## Overview

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

### Budget
- **Total Project Funding:** $625K
  - DOE Share: $625K
- **Funding for FY15:** $625K

### Barriers
- Cost
- Weight
- Performance and Lifetime

### Partners
- Oak Ridge National Laboratory (ORNL) – Power Electronics Lead
- John Deere Electronic Solutions
- 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).

Si
Less efficient = More heat
Lower junction temperature

WBG
More efficient = Less heat
Higher junction temperature
Area can be >75% less → increased heat fluxes
Why thermal management?
• Limit failure, increase reliability
• Margin on component thermal constraints
• Manage heat flow and dissipate or remove heat
• Power density increase

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

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/14</td>
<td>Milestone</td>
<td>Define and list the thermal specifications and constraints for WBG-based inverter.</td>
<td>Met</td>
</tr>
<tr>
<td>03/15</td>
<td>Milestone</td>
<td>Define and list potential material and geometry variations for thermal management analysis.</td>
<td>Met</td>
</tr>
<tr>
<td>06/15</td>
<td>Milestone</td>
<td>Select the modeling approach for power electronic system-level analysis and begin running models with thermal and material variations.</td>
<td>In Progress</td>
</tr>
<tr>
<td>09/15</td>
<td>Milestone</td>
<td>Prepare summary report on comparison of current and proposed cooling strategies for WBG-based inverter and converters.</td>
<td>Upcoming</td>
</tr>
<tr>
<td>9/15</td>
<td>Go/No-Go</td>
<td>If there are concepts that contribute towards meeting 2022 targets, proceed to advanced analysis, simulation, and benchtop testing of concepts</td>
<td></td>
</tr>
</tbody>
</table>
**Go/No-Go Decision Point:** If there are concepts that contribute towards meeting 2022 targets, proceed to advanced analysis, simulation, and benchtop testing of concepts.

**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.
Component coupling can affect system behavior

Change in Size or Materials

Change in Behavior

Change in Coupled Component Behavior

Change in Coupled Component Behavior

System Behavior Changes

Approach/Strategy

Higher power levels produce thermal pathways into undesirable locations.

- **Electric Isolation Film**
- **DC Interconnect Device (IGBT/Diode)**
  - Heat generation
  - Passive stack (substrate, TIM) thermal resistance
- **AC Interconnect**
- **Electrically Active Plate**
- **Thermal Interface Material (TIM)**
**Approach/Strategy**

DC Bus Bars
Joule heating $I^2R$

Capacitor Interconnects

DC Interconnect
Contact resistance

AC Bus Bars
Joule heating $I^2R$

**Resistance Heat Generation**

- Measure thermal, electrical resistances
- Calculate Joule heating.

Photo credit: Scot Waye, NREL
**Approach/Strategy**

**Power Assembly Improvements**
- Increased Integration
- Improved Cooling

**Direct Cooling**

**Double-sided Cooling**

**Motor + Inverter Integration**

**Inverter (Motor + Generator) + Boost Integration**

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**Power Module Packaging Improvements**

- Increased Integration
- Improved Cooling
- Capable for High Frequencies

**Approach/Strategy**

- **Toyota Prius 2010**
  - Standard packaging
  - Ribbon bonding
  - Direct cooling

- **Honda 2010**
  - Epoxy packaging
  - Cu lead bonding
  - Direct cooling

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

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

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

*Photo credits: Yole Développement, 2015, “EV-HEV Market and Technology Trends,” APEC 2015, Charlotte, NC.*
Technical Accomplishments and Progress

• Literature Search
  o Inverter topologies
  o Previously benchmarked PE
  o Cooling strategies
  o Material properties

• Platform Selection
  o 2012 Nissan Leaf (“standard”)
  o Open to examine others
  o Disassembly of inverter

• Modeling Method Selected
  o CAD model
  o Thermal FEA for steady-state conduction/convection → thermal maps and bottlenecks
  o CFD if necessary to examine other cooling strategies
Technical Accomplishments and Progress

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

Technical Accomplishments and Progress

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

Solid Materials
- Substrates
- Solders
- Greases
- TIMs

- Thermal Conductivity
- Density
- Modulus of Elasticity
- Specific Heat
- Poisson’s Ratio
- Coefficient Thermal Expansion
- Thermal Expansion
- Modulus of Elasticity
- Specific Heat
- Poisson’s Ratio
- Coefficient Thermal Expansion
## Technical Accomplishments and Progress

**Developed appropriate database of solder/TIMs**

<table>
<thead>
<tr>
<th>Anand Properties</th>
<th>Material Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (sec-1)</td>
<td>Pre-exponential factor</td>
</tr>
</tbody>
</table>
| Q/R (J/mol)      | Q = Activation energy  
|                  | R = Universal gas constant |
| ŝ (MPa)          | Coefficient for deformation resistance saturation value |
| h₀ (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 |
| s₀ (MPa)         | Initial value of deformation resistance |

- Lead Solders
- Lead-free Solders
- Sintered Silver
Technical Accomplishments and Progress

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

Cu-Mo: 1.6 mm
Solder: 0.04 mm
Device: 0.25 mm

Solder: 0.08 mm
Cu-Mo: 1.6 mm
Diode

Bottom - electrically active
(color due to soaking module to dissolve potting material)

Photo credits: Charlie King, NREL
Responses to Previous Year Reviewers’ Comments

New project for FY15; not reviewed last year.
## Collaboration and Coordination with Other Institutions

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

Actively pursuing additional industry partners (OEM, Tier 1/2 suppliers) interested in providing technical support, suggestions, 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

FY15
• Thermal Model for Module
  o Examine various TIMs and thicknesses.
  o Examine cooling strategies (single-phase liquid, air, two-phase, enhanced surfaces, baseplate removal).
  o Examine different substrate/baseplate/TIM combinations.

FY16
• Expand Thermal Analysis
  o Examine interconnections (bus bars) cooling.
  o Monitor other component thermal constraints (capacitors).
  o Generate assembly topologies to limit thermal exposure.
  o Consider transient behavior.
Summary

• New project aims to identify and create strategies for better thermal management for WBG and high-temperature device use in vehicular power electronics and 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:  
Susan Rogers and Steven Boyd, U.S. Department of Energy

Team Members:  
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Charlie King (NREL)  
Gilbert Moreno (NREL)

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