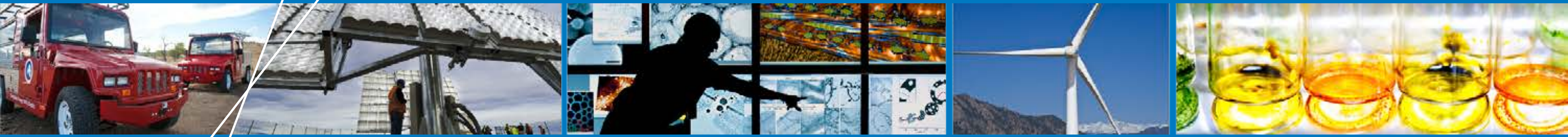
Power Electronics Thermal Management R&D



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DOE Vehicle Technologies Office
Electric Drive Technologies
FY15 Kickoff Meeting

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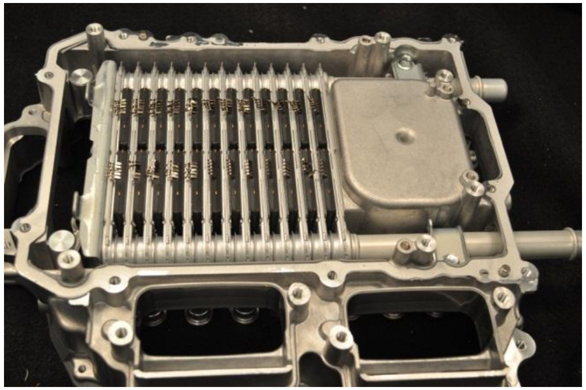
NREL/PR-5400-63002

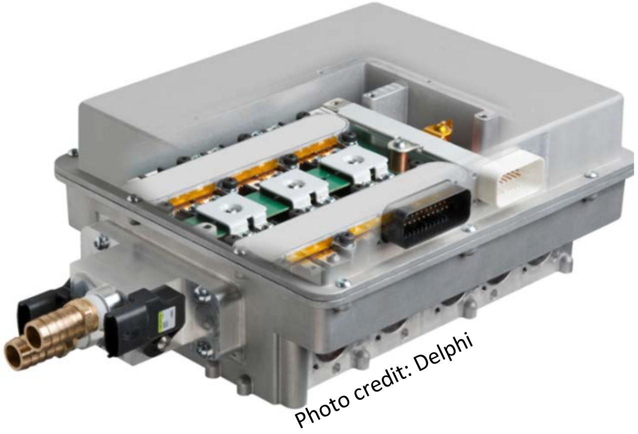
Thermal Management to Enable High-Temperature Power Electronics Based on Wide-Bandgap Devices

State of the Art (SOA)



2013 Toyota Camry Hybrid inverter (also 2008 Lexus LS 600H)

- Double-sided cooling
- Compact size



Delphi Prototype (mid-2015)

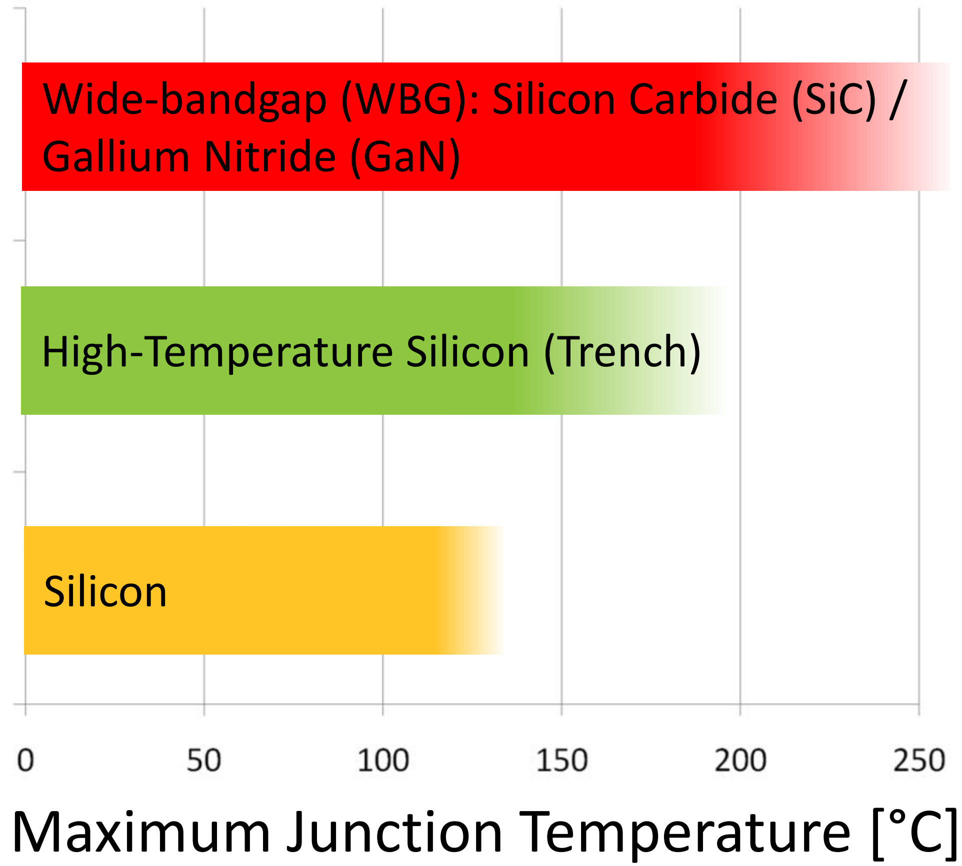
- Meets DOE 2015 targets
- Low-loss semiconductors, thermal stack-up and materials, high-temperature capacitor, and inverter-level packaging concepts, 105°C coolant

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



Challenges/Barriers to Meet Project Goals

Program

- Acceptance of novel cooling technologies
  - 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

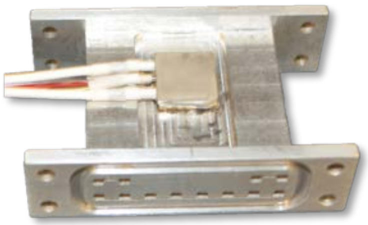
Challenges/Barriers to Meet Project Goals

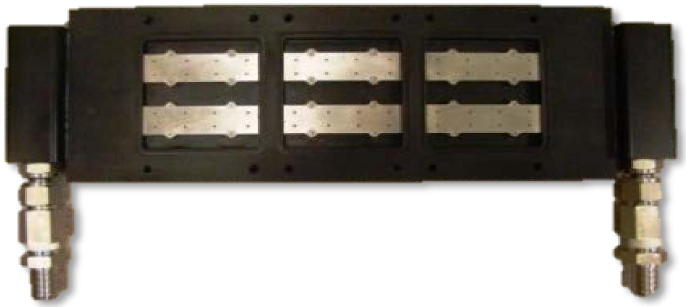
Technical

- Access to state-of-the-art designs
  - 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)

Project Approach

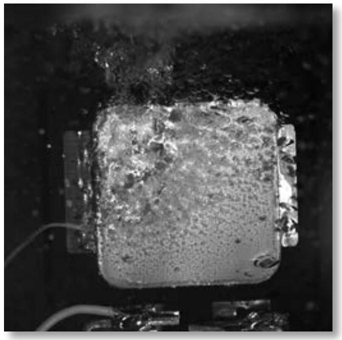
- NREL for the last several years has focused on device- and module-level cooling strategies
  - Single-phase liquid





  - Air cooling

  - Passive two-phase cooling



Project Approach

- WBG devices (SiC, GaN) promise to increase efficiency, but also are challenging for thermal management
  - Higher junction temperatures
  - 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

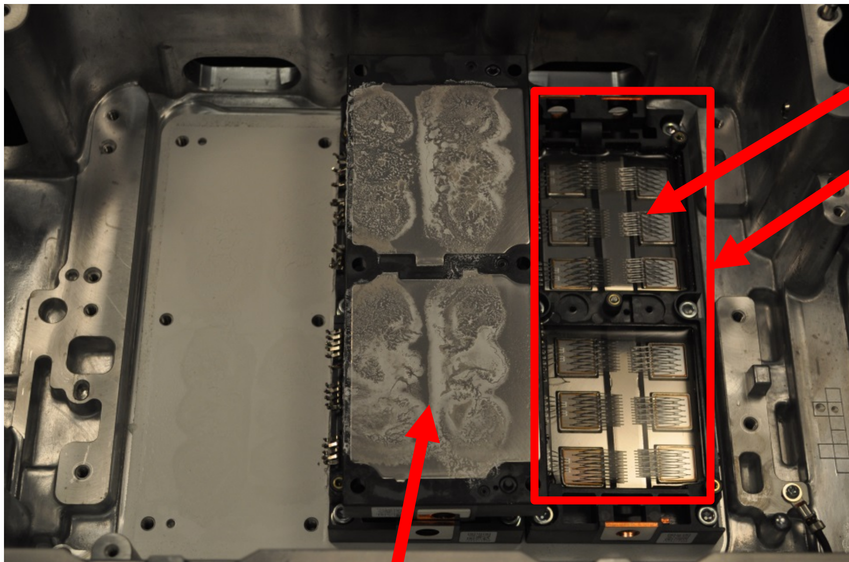
Higher junction temperature

Area can be >75% less ⟶ increased heat fluxes

Project Approach

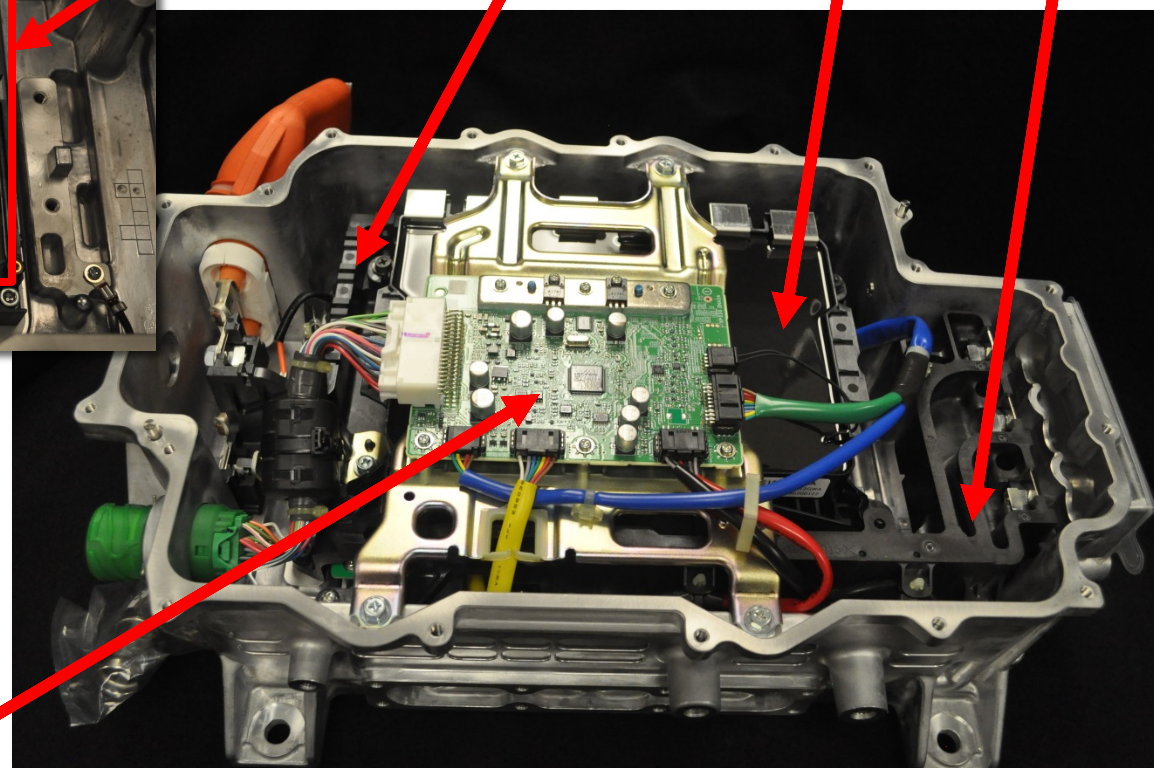
2012 Nissan Leaf Inverter

Higher power levels produce thermal pathways into undesirable locations



Device Module

Thermal interface material (TIM) = grease



Electrical Interconnects

Capacitor

Control Board

Project Approach

- Active cooling of components needed
  - Devices
  - Power modules
  - Electrical interconnects
  - Capacitors
  - Other temperature critical components (e.g., control board)
- Some cooling strategies not compatible with targets
  - High-temperature single-phase liquid coolant desirable to reduce costs
  - 140°C under-hood temperatures
  - 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

Project Approach – Overall

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

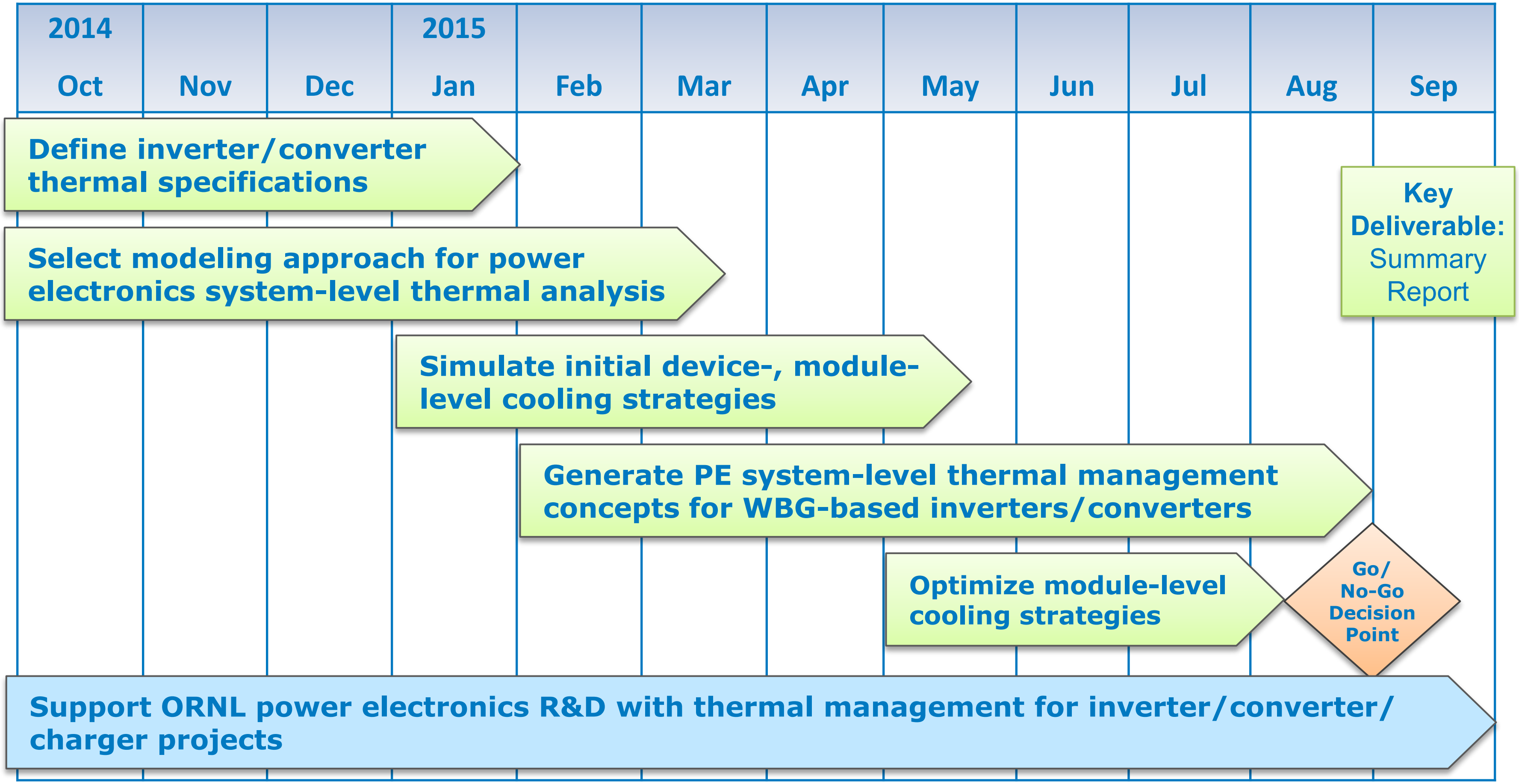
Generate WBG-based inverter/converter thermal management concepts using device- , module-, and system-level simulated cooling strategies

Select and Report

Down-select 1–3 best cooling/packaging approaches

Report results

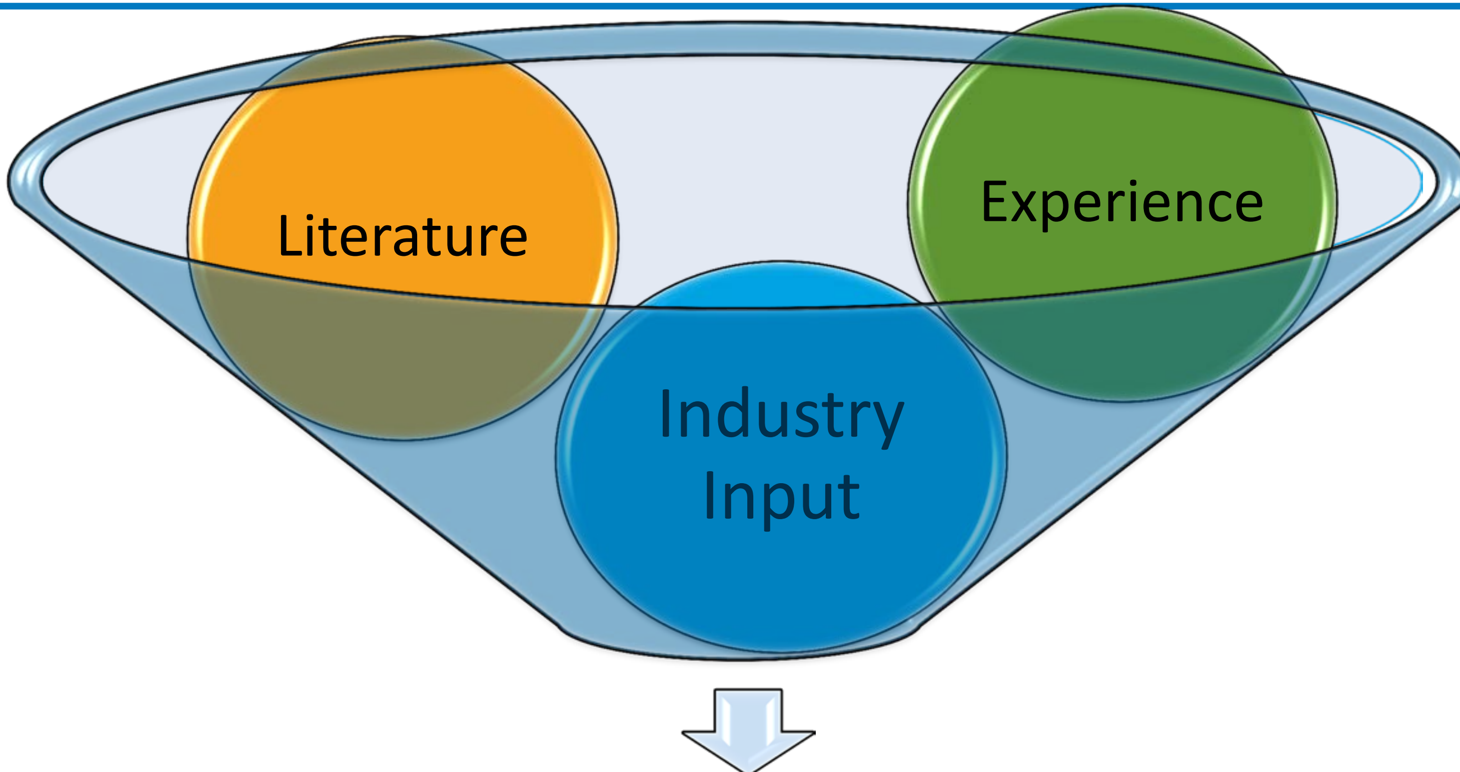
FY15 Tasks to Achieve Key Deliverable



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:

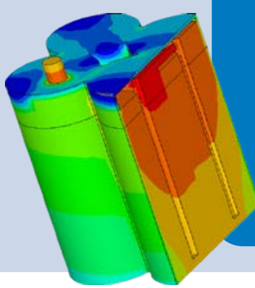
- Temperature limits
- Heat generation from device losses
- Thermal interface materials
- Packaging constraints

Technology Evaluation

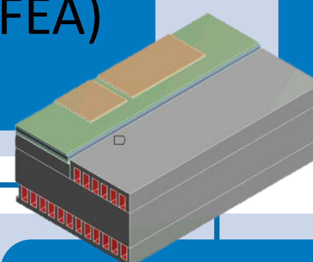
Simulation Approach

- Modeling

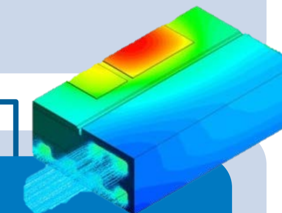
Software

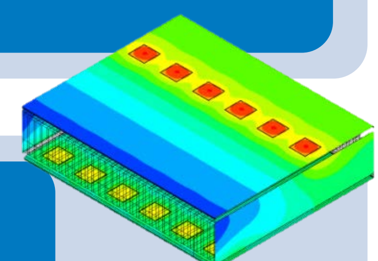


- Finite Element Analysis (FEA)



- Computational Fluid Dynamics (CFD)





Time scale

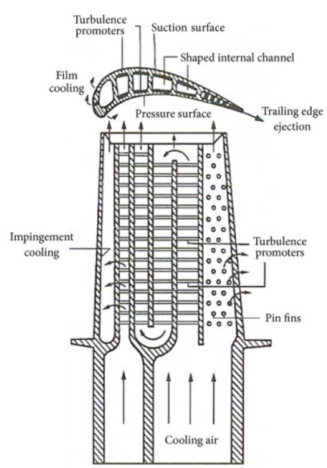
- Steady state
- Transient

Multi-scale Analysis

Thermal Management Strategies

Device

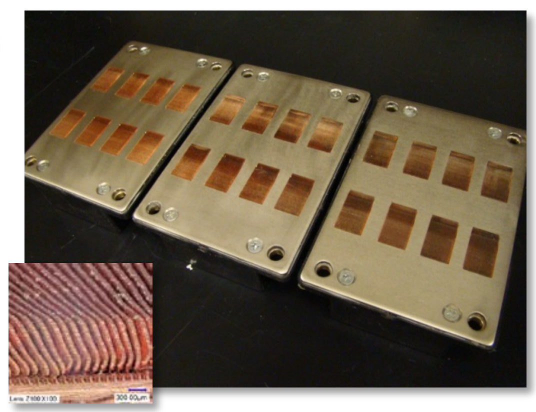
- Die/substrate-integrated thermal management
- Microchannels



Han et al., 2000, Gas Turbine Heat Transfer and Cooling Technology

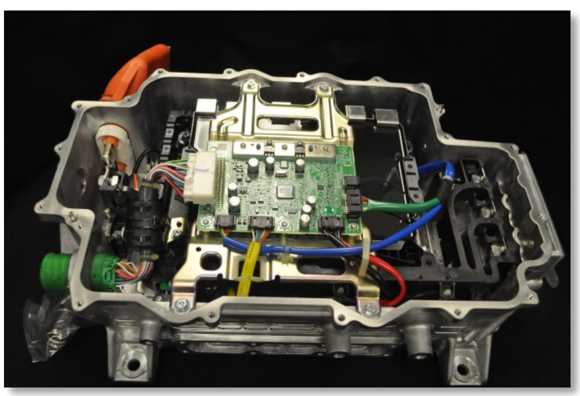
Module

- Enhanced surfaces
- Turbulence promoters



System

- Advanced manufacturing
- Multiple mode cooling

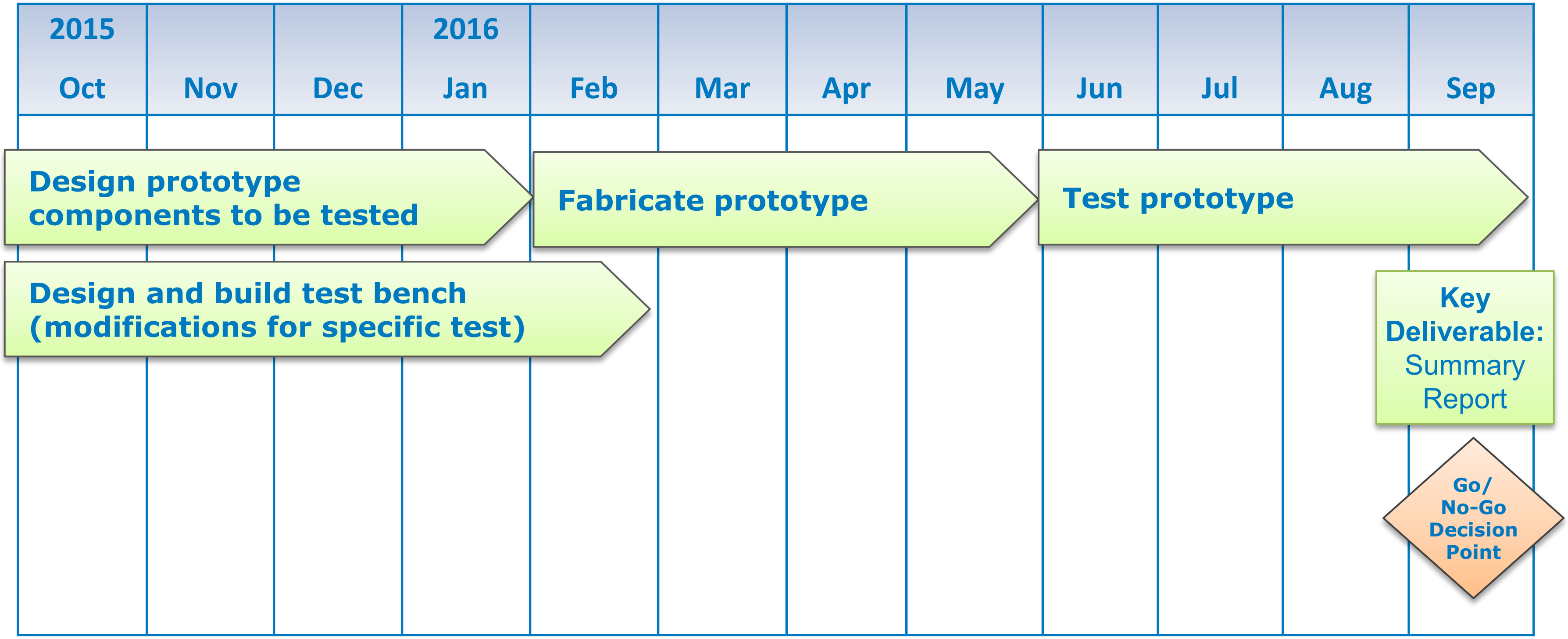


FY15 Tasks in Depth

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

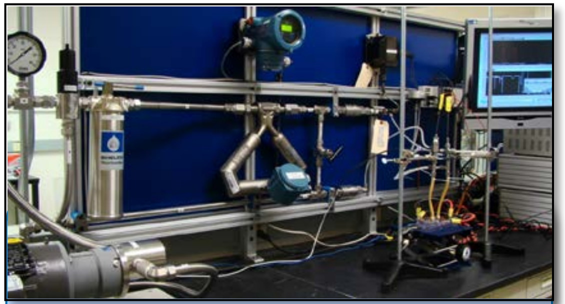


Go / No-Go Decision Point: If there are shortcomings in thermal management or size and weight can be improved from testing, proceed to refine prototype

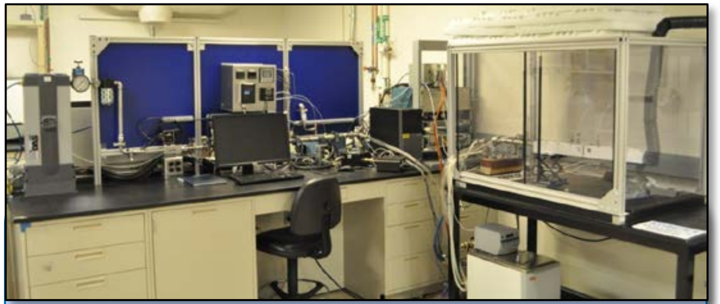
Key Deliverable: Publish results of thermal performance testing

FY16 Task Description

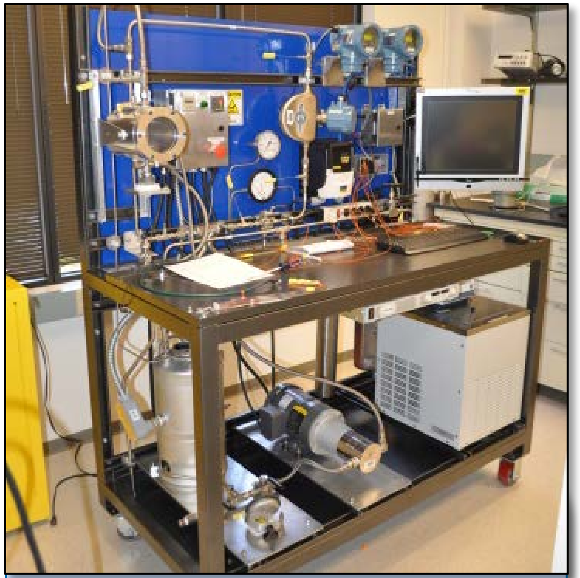
- Fabricate prototype
- Modify or build test bench



WEG Loop

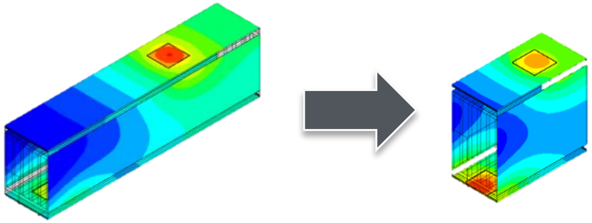


Air Test Bench



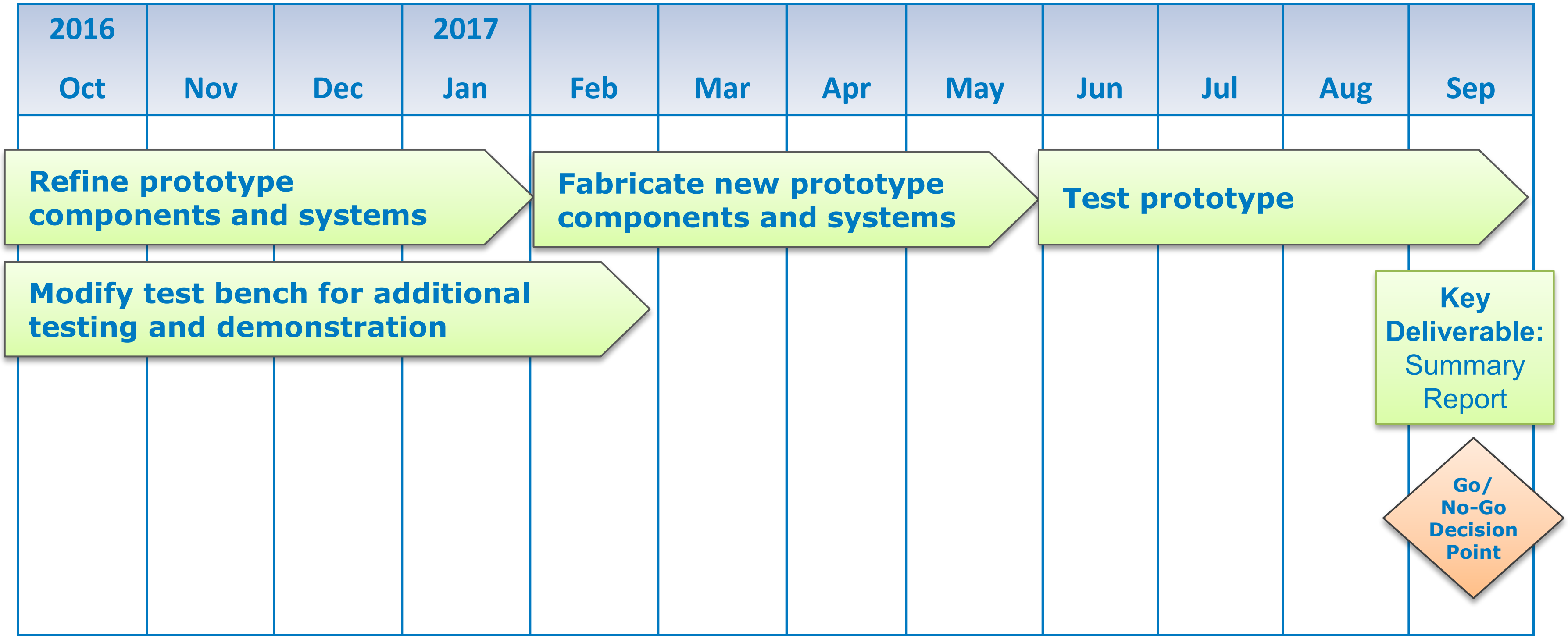
Transmission Fluid Loop

- Test and optimize prototype
- Validate model and optimize



WEG = water-ethylene glycol

FY17 Tasks to Achieve Key Deliverable



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

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

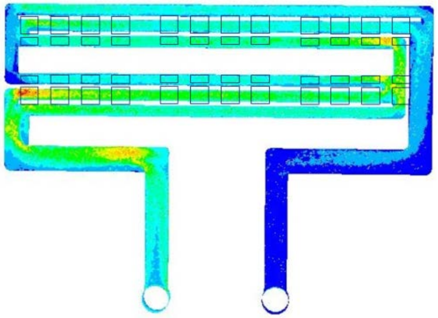
Partners/Collaborators

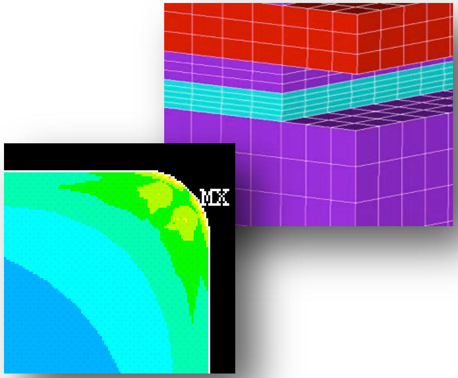
Organization	Role
APEI	Industry input on packaging and thermal management challenges
John Deere Electronic Solutions	Industry technical challenge input and test platform
Oak Ridge National Laboratory	PE R&D (inverter/converter/ charger projects) – NREL will provide thermal management support
PowerAmerica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

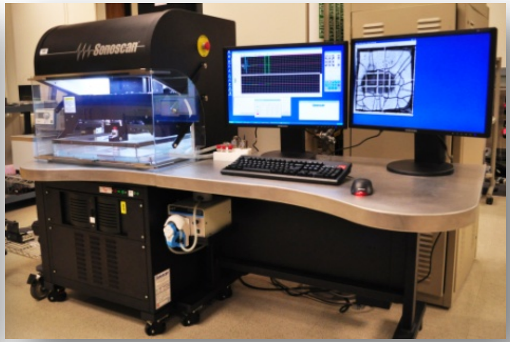
Actively pursuing additional industry partners (OEM, Tier 1/2 suppliers) interested in providing technical input or collaborations.

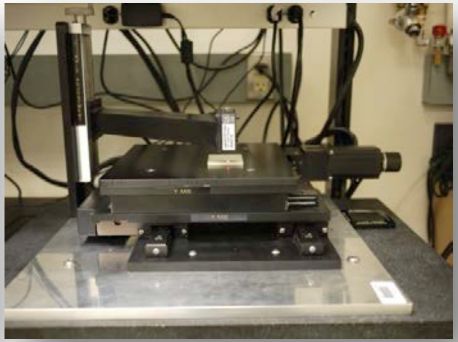
Capabilities

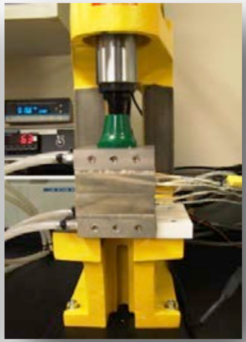
- NREL Core Competency: Thermal management and reliability for power electronics
- High-performance computing cluster for CFD, thermomechanical FEA – parallel computing licenses from ANSYS
- Test benches: liquid (WEG) loop, air cooling, air balance-of-systems, transmission oil loop, two-phase loop
- 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











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