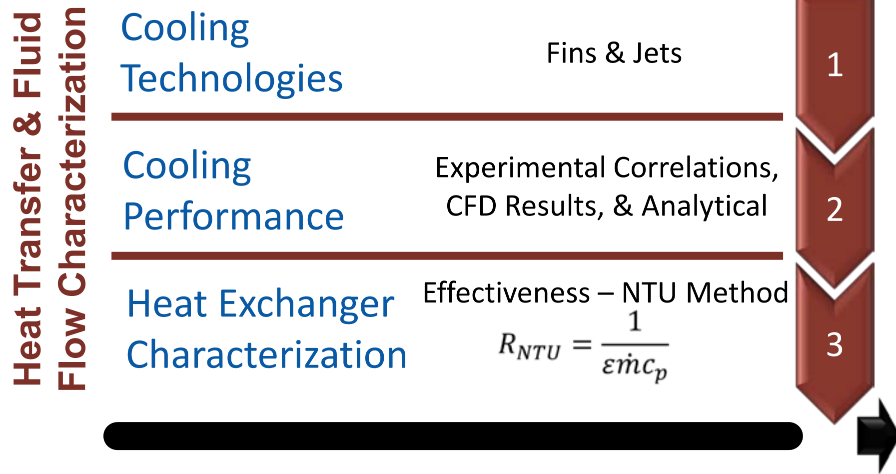
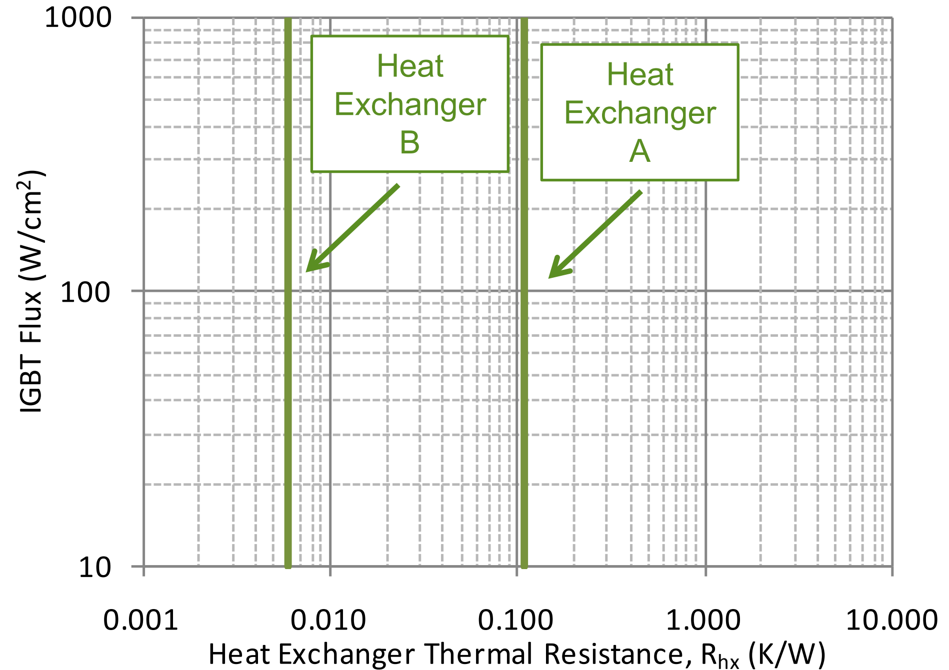
Technical Accomplishments & Progress (2/7)



1. Identify
2. Develop
3. Demonstrate
4. Improve
5. **Implement**

Implemented lessons learned and published application to commercial package (2009 IEEE VPPC).





Technical Accomplishments & Progress (2/7)

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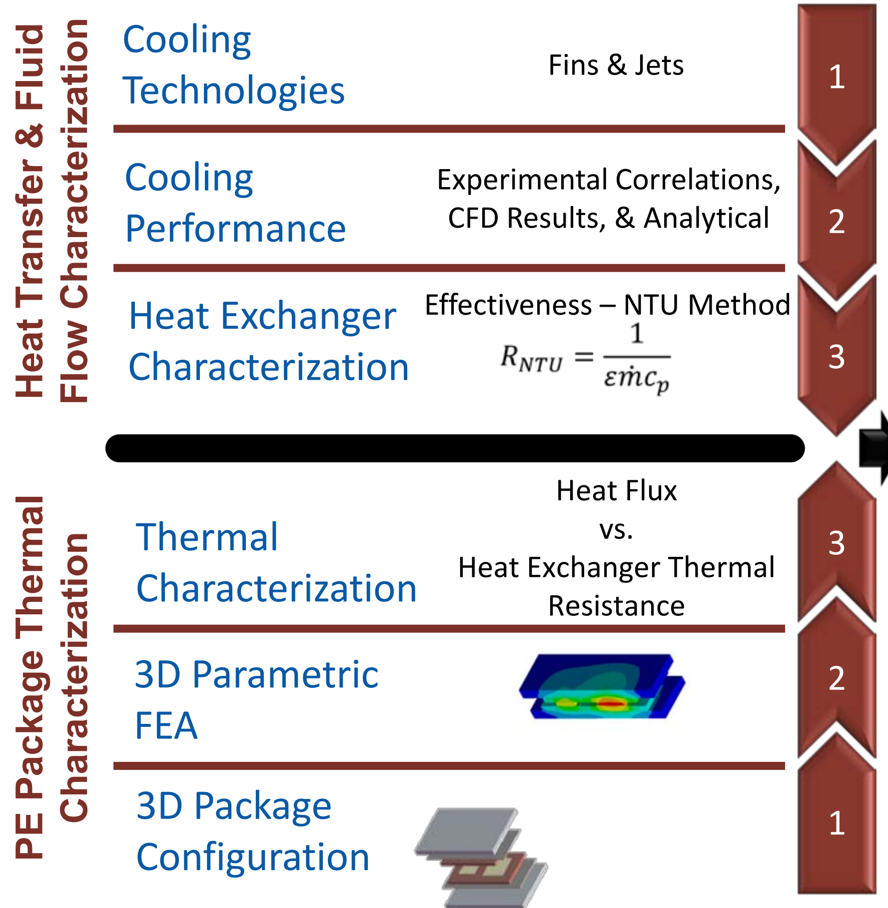
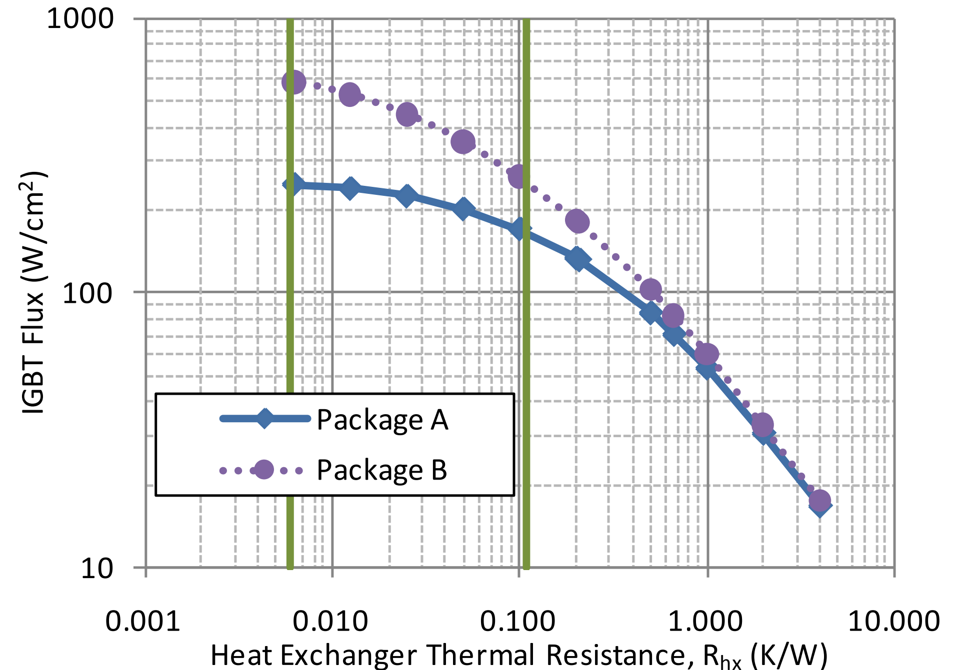
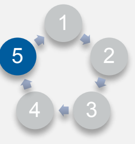




Technical Accomplishments & Progress (2/7)



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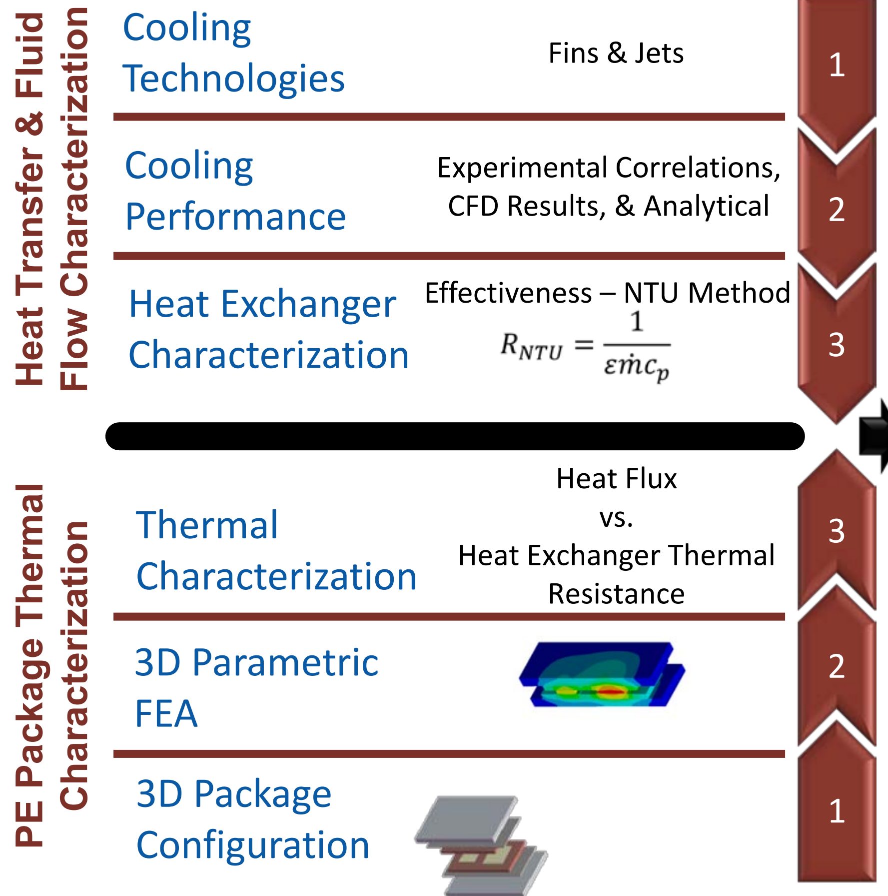
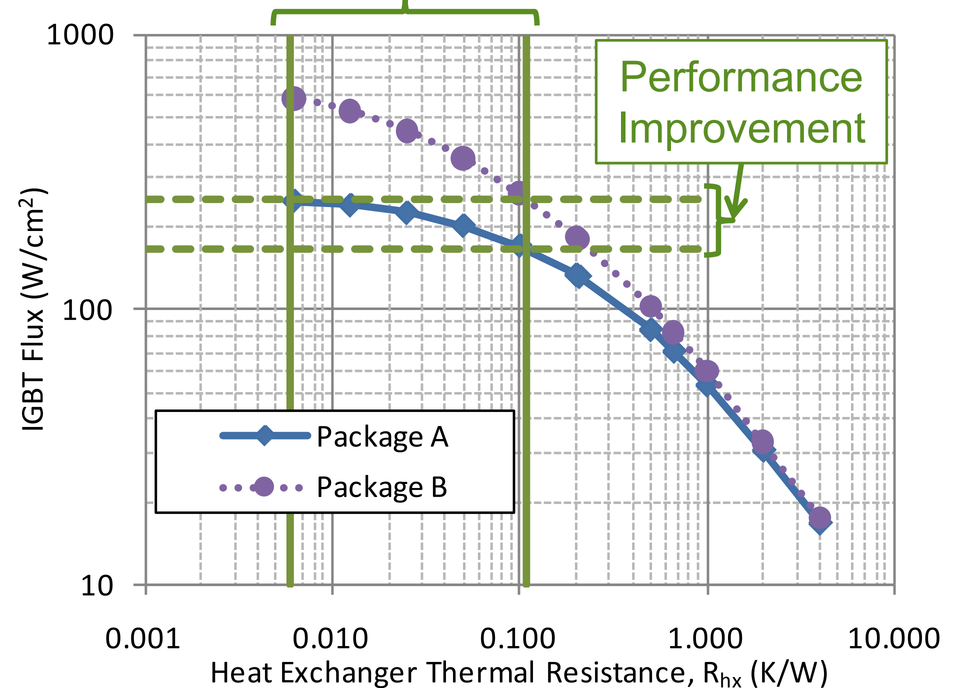
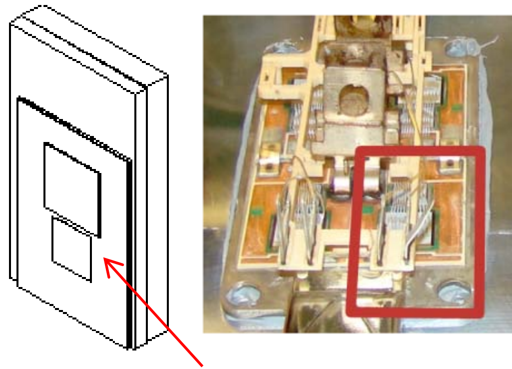




Technical Accomplishments & Progress (3/7)

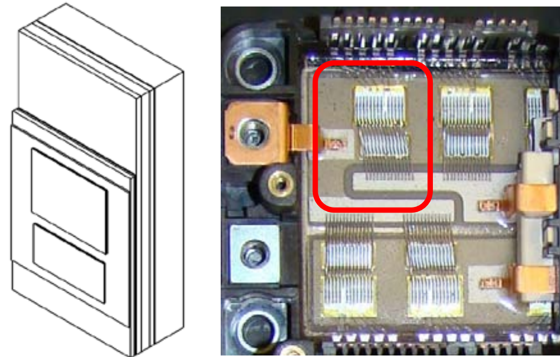
Applied process to range of package configuration examples approximated from in-use commercial packages with different geometries.

Semikron SKM

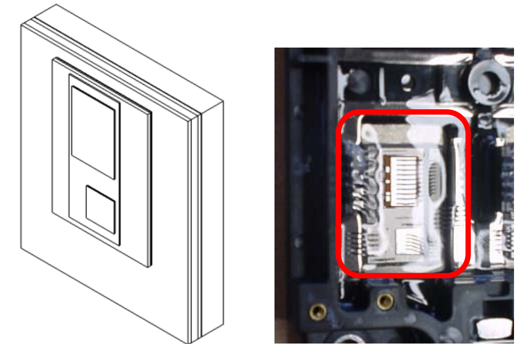


IGBT and diode pair

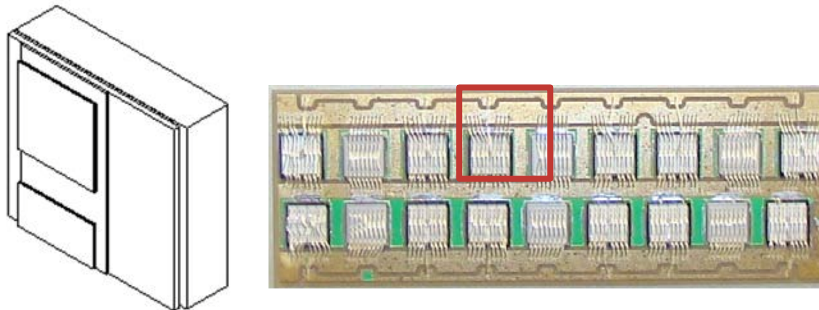
Toyota Camry



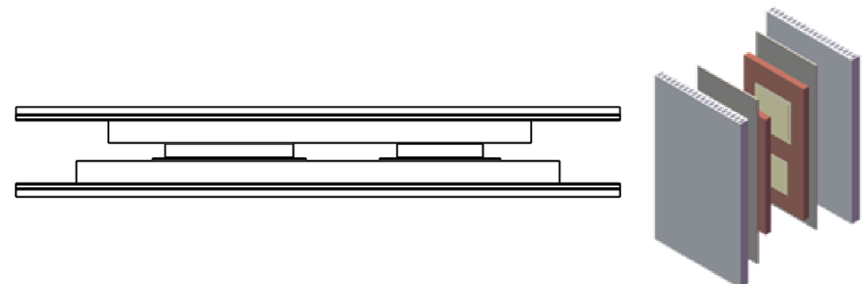
Toyota Prius 2004



Semikron SKAI



Lexus LS 600h



Technical Accomplishments & Progress (4/7)

Two-phase**
Forced convection (l)**
Air cooling**

Camry
Prius
SKM
SKAI
Lexus (d)

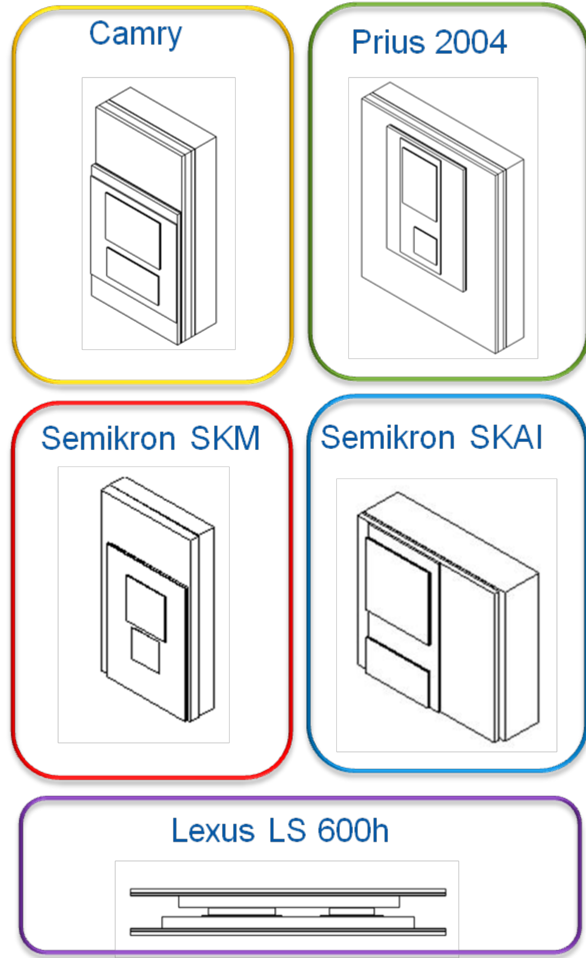
0.452*
0.203*

$R_{th,j\text{-}a}$ (K/W)

10.0
1.0
0.1

1
10
100
1,000
10,000

$R''_{th,h\text{-}a}$ (mm^2-K/W)

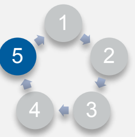


* $R_{th,ja}$ Range Source: Y. Sakai SAE Paper 2007-01-0271

** Cooling Range Source: Mudawar IEEE Transactions 2001

Technical Accomplishments & Progress (5/7)

1. Identify
2. Develop
3. Demonstrate
4. Improve
5. **Implement**



10.00
1.00
0.10
0.01

1 10 100 1,000 10,000

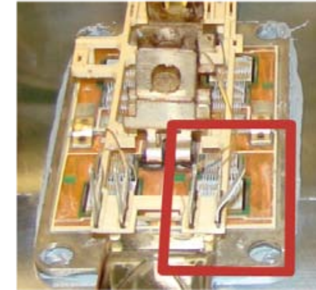
$R_{th,\,j\text{-}a}$ (K/W)

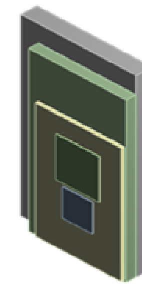
$R''_{th,\,h\text{-}a}$ (mm^2 -K/W)

open symbol: Baseline
gray symbol: DCB
black symbol: DCD

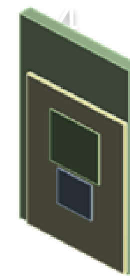
○ Al2O3
□ AlN

Semikron SKM

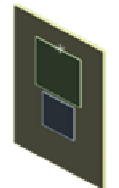




Baseline



Direct Cooled Baseplate (DCB)



Direct Cooled DBC (DCD)

Technical Accomplishments & Progress (6/7)

Package A
Package B1
Package B2
Package B3
Package B4
Package B5

$R_{th,ja}$ (K/W)

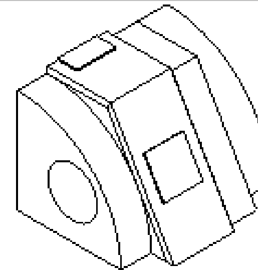
10^0

10^0 10^1 10^2 10^3 10^4

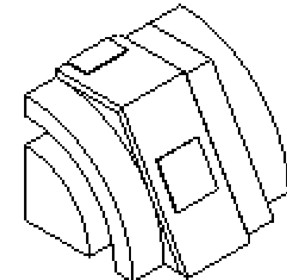
$R''_{th,ha}$ (mm^2-K/W)

Collaboration with Oak Ridge National Laboratory (ORNL) on alternative APEEM activity semiconductor package concepts.

Package A

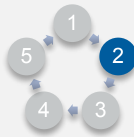


Package B



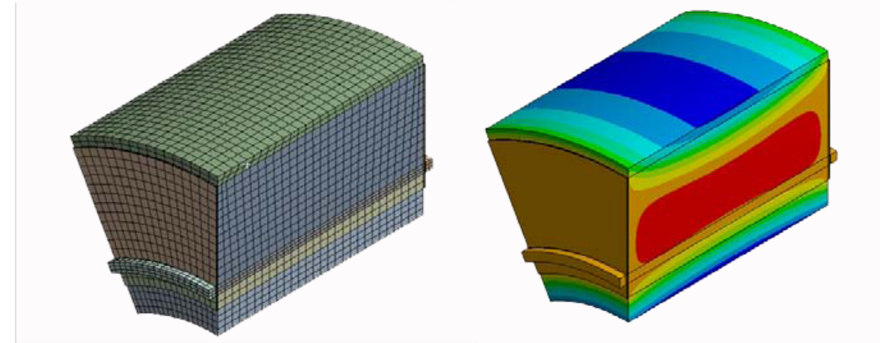
Technical Accomplishments & Progress (7/7)

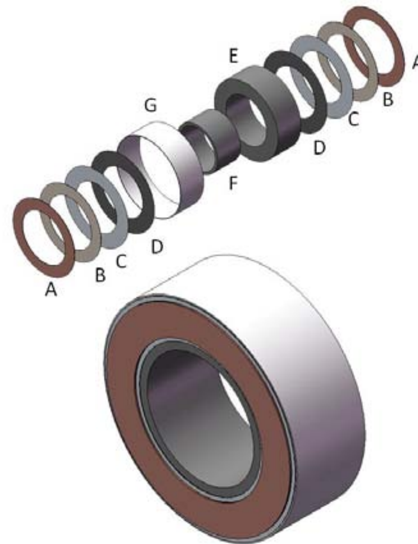
1. Identify
2. **Develop**
3. Demonstrate
4. Improve
5. Implement

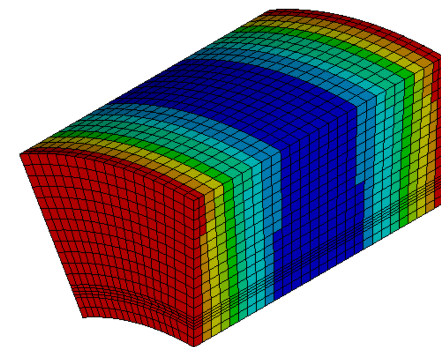


Capacitor Thermal Model

- Emphasis on thermal model development to support future system level PE packaging.
- Progress
  - Parametric 3-D Model
  - Anisotropic conductivity based on resistance network model
  - **Non-uniform heat generation**
    - Windings
    - End spray







Winding heat generation load

Collaboration and Coordination

Industry

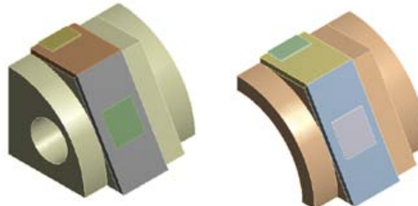
- Delphi: Partner
  - Input on application development of combined power semiconductor package and cooling thermal design.
- Electrical & Electronics Tech Team: Partner
  - Input on plans and accomplishments.

Other Government Laboratories

- Oak Ridge National Laboratory: Partner
  - Collaboration with alternative power semiconductor packaging concepts developed within the APEEM activity.
  - Support from benchmarking activities.

Proposed Future Work (1/2)

- Apply PE packaging thermal performance characterization to support the APEEM PE packaging focus.
    - ORNL collaboration
    - Industry awards



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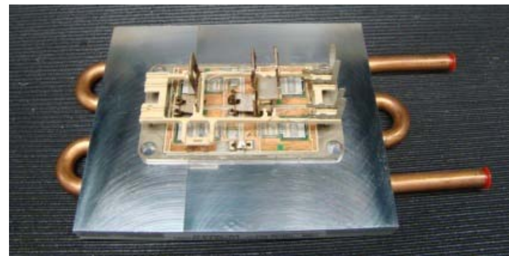
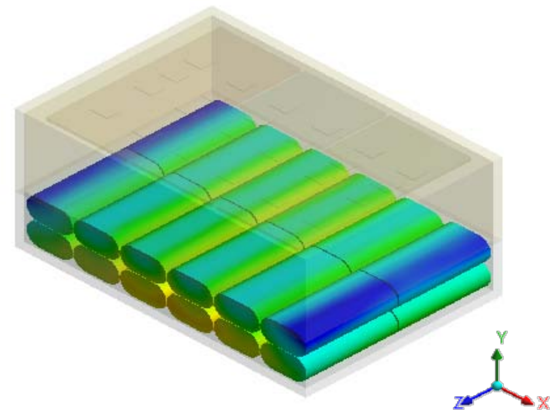
- PE packaging thermal performance hardware validation.



Proposed Future Work (2/2)

- Capacitor thermal model development to support APEEM activity R&D activities.
  - Leverage past experience in thermal control of batteries and ultra-capacitors.
  - Improve refinement.
  - Validate model.
  - Perform design trade-off studies of various form factors.
  - Study the application of these capacitor form factors in alternative packaging designs.



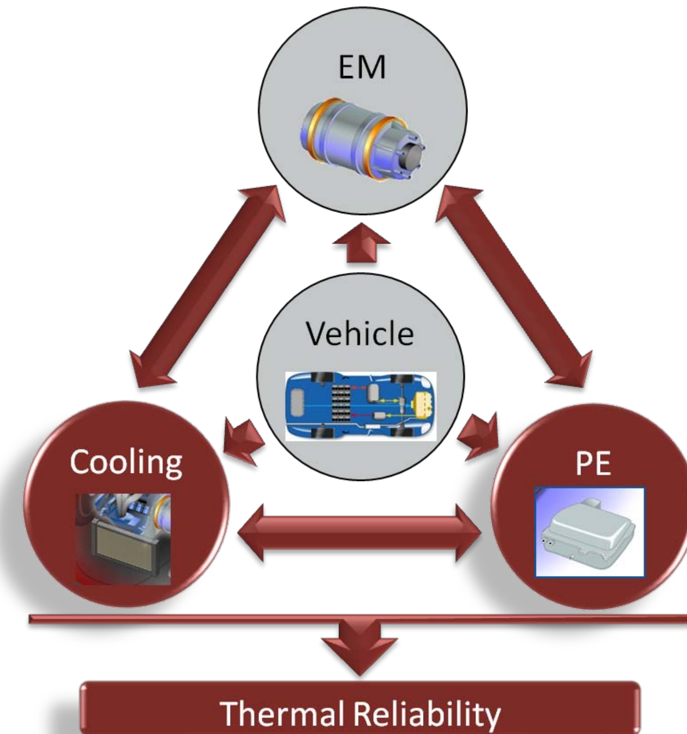
Summary

Relevance

- Facilitate the integration of APEEM thermal management technologies into commercially viable advanced automotive systems.

Approach/Strategy

- Identify system knowledge gaps.
- Develop process.
  - (e.g. model, experiment, or data analysis).
- Demonstrate process.
- Improve process with industry/partner input.
- Implement process.



Summary

Technical Accomplishments

- Integrated thermal trade-off analysis process for semiconductor packaging and cooling technologies.
  - Worked with industry to improve process.
  - Published application.
  - Applied to APEEM packaging activities.
- Capacitor thermal model development.

Collaborations

- Collaborations established with industry & other R&D partners.
  - ORNL
  - Delphi