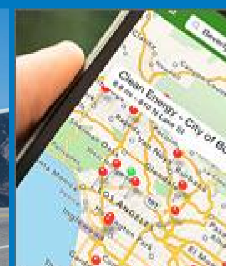
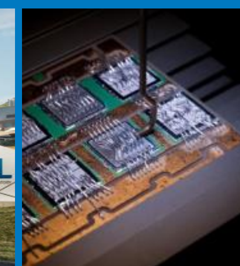
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Power Electronics Thermal Management R&D







P.I.: Gilbert Moreno
National Renewable Energy Laboratory (NREL)
2016 Annual Merit Review
June 8, 2016

EDT069

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:** 30%

Budget

- **Total project funding**
  - DOE share: $1,225 K
- **Funding received in FY 2015:** $625K
- **Funding for FY 2016:** $600K

Barriers

- **Weight**
- **Performance and Lifetime**
- **Cost**

Partners

- John Deere
- Kyocera
- Oak Ridge National Laboratory (ORNL)
- National Renewable Energy Laboratory (NREL) – Project Lead

Relevance

Why is thermal management essential?

- Manage and dissipate heat
- Limit failure, increase reliability
- Increase power density

Transition to wide-bandgap (WBG) devices changes, but does not reduce, need for thermal management

WBG

- More efficient → Less heat
- Reduced area→ Increased heat flux
- Higher junction temperature → Larger temperature gradients, impacts other components that may not tolerate higher temperatures:
  - At the module level: bonded interface materials, thermal greases
  - At the inverter level: DC-link capacitors, electrical boards

Relevance

Objective: Develop thermal management techniques to enable high-temperature, WBG devices in power electronics

- Estimate component temperatures (e.g., capacitor, electrical board, solders) under elevated device temperature conditions
- Evaluate the effect of different under-hood (all-electric, hybrid-electric) temperature environments on component temperatures

Approach/Milestones

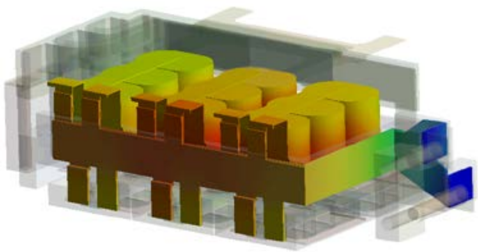
Month / Year	Description of Milestone or Go/No-Go Decision	Status
December 2015	**Milestone:** Complete inverter-scale thermal simulations.	Complete
March 2016	**Milestone:** Complete identification and assessment of thermal bottlenecks in the inverter and converter systems.	Complete
June 2016	**Go/No-Go:** Determine strategy to overcome the thermal bottlenecks and limitations.	In progress
September 2016	**Milestone:** Complete modeling of the performance of the improved inverter-scale thermal management concepts and prepare a report to summarize the project results.	Upcoming

Approach/Strategy

Power Electronics Thermal Management R&D

Application Thermal Research

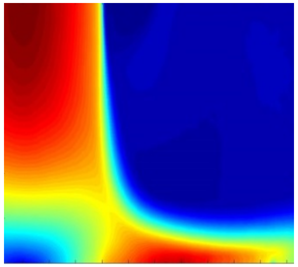
WBG Power Electronics Thermal Management



Advanced Cooling Technologies for John Deere Inverter (cooperative research and development agreement [CRADA])

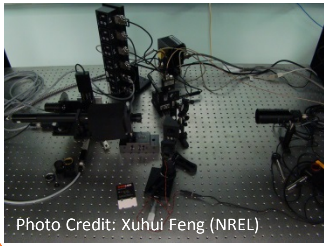
Thermal and Fluid Measurement Research

Fluids/coolants



Particle image velocimetry to understand heat transfer mechanisms of jets impinging on micro-structure surfaces

Advanced Materials



Phase-sensitive transient thermoreflectance to measure thermal properties of new interface materials

Interactions with other DOE projects: Thermal Performance Benchmarking (NREL), Motor Thermal Management R&D (NREL), Performance and Reliability of Bonded Interfaces for High-Temperature Packaging (NREL), EDT System Benchmarking (ORNL)

Approach/Strategy

WBG Power Electronics Thermal Management

Create thermal models of an automotive inverter

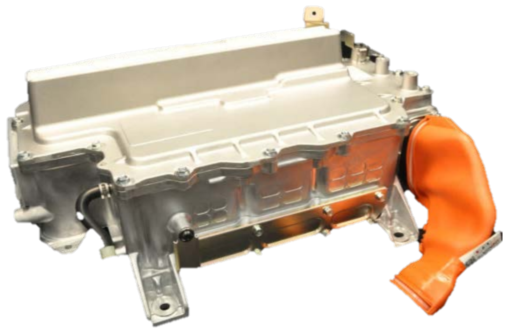
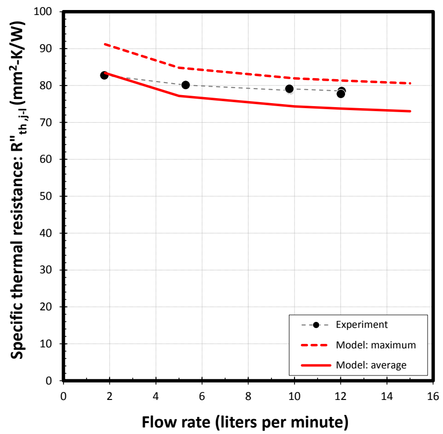
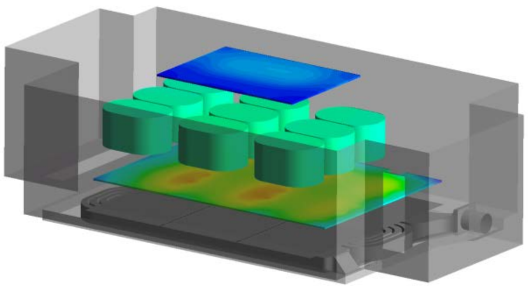


Photo Credit: Scot Waye (NREL)

Validate the thermal models



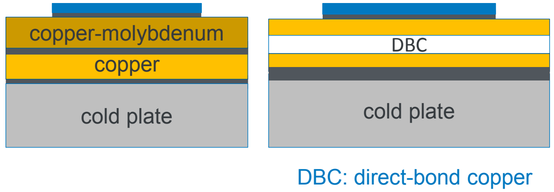
Simulate WBG operation using the inverter model



Quantify the inverter component temperatures under elevated device temperatures

Identify the primary thermal paths through which heat is conducted from the devices to the other components

Explore advanced cooling strategies



Evaluate different module topologies

Develop thermal management concepts to enable WBG power electronics

Experimentally validate some key thermal management concepts

Accomplishments: Automotive Inverter Thermal Model

- Created thermal models of the 2012 Nissan LEAF (80 kW) and used them to simulate WBG conditions
- Will create several inverter models to evaluate different inverter designs
- Working to develop thermal solutions that can be applied across a wide range of inverter designs

2012 LEAF

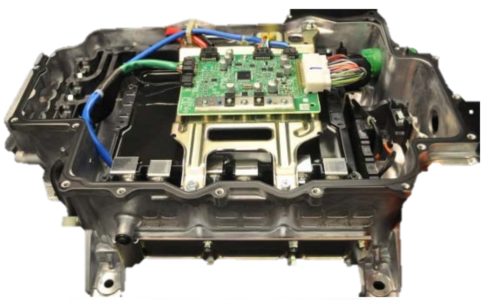
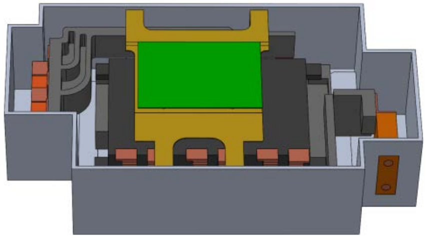
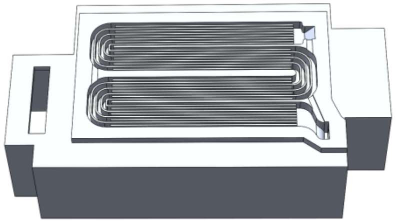


Photo Credit (all images): Scot Waye (NREL)

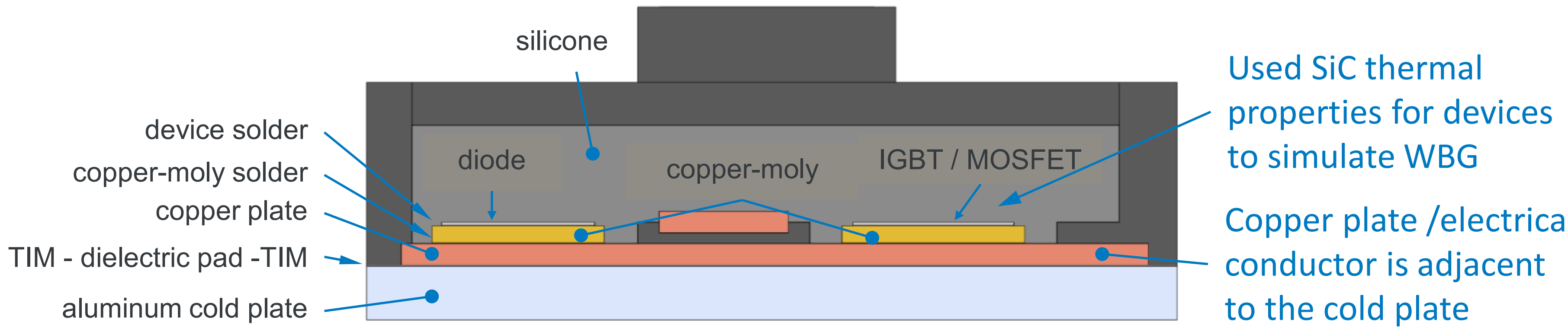
Model





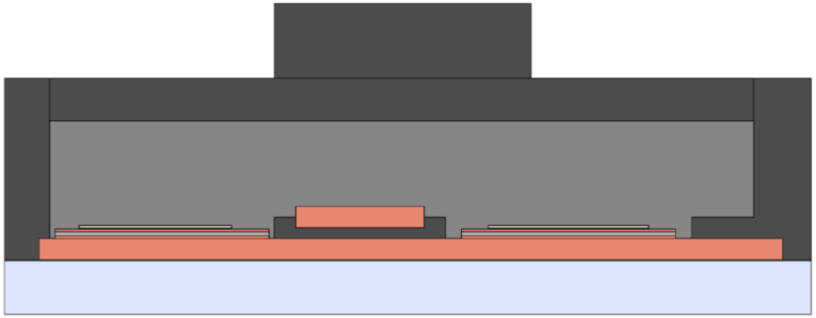
Accomplishments: Model Description

LEAF Module

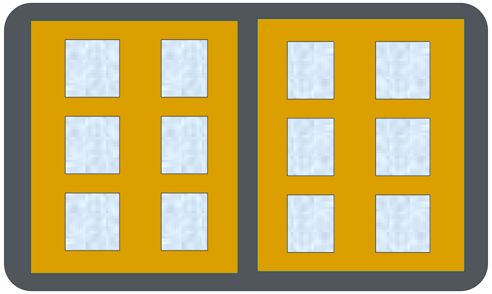


Other module configurations to be evaluated (future work)

DBC-based configuration



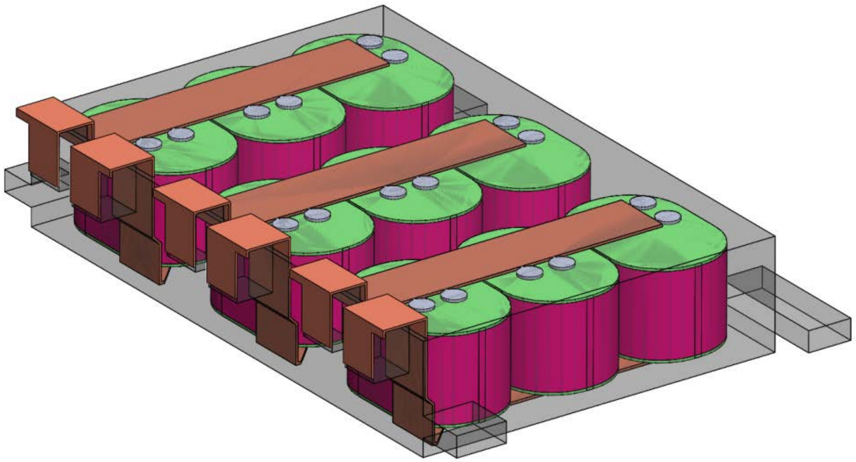
WBG module

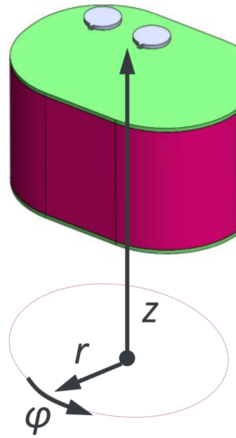


IGBT: insulated gate bipolar transistor, MOSFET: metal-oxide-semiconductor field-effect transistor, SiC: silicon carbide, TIM: thermal interface material

Accomplishments: Model Description

Capacitors: Metalized film



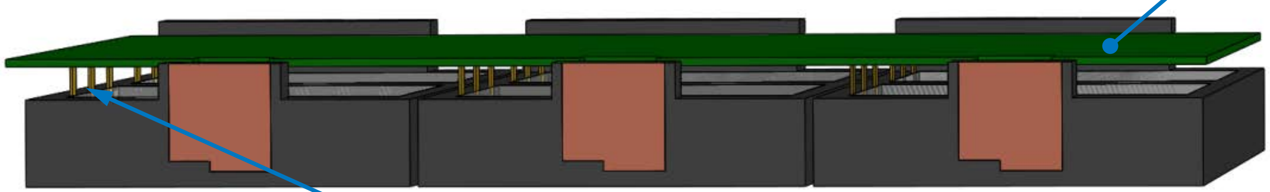


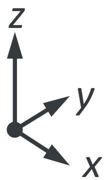
Capacitor winding thermal conductivity (k)

$k_z = k_\varphi = 0.46$ W/m-K

$k_r = 0.16$ W/m-K

Power modules and gate driver board





Electrical board thermal conductivity (k)

$k_x = k_y = 0.81$ W/m-K

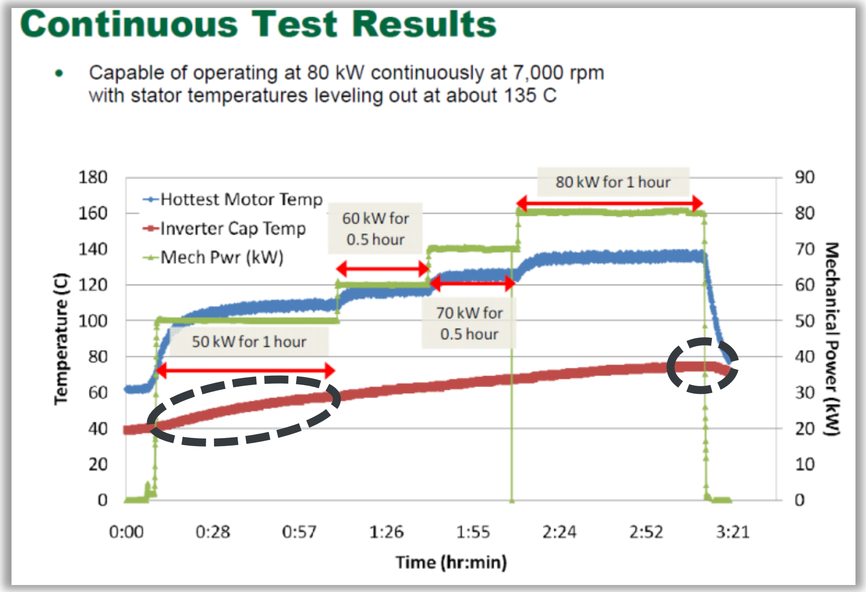
$k_z = 0.29$ W/m-K

Electrical pins included to account for the thermal path from the devices to the gate driver board

Accomplishments: Model versus Experiment

- Validated the junction-to-coolant thermal resistance in the Thermal Benchmarking project
  - Model within 6% of experimental results

- Used ORNL's test data to validate the capacitor's thermal performance
  - Water-ethylene glycol (WEG) inlet temperature = 65°C, DC voltage = 375 V
  - Used the 50-kW transient and 80-kW steady-state test data for comparison



Source: Burress, T. 2012 "Benchmarking of Competitive Technologies," 2012 DOE VTO Annual Report

Accomplishments: Model versus Experiment

Estimated component heat dissipation

Heat on all components imposed as a volumetric heat generation value

Mechanical power/ ($\eta_{inverter} \times \eta_{motor}$)

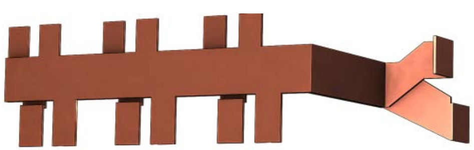
Photo Credit: Scot Waye (NREL)

Total Heat

Mechanical power/ η_{motor}

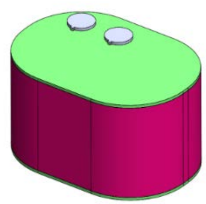
Photo Credit: Scot Waye (NREL)

Mechanical power



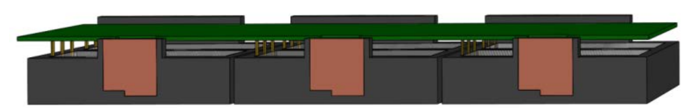
Bus bar heat

$I^2_{DC,\,AC} \times \Omega_{copper}$



Capacitor heat

$I^2_{ripple} \times ESR$



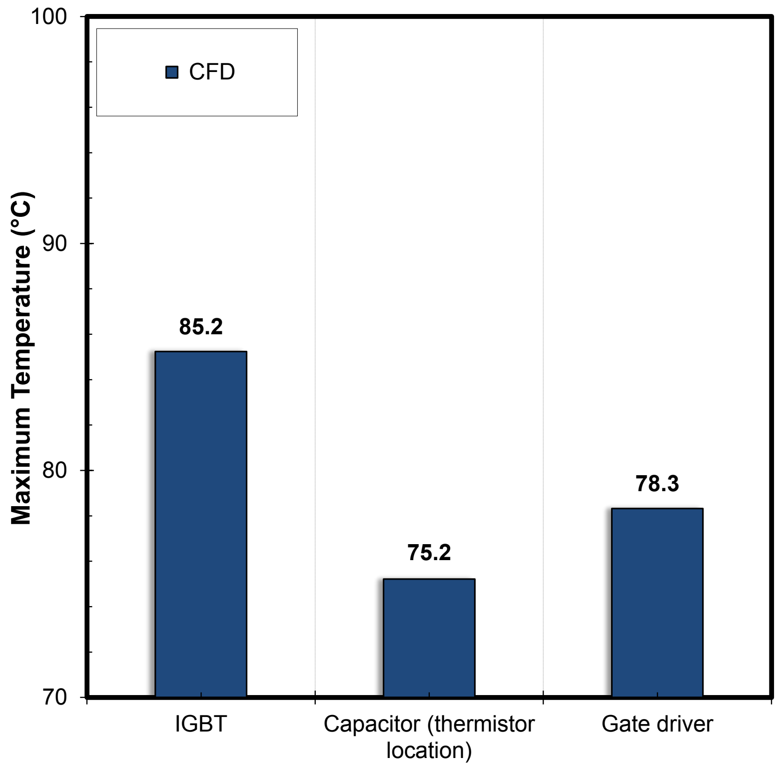
Power module heat

- Equal to the total heat minus the bus bar and capacitor heat
- Assumed a 3-to-1 IGBT-to-diode heat loss ratio

η: efficiency, *I*: current , Ω: electrical resistance, ESR: equivalent series resistance

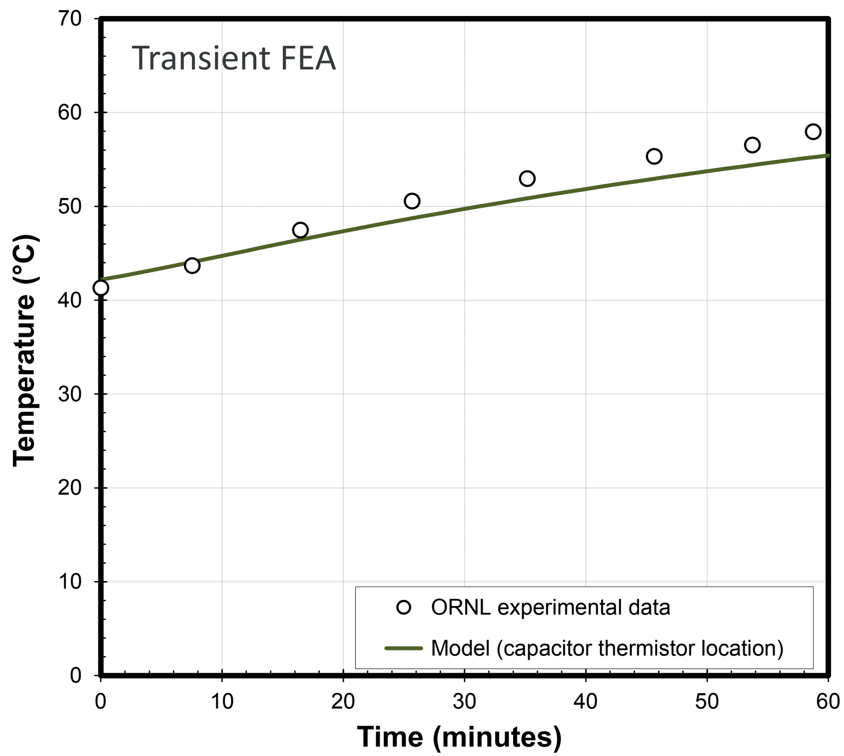
Accomplishments: Model versus Experiment

80 kW, steady-state condition



Model-predicted capacitor temperature compares well with measured value of ~75°C

50 kW, transient condition

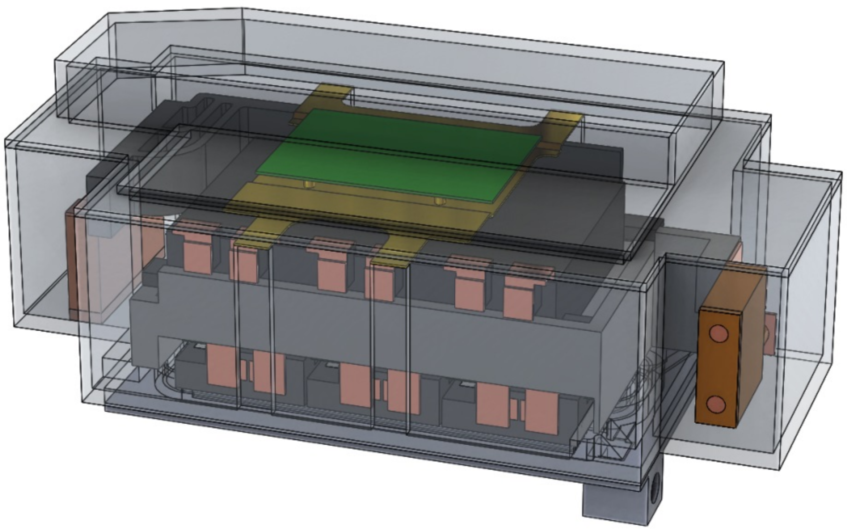


Model-predicted capacitor temperature versus time response compares well with test results

CFD: computational fluid dynamics, FEA: finite element analysis

Accomplishments: Simulating WBG Conditions

- Simulated WBG conditions by increasing the device (MOSFET) temperatures to 175°C, 200°C, and 250°C
- Quantified component (capacitors, boards) temperatures under elevated device temperatures
- Varied the under-hood temperature to simulate all-electric and hybrid-electric vehicle environments

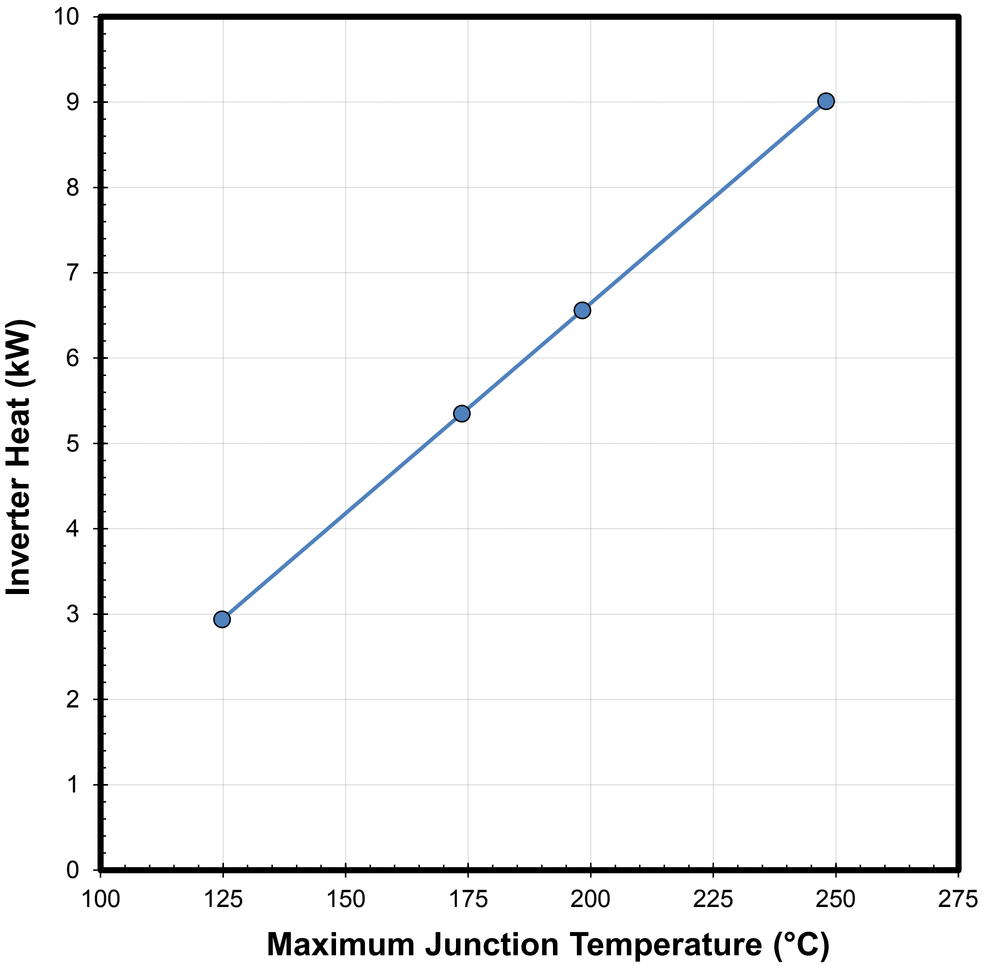


Under-hood temperatures evaluated:

- 75°C all-electric
- 125°C hybrid-electric
- 140°C hybrid-electric (near engine)

Accomplishments: Simulating WBG Conditions

- Increasing the device temperatures requires increasing the device heat (assuming device size and count remains the same)
- Increasing inverter power beyond 80 kW would require re-designing the inverter (larger bus bars, more capacitors)
- Challenging to compute heat loads for the bus bars and capacitors at power levels greater than 80 kW



Accomplishments: Simulating WBG Conditions

Modeled three cases to compute component temperatures

- **Case 1**: Only the modules generated heat

Case	Capacitors (total)	Bus bars (total)
1	0	0

- **Case 2**: Module heat plus the bus bar and capacitor heat values computed at 125°C junction temperature condition
  - Assuming that the bus bar size and number of capacitors would increase to accommodate the increased power, but the heat dissipated per component remains the same

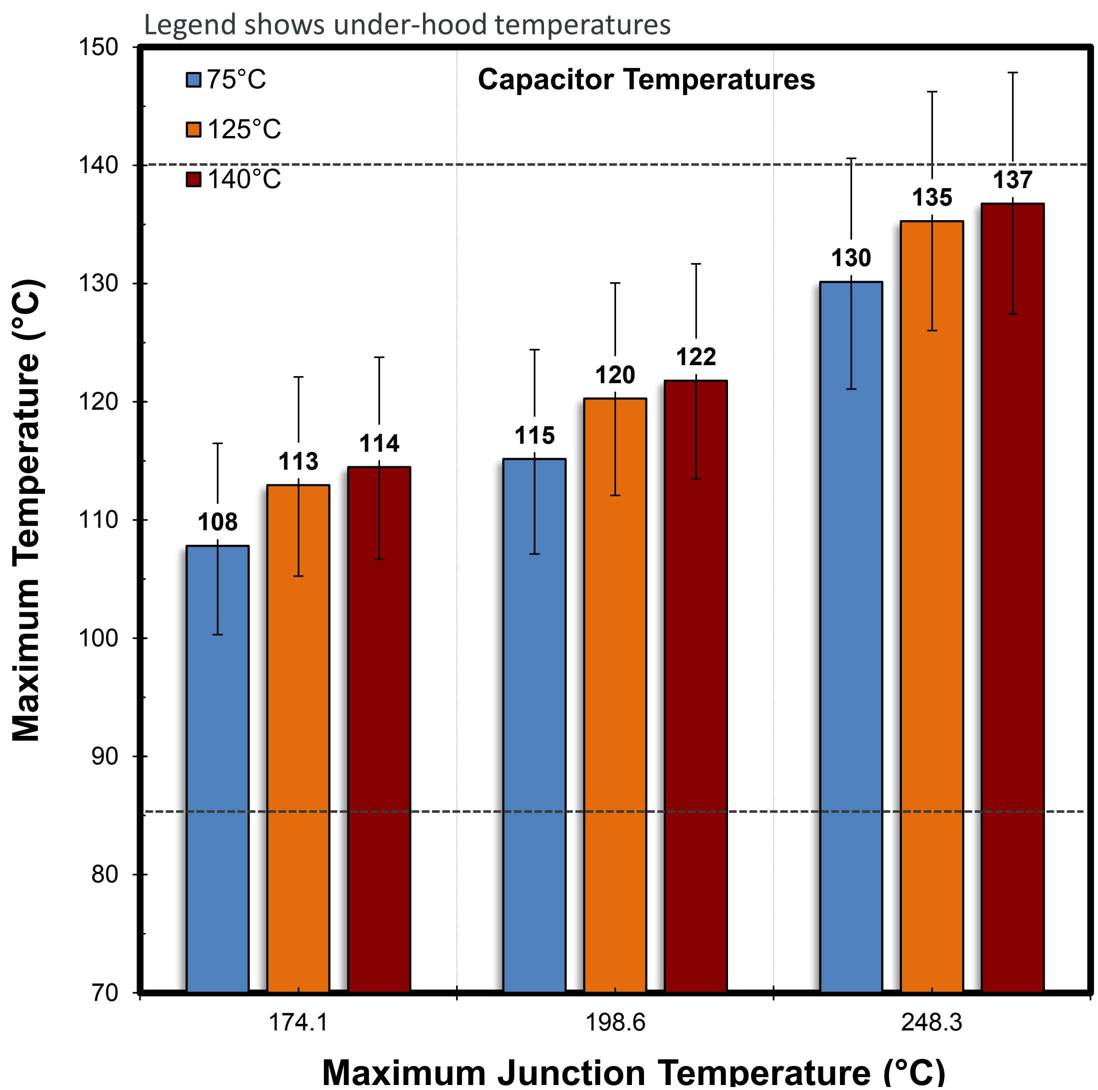
Case	Capacitors (total)	Bus bars (total)
2	1.6 W	21.2 W

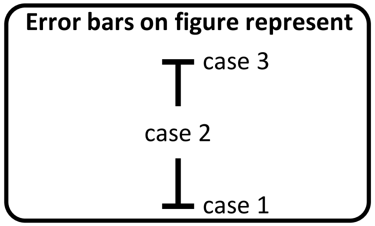
- **Case 3**: Module heat plus the bus bar and capacitor heat computed as a percentage of the module heat. Percentage taken at the 125°C junction temperature condition

Case	Capacitors (total)	Bus bars (total)
3	0.06% of module heat	0.72% of module heat

Accomplishments: CFD-Estimated Capacitor Temperatures

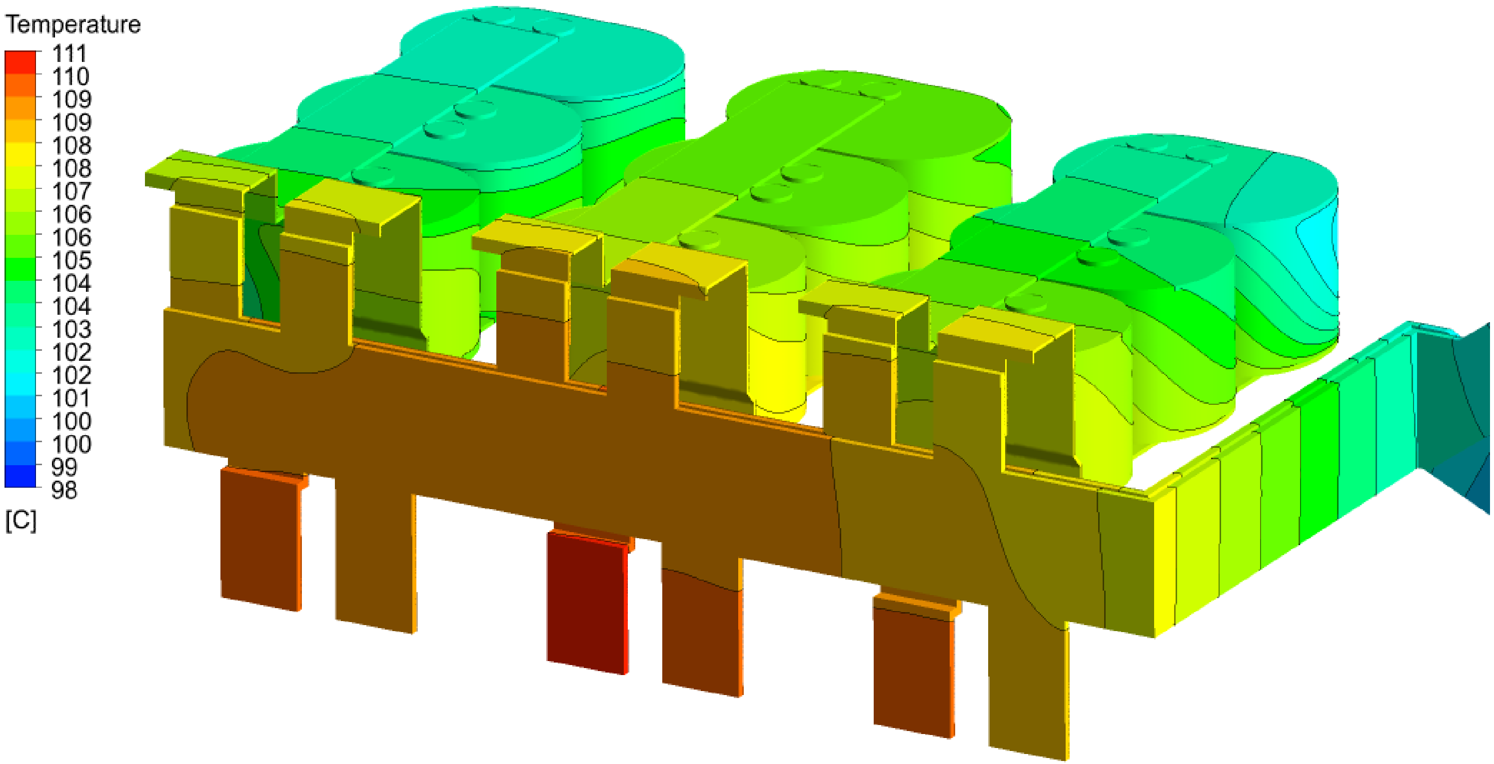
- For all cases, capacitors exceed 85°C (typical limit of polypropylene film capacitors)
- Capacitor temperature target of 140°C seems appropriate for junction temperatures up to 250°C
- Increasing under-hood temperature does not have a significant effect on capacitor temperatures





Accomplishments: CFD-Estimated Capacitor Temperatures

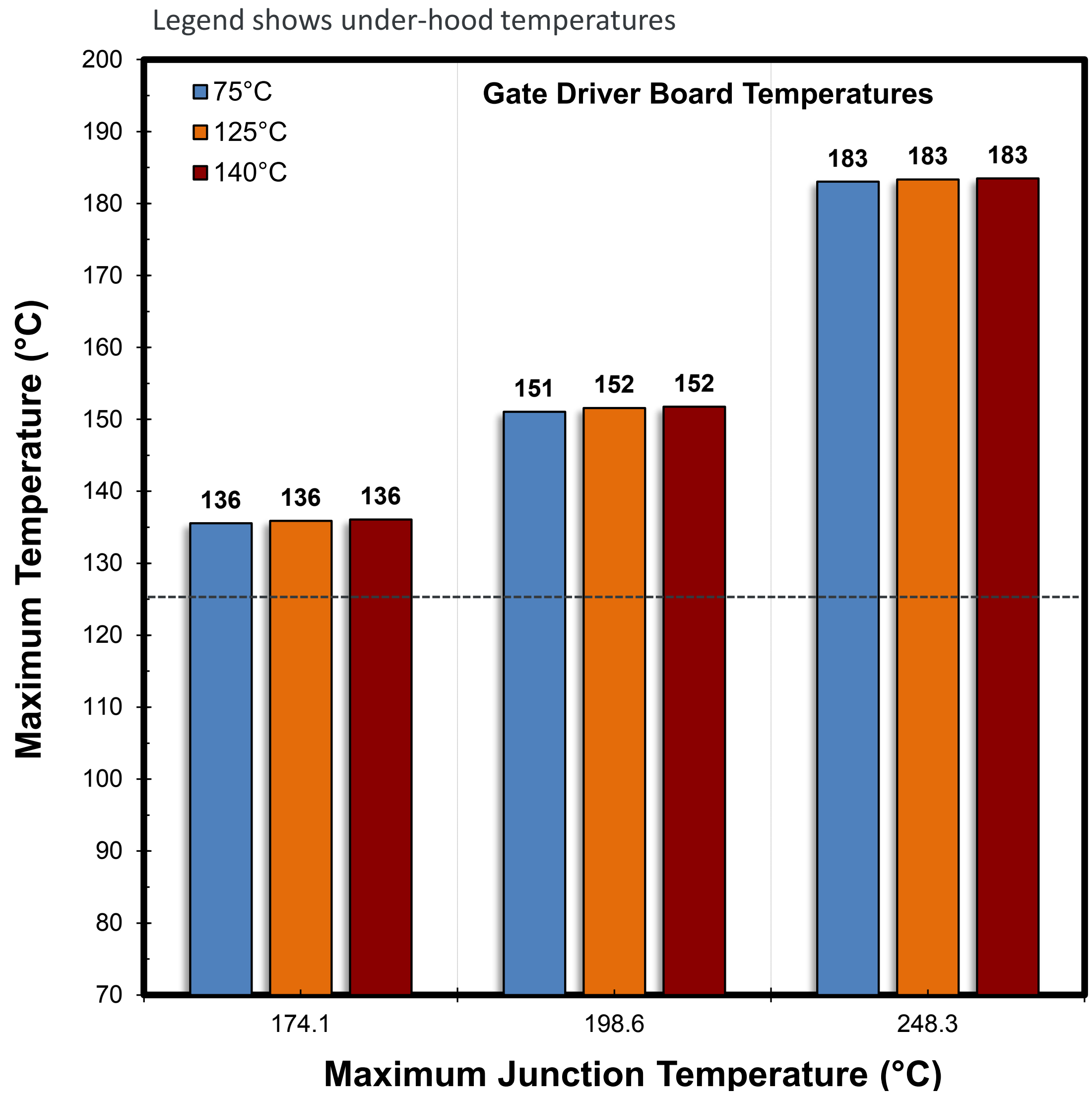
175°C junction temperature, 75°C under-hood temperature



- High capacitor temperatures not a result of capacitor self heating, but associated with heat conducted from the power modules via the bus bars
- Developing methods to cool the bus bars will be a focus of the project

Accomplishments: CFD-Estimated Gate Driver Temperatures

- Increasing the under-hood temperature has minimal effect on board temperatures
- For all cases, gate driver board exceeds 125°C (typical temperature limit for electrical boards)

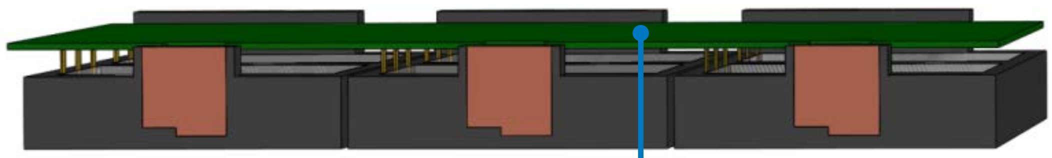


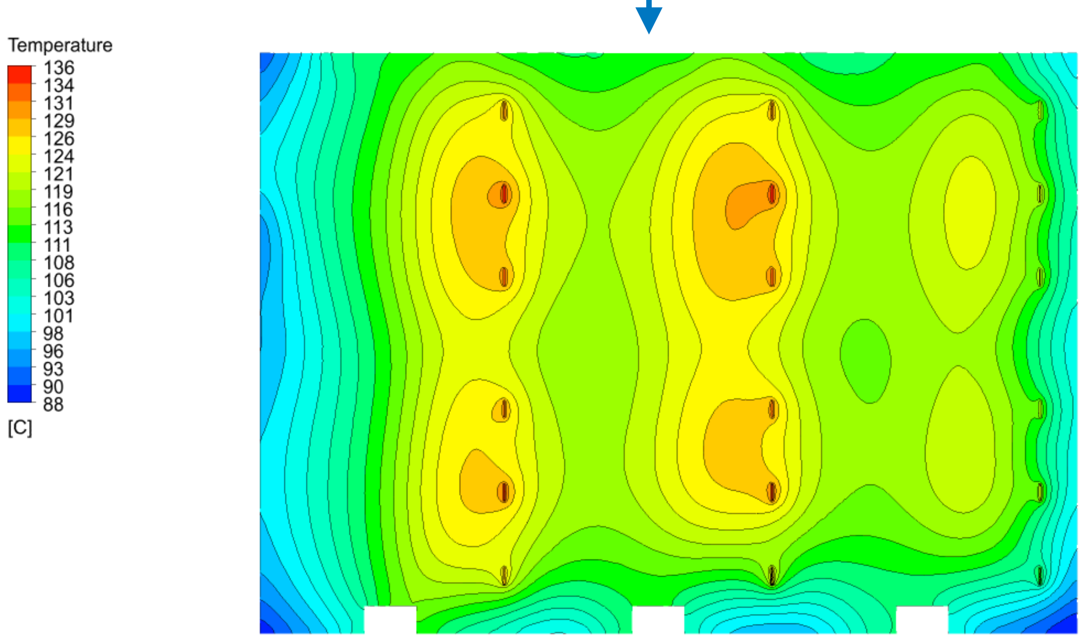
Accomplishments: CFD-Estimated Gate Driver Temperatures

175°C junction temperature, 75°C under-hood temperature

- Proximity of the gate driver board to the modules exposes them to high temperatures

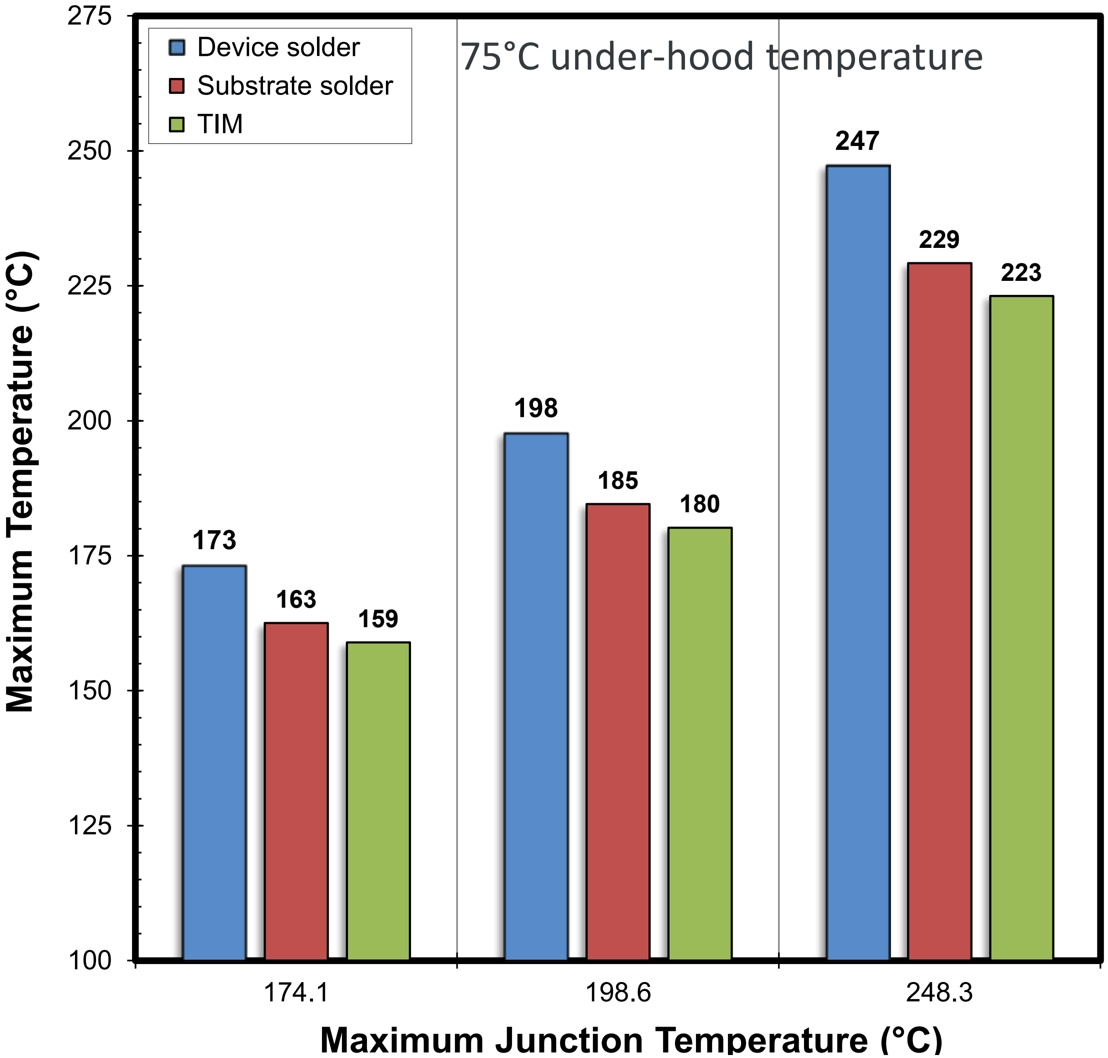
- Hottest location is where the electrical pins contact the board → heat is conducted from the devices to the board via the electrical pins





Accomplishments: CFD-Estimated Solder and TIM Temperatures

- Device solder essentially at the junction temperature
- High-temperature bonding materials are required for die and substrate attach layers
- High-temperature TIMs are required (~165°C – 200°C typical maximum operating temperature for TIMs)
- Power module temperatures not affected by under-hood temperatures



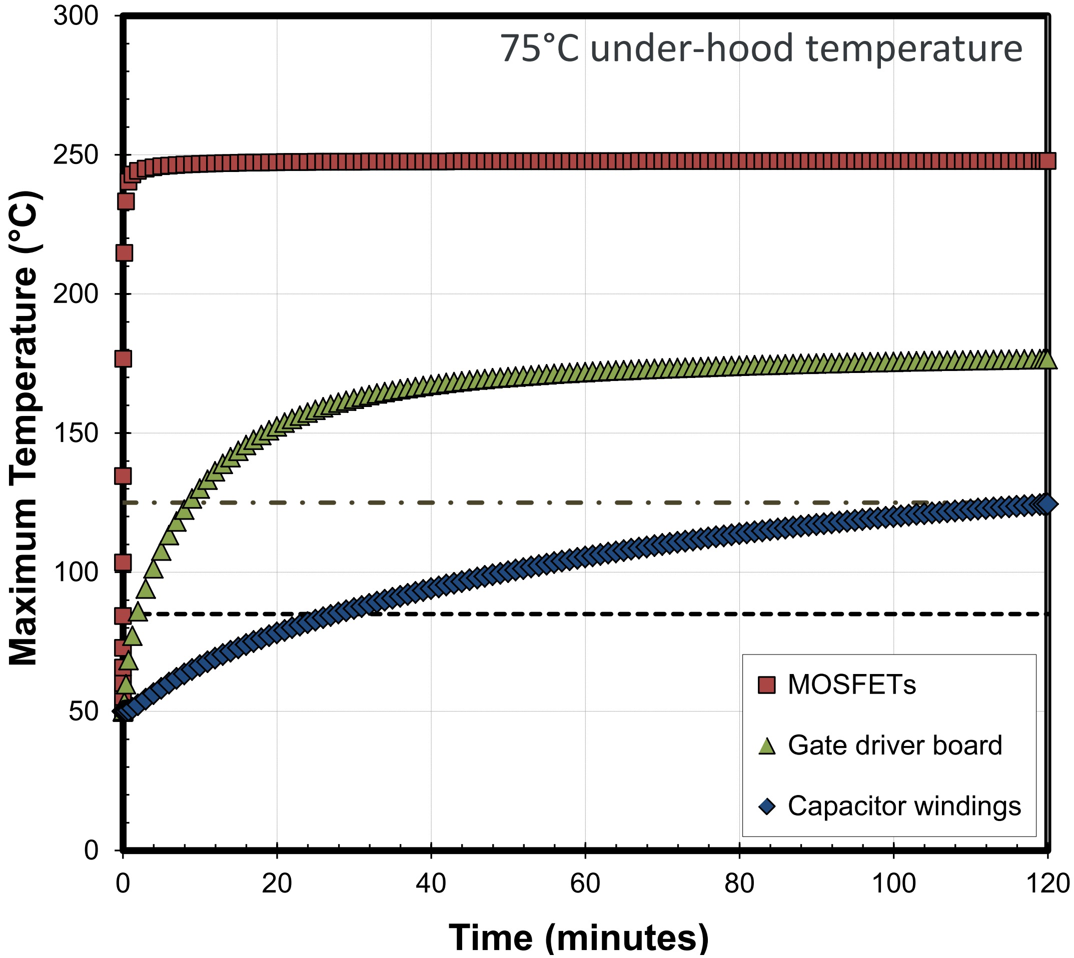
Accomplishments: Transient FEA

- MOSFETs achieve maximum temperature within a few seconds

- Capacitors take minutes to achieve maximum temperatures

- Opportunities to operate at full power for short periods of time without exceeding board or capacitor temperature limits

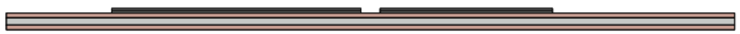
250°C Junction Condition



Accomplishments: Advanced Cooling Concepts

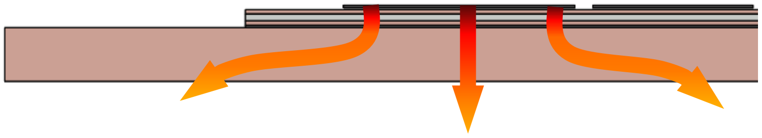
- Conducted analyses to compare the thermal performance of baseplate-cooled and DBC-cooled configurations

Baseplate Cooled

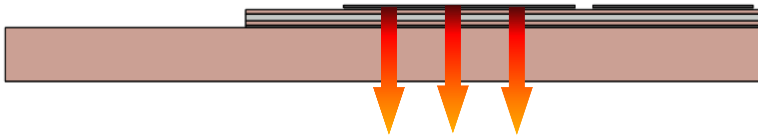


DBC Cooled

- Identified the convective cooling performance required to enable DBC-cooled configurations to outperform baseplate-cooled configurations

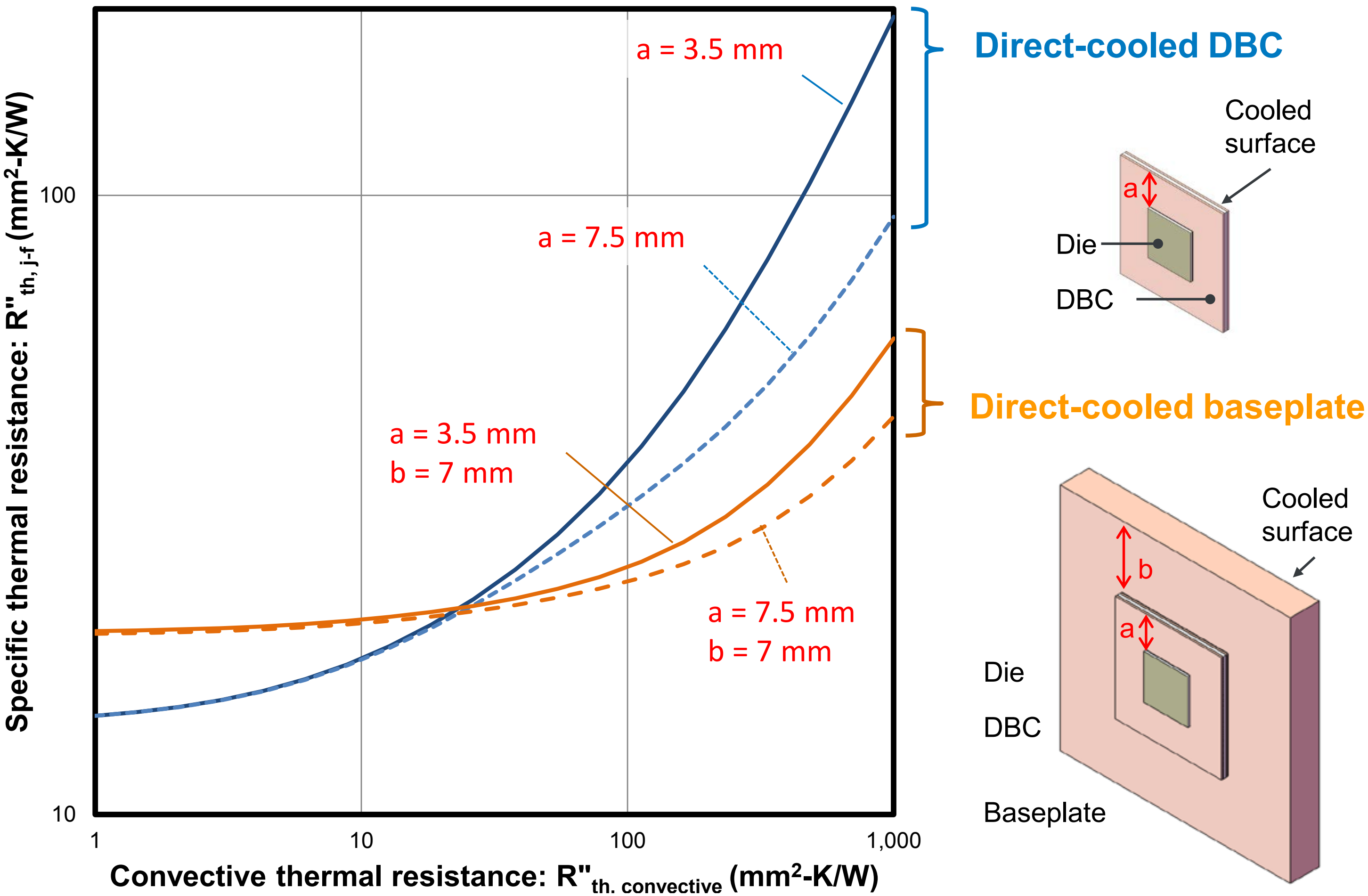


High Convective Resistance: Increased area from the baseplate is beneficial



Low Convective Resistance: Less heat spreading, removing layers (e.g., baseplate) is beneficial

Accomplishments: DBC versus Baseplate-Cooled FEA Results



Layers
SiC
Solder
Cu
SiN (substrate)
Cu
Solder
AlSiC (baseplate)

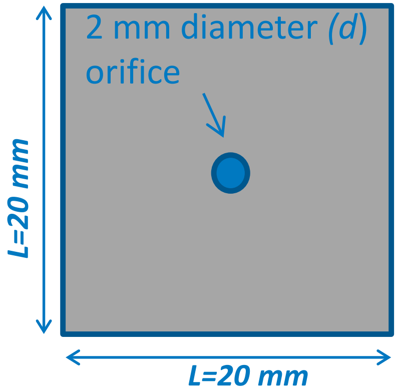
Die area: 5 mm × 5 mm

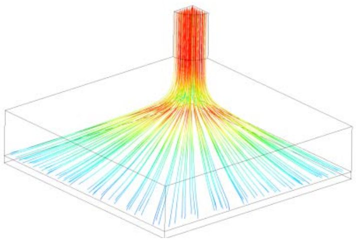
AlSiC: aluminum silicon-carbide
Cu: copper
SiN: silicon nitride

- Heat spreading is more effective at higher convective resistance values
- Direct cooling of the DBC is superior when convective resistance is less than ~20 mm^2-K/W (heat transfer coefficient of >~50,000 W/m^2-K)

Accomplishments: WEG Jet Impingement CFD Results

Round orifice jet





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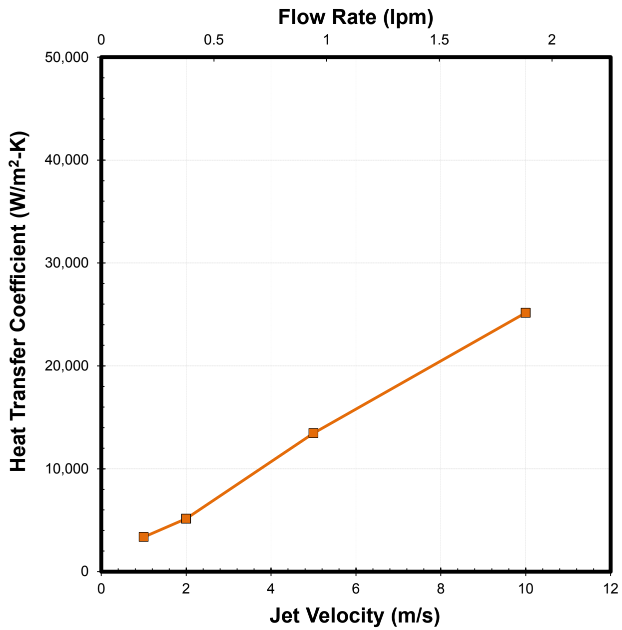
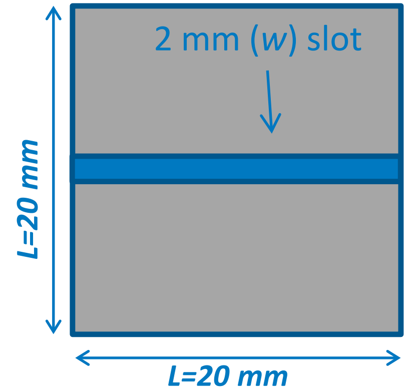
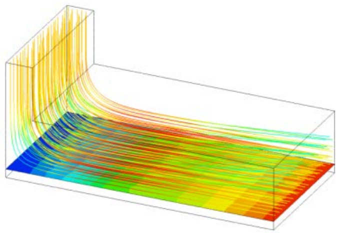


Slot jet





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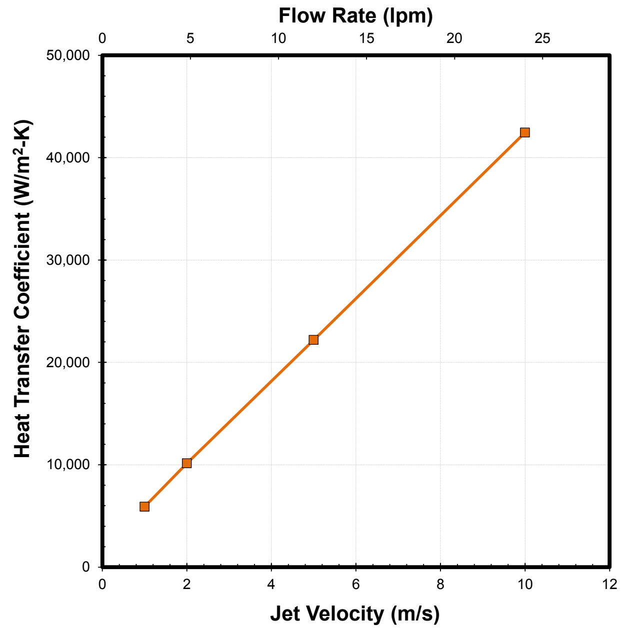

- WEG submerged jet impingement cases evaluated cannot achieve the 50,000 W/m^2-K target
- Continue to evaluate other cooling options

Response to Previous Year Reviewers' Comments

- **Reviewer Comment:** "This reviewer found a nice simple introduction of the heat transfer challenges and the relevance of the project, but thought it would be nice to **include the management of heat flows through other components of the complete system** (not just the inverter module) **and heat generation in other components**. Complex and quite geometry, materials, and design specific – should span a range of technology and design options."

  We agree with the reviewer and have included the majority of the inverter components in the thermal models including the capacitors, bus bars, electrical boards. We have also included heat dissipation for the power modules, capacitors, and bus bars.

- **Reviewer Comment: "**The reviewer expects that next year the team should be able to **demonstrate how they actually worked together rather than just talking about getting CRADAs** and non-disclosure agreements (NDAs) in place."

  We have established a CRADA project with John Deere and are working with them to develop a power-dense, two-phase-cooled inverter.

Collaboration and Coordination with Other Institutions

- **John Deere (industry):** CRADA project to develop a power-dense, two-phase-cooled inverter
- **Kyocera (industry):** Evaluating substrate cooling configurations
- **ORNL (national laboratory):** Interactions related to ORNL's benchmarking work
- **Interactions with other industry contacts**

Remaining Challenges and Barriers

- Every inverter is unique, which makes it difficult to develop cooling strategies that are applicable to all inverters
- We are working to develop thermal management concepts that are applicable to a wide range of inverter designs

Proposed Future Work

FY 2016

- Evaluate different power module designs to see effect on component temperatures
- Develop methods to prevent heat from spreading to the capacitors and electrical boards

FY 2017

- Evaluate motor-related heating effects
- Estimate the effect of degrading thermal properties on component temperatures
- Conduct experimental validation of key thermal concepts developed

Summary

Relevance

- Develop thermal management techniques to enable increased efficiency and power density via WBG power electronics

Approach/Strategy

- Model the effects of high-temperature WBG devices in an automotive inverter
- Compute inverter component (e.g., capacitors, boards, bonded interfaces) temperatures under elevated device temperatures
- Develop thermal strategies to enable WBG power electronics

Technical Accomplishments

- Created thermal models of an automotive inverter and used them to simulate WBG conditions
- Estimated the inverter components (e.g., capacitors, boards, bonded interfaces) temperatures at WBG device temperatures of 175°C, 200°C, and 250°C
- Identified the electrical interconnections as the primary paths that conduct heat from the devices to the other passive components
- Working with John Deere to use advanced cooling technologies and develop a power-dense inverter

Collaborations

- John Deere
- Kyocera
- ORNL

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