Power Electronics Thermal Management R&D

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DOE Vehicle Technologies Office
Electric Drive Technologies
FY15 Kickoff Meeting

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This presentation does not contain any proprietary or confidential information.
Thermal Management to Enable High-Temperature Power Electronics Based on Wide-Bandgap Devices

State of the Art (SOA)

2013 Toyota Camry Hybrid inverter (also 2008 Lexus LS 600H)
- Double-sided cooling
- Compact size

Delphi Prototype (mid-2015)
- Meets DOE 2015 targets
- Low-loss semiconductors, thermal stack-up and materials, high-temperature capacitor, and inverter-level packaging concepts, 105°C coolant
Proposed Technology Strategy to Address Limitations of SOA

System-level thermal management for inverter/converter components for scales from device to module to system

Limitations Addressed

- Device- to system-level thermal management and overall cooling strategies for high-temperature power electronic systems

Maximum Junction Temperature [°C]

- Wide-bandgap (WBG): Silicon Carbide (SiC) / Gallium Nitride (GaN)
- High-Temperature Silicon (Trench)
- Silicon
Challenges/Barriers to Meet Project Goals

Program

• Acceptance of novel cooling technologies
  o New technology needs to be placed in context similar to current SOA and shown how it replaces current system within packaging constraints

• Simulation useful for down-selection and comparison of technologies, but demonstration/validation key to proving merit

• Cost of flow/heat transfer enhancements must be considered
Challenges/Barriers to Meet Project Goals

Technical

• Access to state-of-the-art designs
  o Input from laboratory and industry collaborators providing computer-aided design of intellectual property protected systems (inverters, converters, chargers) allows for best analysis of current technologies

• Identifying acceptable packaging and thermal interface concepts to remove heat from capacitors, interconnects, control boards

• Some potential technologies or manufacturing techniques are in early stages of development and characterization (e.g., microchannels, three-dimensional printing, integrated casting)
NREL for the last several years has focused on device- and module-level cooling strategies

- Single-phase liquid
- Air cooling
- Passive two-phase cooling
Project Approach

• WBG devices (SiC, GaN) promise to increase efficiency, but also are challenging for thermal management
  o Higher junction temperatures
  o Decreased area (due to higher efficiency and desirable for lower cost [smaller or fewer devices])

Less efficient = More heat
Lower junction temperature

More efficient = Less heat
Higher junction temperature

Area can be >75% less → increased heat fluxes
Higher power levels produce thermal pathways into undesirable locations.

Thermal interface material (TIM) = grease

Control Board

Device Module

Electrical Interconnects Capacitor

2012 Nissan Leaf Inverter
Project Approach

• Active cooling of components needed
  o Devices
  o Power modules
  o Electrical interconnects
  o Capacitors
  o Other temperature critical components (e.g., control board)

• Some cooling strategies not compatible with targets
  o High-temperature single-phase liquid coolant desirable to reduce costs
  o 140°C under-hood temperatures
  o 85°C capacitor must be kept cool

• TIMs between components need to have low thermal resistance to increase thermal performance and also be reliable at functional temperatures
Simulate inverter components from device- to system-level
Examine WBG-based inverter/converter thermal management cooling strategies from device- to system-level

Design, fabricate, and test prototype concepts
Create prototype for relevant thermal management locations. Conduct experiments to examine where the concept can be improved

Refine prototype and demonstrate concept(s)
Show technology meeting technical targets or pathway to meet targets through refined prototype design, fabrication, and testing
Project Approach – FY15

Define system-level inverter/converter

Define target application baseline system (with Oak Ridge National Laboratory [ORNL] input) with thermal specifications and constraints

Select simulation (modeling) approach

Simulate thermal management for system

Generate WBG-based inverter/converter thermal management concepts using device-, module-, and system-level simulated cooling strategies

Select and Report

Down-select 1–3 best cooling/packaging approaches

Report results
FY15 Tasks to Achieve Key Deliverable

<table>
<thead>
<tr>
<th>2014</th>
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- **Define inverter/ converter thermal specifications**
- **Select modeling approach for power electronics system-level thermal analysis**
- **Simulate initial device-, module- level cooling strategies**
- **Generate PE system-level thermal management concepts for WBG-based inverters/converters**
- **Optimize module-level cooling strategies**
- **Support ORNL power electronics R&D with thermal management for inverter/ converter/ charger projects**

**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
Specification Development

Thermal Specifications and Constraints:
- Temperature limits
- Heat generation from device losses
- Thermal interface materials
- Packaging constraints
Technology Evaluation

Simulation Approach

Software

Time scale

Modeling

Finite Element Analysis (FEA)

Computational Fluid Dynamics (CFD)

Steady state

Transient
Multi-scale Analysis

Thermal Management Strategies

Device
- Die/substrate-integrated thermal management
- Microchannels

Module
- Enhanced surfaces
- Turbulence promoters

System
- Advanced manufacturing
- Multiple mode cooling

Han et al., 2000, Gas Turbine Heat Transfer and Cooling Technology
FY15 Tasks in Depth

1. Define target application baseline system from experience, literature survey, ORNL, and industry input for thermal specifications and constraints specific to WBG-based inverter/converter

2. Select the modeling (simulation) approach to be used for power electronic system-level analysis (e.g.— FEA, CFD, steady-state, transient)

3. Simulate initial device-, module-level cooling strategies

4. Generate power electronics system-level thermal management concepts for WBG-based inverters/converters

5. Optimize device-level cooling strategies

6. Down-select 1–3 best cooling/packaging approaches for application

7. Prepare a summary report and publish findings that include a comparison of current and proposed strategies

Support ORNL power electronics R&D in thermal management for inverter/converter/charger development
FY16 Tasks to Achieve Key Deliverable

**Go / No-Go Decision Point:** If there are shortcomings in thermal management or size and weight can be improved from testing, proceed to refine prototype

**Key Deliverable:** Publish results of thermal performance testing
FY16 Task Description

- Fabricate prototype
- Modify or build test bench

WEG Loop

Air Test Bench

- Test and optimize prototype
- Validate model and optimize

Transmission Fluid Loop

WEG = water-ethylene glycol
## FY17 Tasks to Achieve Key Deliverable

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- **Refine prototype components and systems**
- **Fabricate new prototype components and systems**
- **Test prototype**

**Go/No-Go Decision Point:**
Outline any targets not met and outline pathway to reach them (light-weighting, size reduction, lower material and manufacturing costs)

**Key Deliverable:**
Demonstrate system meeting technical targets. Publish results.
**Project Summary**

**Project Duration:** FY15 – FY17

**Overall Objective (all years):** Provide thermal management solutions for WBG-based (and high-temperature Si) power electronics systems

<table>
<thead>
<tr>
<th>FY15 Focus: Define thermal specifications for inverter components, simulate baseline and proposed cooling strategies, down-select most promising concepts</th>
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<tr>
<td>Go/No-Go Decision Point: Down selection of packaging concept with cooling strategy that meets 2020 targets and beyond.</td>
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<tr>
<th>FY16 Focus: Design, fabricate, and test prototype packaging concept with cooling strategy</th>
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<td>Deliverable: Publish results of thermal performance testing.</td>
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<td>Go/No-Go Decision Point: If there are shortcomings in thermal management or size and weight can be improved, proceed to refine prototype.</td>
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<tr>
<th>FY17 Focus: Refine and update prototype to increase thermal performance, size, and weight, balancing fabrication process (cost) with thermal performance</th>
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<td>Deliverable: Demonstrate system meeting or exceeding technical targets. Publish results.</td>
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<td>Go/No-Go Decision Point: Outline any targets not met and outline pathway to reach them</td>
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Technology-to-Market Plan

• Support ORNL 55-kW inverter and ORNL 6.6-kW isolation converter development

• The concepts generated for thermal management will provide guidance to industry on potential solutions for active cooling of electrical interconnects

• Collaborations with industry will provide timely input on impactful technology implementation of thermal interface materials and cooling strategies for inverter/converter development
## Partners/Collaborators

<table>
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<tr>
<th>Organization</th>
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<tr>
<td>APEI</td>
<td>Industry input on packaging and thermal management challenges</td>
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<tr>
<td>John Deere Electronic Solutions</td>
<td>Industry technical challenge input and test platform</td>
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<tr>
<td>Oak Ridge National Laboratory</td>
<td>PE R&amp;D (inverter/converter/charger projects) – NREL will provide thermal management support</td>
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<tr>
<td>PowerAmerica (WBG Institute)</td>
<td>Collaborations and interactions with Institute members on thermal management challenges</td>
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Actively pursuing additional industry partners (OEM, Tier 1/2 suppliers) interested in providing technical input or collaborations.
Capabilities

• NREL Core Competency: Thermal management and reliability for power electronics

• High-performance computing cluster for CFD, thermomechanical FEA – parallel computing licenses from ANSYS

• Test benches: liquid (WEG) loop, air cooling, air balance-of-systems, transmission oil loop, two-phase loop

• Thermal resistance characterization (ASTM TIM stand, xenon flash, high potential tester, transient thermal tester, acoustic microscopy, laser profilometer, sample synthesis)

• DC power supplies (various voltages, current)s
Acknowledgments:

- Susan Rogers & Steven Boyd
  U.S. Department of Energy

Team Members:

- Gilbert Moreno
- Madhu Chinthavali (ORNL)

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