Integrated Power Module Cooling

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National Renewable Energy Laboratory
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Project ID: APE047

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

Project Start Date: FY 2012
Project End Date: FY 2013
Percent Complete: 75%

Budget

Total Project Funding:
DOE Share:$750K (FY12-FY13)

Funding Received in FY12: $350K

Funding for FY13: $400K

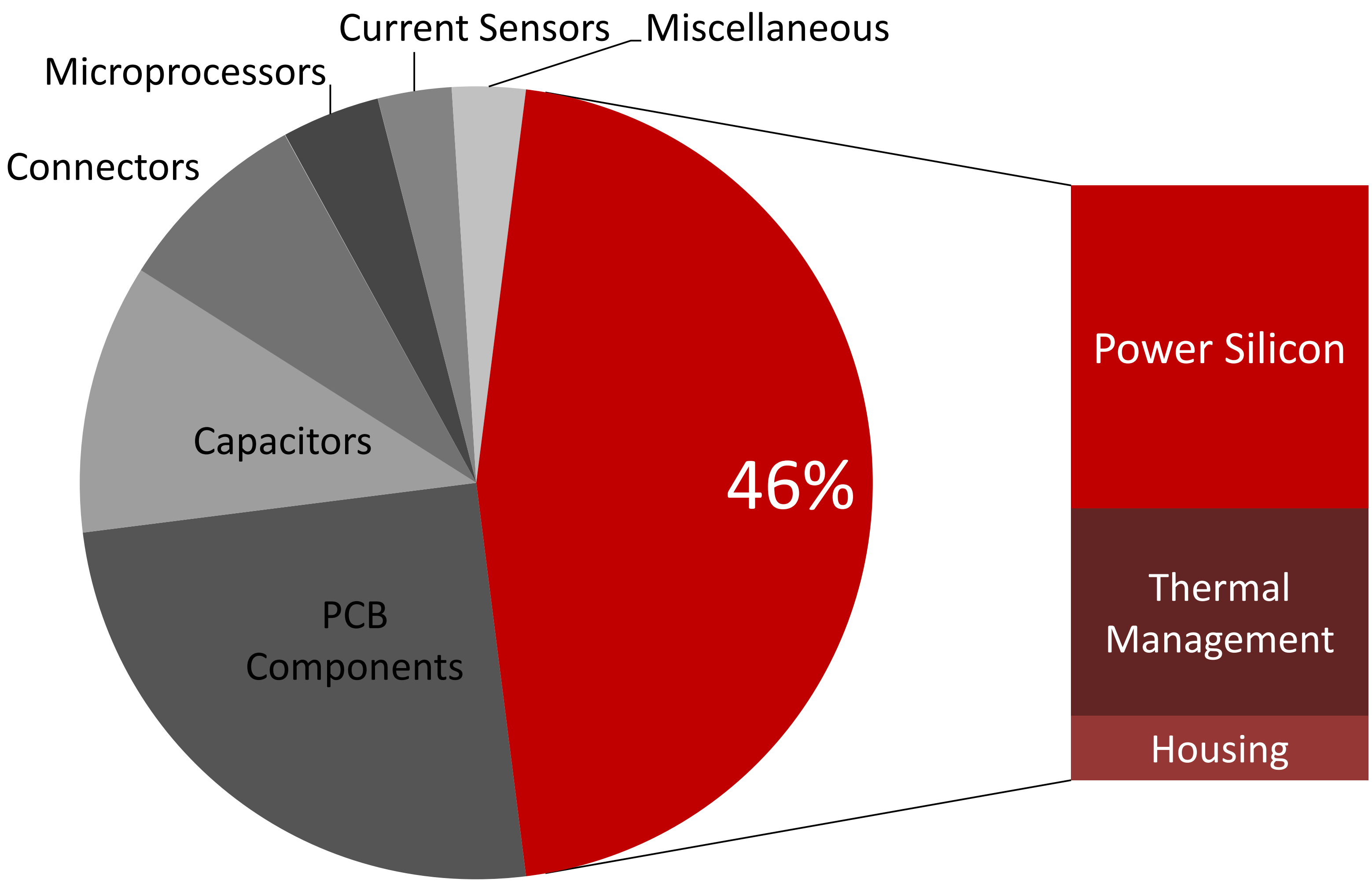
Barriers and Targets

- Cost
- Weight
- Volume
- Performance (Power Density)

Partners

- Interactions/collaborations
  - Sapa
  - Oak Ridge National Laboratory
- Project lead
  - National Renewable Energy Laboratory

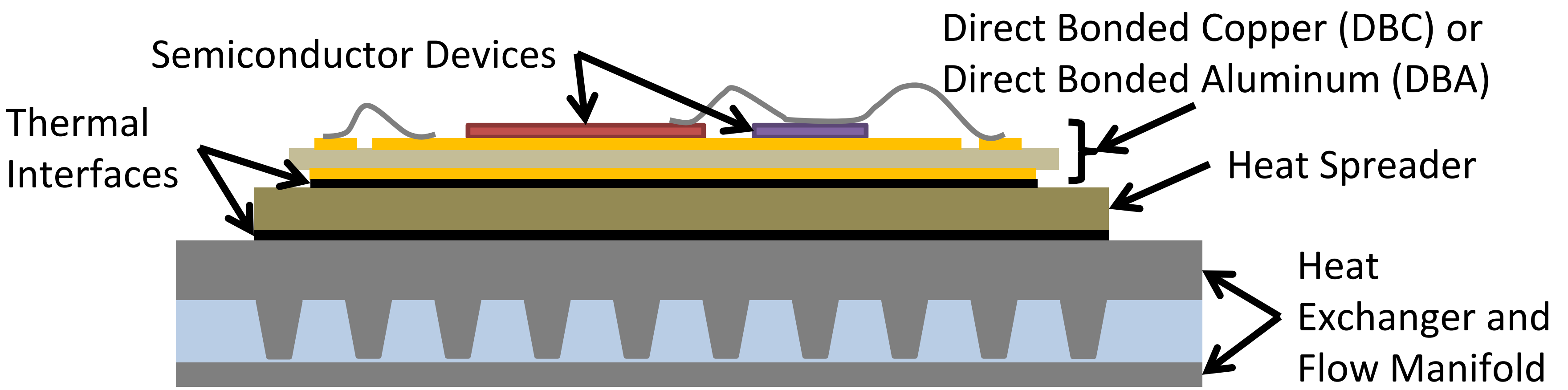
Relevance



Synthesis Partners Projected Inverter Cost Drivers to 2016

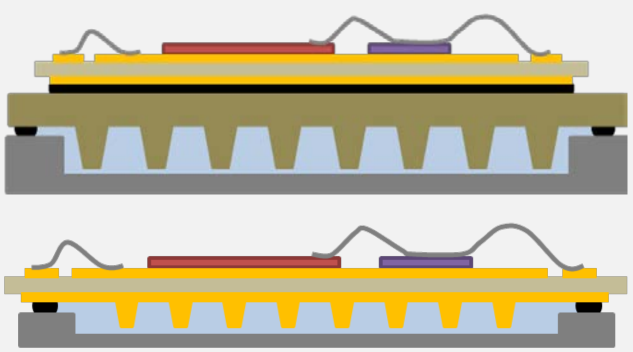
Synthesis Partners LLC. “Technology and Market Intelligence: Hybrid Vehicle Power Inverters and Cost Analysis.” July 2011.

Relevance

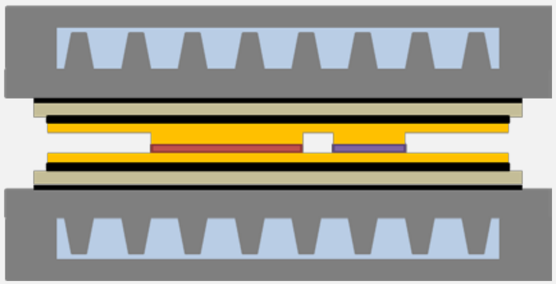


Improved heat dissipation is needed to increase power for robust operation within cost and size constraints

Direct Cooling



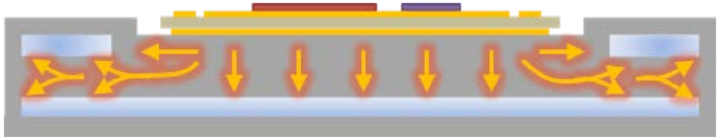
Double-Sided Cooling

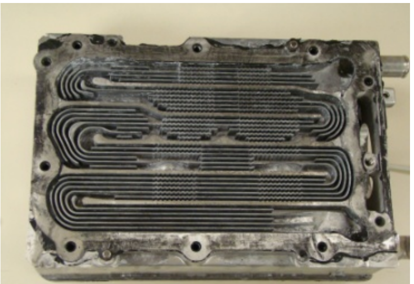


Objectives

- Cost
  - Improve power per die area with comparable or better power density
  - Low cost, scalable, and low waste manufacturing methods
- Volume
  - Maintain equivalent or better power density
- Weight
  - Eliminate large cast heat exchangers
- Reliability
  - Remove internal fluid seals to reduce leak-induced failure modes
  - Increase passive thermal stack thermal capacitance for transient heat loads

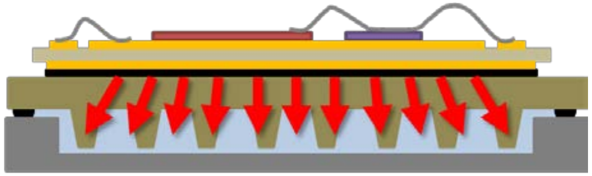
Integrated Heat Spreader, Heat Exchanger, and Flow Manifold





Credit: Kevin Bennion, NREL

Direct Cooled Baseline with Seals



Milestones

Date	Description
September 2011	Milestone • Patent application submitted
February 2012	Go/No-Go • Computer simulations of heat spreader design matched preliminary analysis expectations. • Proceeded to hardware prototype design for targeted convective cooling performance.
September 2012	Milestone • Completed prototype design iterations through computational fluid dynamics modeling, balancing fabrication cost and thermal performance.
February 2013	Go/No-Go • Validated models and confirmed prototype heat exchanger hardware matches design performance from modeling and analysis.
September 2013	Milestone • Report on hardware validation of model results and demonstration of application to power semiconductor package cooling.

Approach/Strategy

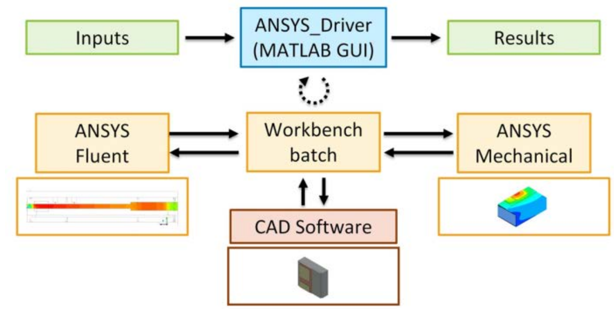
2012			2013								
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Model Validation

- Complete experimental and hardware test setup
- Validate model fluid and thermal performance

(1) Go/ No-Go

Model matches test results



Investigate heat exchanger surface design improvements in collaboration with industry partners

Investigate application and redesign for semiconductor package in collaboration with industry and laboratory partners

(2) Go/ No-Go

Sufficient data for industry transition

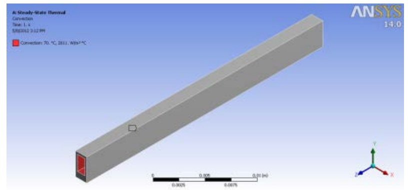
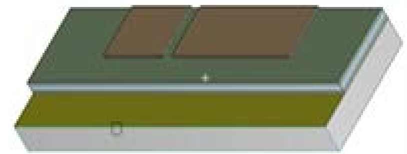
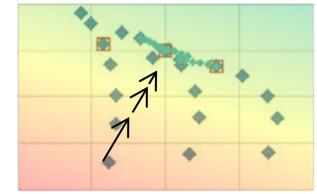
Legend

Complete

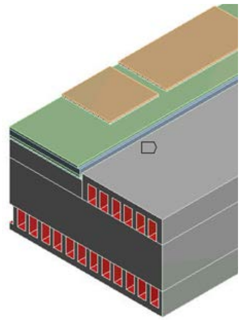
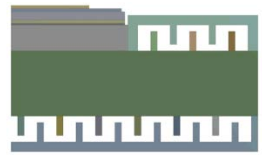
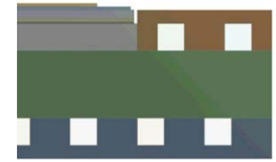
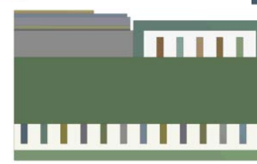
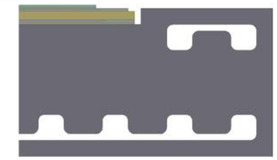
In Progress

Approach/Strategy

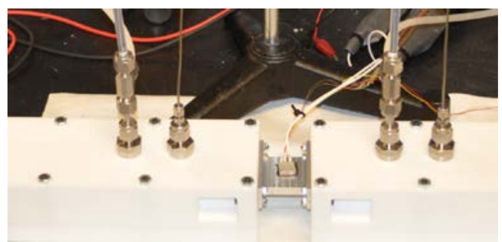
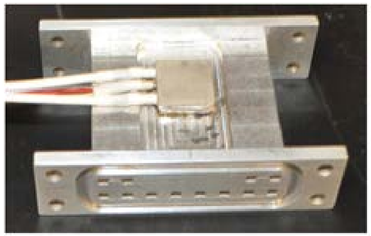
Heat Spreader Optimization (FEA)

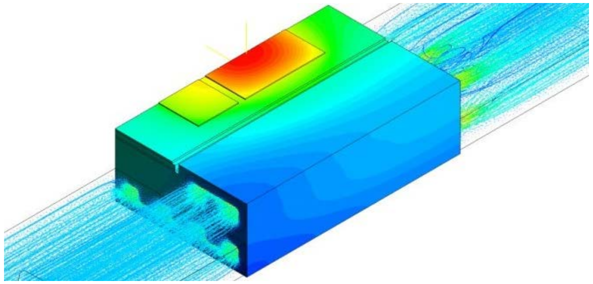
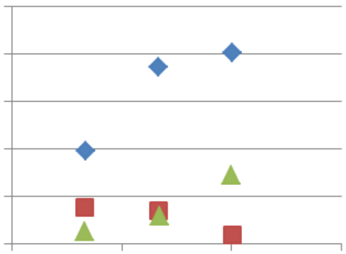
Develop Fin Geometry (CFD)

Build, Test Prototype

Confirm System Impact

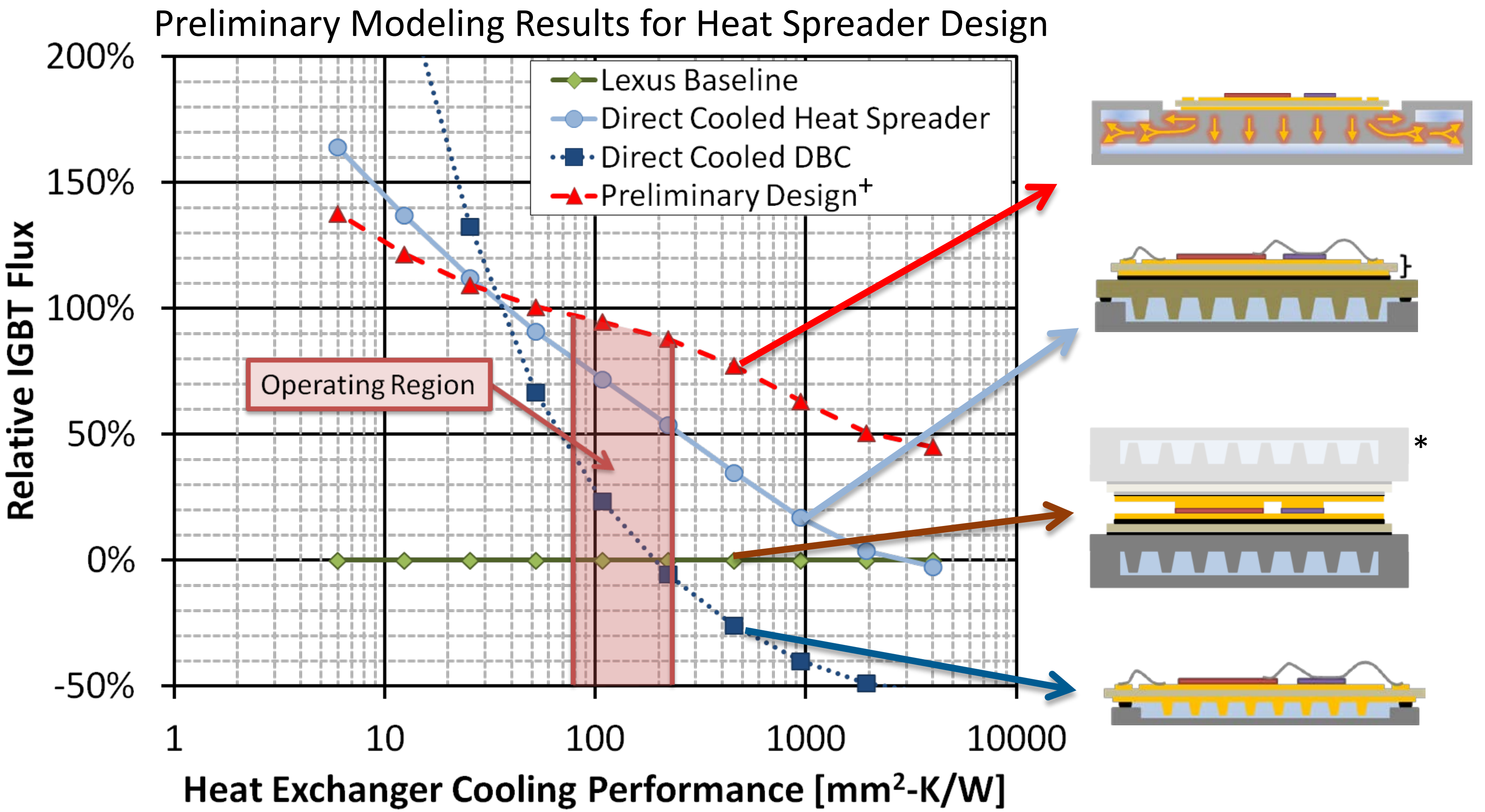



FEA: Finite Element Analysis

CFD: Computational Fluid Dynamics

Photo Credits: Kevin Bennion, NREL

Technical Accomplishments and Progress



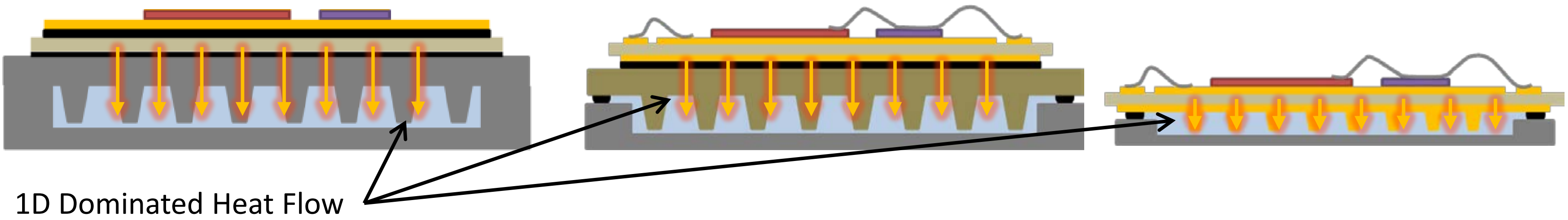
Insulated gate bipolar transistor (IGBT) heat flux comparison of preliminary heat spreader design showing target heat exchanger operating region

* All packages are compared based on single – sided cooling for consistency.
+ Subsequent heat spreader designs increased performance beyond 100% to meet design objectives.

Technical Accomplishments and Progress

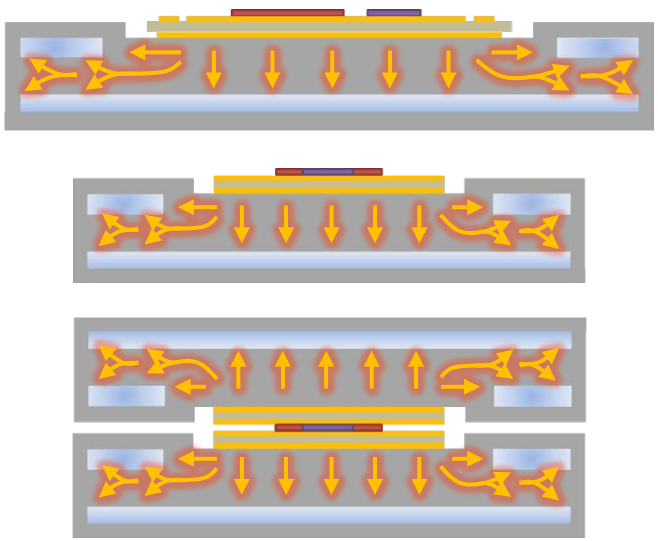
Current State-of-Art:

- Reduce resistance by removing layers
- Require increasingly aggressive cooling techniques (potentially expensive)
- Rely on one-dimensional (1D) heat transfer through the stack



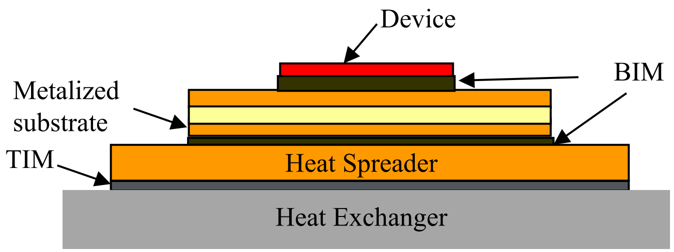
Conceptual Thermal Design:

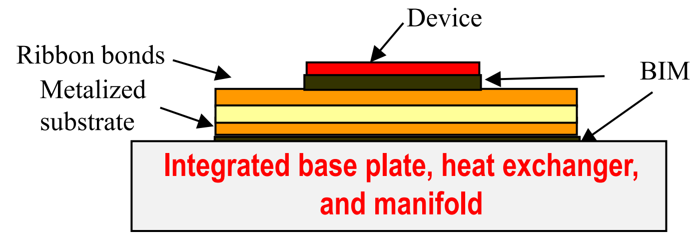
- Enables multi-dimensional heat transfer
- Utilizes multiple cooling “zones”
- Compatible with multiple heat exchanger fabrication methods and area enhancements
    - Current design focuses on extrusion processes
        - Reduced heat exchanger cost
        - Increased flexibility
- Supports single and double-sided cooling
- Integrates channels (reduces seals)



Technical Accomplishments and Progress

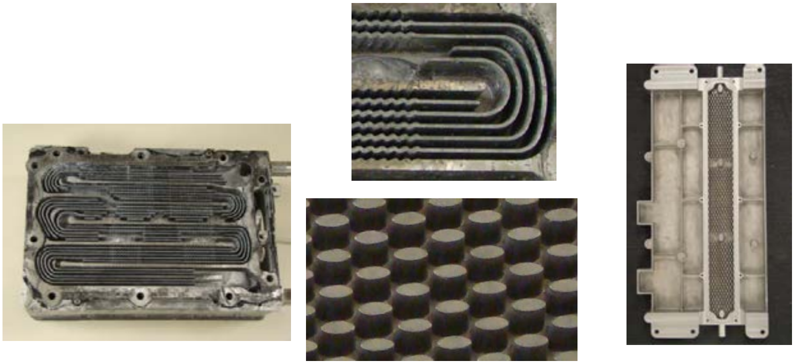
Heat exchanger, baseplate, and manifold are combined into a single part



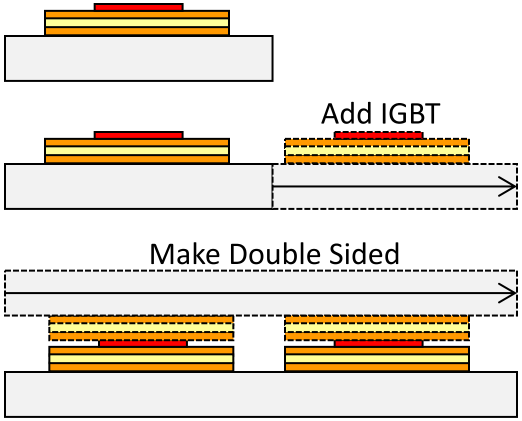


TIM: Thermal Interface Material
BIM: Bonded Interface Material

Designed to be extruded, easily scalable, and allow double sided cooling with no modification to design



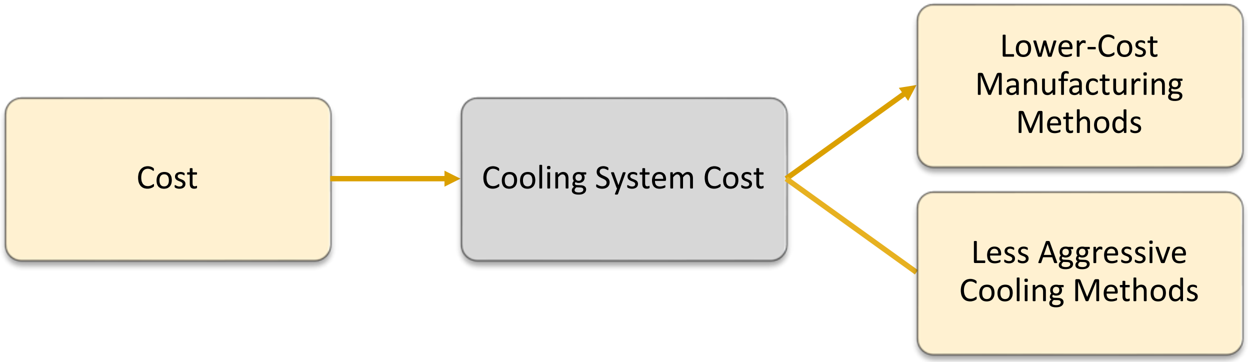
Significant redesign between heat exchangers ($$$)



Same design can be scaled to suit needs

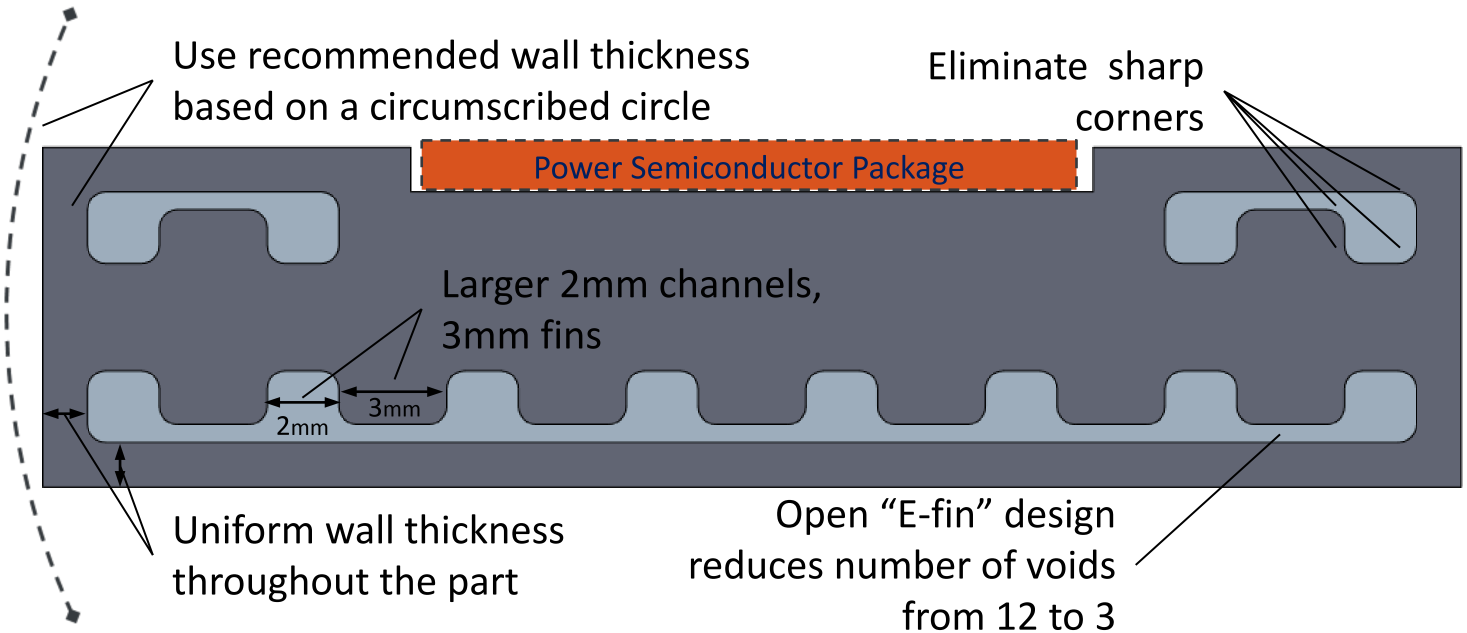
Photo Credits: Kevin Bennion, NREL

Technical Accomplishments and Progress



Designed under Sapa's extrusion guidelines[1]

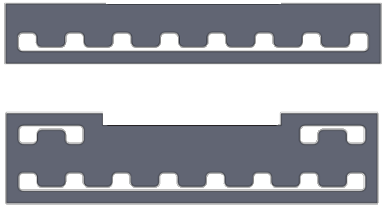
- Extrusion cost and die stress are minimized by:



[1] Sapa Design Manual, Sapa AB, Rosemont, IL, 2009

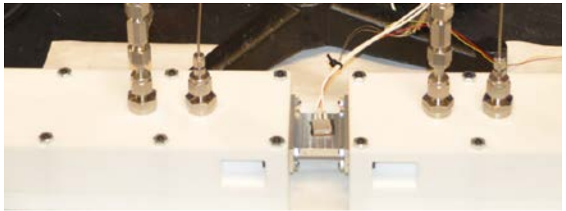
Technical Accomplishments and Progress

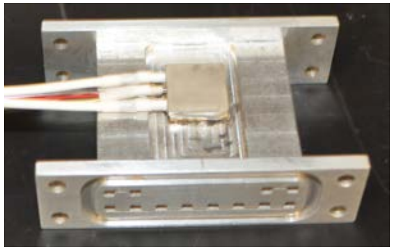
Validated heat exchanger modeling with experimental results.

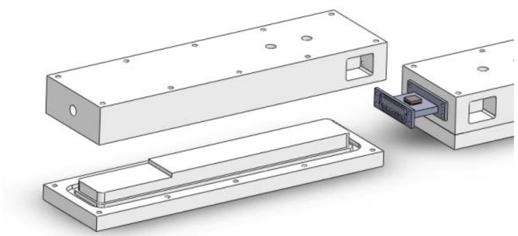


Geometry	Material	Discrepancy between Modeling and Experimental Results	
		Pressure Difference	Temperature Difference
Baseline	Al 6061	<8%	<2%
Design	Al 6061	<9%	<0.4%
Design	Al 6063	<8%	<0.8%

Flow Rate: 0.034 – 0.1 kg/s (1.9 – 5.6 L/min)







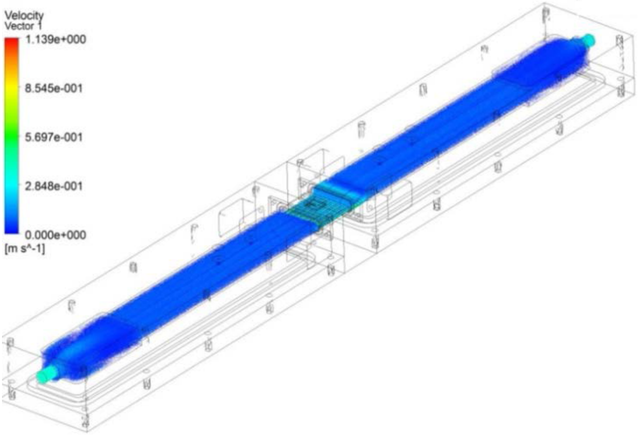
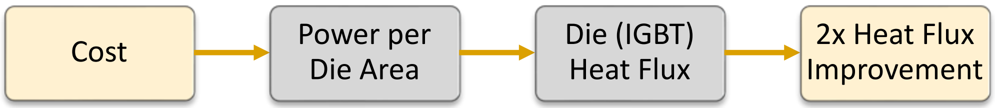
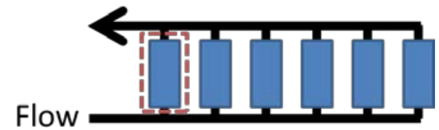


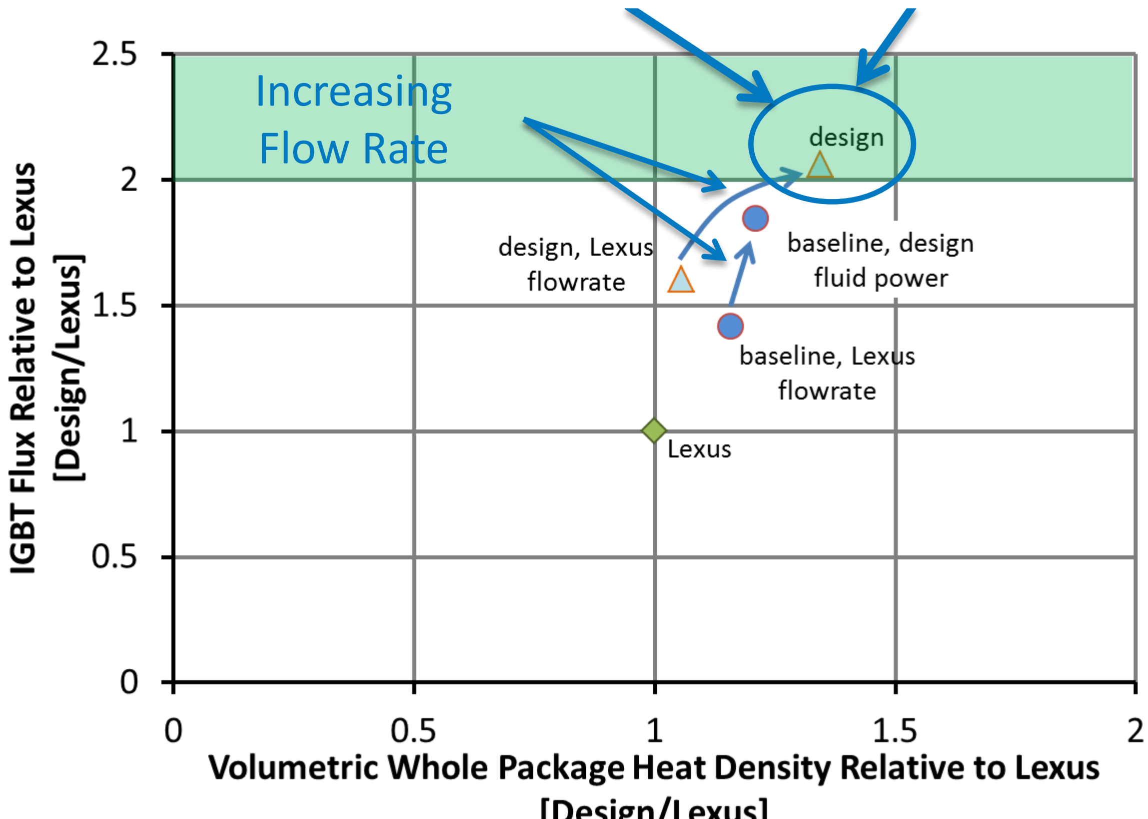
Photo Credits: Kevin Bennion, NREL

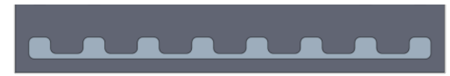
Technical Accomplishments and Progress



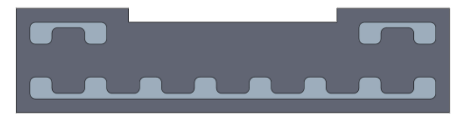
Design meets >2x heat flux improvement at target flow rate (10 L/min split among 6 branches)







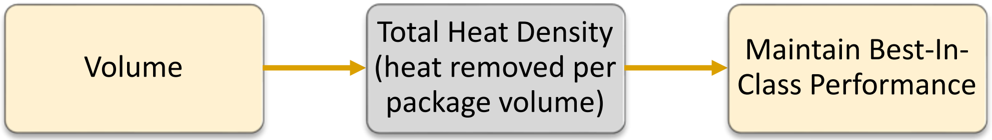
- Baseline increases coefficient of performance (COP) by a factor of 4.1 at same flow rate as Lexus*



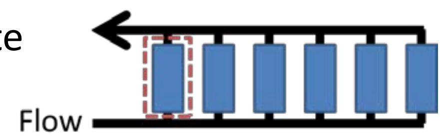
- Proposed design increases COP by a factor of 7.9 at same flow rate as Lexus*
- Design gives additional 12% performance increase relative to baseline at equivalent parasitic fluid power (system flow rate of 10 L/min split between 6 branches)
- Compatible with double-sided cooling and bus bar cooling

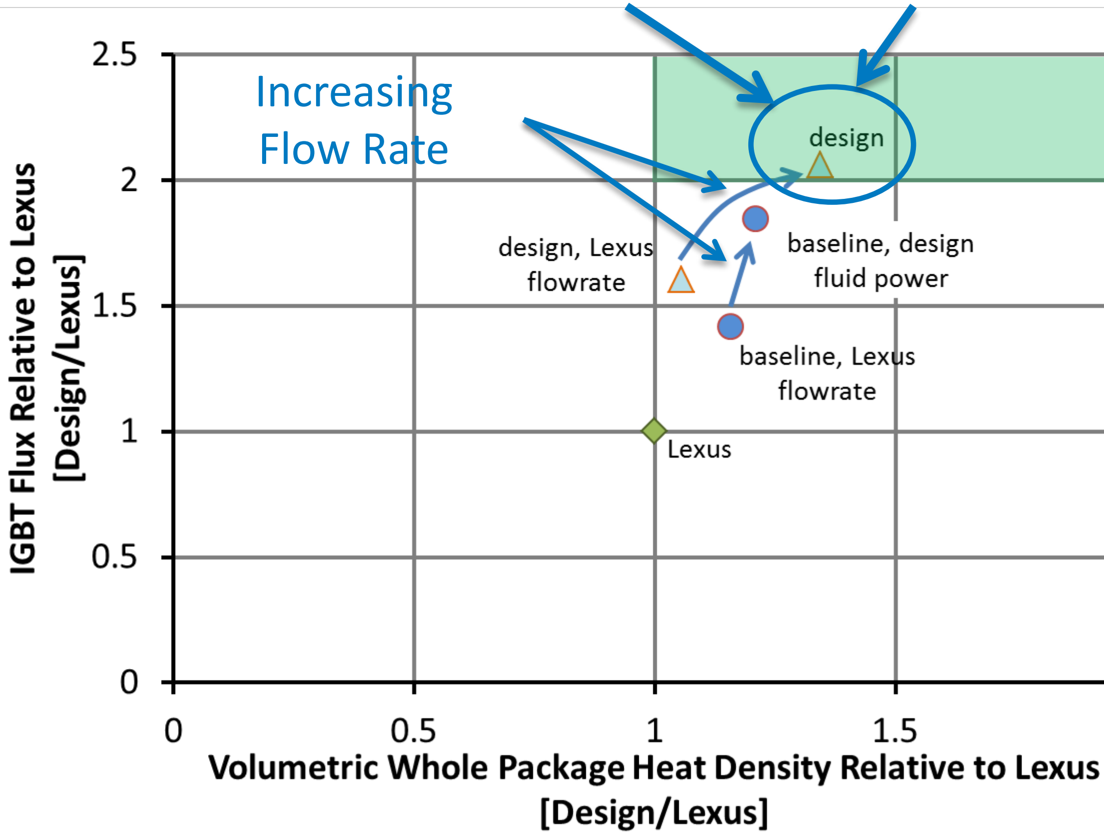
*Estimated at 0.0086 kg/s per side of package

Technical Accomplishments and Progress



Heat density increased by 34% (Exceeded Objective) over Lexus at target flow rate (10 L/min split among 6 branches)





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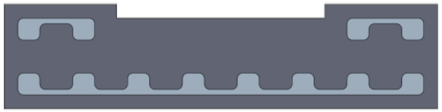

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Collaboration and Coordination

Other Government Laboratories

Oak Ridge National Laboratory/APEEM Program

- Support from benchmarking activities
- Ensure thermal design space is appropriate and modeling assumptions are consistent with other aspects of APEEM research

Industry

Heat Exchanger Collaboration Partner (Sapa)

Power Semiconductor Packaging Partner Input

Plan

Model Validation

Investigate heat exchanger surface design improvements

Investigate application and redesign for semiconductor package in collaboration with industry and laboratory partners

Future Work

2012 Oct	Nov	Dec	2013 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Investigate heat exchanger surface design improvements in collaboration with industry partners. (Oct – Jul)

Investigate application and redesign for semiconductor package in collaboration with industry and laboratory partners. (Mar – Aug)

- The project is scheduled to end in FY13
- Future work:
  - Investigate heat exchanger surface area enhancement design improvements and incorporate lessons learned from initial prototype fabrication.
  - Investigate application to specific semiconductor package with industry input.

Summary

Relevance

- Increased heat dissipation is necessary to reduce power semiconductor cost, weight, and volume.
- Integration of the power electronics package, thermal design, and the cooling design can improve power semiconductor performance.
- A modular and scalable thermal approach can reduce the need for custom heat exchanger redesigns as applications scale in power.

Approach/Strategy

- Reduce cost by increasing semiconductor heat flux at equivalent or smaller volume
- Reduce cost by enabling less aggressive and lower cost cooling methods
- Enable compatibility to alternative power semiconductor packaging technologies

Technical Accomplishments

- Built three prototype designs and validated model results against experimental results
- Met or exceeded project design targets

Collaborations

- Established collaboration with heat exchanger development partner (Sapa)

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Acknowledgments:

Susan Rogers and Steven Boyd,
U.S. Department of Energy

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