

# Thermal Performance Benchmarking



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**National Renewable Energy Laboratory**  
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EDT070

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# Overview

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## Timeline

- **Project start date: FY15**
- **Project end date: FY18**
- **Percent complete: 30%**

## Budget

- **Total project funding: \$400K**
  - DOE share: \$400K
- **Funding received in FY 2015: \$200K**
- **Funding for FY 2016: \$200K**

## Barriers

- **Performance**
- **Efficiency**
- **Cost**

## Partners

- **Oak Ridge National Laboratory (ORNL)**

# Relevance

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- **Overall objective:** To benchmark the thermal performance of the power electronics and electric motor thermal management systems
- **FY16 Objective:** Benchmark the thermal management systems for the 2014 Honda Accord power electronics system and 2015 BMW i3 power electronics and motor

# Relevance: Impact

**The information collected from these benchmarking activities will:**

- Evaluate advantages and disadvantages of different thermal management systems
- Identify areas of improvement to advance the state of the art
- Establish baseline metrics for the thermal management systems
- Increase the publicly-available information related to automotive traction drive thermal management systems
- Help guide future EDT R&D efforts
- Help industry reduce the weight, volume, and cost of vehicle traction-drive systems by providing information that may influence future product designs

NREL is working with ORNL to determine the operating temperatures for the EDT components in real-world operation

# Milestones


Month / Year	Description of Milestone or Go/No-Go Decision	Status
December 2015	Go/No-Go: Work with DOE and ORNL to identify and thermally benchmark vehicle subsystem(s) that meet DOE VTO EDT research benchmarking goals.	Vehicle subsystems identified
March 2016	Complete the thermal benchmarking test plan and prepare the test loops for the power electronics and electric motor system to be evaluated.	Completed
June 2016	Calibrate the various sensors (e.g., thermocouples, pressure transducers). Instrument the test articles (e.g., power module in the inverter) with temperature and pressure sensors for the experiments.	On track
September 2016	Complete thermal characterization of the power electronics and electric motor thermal management systems and summarize results in a report (to be part of the Annual VTO EDT report).	On track

# Approach/Strategy


**Collaborate with industry and ORNL to identify the vehicle system to benchmark**



## **Experimentally measure thermal performance**

- Measure the junction-to-coolant thermal resistance at different coolant flow rates
  - Measure component thermal properties
  - Use results to validate models
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## **Model the performance**

- Validate the models using experimental results
  - Compute thermal resistances that cannot be experimentally measured
  - Create transient thermal models
  - Establish baseline metrics for the thermal management systems
  - Identify thermal bottlenecks in the systems and provide solutions to improve the state of the art
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**Share results with industry and research institutions**

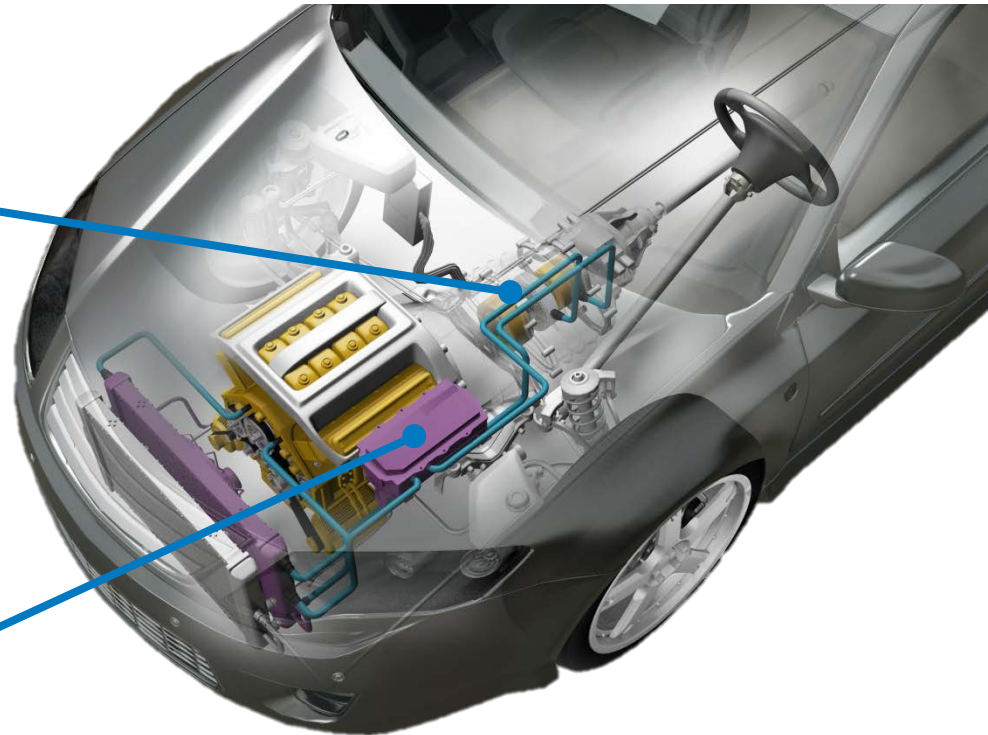
# Approach/Strategy: Thermal Measurements

## Electric motor thermal management

- Winding-to-liquid thermal resistance
- Motor lamination and winding thermal properties
- Pressure drop through the heat exchanger
- Volume and weight of the heat exchanger

## Power electronics thermal management

- Junction-to-liquid thermal resistance
- Interface material thermal resistance
- Thermal resistance and pressure drop through the heat exchanger
- Volume and weight of the heat exchanger





# Technical Accomplishments

## 2012 Nissan LEAF inverter

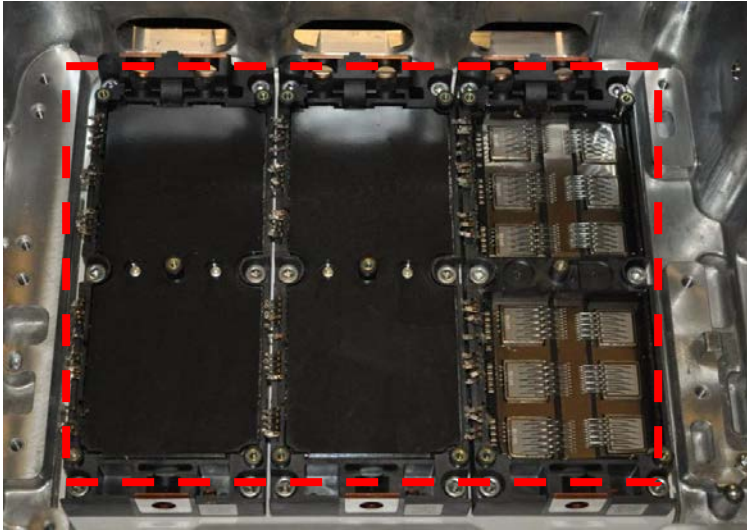


Photo credit: Gilbert Moreno, NREL

- Three power modules are mounted to a cast-aluminum cold plate
- Thermal interface materials (TIMs) are applied between the module and cold plate

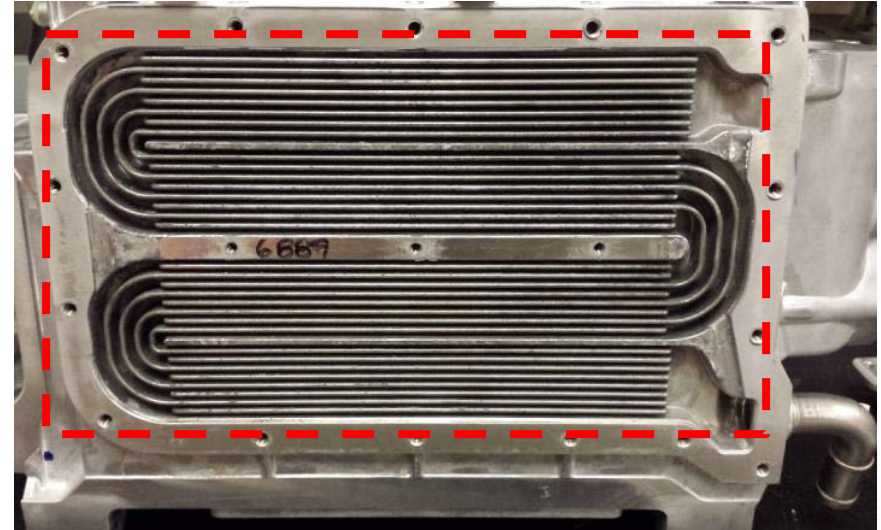


Photo credit: Gilbert Moreno, NREL

- Cold plate integrated into the housing
- Power modules fit within the finned area



# Technical Accomplishments

## 2012 Nissan LEAF inverter

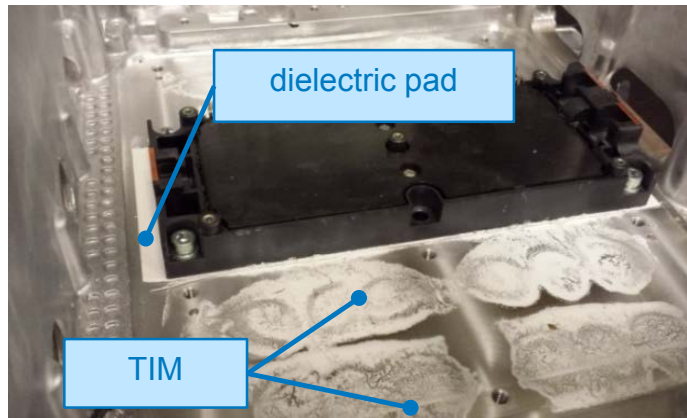
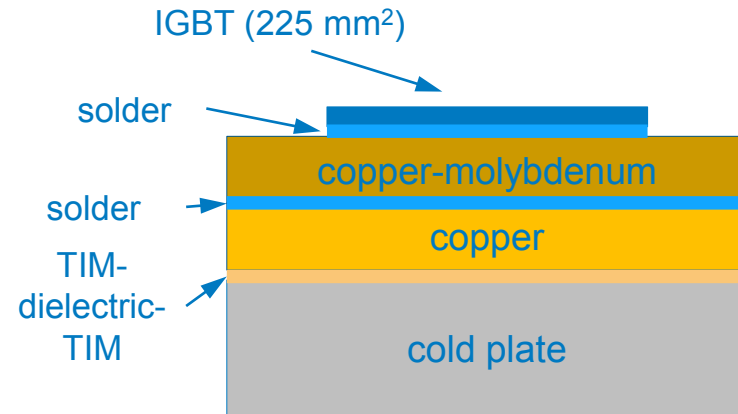


Photo credit: Gilbert Moreno, NREL



IGBT: insulated gate bipolar transistor

- The analysis of the structure of the inverter was conducted.
- Modules use dielectric pads for insulation instead of metalized-ceramic substrates.
- TIMs are provided on both sides of the dielectric pad to reduce the thermal resistance.
- Placing the electrically active copper plate next to the cold plate provides a form of bus bar cooling that is unique to the LEAF design.

# Technical Accomplishments: Characterization procedure

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- Measure
  - Junction-to-coolant thermal resistance
  - Material thermal properties
- Evaluate the effect of varying the flow rate on the thermal resistances
- Use results to validate the computational fluid dynamics (CFD) and finite element analysis (FEA) models

# Technical Accomplishments: Test Procedures

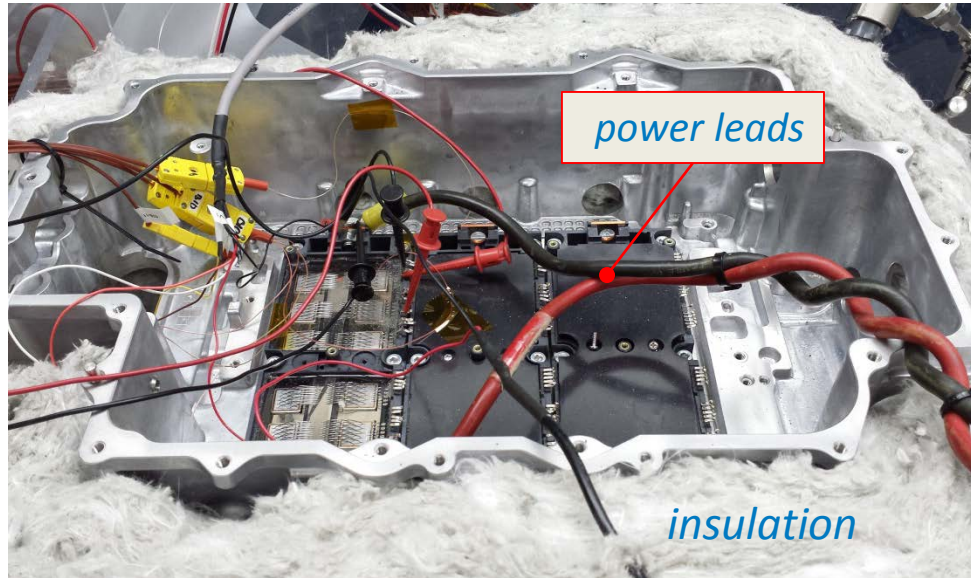


Photo credit: Gilbert Moreno, NREL

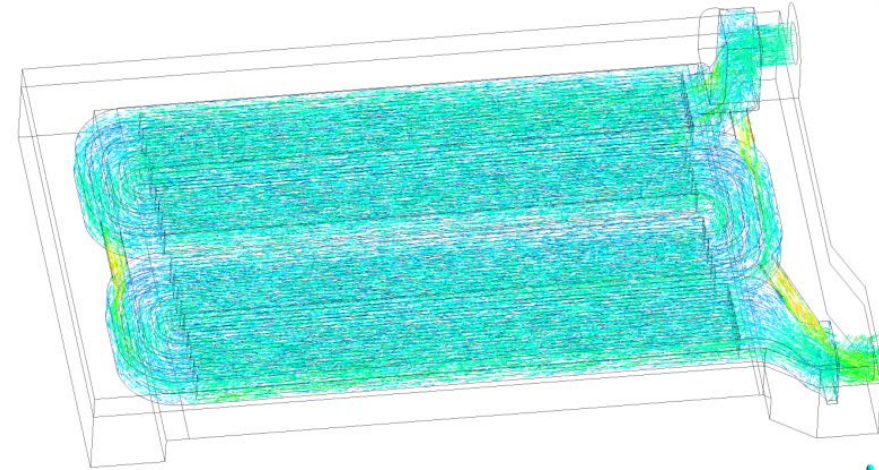
$$R''_{th, j-l} = \frac{(T_j - \bar{T}_f)}{Q_{IGBT}} \times A_{IGBT}$$

- The power electronics systems were connected to a test bench and water-ethylene glycol (WEG) (50/50) at 65°C was circulated through the cold plates at different flow rates [2, 5, 10, and 12 liters per minute (lpm)].
- The transient thermal tester (T3ster) was used to power the devices.

# Technical Accomplishments: CFD and FEA Models

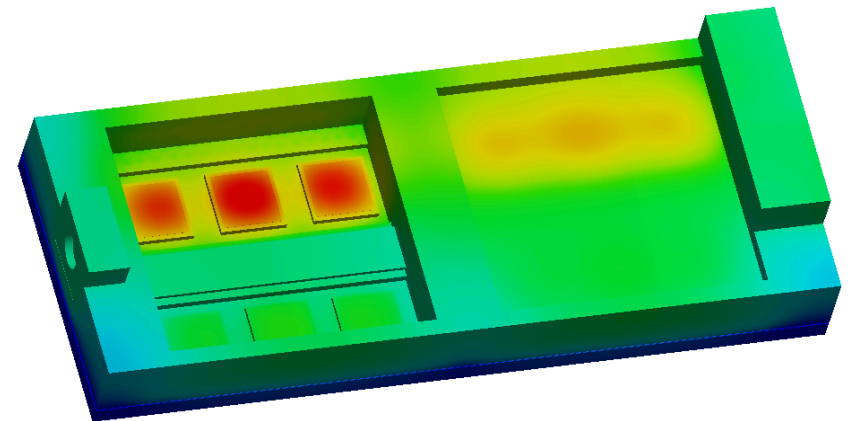
- A CFD model was utilized to derive the heat transfer coefficients within the cold plates at various WEG flow rates.
- The computed average heat transfer coefficients were used as boundary conditions in the FEA model to obtain the temperature profile in the passive stack up structure.

Velocity  
1.98  
1.49  
0.99  
0.50  
0.00  
[m s<sup>-1</sup>]



B: Steady-State Thermal  
Temperature  
Type: Temperature  
Unit: °C  
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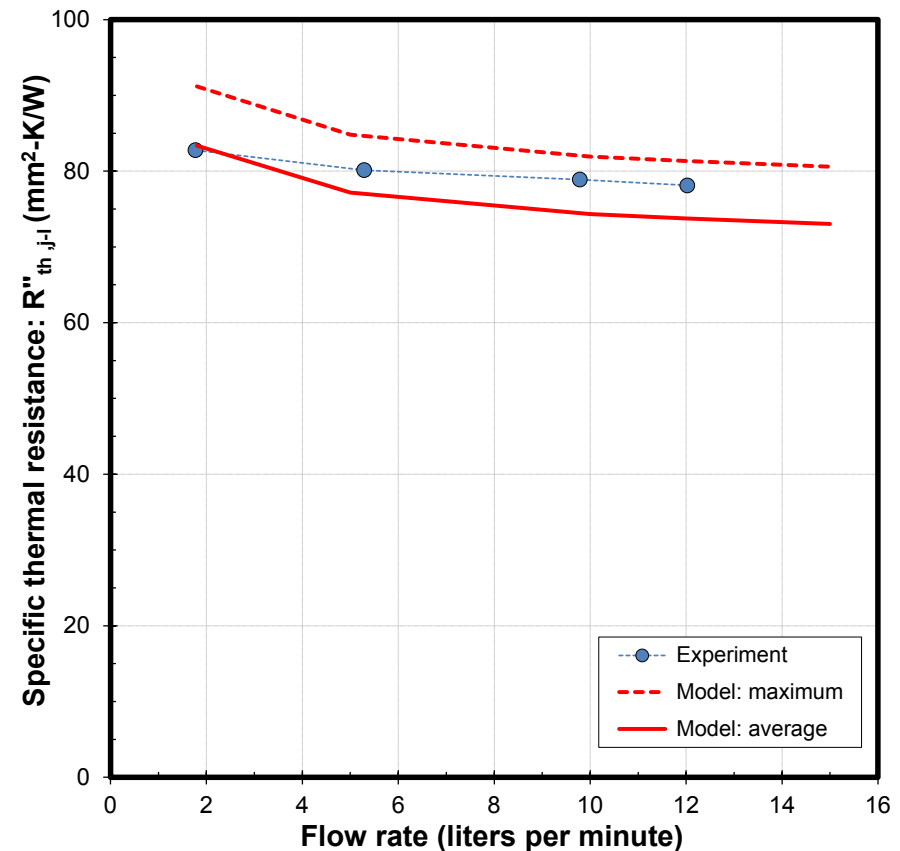
200 Max  
191  
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99.4  
90.3  
81.1  
72 Min



# Technical Accomplishments: Thermal Resistance

## 2012 Nissan LEAF inverter

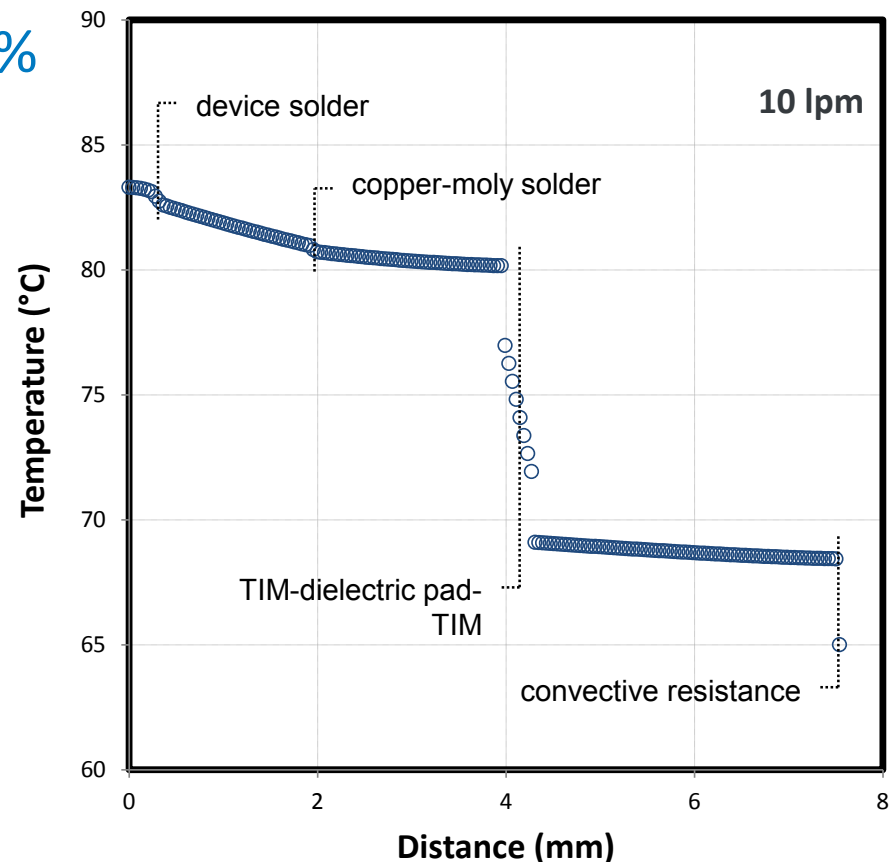
- The average and maximum thermal resistances at each flow rate were obtained from the FEA models.
- Model results vary within ~6% of experimental results.
- Minimal effect of flow rate on the thermal resistance indicates that a passive stack provides the dominant resistance in the system.



# Technical Accomplishments: Temperature Profile

## 2012 Nissan LEAF inverter

- Passive stack is the dominant factor that accounts for about 80% of the total thermal resistance.
- Dielectric pad interface is the largest resistance (~60% of the total temperature drop).
- Compared to traditional power modules (metalized-ceramic substrates), the LEAF design has higher thermal resistance, indicating that there are opportunities for improvement.
- LEAF design may have cost and reliability advantages.



# Technical Accomplishments

## 2014 Honda Accord power electronics system

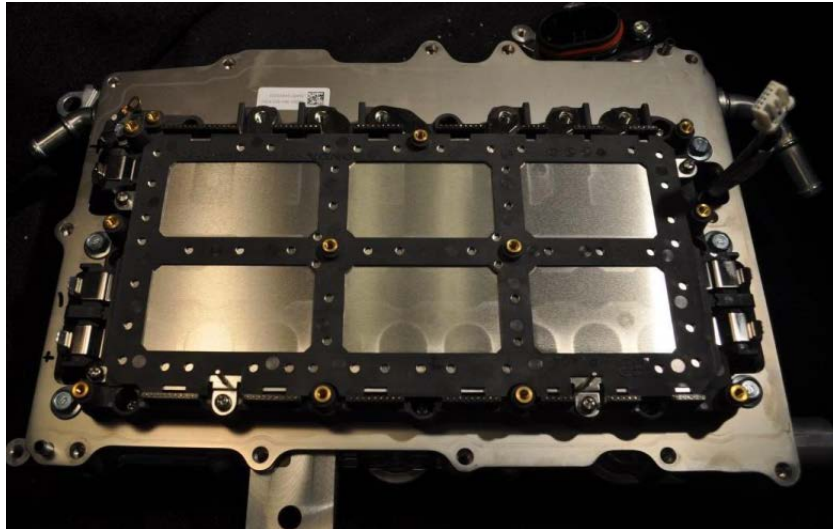
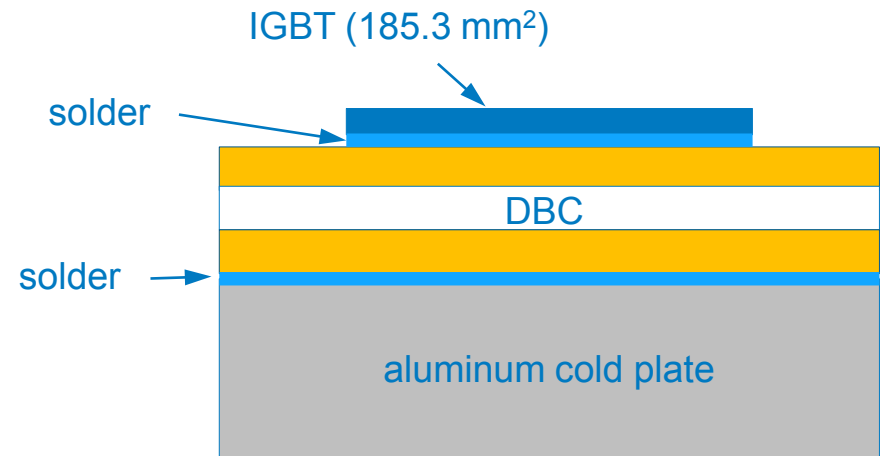


Photo credit: Gilbert Moreno, NREL



- The IGBTs and diodes are soldered onto a DBC.
- Silicon nitride ceramic layer is used in the DBC.
- Thermal grease is not utilized as a TIM.

DBC: direct-bond-copper



# Technical Accomplishments

## 2014 Honda Accord power electronics system



Photo credit: Gilbert Moreno, NREL



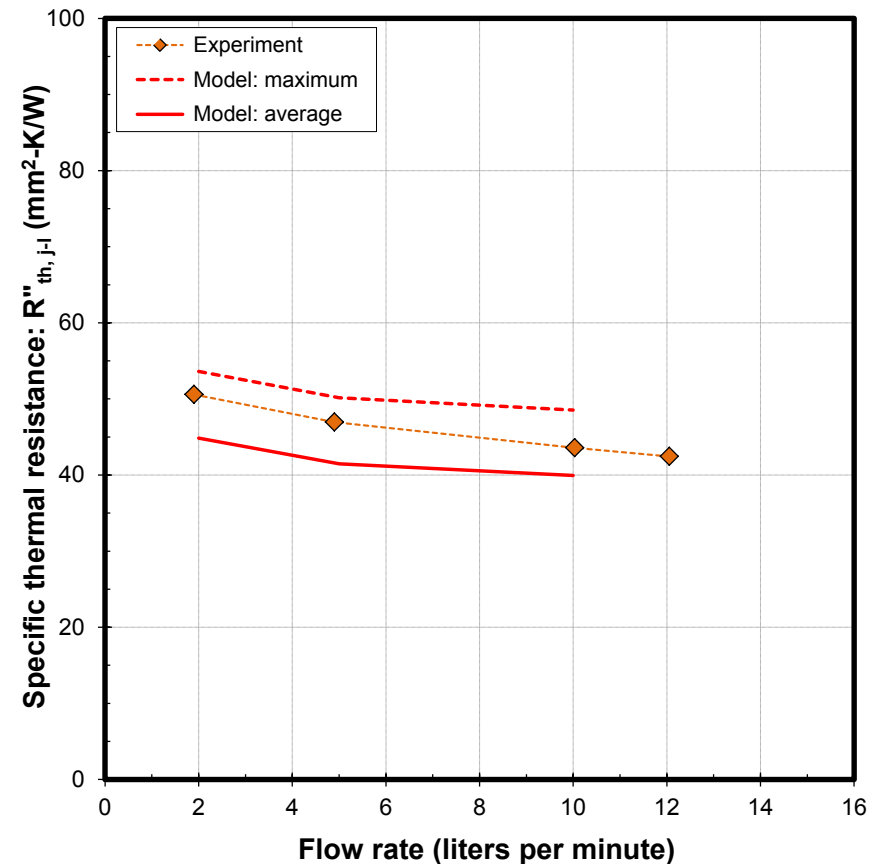
Photo credit: Gilbert Moreno, NREL

- Cold plate with intricate finned structures with fin channel widths  $\sim 0.95$  mm.
- The fins appear to be machined onto the aluminum cold plate.

# Technical Accomplishments: Thermal Resistance

## 2014 Honda Accord power electronics system

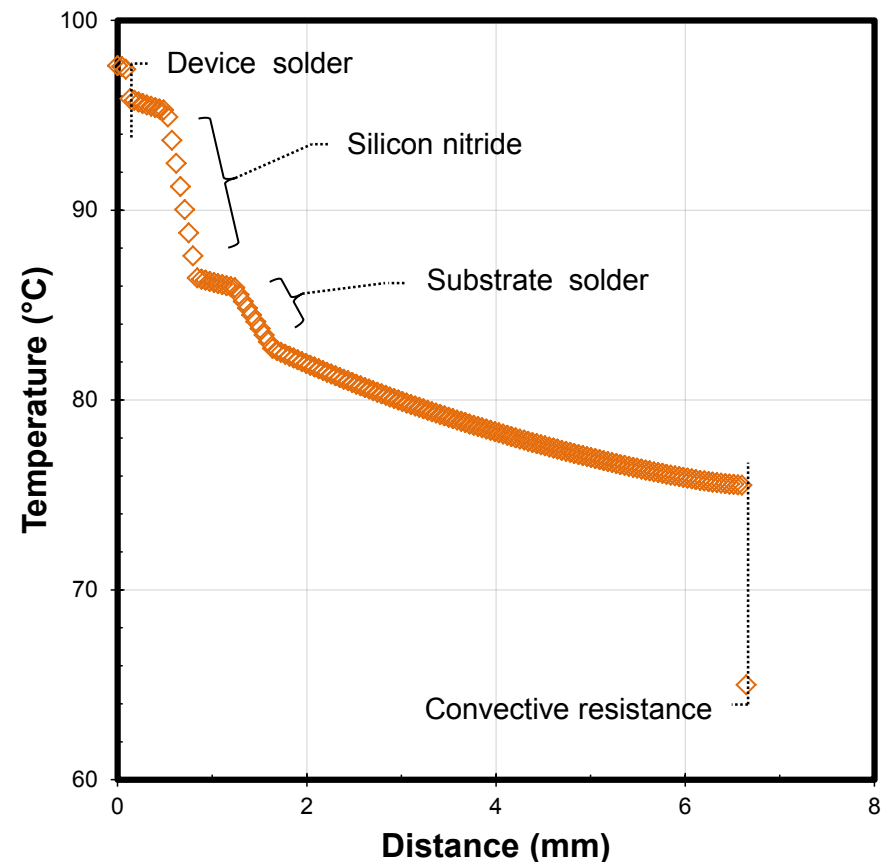
- At 10 lpm, the junction-to-coolant thermal resistance of the Accord is about 44% lower than that of the 2012 LEAF.
- The lack of a thermal grease layer in the Accord reduces its passive-stack thermal resistance to  $\sim 50 \text{ mm}^2\cdot\text{K}/\text{W}$ .
- The model-predicted thermal resistances match well with the experimental values.



# Technical Accomplishments: Temperature Profile

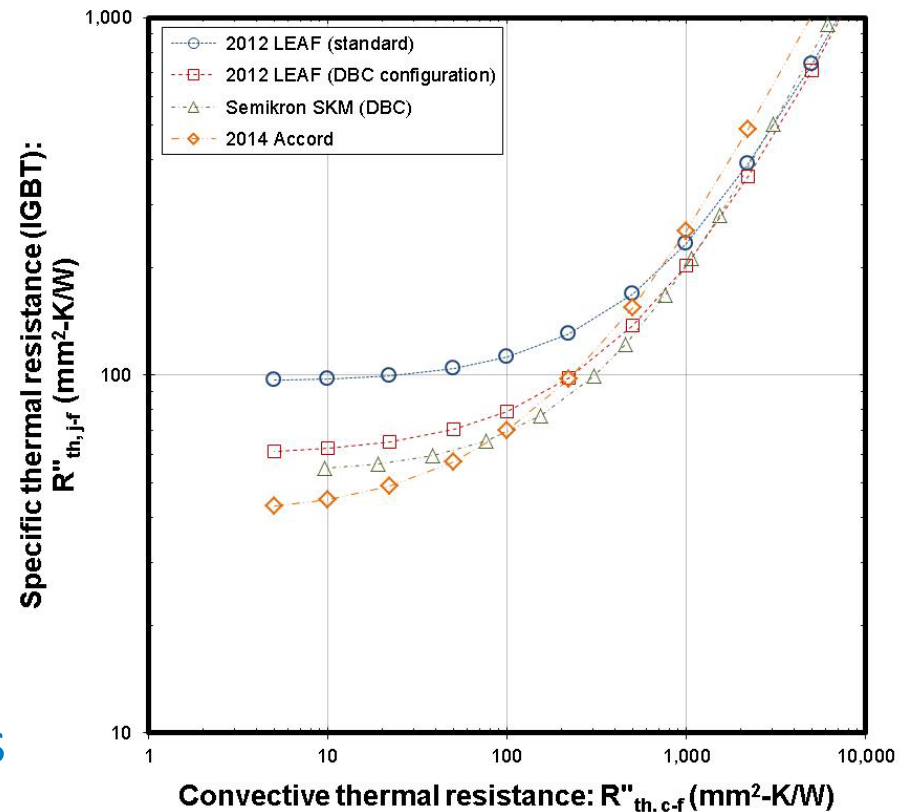
## 2014 Honda Accord power electronics system

- The silicon nitride layer contributes the largest thermal resistance within the passive stack up structure.
- The thermal performance of the 2014 Accord inverter is more sensitive to the convective heat transfer.
- The 2014 Accord inverter thermal management system is more costly compared with the LEAF system.



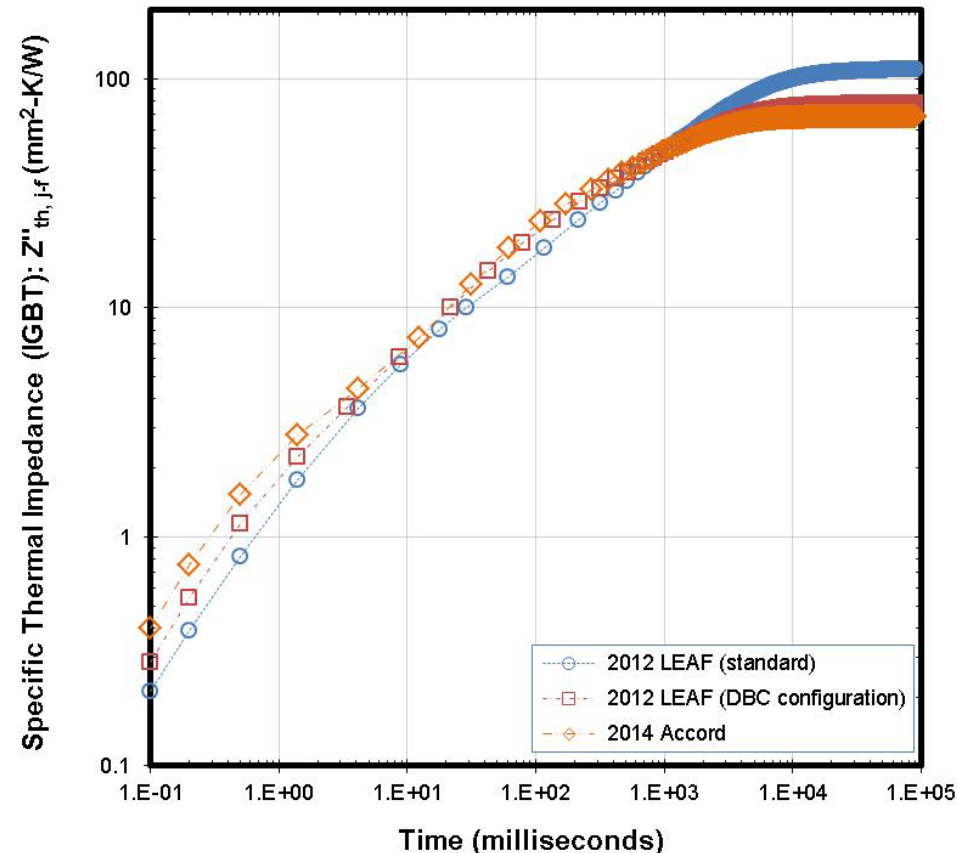
# Technical Accomplishments: Comparison

- At a convective thermal resistance value of  $100 \text{ mm}^2\cdot\text{K}/\text{W}$ , the Accord module's thermal resistance is approximately 38% and 12% lower than the LEAF and DBC-modified LEAF designs, respectively.
- The Accord module's thermal resistance decreases at a faster rate with decreasing convective thermal resistance, showing its passive stack thermal resistance is lower than the LEAF, DBC-modified LEAF, and Semikron DBC-based module.



# Technical Accomplishments: Comparison

- The LEAF module shows lower transient thermal impedance at a time scale lower than 1 second.
- The LEAF's use of a highly conductive copper molybdenum plate directly under the IGBT spreads the heat and provides thermal capacitance to improve transient performance.
- The Accord module has better thermal performance at steady state.



# Technical Accomplishments: Comparison

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- The LEAF power electronics system demonstrates lower transient thermal impendence at a time scale less than 1 second because of the highly thermally conductive materials used.
- The Accord system has better steady-state thermal performance due to removal of thermal grease in the package.
- From a cost perspective, the LEAF thermal design appears to be a less expensive option because it uses a dielectric pad instead of DBC, and cast-aluminum cold plates instead of precisely machined plates.
- The thermal design is strongly dependent on the thermal requirements and budget.

# Response to Previous Year Reviewers' Comments

- **Reviewer Comment:** “The reviewer saw that progress was being made, but was not sure how valuable data generated will be, because thermal data tends to be very specific for a particular solution. “
- The 2012 Nissan LEAF inverter and motor were evaluated in the first year of this project. The project concept is to evaluate a different vehicle system every year—similar to ORNL’s benchmarking of electric vehicle and hybrid electric vehicle technologies approach. In FY16, we plan to evaluate the 2014 Honda Accord Hybrid inverter and the 2015 BMW i3 inverter and motor. Every new system benchmarked will provide insight into different thermal management strategies.
- **Reviewer Comment:** “Temperature map is used to develop thermal resistance data for various key points/locations in electric motor. Only copper losses or thermal load due to copper losses are considered in the motor, when iron losses are also incepted, heat flow path could be altered resulting in different values of thermal resistances.”
- We agree with the reviewer in that the iron losses should also be considered. The experimental work was used to validate thermal models and not to replicate automotive conditions. The validated thermal models were then used to understand heat flow through the motor and identify thermal bottlenecks. The models can be used to simulate automotive conditions where heat is generated at various locations within the motor (including the iron laminations and magnets).



# Collaboration and Coordination with Other Institutions

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- ORNL: Work is aligned with ORNL's Benchmarking of EV and HEV Technologies project

# Remaining Challenges and Barriers

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- Experiments may not exactly replicate the actual automotive environments or operating conditions.
- More information is needed to identify the power electronics systems that provide the best thermal performance at its cost.

# Proposed Future Work

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## FY16

- Characterize and identify methods to improve the thermal management system for the 2014 Honda Accord power electronics system
- Characterize and identify methods to improve the thermal management system for the 2015 BMW i3 power electronics system

## FY17

- Characterize the thermal performance of the 2015 BMW i3 electric motor thermal management system (oil-cooled system)
- Identify methods to improve the performance of the benchmarked thermal management systems

# Summary

## DOE Mission Support

- Understand and quantify the state-of-the-art in thermal management systems in electric-drive vehicles
- Accelerate the adoption of electric-drive vehicles through improved thermal management

## Approach

- Collaborate with industry and ORNL to identify the appropriate vehicle to benchmark
- Characterize the thermal performance of the inverter and motor thermal management systems and share the results with industry
- Identify areas of improvement to advance the state of the art and establish baseline metrics for the thermal management systems

## Accomplishments

- Completed characterization of 2012 Nissan LEAF and 2014 Honda Accord power electronics thermal management systems
- Acquired the 2015 BMW i3 motor and inverter for FY16 benchmarking studies

# Summary

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## Future work

- Characterize the thermal performance of the 2015 BMW i3 power electronics and motor thermal management systems

## Collaborations

- ORNL



### **Acknowledgment:**

**Susan Rogers and Steven Boyd,**  
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**Kevin Bennion**  
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