Power Electronics Thermal Management R&D

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National Renewable Energy Laboratory (NREL)

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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:** FY15
- **Project End Date:** FY17
- **Percent Complete:** 15%

Barriers

- Cost
- Weight
- Performance and Lifetime

Budget

- **Total Project Funding: $625k**
  - DOE Share: $625k
- **Funding for FY15: $625k**

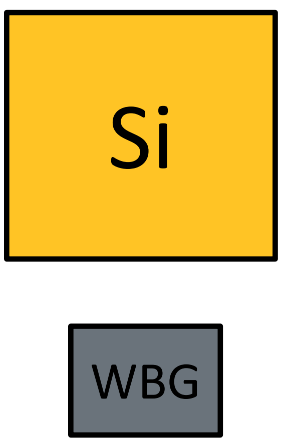
Partners

- Oak Ridge National Laboratory (ORNL) – Power Electronics Lead
- John Deere
- Arkansas Power Electronics International (APEI)
- PowerAmerica

Relevance

Objective: Identify and create strategies along thermal and electrical path for better thermal management and reliability through cooling approaches and material selection to enable high-temperature Si and wide-bandgap (WBG) (SiC) devices in power assemblies.

WBG devices (SiC, GaN) promise to increase efficiency, but will be driven as hard as they will go. This still creates challenges for thermal management (and reliability).



Less efficient = More heat
Lower junction temperature

More efficient = Less heat
Higher junction temperature
Area can be >75% less → increased heat fluxes

Relevance

Why thermal management?

- Limit failure, increase reliability
- Margin on component thermal constraints
- Goal to manage heat flow and dissipate or remove heat.

What feature(s) could be engineered to get more out of the same components?

What are the tradeoffs and where can dividends in improved technology pay off?

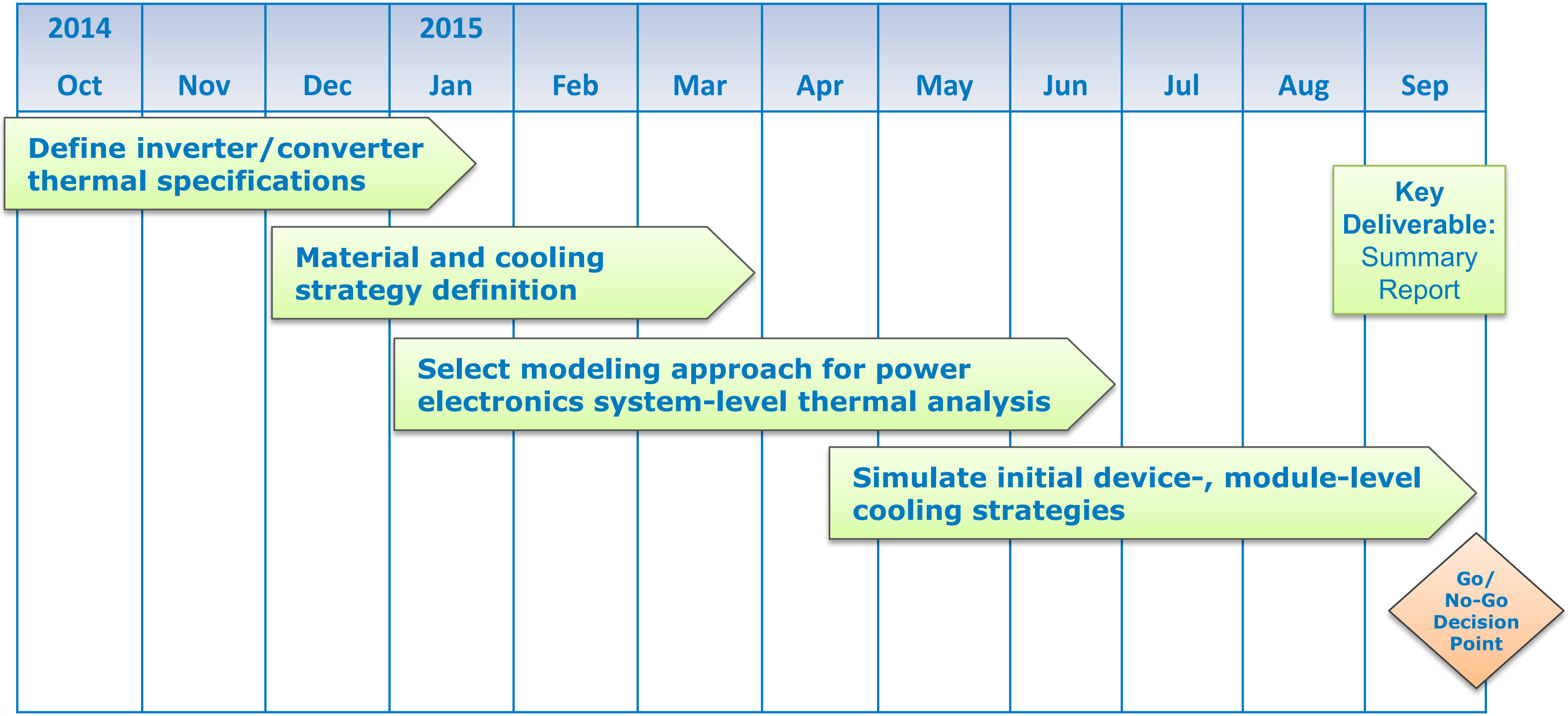
Cost tradeoffs to get higher performance, lower volume and weight:

- Material costs
- Production costs (capacity costs, throughput/yield)
- Process cost
- Reliability (replacement cost, de-rating, safety, reputation).

Milestones

Month/ Year	Milestone or Go/No-Go Decision	Description	Status
12/14	Milestone	Define and list the thermal specifications and constraints for WBG-based inverter.	Met
03/15	Milestone	Define and list potential material and geometry variations for thermal management analysis.	Met
06/15	Milestone	Select the modeling approach for power electronic system-level analysis and begin running models with thermal and material variations.	In Progress
09/15	Milestone	Prepare summary report on comparison of current and proposed cooling strategies for WBG-based inverter and converters.	Upcoming

Approach/Strategy – Schedule



Go/No-Go Decision Point: If there are concepts that meet 2020 targets, proceed to designing prototype.

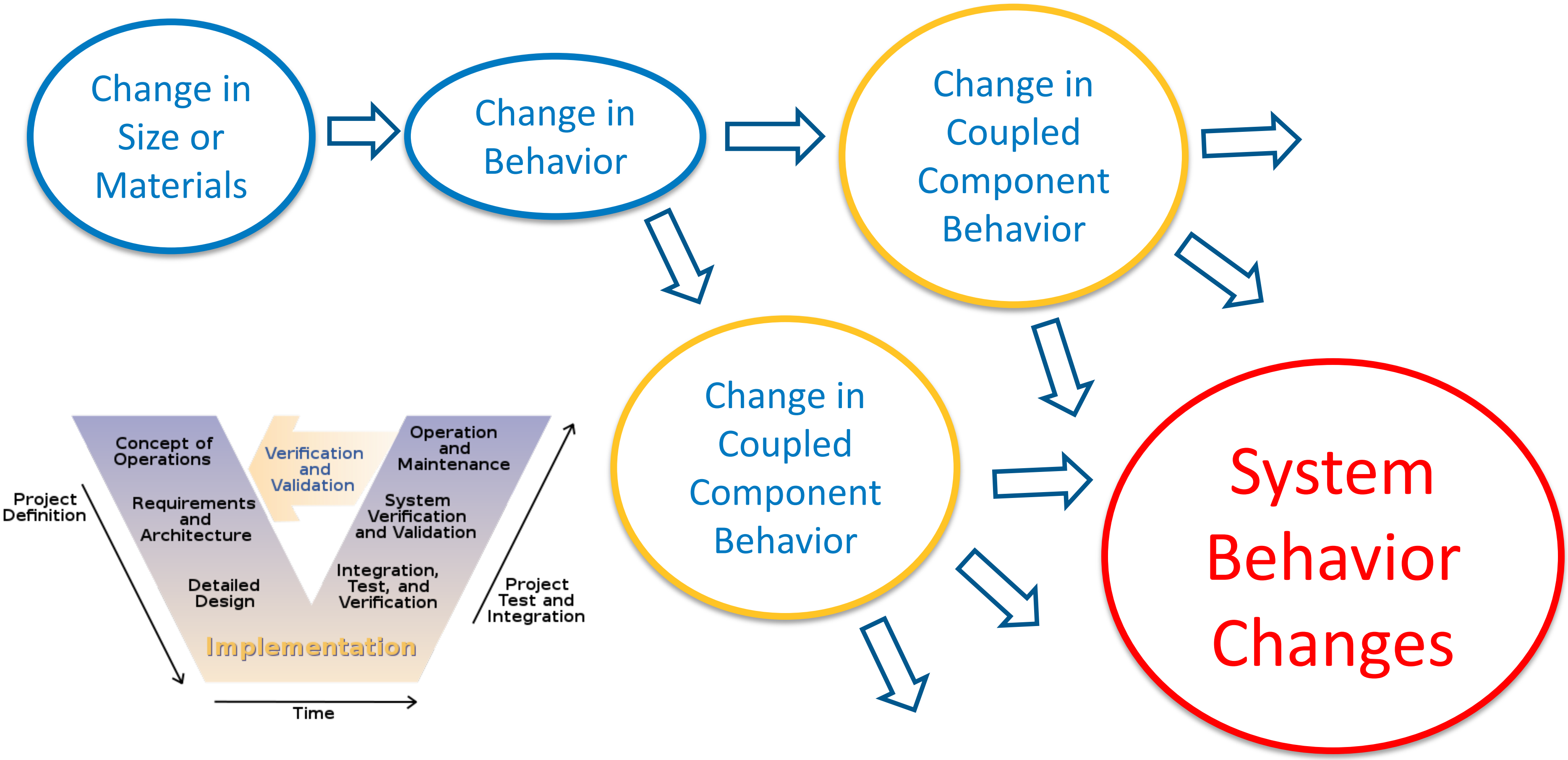
Key Deliverable: Summary report (incorporated into annual report) providing comparison of packaging concepts and cooling strategy thermal performance.

Approach/Strategy

1) Look at existing technology (baseline benchmarking).
2) Examine system with high-temperature devices.
3) Define where there are thermal bottlenecks.
4) Examine what can be enhanced (materials, cooling strategies) considering costs and manufacturing process.
5) Create alternatives to reduce or mitigate impact of thermal bottlenecks.

Approach/Strategy

Component coupling can affect system behavior



Federal Highway Administration, 2005, “Clarus, Concept of Operations,” Publication No. FHWA-JPO-05-072.

Approach/Strategy

Higher power levels produce thermal pathways into undesirable locations.

2012 Nissan Leaf Inverter

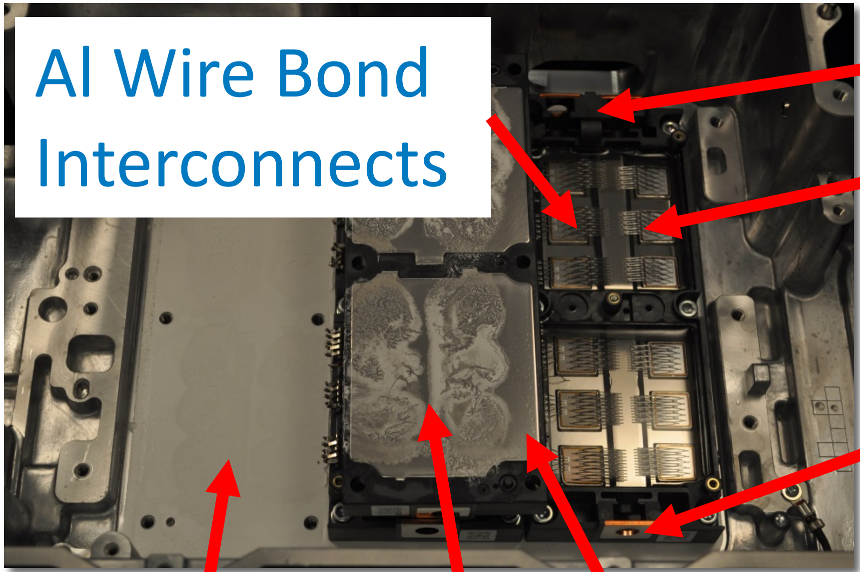


photo credit: Scot Waye, NREL

DC Interconnect

Device (IGBT/Diode)

- Heat generation
- Passive stack (substrate, TIM) thermal resistance

AC Interconnect

Electrically Active Plate

Electric Isolation Film

Thermal Interface Material (TIM)

Approach/Strategy

2012 Nissan Leaf Inverter

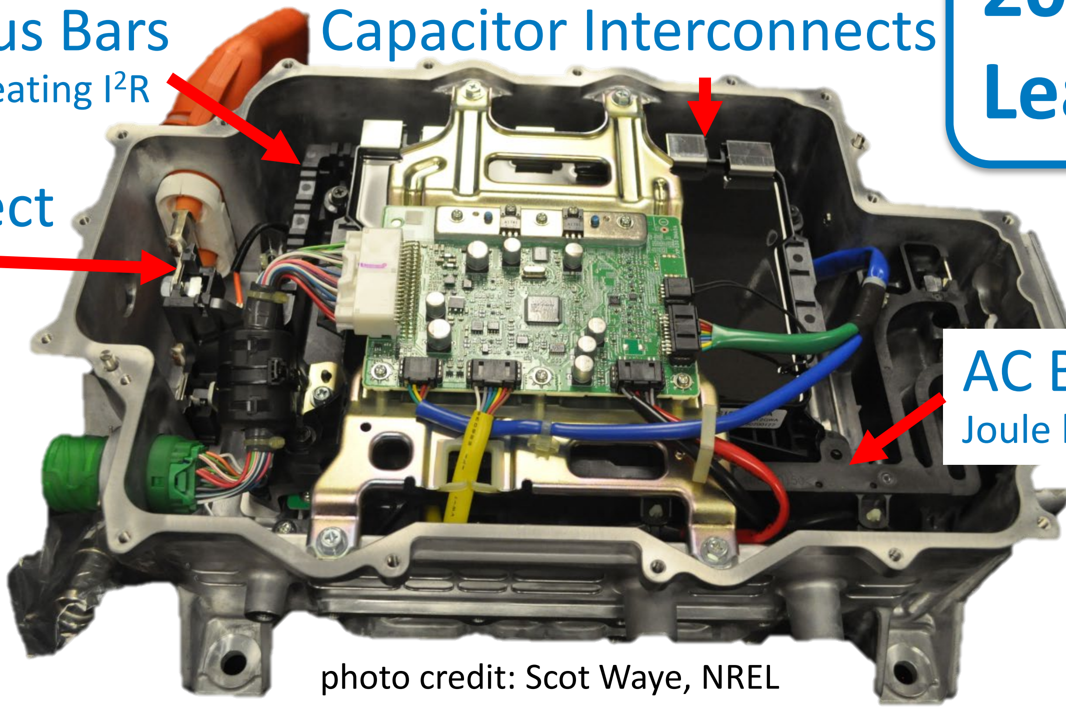


photo credit: Scot Waye, NREL

Resistance Heat Generation

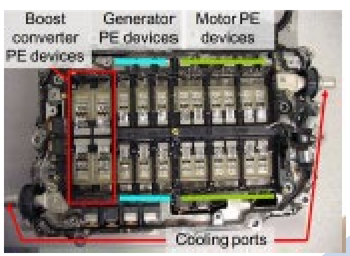
- Measure thermal, electric resistances
- Calculate Joule heating.

Approach/Strategy

<u>Power Assembly Improvements</u>

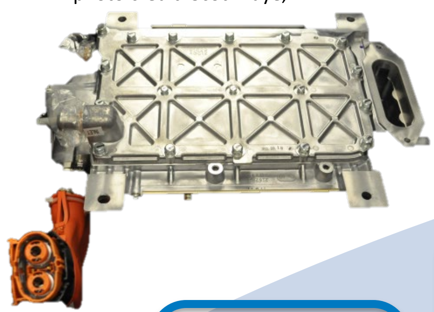
- Increased Integration
- Improved Cooling

[1]



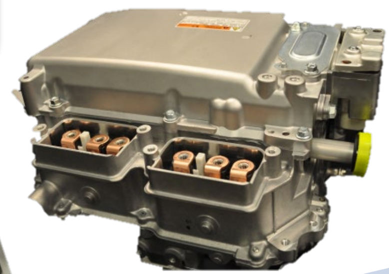
Inverter + Generator + Boost Integration

photo credit: Scot Waye, NREL



Direct Cooling

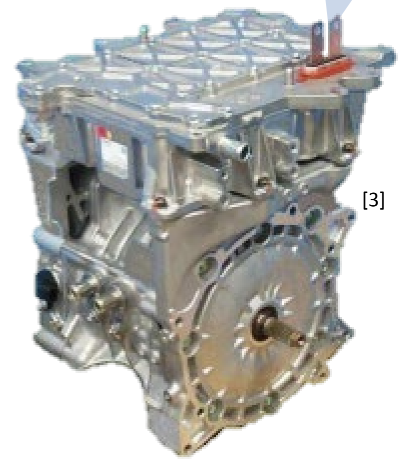
photo credit: Gilbert Moreno, NREL



Double-sided Cooling

[1]

Motor + Inverter Integration



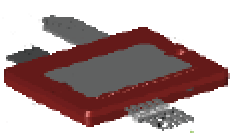
[3]

[1] Yole Développement, 2015, "EV-HEV Market and Technology Trends," APEC 2015, Charlotte, NC.
[2] Shimizu et al., 2013, "Development of an Integrated Electrified Powertrain for a Newly Developed Electric Vehicle," SAE International, Detroit, MI.
[3] Grewe et al., 2015, "Generation Two VOLTEC Drive System," SAE EV/HEV Symposium, Los Angeles, CA.

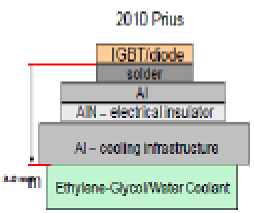
Approach/Strategy

Power Module Packaging Improvements

- Increased Integration
- Improved Cooling
- Capable for High Frequencies

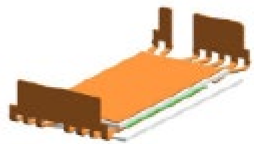


Denso/Lexus 600h 2008
Single IGBT/Diode package
Flip-chip soldering
Double-sided cooling
Costly (improved for 2012 Camry)

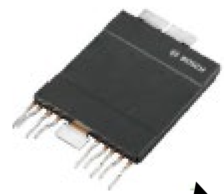


Toyota Prius 2010
Standard packaging
Ribbon bonding
Direct substrate cooling

Honda 2010
Epoxy packaging
Cu lead bonding
Direct substrate cooling



Delphi 2010
Single IGBT/diode package
Flip-chip soldering
Direct substrate cooling



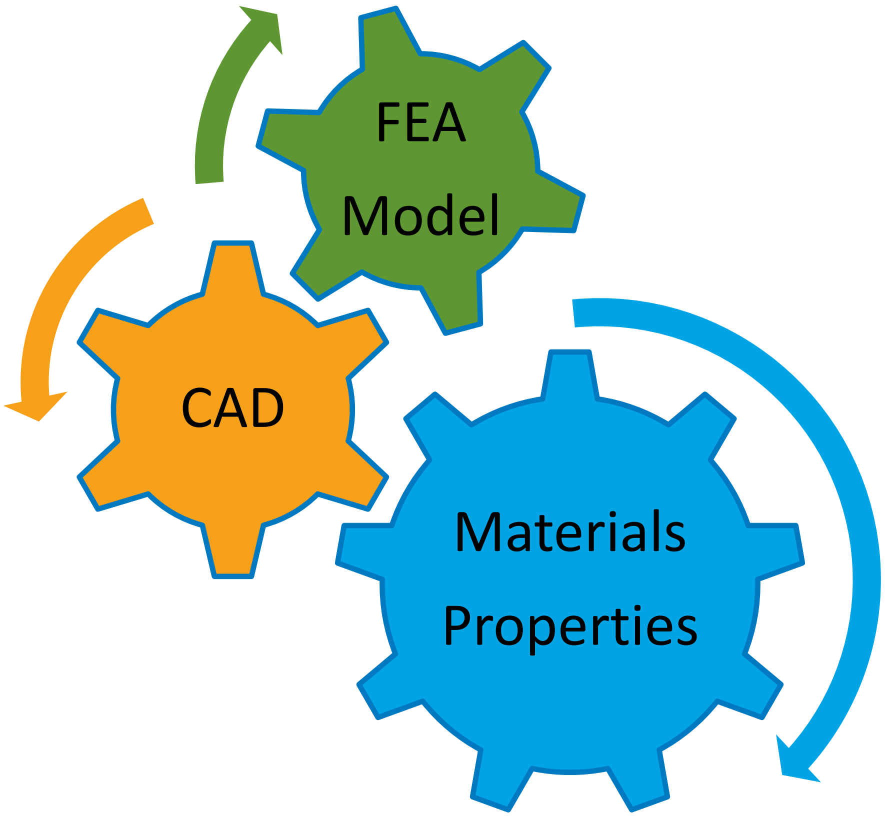
Bosch 2013
Molded package
Die on leadframe
Copper layer for thermal spreading
Direct substrate cooling

Mitsubishi 2014
Six-pack IGBT/Diode package
Cooling fin
Copper layer for thermal spreading
Direct substrate cooling

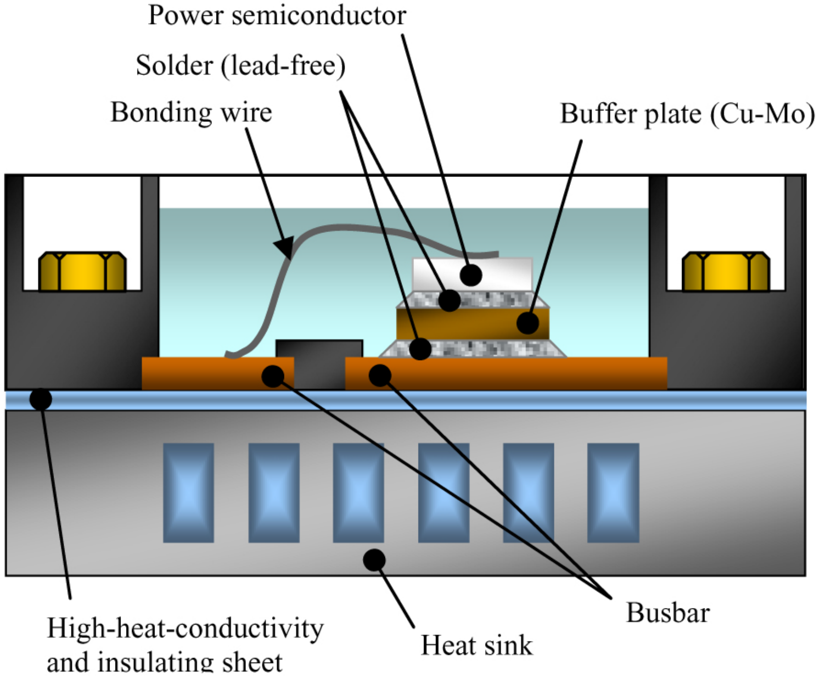
Photo credits: Yole Développement, 2015, "EV-HEV Market and Technology Trends," APEC 2015, Charlotte, NC.

Technical Accomplishments and Progress

- Literature Search
  - Inverter topologies
  - Previously benchmarked PE
  - Cooling strategies
  - Material properties
- Platform Selection
  - 2012 Nissan Leaf ("standard")
  - Open to examine others
  - Disassembly of inverter
- Modeling Method Selected
  - CAD model
  - Thermal FEA for steady-state conduction/convection → thermal maps and bottlenecks
  - CFD if necessary to examine other cooling strategies



Technical Accomplishments and Progress



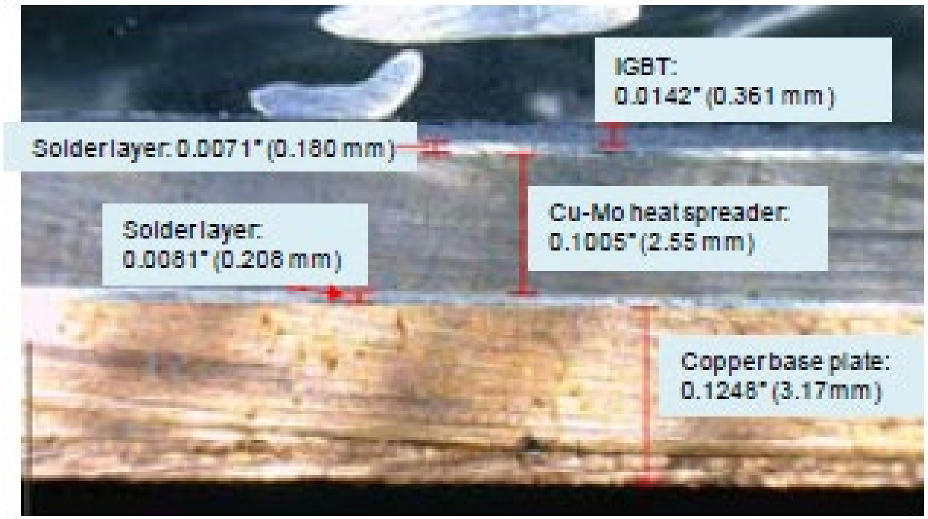
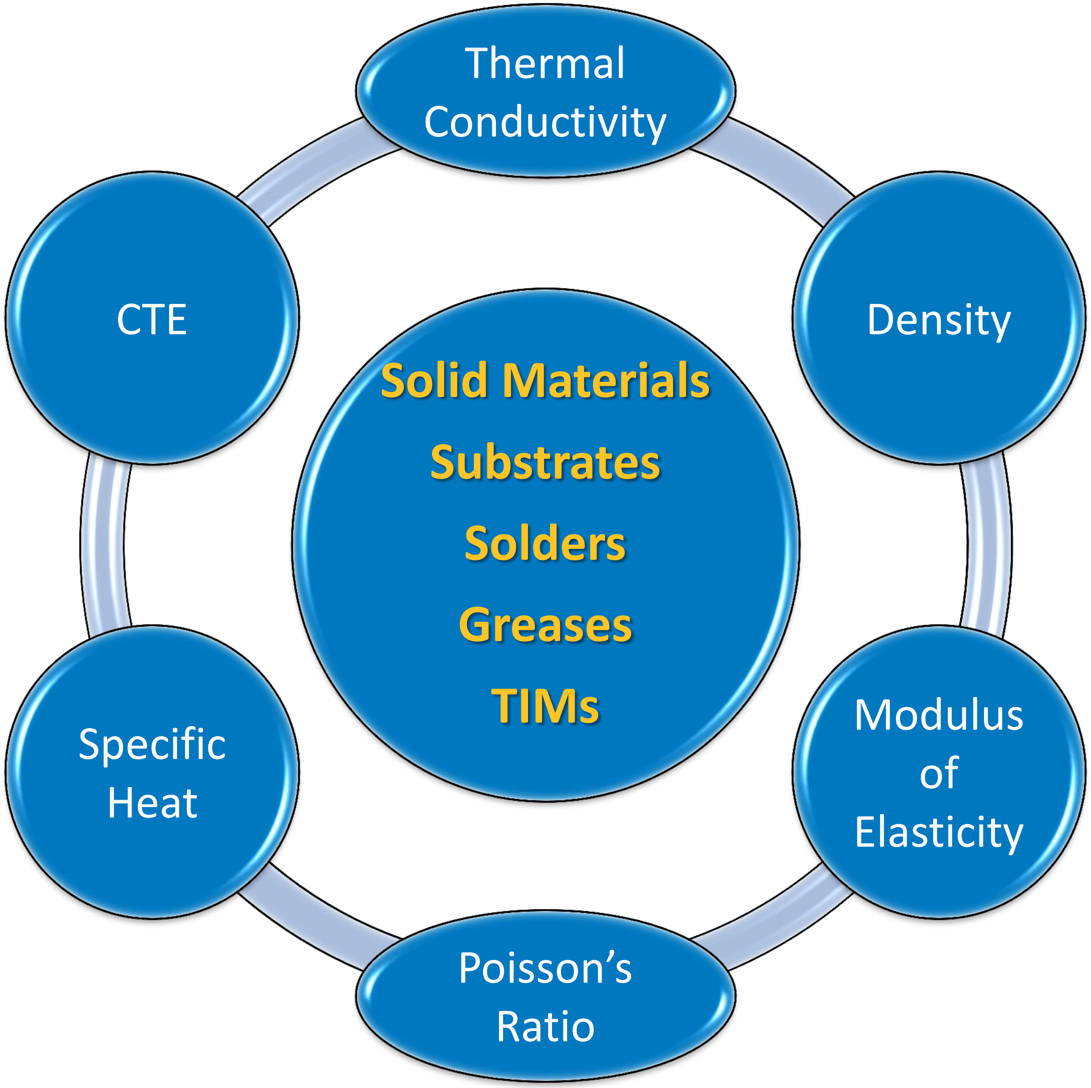


photo credit: Tim Burress, ORNL

- 2012 Nissan Leaf benchmarking (ORNL) defined thermal stack-up (also seen at NREL)
- NREL conducting thermal benchmarking

Sato et al., 2011, "Development of High Response Motor and Inverter System for the Nissan LEAF Electric Vehicle," SAE International, Detroit, MI.

Technical Accomplishments and Progress



Established database of material properties to consider for package assembly and power assembly

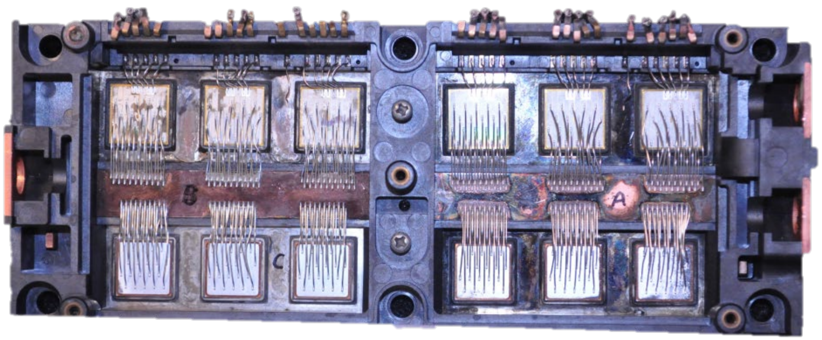
Technical Accomplishments and Progress

Developed appropriate database of solder/TIMs

Anand Properties	Material Property
A (sec-1)	Pre-exponential factor
Q/R (J/mol)	Q = Activation energy R = Universal gas constant
Ŝ (MPa)	Coefficient for deformation resistance saturation value
h_0 (MPa)	Hardening/softening constant
ξ	Stress multiplier
m	Strain rate sensitivity of stress
n	Strain rate sensitivity of saturation (deformation resistance)
a	Strain rate sensitivity of hardening or softening
s_0 (MPa)	Initial value of deformation resistance

- Lead Solders
- Lead-free Solders
- Sintered Silvers

Technical Accomplishments and Progress



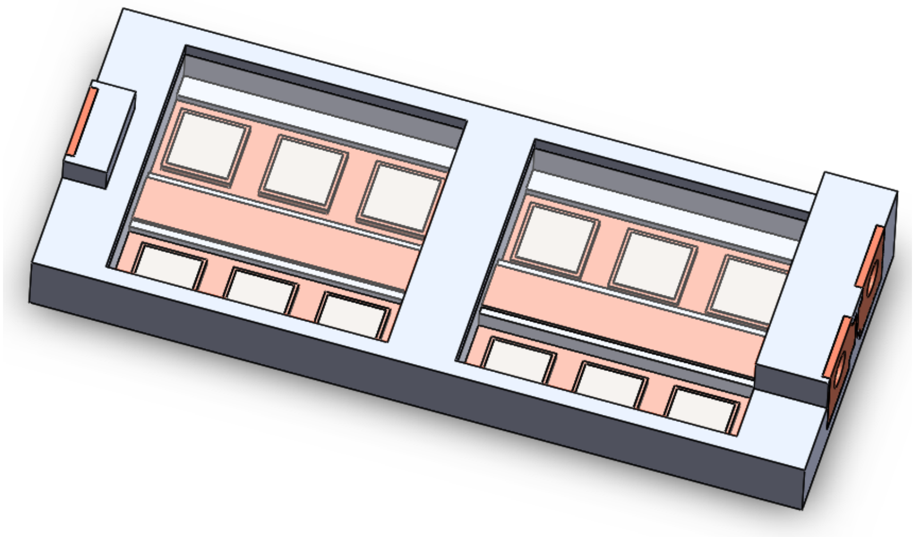
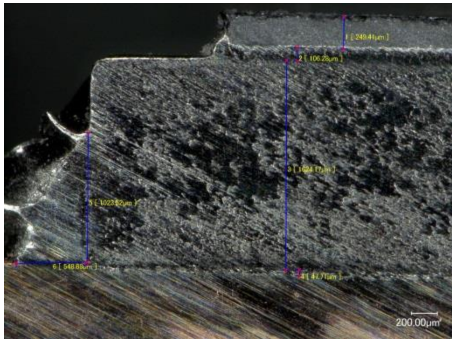
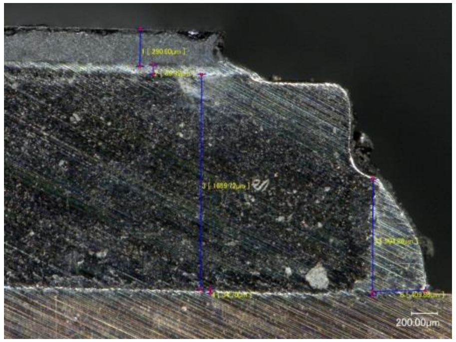


photo credits: Charlie King, NREL





CAD model of module drawn and being imported into thermal FEA model setup

Responses to Previous Year Reviewers' Comments

New project for FY15; not reviewed last year.

Collaboration and Coordination with Other Institutions

Organization	Role
APEI	Industry comments on packaging and thermal management challenges
John Deere Electronic Solutions	Industry technical challenge information
Oak Ridge National Laboratory	PE R&D (inverter/converter/charger projects) – NREL will provide thermal management support
PowerAmerica (WBG Institute)	Collaborations and interactions with Institute members on thermal management challenges

Actively pursuing additional industry partners (OEM, Tier 1/2 suppliers) interested in providing technical input or collaborations.

Remaining Challenges and Barriers

- **Understanding tradeoffs of:**
  - Thermal performance (low resistance)
  - Reliability of materials, cooling strategies
  - Cost of implementing into system
  - Integration effects on other components/systems

Proposed Future Work

<u>FY15</u>

- Thermal Model for Module
  - Examine various TIMs and thicknesses.
  - Examine cooling strategies (single-phase liquid, air, two-phase, enhanced surfaces, baseplate removal).
  - Examine different substrate/baseplate/TIM combinations.

<u>FY16</u>

- Expand Thermal Analysis
  - Examine interconnections (bus bars) cooling.
  - Monitor other component thermal constraints (capacitors).
  - Generate assembly topologies to limit thermal exposure.
  - Consider transient behavior.

Summary

- New project aims to identify and create strategies for better thermal management for WBG and high-temperature device use in vehicle power assemblies.
- Approach is to travel along thermal and electrical path to identify and generate solutions to thermal bottlenecks.
- Modeling will be used – experiments may validate models or concepts.
- What features can be engineered or the process modified to get more out of the system for relatively incremental cost penalties?
- What change in assembly can protect critical components from excessive thermal exposure?
- Modeling efforts have begun as information gathering is completed.

Acknowledgments:

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Team Members:

Kevin Bennion (NREL)
Charlie King (NREL)
Gilbert Moreno (NREL)

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Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Reviewer-Only Slides

(Note: please include this “separator” slide between those to be presented and the “Reviewer-Only” slides. These slides will be removed from the presentation file and the DVD and Web PDF files.)

If you do not submit Reviewer-Only slides, your Merit Review score will likely be reduced.

If you have a poster presentation, submit the Reviewer-Only slides with your presentation to Alliance Technical Services but do not include them in your presented poster.

Publications and Presentations

- New project

Critical Assumptions and Issues

- Is thermal management the most important aspect of reliability, and how do other aspects factor in, like CTE mismatch, thermal cycling?
  - Reliability aspects will be considered and the tradeoffs noted (such as CTE, other properties that may negate thermal benefits).
- For some materials, how does integration affect manufacturing processes and ultimately cost?
  - Applying some materials takes more time or takes a more difficult process. As much as possible, these will be considered in discussion with project partners and other collaborators and interactions.
- There are numerous iterations of designs, so how does using one or several platforms give enough general information to apply to many different design needs and constraints among industry?
  - Generalized results may provide at least qualitative information and at most quantitative comparisons of several technologies that create options for industry.