Thermal Management of Power Semiconductor Packages – Matching Cooling Technologies with Packaging Technologies

IMAPS 2nd Advanced Technology Workshop on Automotive Microelectronics and Packaging

Kevin Bennion

Gilbert Moreno

Dearborn, MI

April 27, 2010

NREL/PR-540-48147

Acknowledgements

- Jason Lustbader, National Renewable Energy laboratory (NREL)
- Advanced Power Electronics and Electric Machines Benchmarking, Oak Ridge National Laboratory (ORNL)

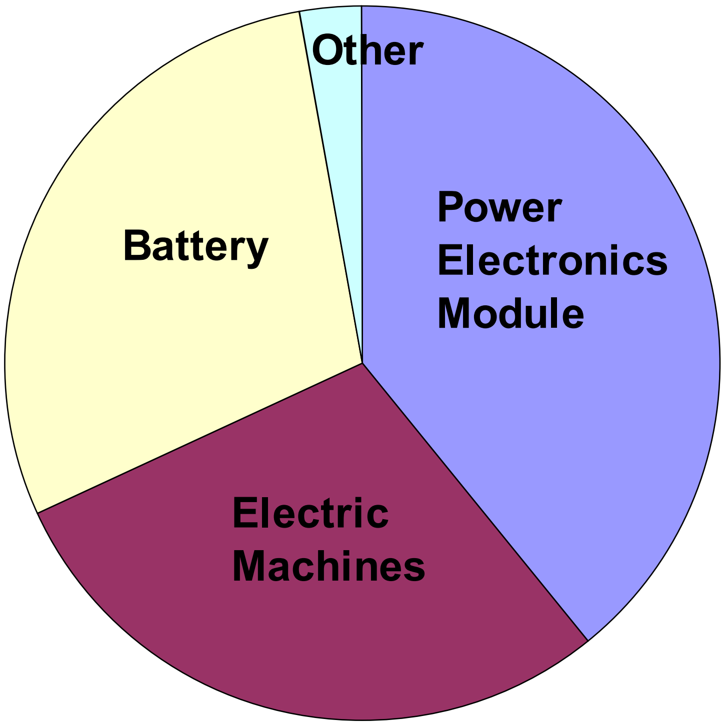
Funding Provide by:

Susan Rogers, Office of Vehicle Technology, U.S. Department of Energy

Objective

1. Efficient heat transfer technologies can enable increased power density and specific power.
2. Thermal management is a path to reduce cost and maintain robust operation.
3. Thermal management should not be an afterthought but should involve an integrated systems approach.
4. Cost-effective solutions require **integration** of capabilities for **cooling**, **packaging** (materials/geometry), and **reliability** prediction.

Toyota Camry - 2007

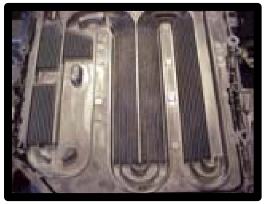


Source: Technology and Cost Report of the MY2007 Toyota Camry - ORNL

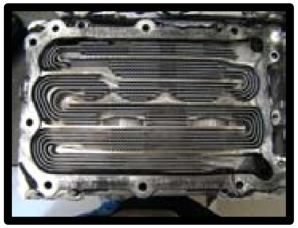
Relevance of Thermal Management

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

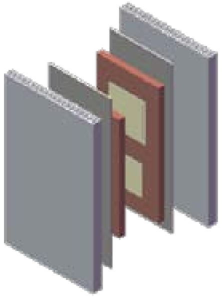
Prius PE MY 2004



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."

Concern: Heat

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

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

Outline

Background

- Department of Energy's Advanced Power Electronics and Electric Machines (APEEM) activity.
- Thermal management for power electronics cooling.

Problem

- Quantify trade-off interaction between packaging configuration and cooling technology.
- Identify effective packaging and cooling combinations.

Approach

Results

Background

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

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

U.S. DEPARTMENT OF ENERGY

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

FreedomCAR & Fuel Partnership

USCAR

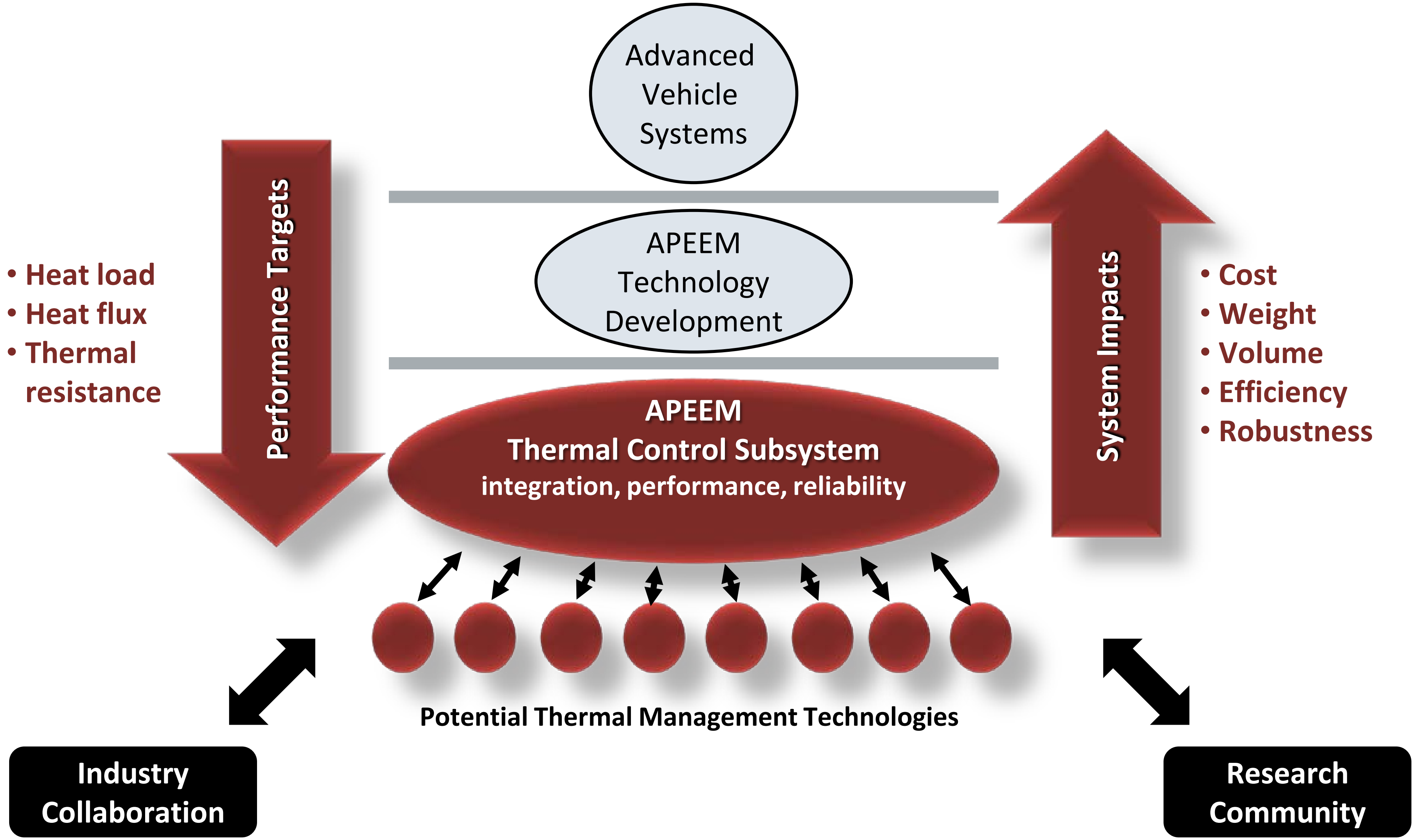
+

Other Industry Partners and Universities

Industry and Academia

Background

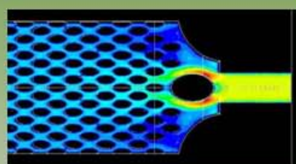
- NREL Advanced Power Electronics Thermal Overview

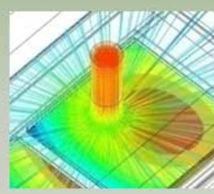


Background

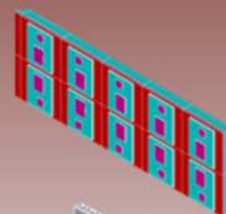
- NREL Advanced Power Electronics Thermal Focus Areas

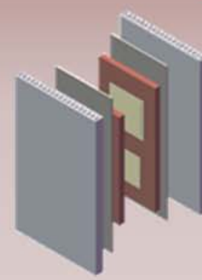
Advanced Heat Transfer



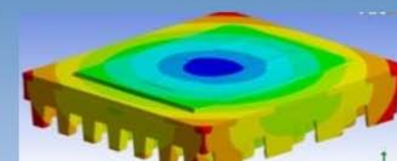


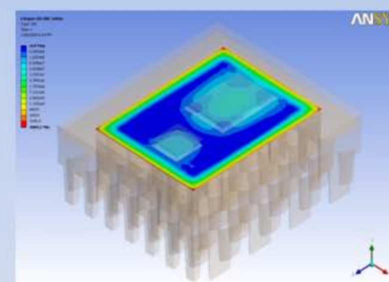
Thermal Systems Integration





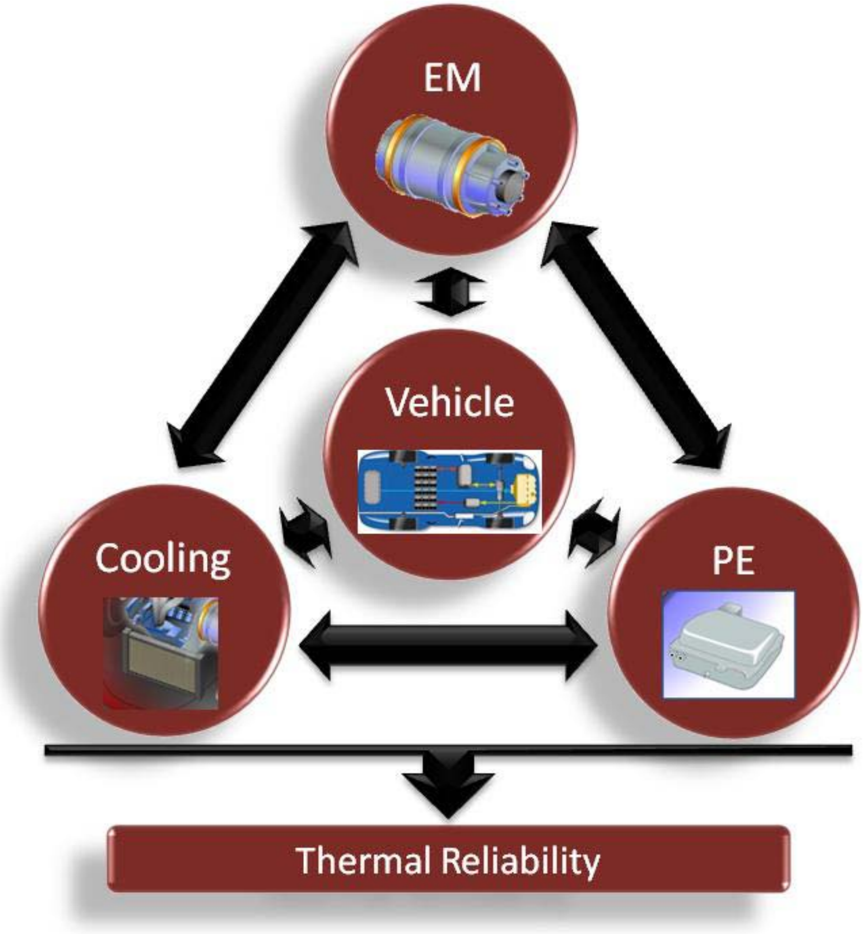
Thermal Stress and Reliability





Background

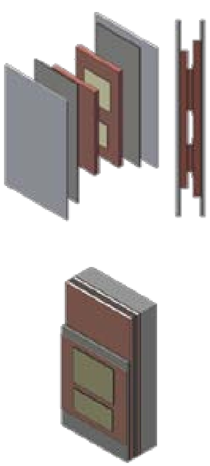
- Defines thermal requirements
- Links thermal technologies to electric traction drive systems



Problem

How do developments in APEEM technologies influence cooling technology selection?

How do developments in cooling impact APEEM technology selection?

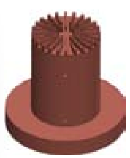


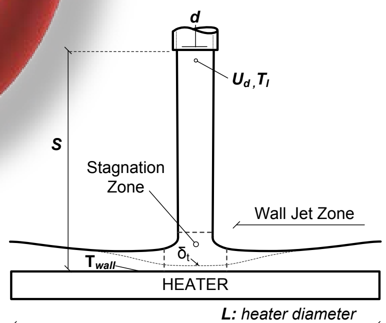
Advanced Vehicle Systems

APEEM Technology Development

APEEM
Thermal Control Subsystem
integration, performance, requirements

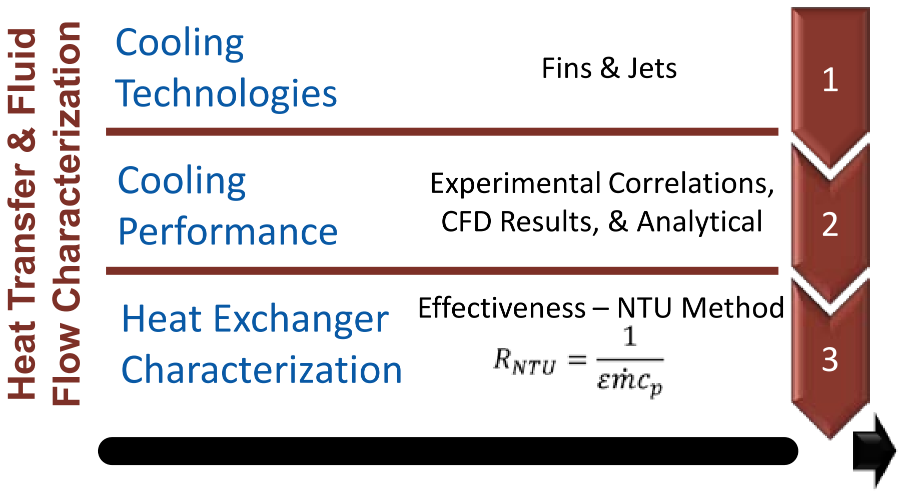
Potential Thermal Management Technologies

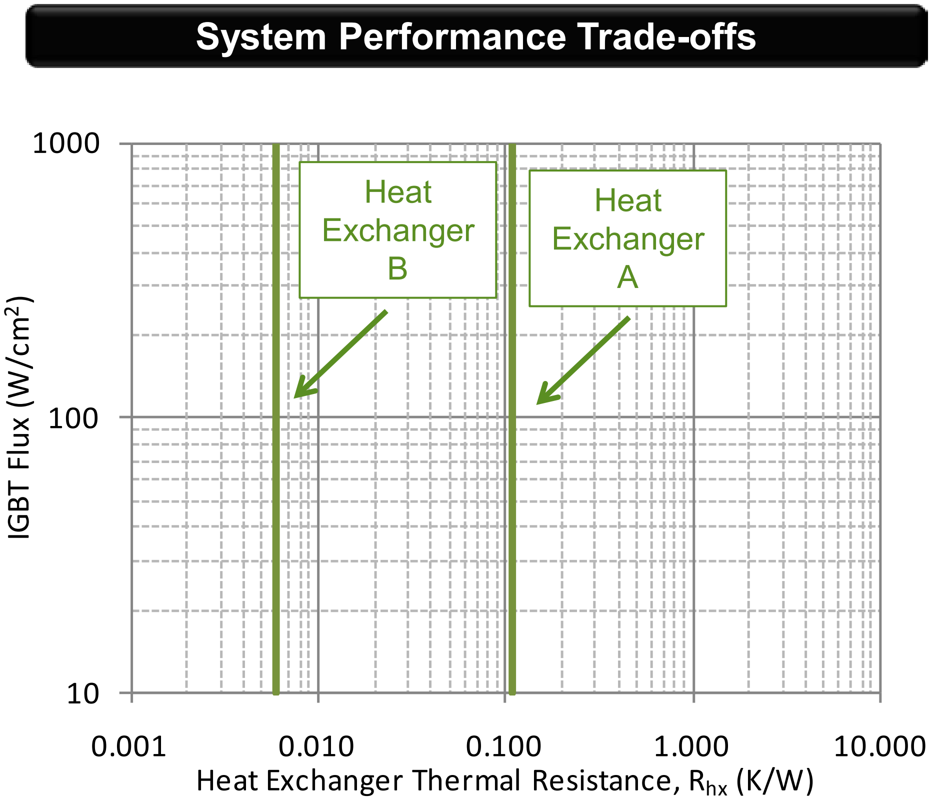




Approach

Quantify interaction between package configuration and cooling technology on total thermal performance.





Approach

Quantify interaction between package configuration and cooling technology on total thermal performance.

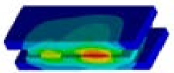
Heat Transfer & Fluid Flow Characterization

1. Cooling Technologies — Fins & Jets
2. Cooling Performance — Experimental Correlations, CFD Results, & Analytical
3. Heat Exchanger Characterization — Effectiveness – NTU Method

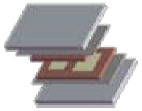
$$R_{NTU} = \frac{1}{\varepsilon \dot{m} c_p}$$

PE Package Thermal Characterization

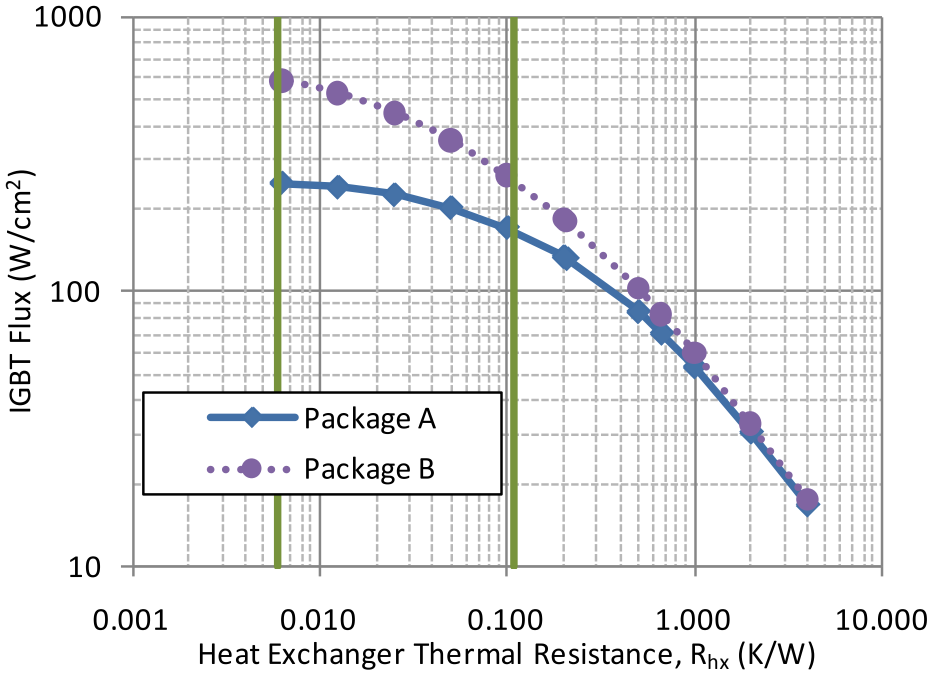
3. Thermal Characterization — Heat Flux vs. Heat Exchanger Thermal Resistance
2. 3D Parametric FEA



1. 3D Package Configuration



System Performance Trade-offs



Approach

Quantify interaction between package configuration and cooling technology on total thermal performance.

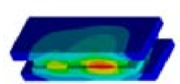
Heat Transfer & Fluid Flow Characterization

1. **Cooling Technologies** — Fins & Jets
2. **Cooling Performance** — Experimental Correlations, CFD Results, & Analytical
3. **Heat Exchanger Characterization** — Effectiveness – NTU Method

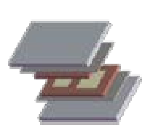
$$R_{NTU} = \frac{1}{\varepsilon \dot{m} c_p}$$

PE Package Thermal Characterization

3. **Thermal Characterization** — Heat Flux vs. Heat Exchanger Thermal Resistance
2. **3D Parametric FEA**

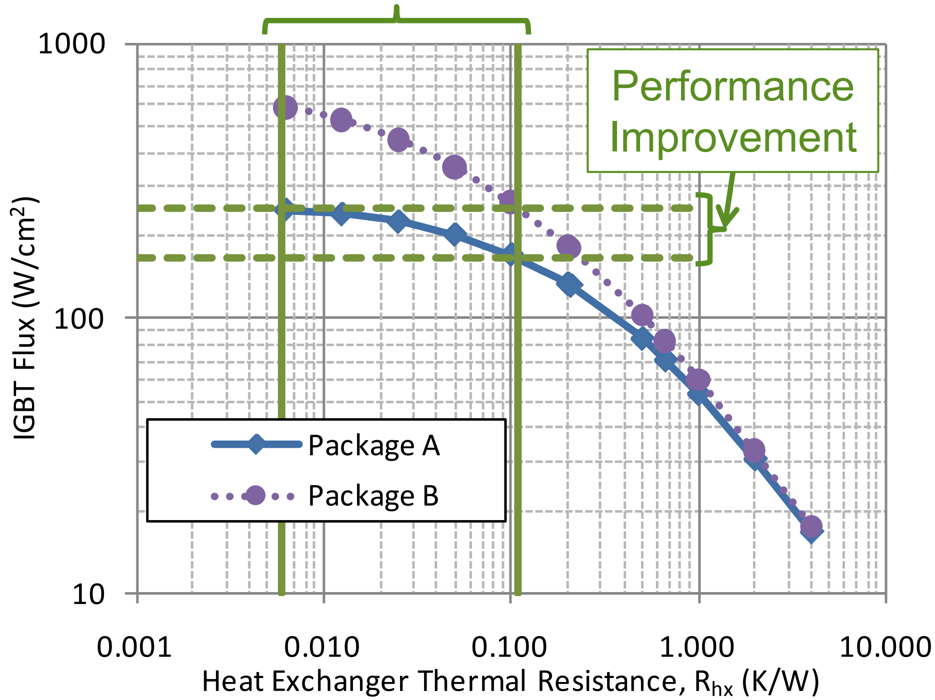


1. **3D Package Configuration**



System Performance Trade-offs

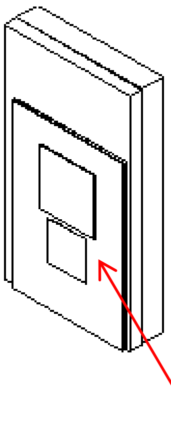
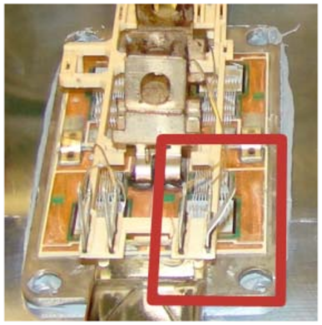
Required heat exchanger improvement for equivalent performance gain.



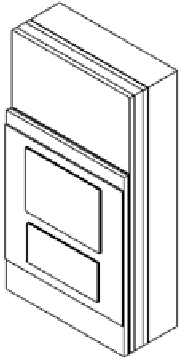
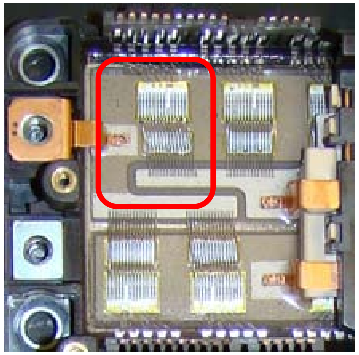
Approach

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

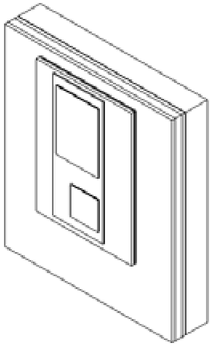
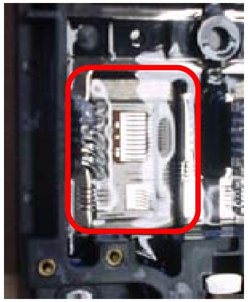
Semikron SKM

Toyota Camry

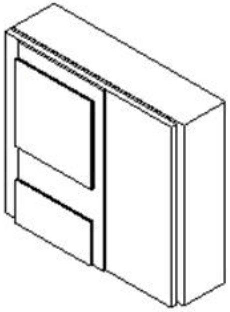
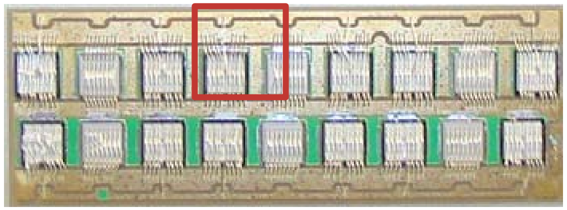



Toyota Prius 2004

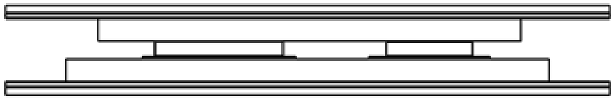
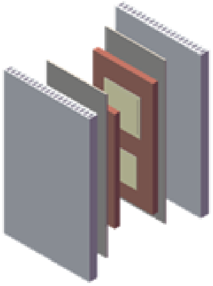



IGBT and diode pair

Semikron SKAI

Lexus LS 600h

Approach

Layer		Baseline Package Configurations: SKM	SKAI	Prius	Camry	Ls 600H
IGBT/Diode (Si)		x	x	x	x	See referenced paper below
Solder		x	x	x	x	
Cu		x	x	x**	x**	
Substrate	AlN	NA*	x	x	x	
	Al_2O_3	x	NA	NA	NA	
Cu		x	x	x	x	
Solder		x	NA	x	x	
Heat Spreader	Cu	x	NA	NA	NA	
	Cu-Mo-Cu	NA	NA	x	x	
TIM		x	x+	x	x	
Heat Sink		x	x	x	x	
Cooled Surface Footprint Area: [cm^2]		15.34	3.90	16.86	7.68	15.00++

* Included additional model variation with AlN.

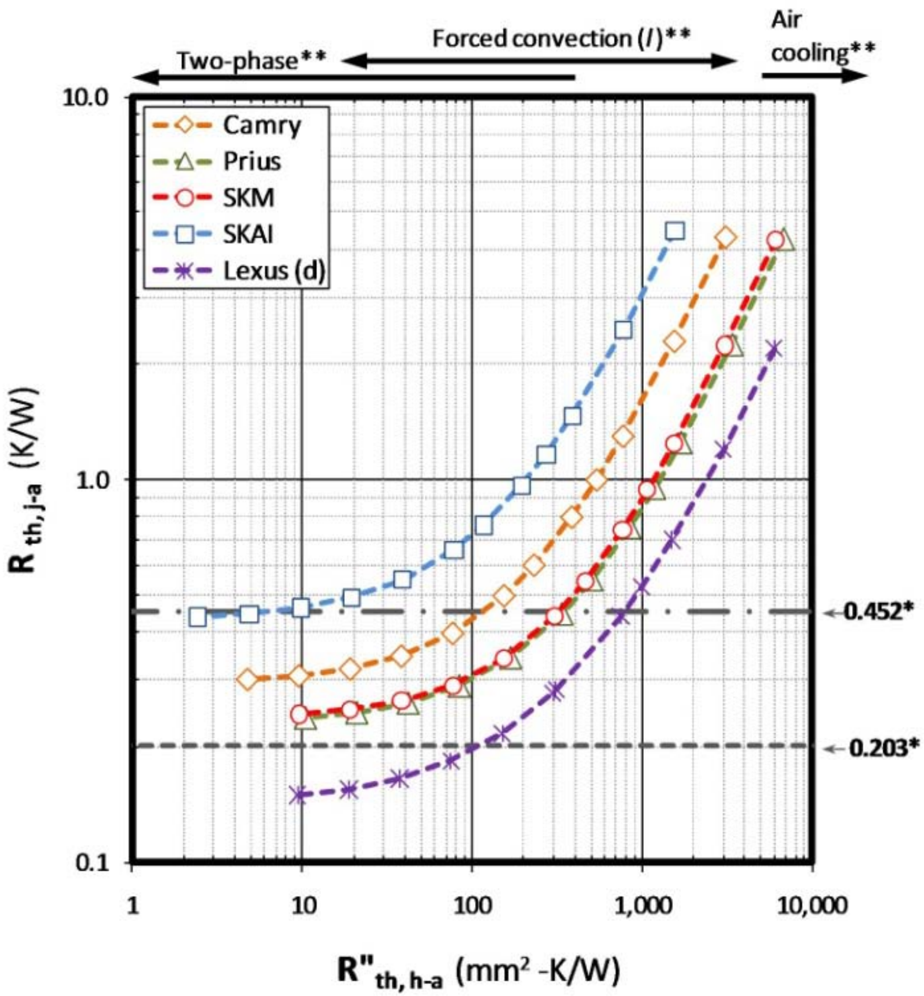
\+ Modeled with reduced thermal interface material thickness of 0.05 mm.

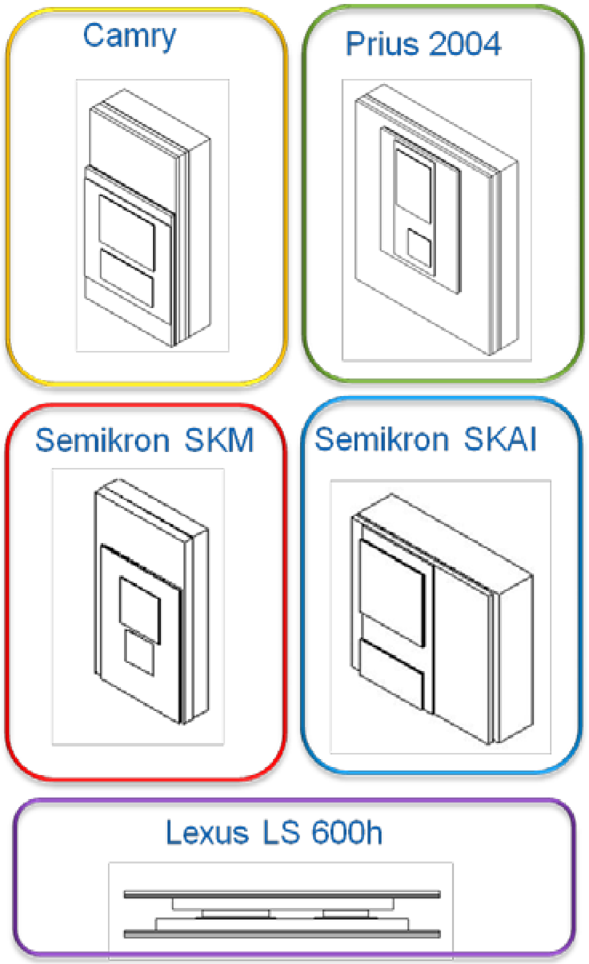
** Assumed copper metallization layer.

++ Listed area is for one side of the package, and it is the same on each side of the package.

Reference:
K. Bennion and K. Kelly, "Rapid Modeling of Power Electronics Thermal Management Technologies," IEEE Vehicle Power and Propulsion Conference, Sept. 7-11, 2009.

Results

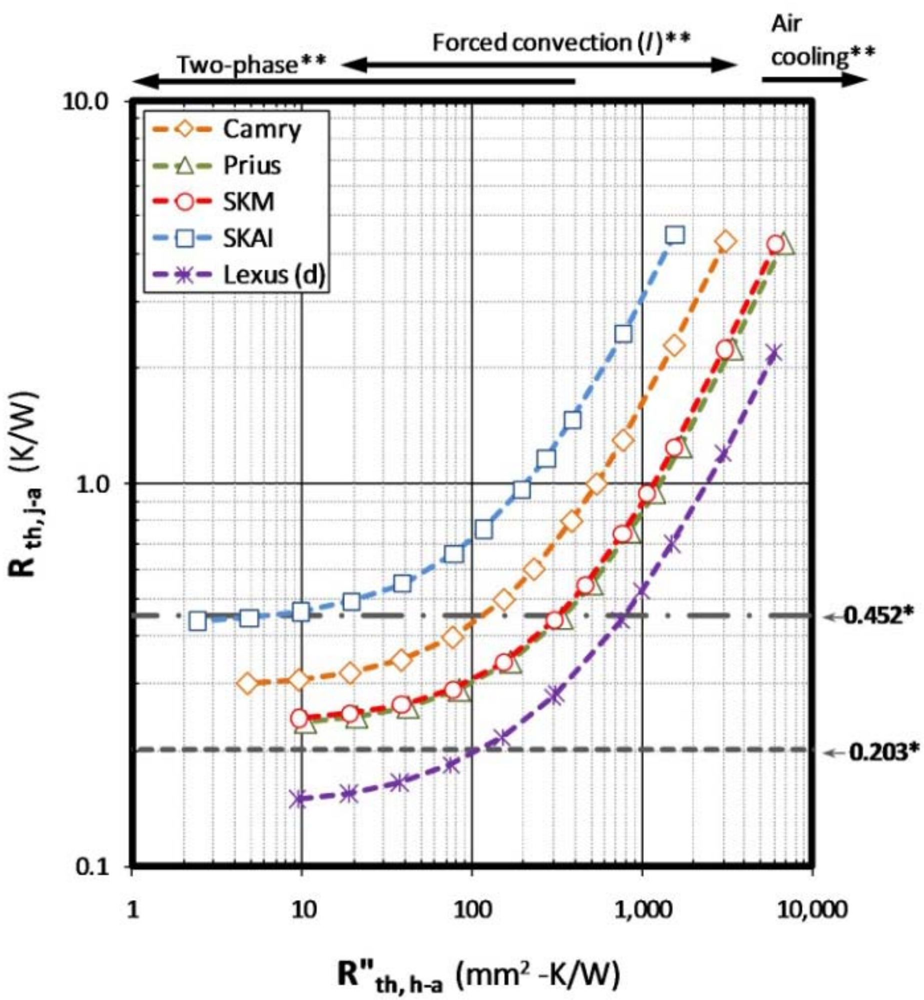




* Sample single-sided and double-sided total thermal resistance. (Source: Y. Sakai, H. Ishiyama, and T. Kikuchi, "Power control unit for high power hybrid system," SAE 2007 World Congress, Detroit, MI, April 16-19, 2007, SAE Paper 2007-01-0271.)

** Sample cooling performance. (Source: I. Mudawar, "Assessment of high-heat-flux thermal management schemes," IEEE Transactions on Components and Packaging Technologies, vol. 24, no. 2, pp. 122-141, June 2001.

Results

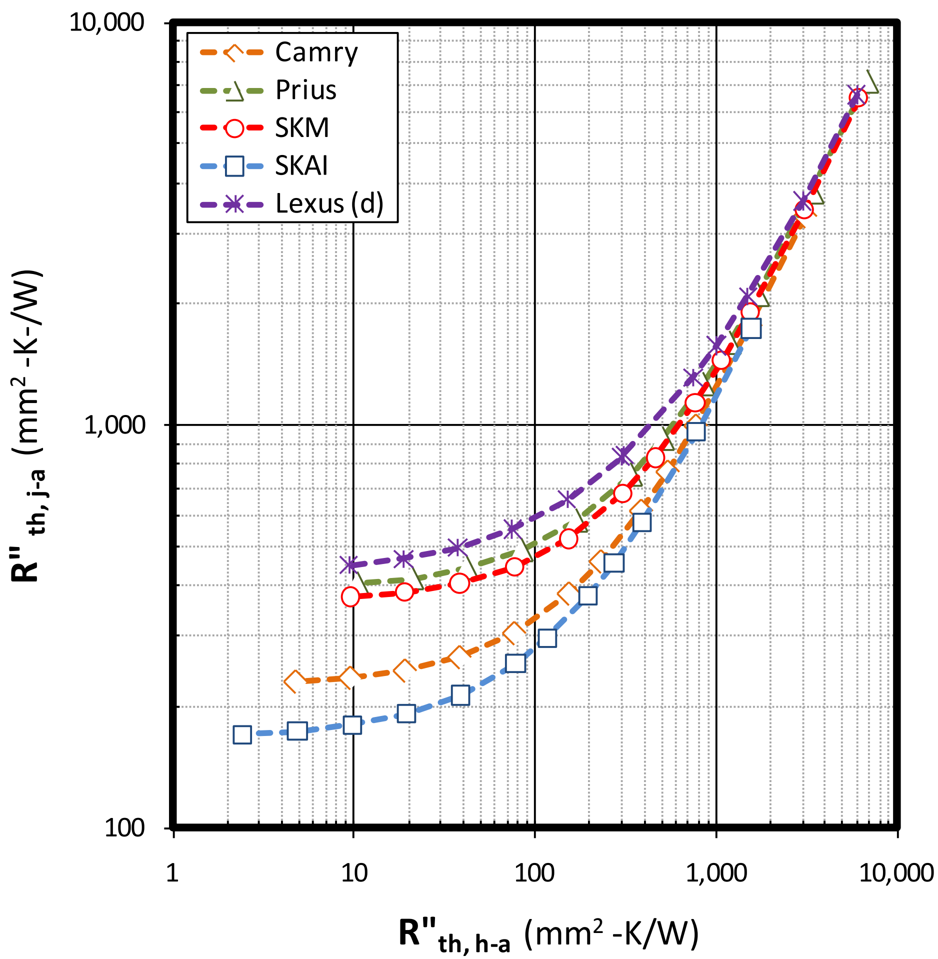


- All curves flatten as the heat exchanger performance improves ($R''_{h,h\text{-}a}$ decreases).
- Package becomes thermal limitation.
- Difference in total thermal performance ($R''_{th,j\text{-}a}$) is affected by the footprint area available for cooling.
- Method for comparing alternative heat exchanger technologies and package configurations.

* Sample single-sided and double-sided total thermal resistance. (Source: Y. Sakai, H. Ishiyama, and T. Kikuchi, "Power control unit for high power hybrid system," SAE 2007 World Congress, Detroit, MI, April 16-19, 2007, SAE Paper 2007-01-0271.)

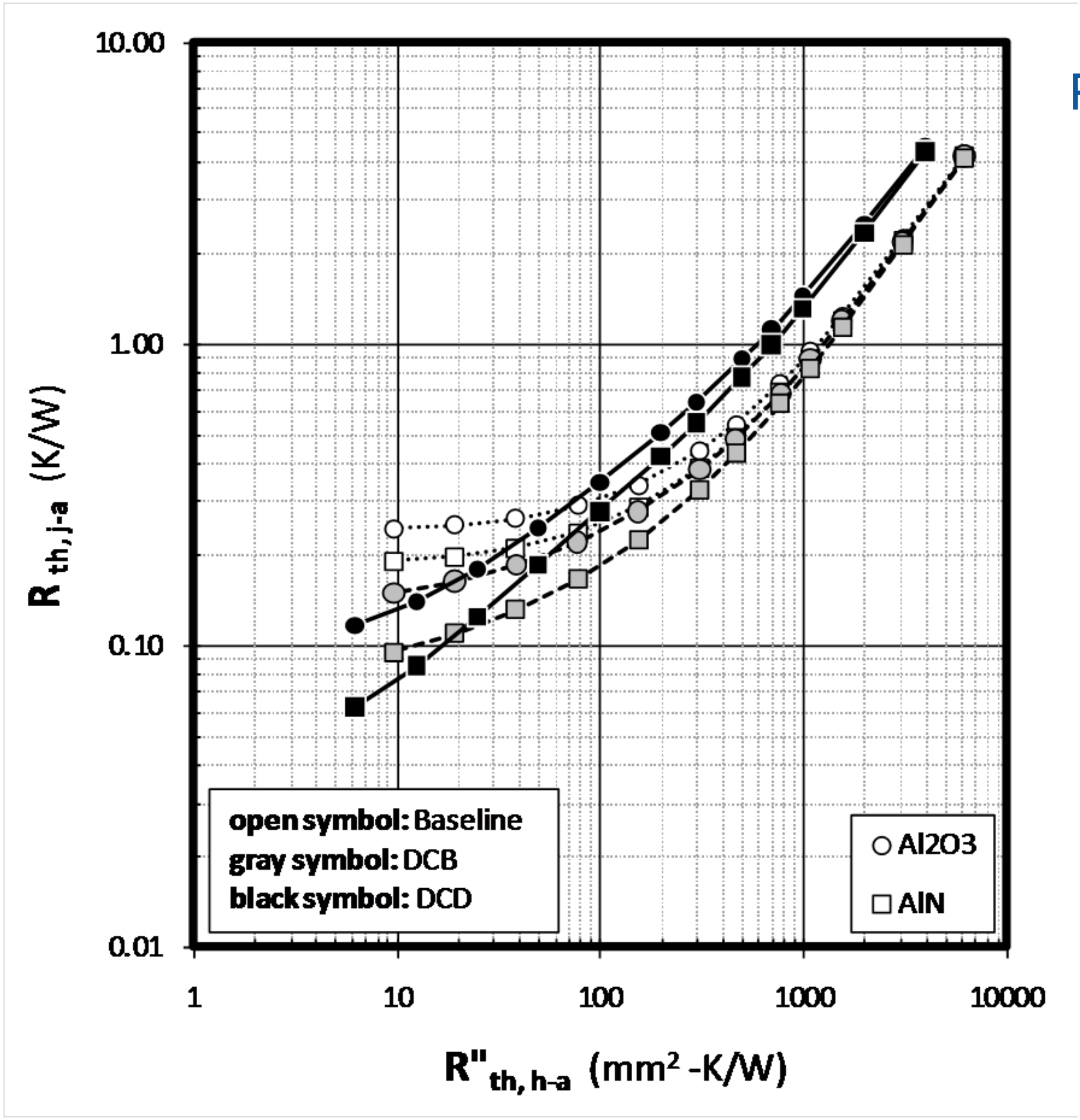
** Sample cooling performance. (Source: I. Mudawar, "Assessment of high-heat-flux thermal management schemes," IEEE Transactions on Components and Packaging Technologies, vol. 24, no. 2, pp. 122-141, June 2001.

Results

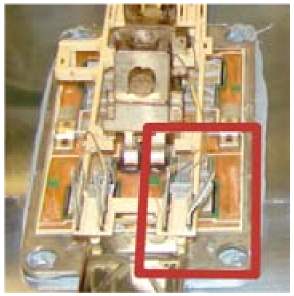


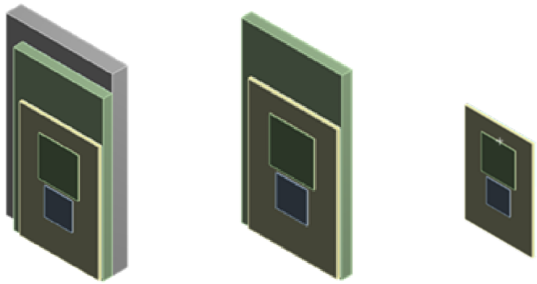
- Weight the total thermal performance ($R_{th,j-a}$) by the total footprint area available for cooling.
- Curves collapse onto a single curve as the heat exchanger resistance increases.
- Removes effect of different package footprint areas.

Results

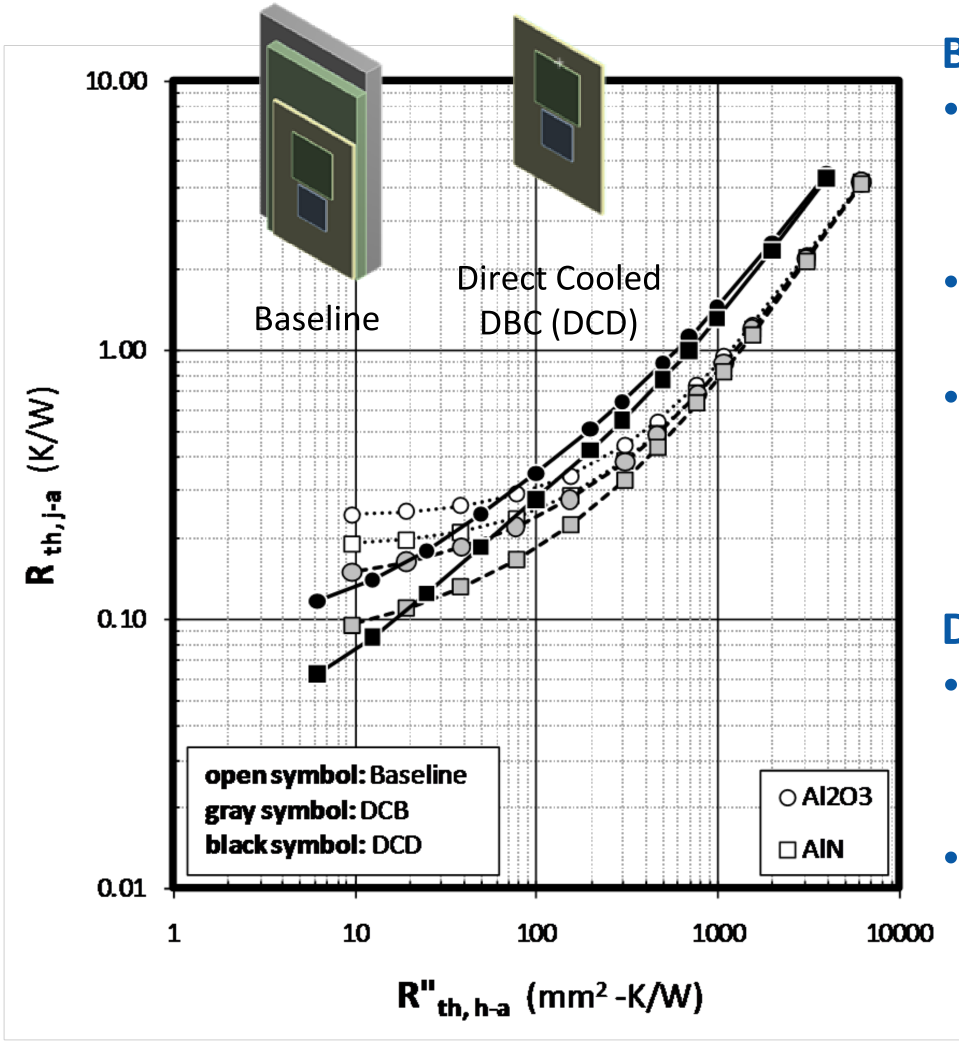


Package geometry, material, and cooling trade-offs





Results



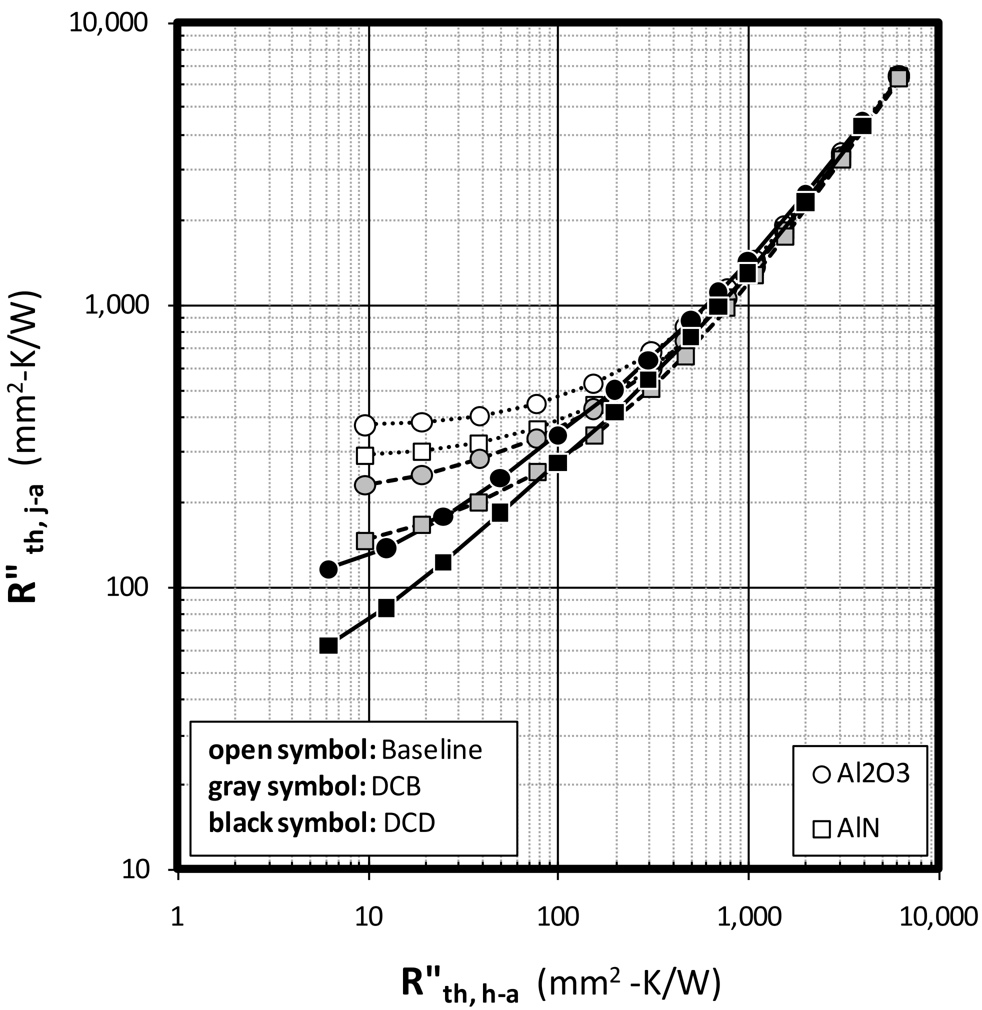
Baseline

- At low $R_{th,h\text{-}a}$, the separation between $AL_2 0_3$ and AlN package resistance is more significant.
- Trade-off between material cost and heat exchanger performance cost.
- At about 100 mm^2-K/W, switching to AlN would have a similar benefit to a 10X heat exchanger improvement.

Direct Cooled DBC (DCD)

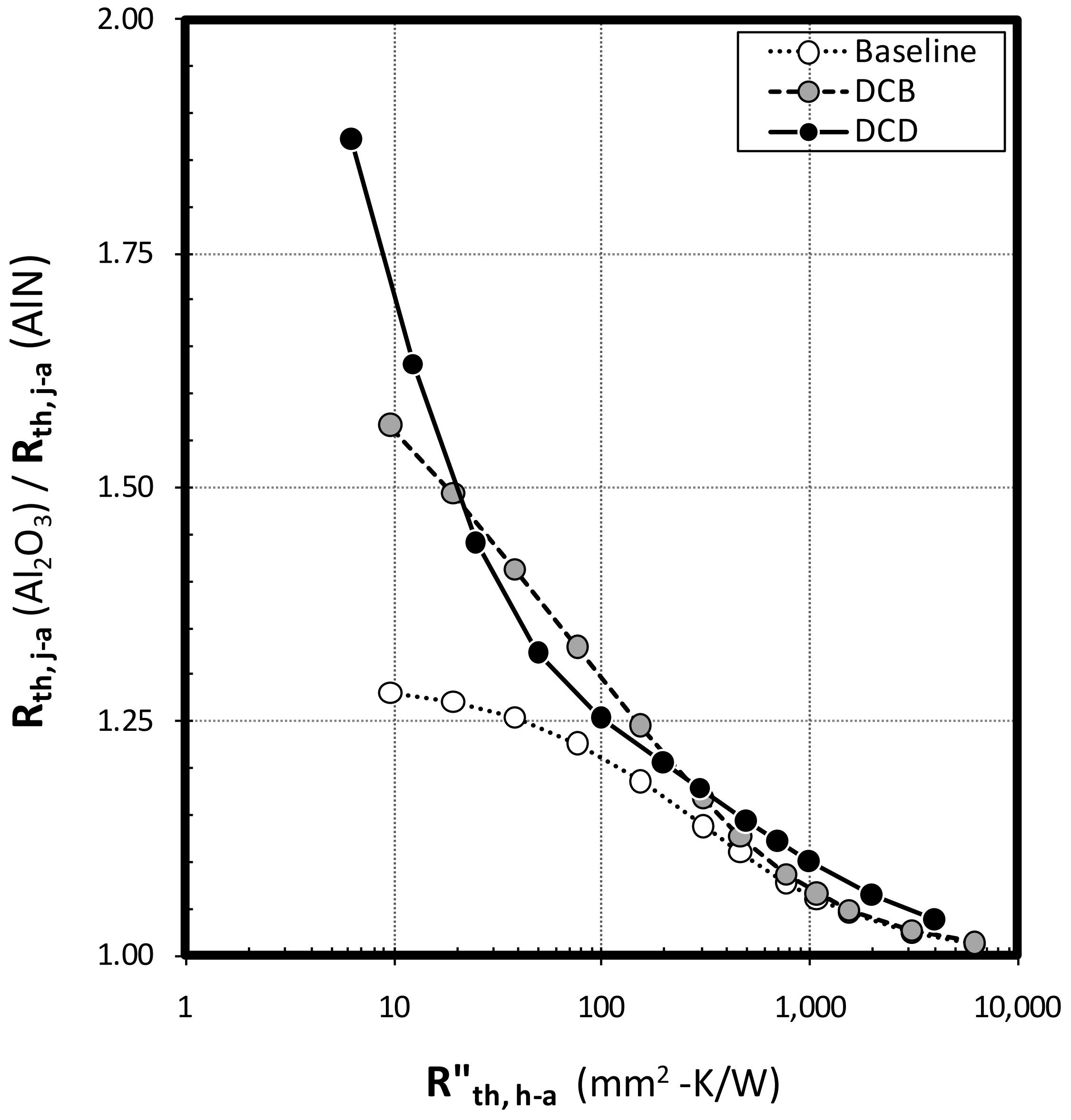
- At high $R_{th,h\text{-}a}$, the cooling area footprint and heat exchanger resistance dominate thermal performance.
- As the cooling technology improves, the thermal characteristics of the package become more important.

Results



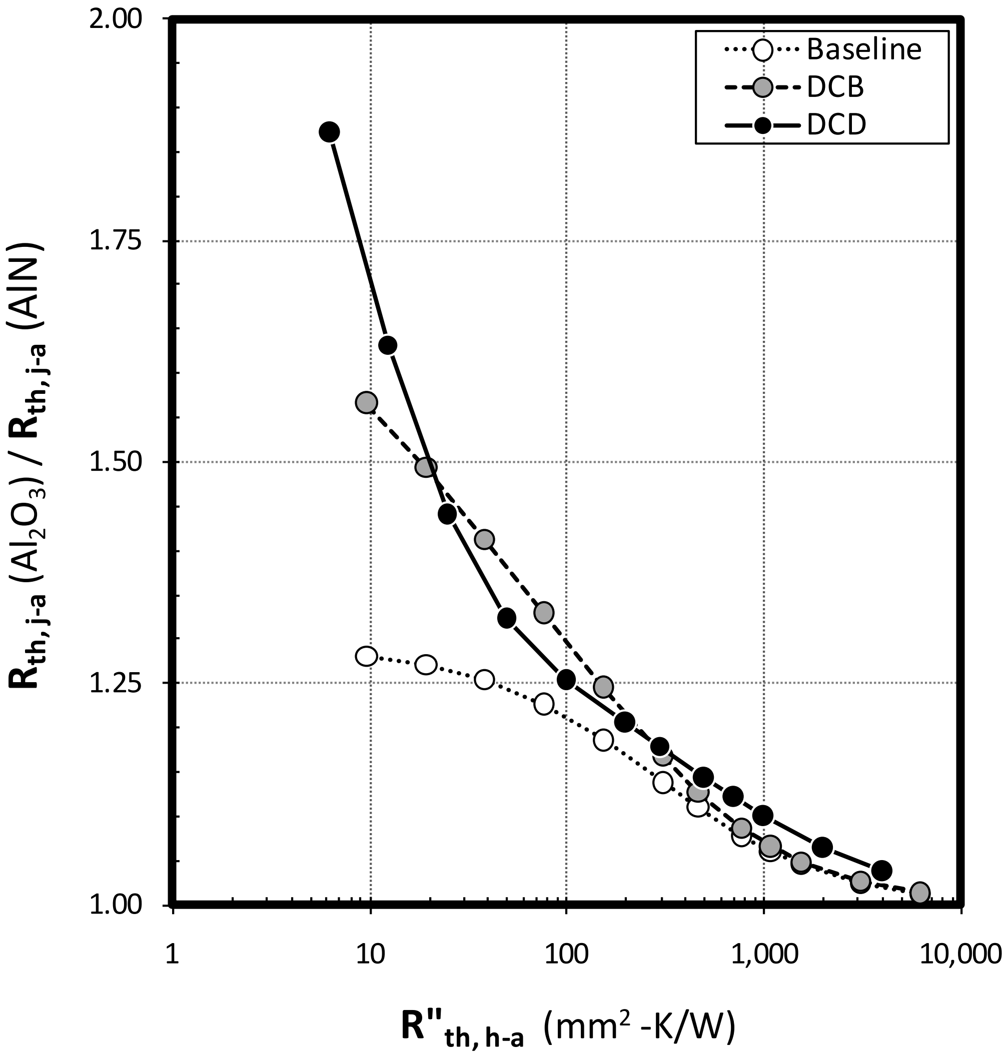
- Weight the total thermal performance ($R_{th,j\text{-}a}$) by the total footprint area available for cooling.
- Curves collapse onto a single curve as the heat exchanger resistance increases.
- Removes effect of different package footprint areas.
- Highlights impact of package.

Results



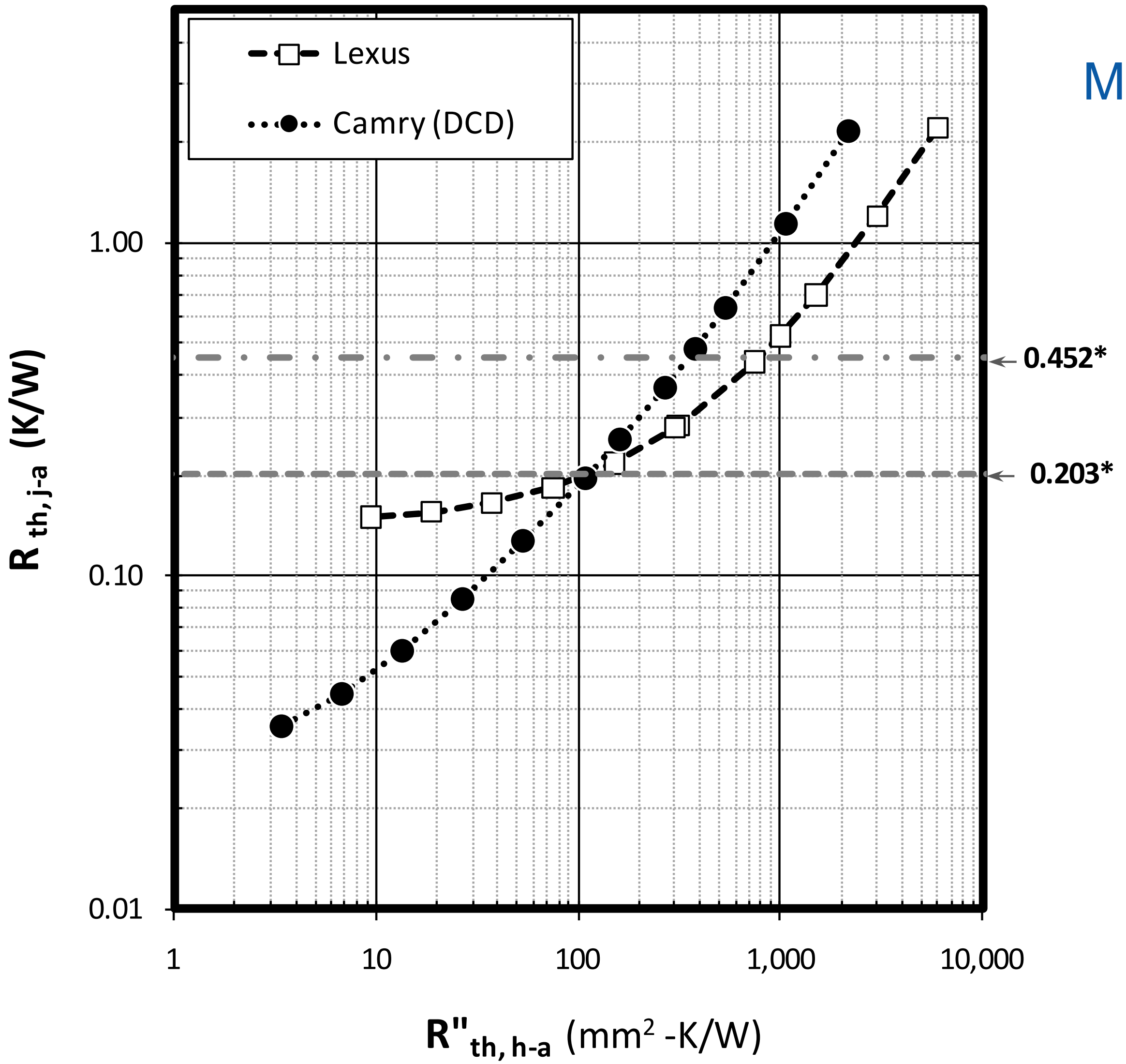
Baseline
DCB
DCD
2.00
1.75
1.50
1.25
1.00
1
10
100
1,000
10,000
$R_{th, j\text{-}a} (Al_2O_3) / R_{th, j\text{-}a} (AlN)$
$R''_{th, h\text{-}a}$ (mm^2 -K/W)

Results



- The impact of a material with improved thermal conductivity depends on the package configuration and heat exchanger performance.
- The cost/benefit trade-off improves for more aggressive cooling and packages with fewer thermal bottlenecks.
- Relationship between package thermal performance and cooling technology can lead to a more expensive system than necessary if the relationship is not used properly.

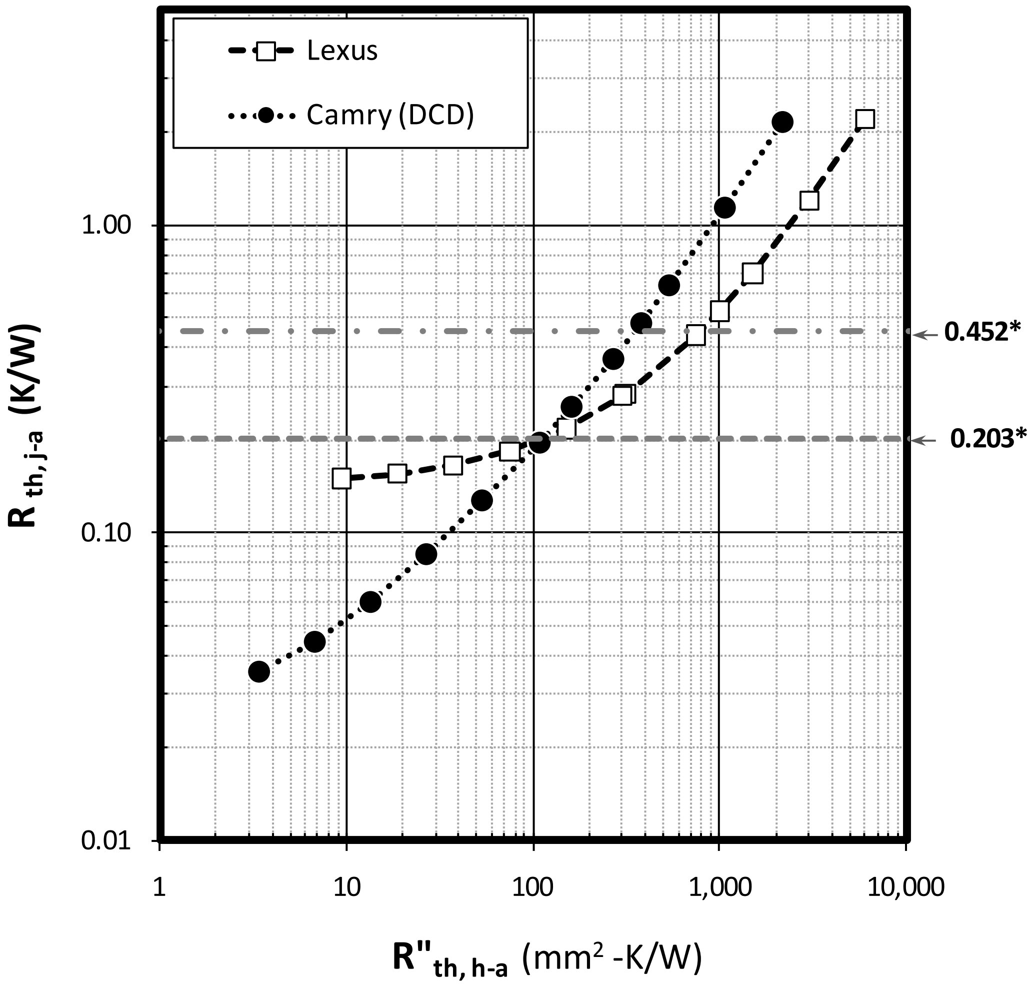
Results



Matching package geometry and cooling technology

* Sample single-sided and double-sided total thermal resistance. (Source: Y. Sakai, H. Ishiyama, and T. Kikuchi, "Power control unit for high power hybrid system," SAE 2007 World Congress, Detroit, MI, April 16-19, 2007, SAE Paper 2007-01-0271.)

Results



Matching package geometry and cooling technology

- To maximize the thermal performance, the package and heat exchanger technology should be investigated together.
- Identify appropriate cooling methods for a given package technology.
- Identify appropriate packaging options for a given cooling approach.

* Sample single-sided and double-sided total thermal resistance. (Source: Y. Sakai, H. Ishiyama, and T. Kikuchi, "Power control unit for high power hybrid system," SAE 2007 World Congress, Detroit, MI, April 16-19, 2007, SAE Paper 2007-01-0271.)

Conclusion

- Thermal management plays an important part in the cost of electric drives in terms of power electronics packaging.
- Cost-effective solutions require an appropriate balance between package and thermal management design.
- Appropriate cooling technology depends on
  - Package application
  - Reliability
- **Integration** of capabilities for **cooling**, **packaging** (materials/geometry), and **reliability** prediction provide a system view of technology developments.