Power Electronics Thermal Management

Keystone Project 1

P.I.: Gilbert Moreno
National Renewable Energy Laboratory
June 11, 2019

DOE Vehicle Technologies Office
2019 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT211

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2021
- Percent complete: 15%

Barriers

- Size and weight
- Cost
- Performance and lifetime

Budget

- Total project funding
  - DOE share: $350K
- Funding for FY 2019: $350K

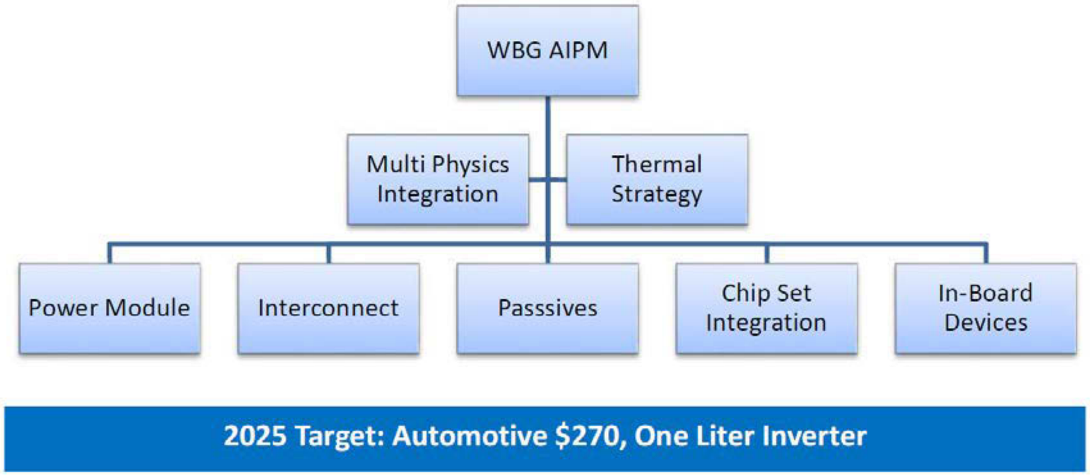
Partners

- John Deere
- Elementum3D
- Dielectric fluid manufacturers
- Oak Ridge National Laboratory (ORNL)
- Project Lead – National Renewable Energy Laboratory

Relevance

- Thermal management is essential to increase power density and reliability.

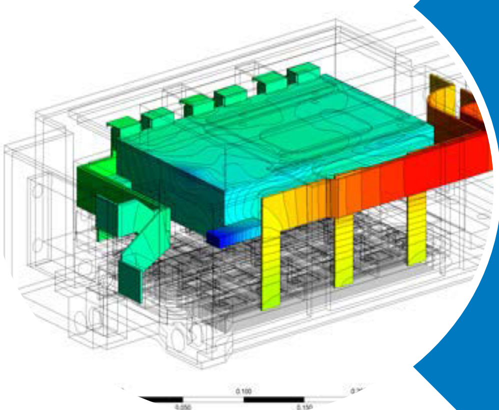
- **Objective:** Develop thermal management techniques to enable achieving the (year 2025) DOE 100 kW/L power density target.
  - Challenge is to create a thermal solution that allows for packaging high temperature (250°C) and high heat flux wide-bandgap (WBG) devices next to capacitors that typically cannot exceed 100°C.



From 2017 Electrical and Electronics Technical Team Roadmap

AIPM: advanced integrated power module

Resources



Modeling tools

- Finite element analysis (FEA)
- Computational fluid dynamics (CFD)

Photo Credit: Doug DeVoto (NREL)

Experimental equipment

- Dielectric fluid loop
- Water ethylene glycol loop
- T3ster (transient thermal tester)
- Xenon flash

Milestones / Approach

Date	Description of Milestone or Go/No-Go Decision
December 2018 (*complete*)	**Go/No-Go:** Develop thermal management design concept(s) and potential strategies to enable achieving 100 kW/L power density target. Do concepts enable achieving the power density target?
March 2019 (*complete*)	**Milestone:** Conduct experiments to characterize the thermal performance of the two-phase cooling system for the John Deere inverter (CRADA work).
June 2019 (*in-progress*)	**Milestone:** Conduct experiments to validate the thermal management strategy. Evaluate effects of fluid temperature (-40°C to 70°C) and flow rate.
September 2019 (*in-progress*)	**Milestone:** Create a report to summarize the research results. Submit manuscript(s) to journal for potential publication.

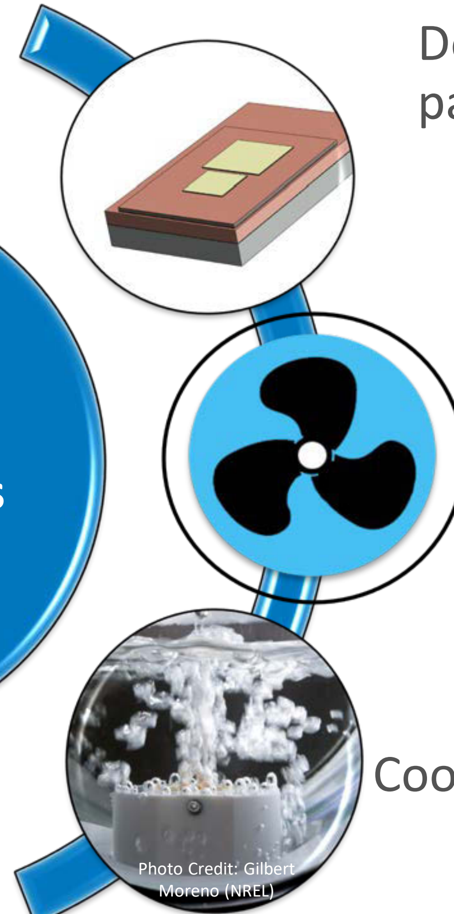
CRADA: cooperative research and development agreement

Approach

Thermal strategy to reach a power density of 100 kW/L

Define the thermal target to achieve 100 kW/L

Design the cooling strategies



Device packaging

Convective cooling

Cooling fluid

Heat load (100 kW inverter): 2,150 W
Maximum device temperature: 250°C
Module and cold plate volume: < 240 mL

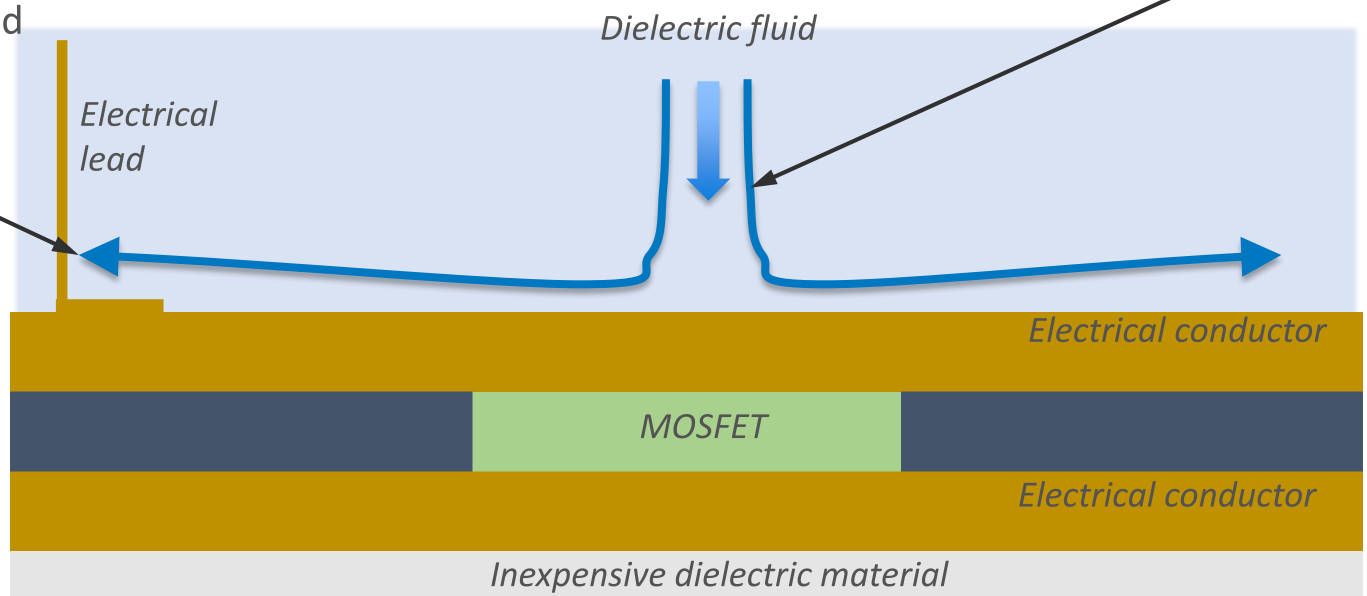
Volumetric thermal resistance target: 21 cm^3-K/W

Dielectric cooling (single-phase heat transfer) planar package concept

Dielectric Cooling Concept

Cooling of the bus bars/electrical interconnects to lower capacitor and gate driver temperatures

Improved cooling (single-phase) via jet impingement and finned surfaces



Eliminates expensive ceramic materials

Improved performance over conventional direct-bond-copper (DBC) based designs

MOSFET: metal–oxide–semiconductor field-effect transistor

Dielectric Fluid Selection

- Selected synthetic hydrocarbons that are used in electronics cooling (single-phase) applications:
  – Alpha 6: DSI Ventures
  – AmpCool (AC)-100: Engineered Fluids
- Potential to use automatic transmission fluid (ATF) to decrease cost, use fluid already qualified for automotive use, enable motor–inverter integration.
- Challenge is to create a cooling system with high thermal performance using fluids with relatively inferior heat transfer properties as compared to water-ethylene glycol (WEG).

Fluid *(properties at 70°C)*	Thermal conductivity [W/m-K]	Specific heat [J/kg-K]	Density [kg/m³]	Viscosity [Pa-s]	Flash point [°C]	Pour point [°C]
Alpha 6 [1]	0.14	2,308	792	0.0091	246	-57
AC-100 [1]	0.13	2,326	761	0.0025	180	-55
ATF [2]	0.16	2,131	836	0.012	199	-45
WEG (50/50) [3]	*0.42*	*3,513*	*1,034*	*0.0013*	*> 121* [4]	*-36* [5] *(freeze point)*

[1] Communications with vendor (DSI Ventures or Engineered Fluids)
[2] Kemp, Steven P., and James L. Linden. 1990. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." SAE Technical paper.
[3] Alshamani, Kaisar. 2003. "Equations for Physical Properties of Automotive Coolants." SAE Technical Paper.
[4] "Safety Data Sheet ZEREX HD Nitrile Free Extended Life 50/50 Antifreeze Coolant." Valvoline. Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.
[5] "Product Information: Valvoline ZEREX G05 Antifreeze Coolant." 2018. US_Val_ZXG05_AFC_HD_EN.Pdf. 2018. https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

Cooling System Design: Modeling Results

Technical Accomplishments

Optimized dimensions

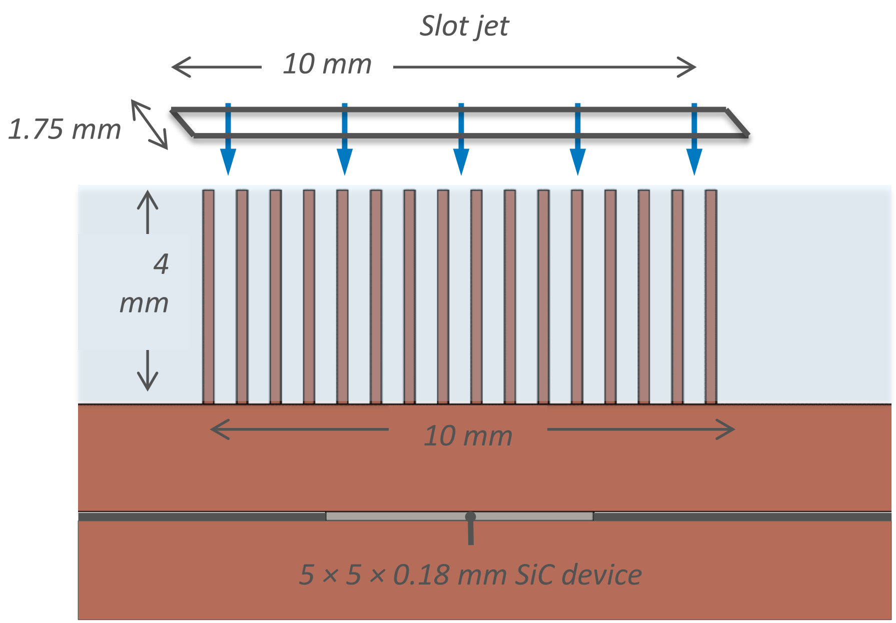
- Slot jet (1.75 × 10 mm) impinging on fins (0.2 × 4 × 10 mm)

Achieved high thermal performance

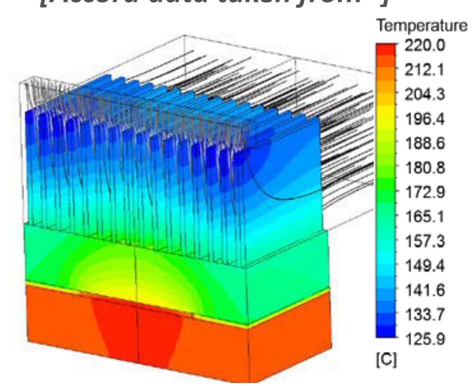
- Heat transfer coefficient 17,300 W/m^2-K at a relatively low jet velocity of 0.3 m/s
- Higher performance possible

Decreased size

- Predict we can dissipate 2.2 kW with 12 devices. Results in a heat flux ~718 W/cm^2 at $T_j \approx 220$°C
- **50% lower thermal resistance compared to 2014 Accord Hybrid** ***[Accord data taken from [1]]***



Planar module, dielectric cooling concept



Module temperature contours

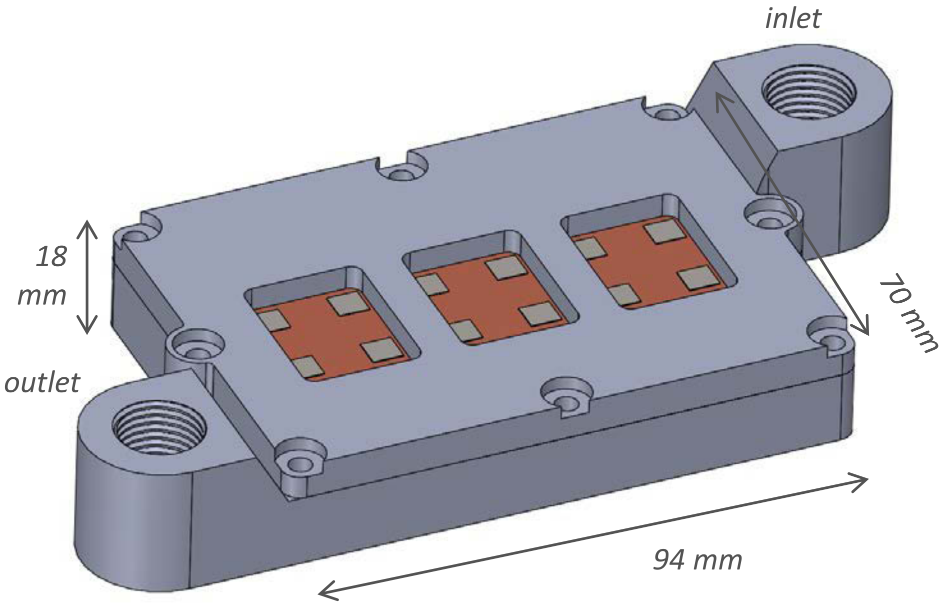
Results using Alpha 6 fluid at T_{inlet} = 65°C

[1] Moreno, Gilberto, et al. "Evaluation of performance and opportunities for improvements in automotive power electronics systems." *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*. IEEE, 2016.

Cooling System Design: Modeling Results

Designed fluid manifold to distribute flow to 12 devices.

- Reduced size: 120 mL total cold plate and power module volume
- Total flow rate 4.1 Lpm at 0.33 psi pressure drop
- Reduced pumping power: 80% lower parasitic power compared to 2014 Honda Accord Hybrid



CAD model of the cold plate with finned heat spreaders

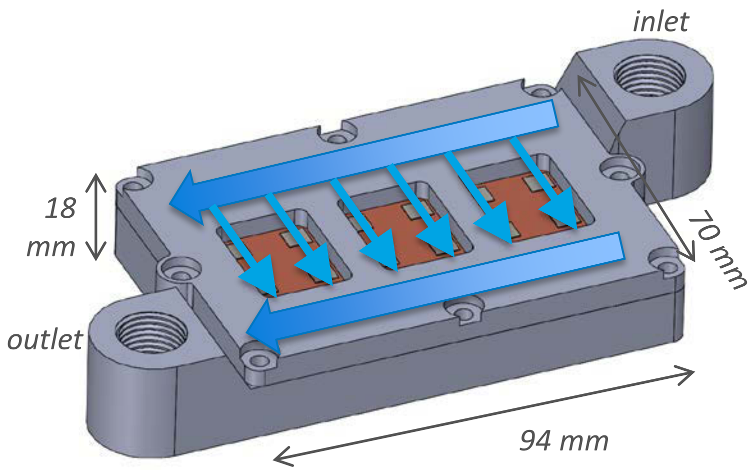
Results using Alpha 6 fluid at T_{inlet} = 65°C

CAD: computer-aided design

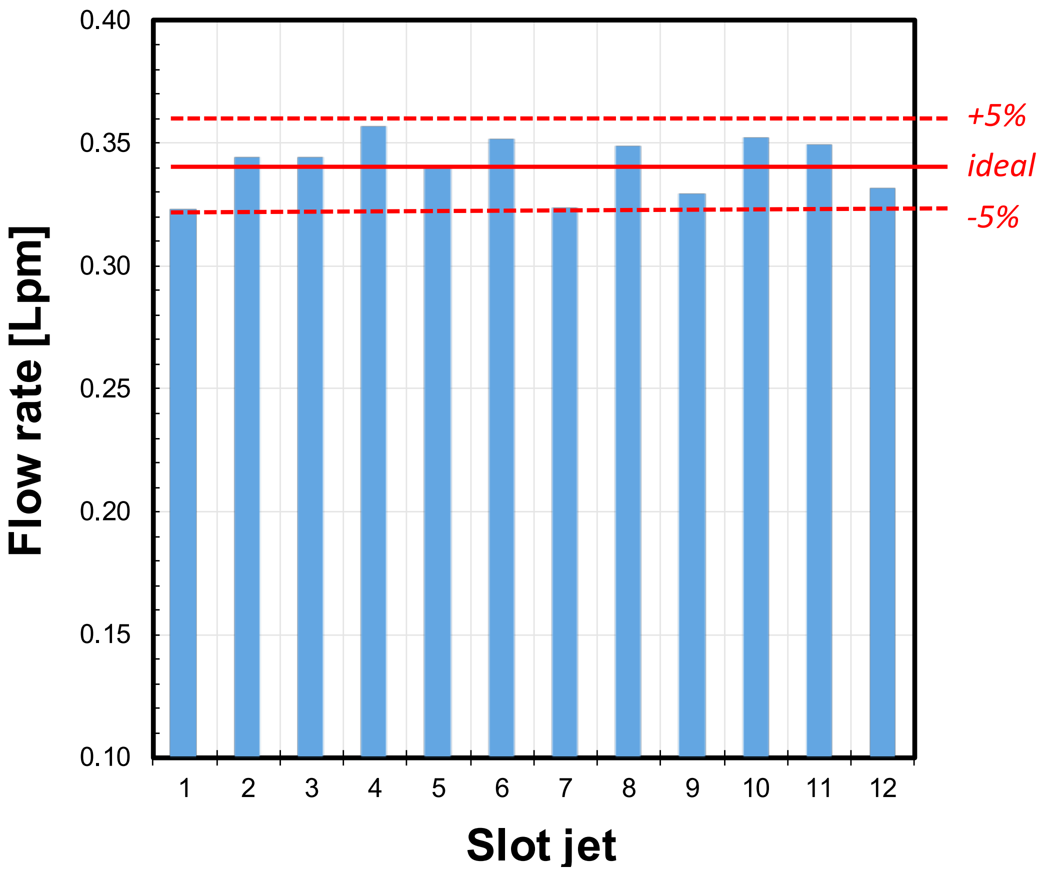
Cooling System Design: Modeling Results

Designed fluid manifold to distribute flow to 12 devices

- Predict +/- 5% flow variation



Manifold flow distribution

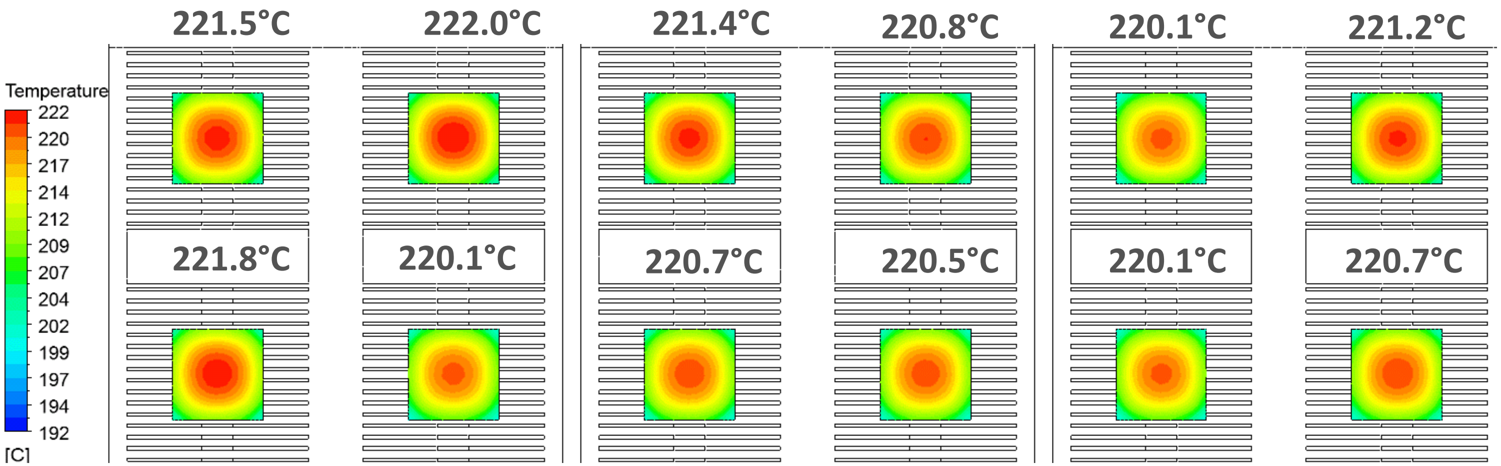


Flow distribution through 12 slot jets

Results using Alpha 6 fluid at T_{inlet} = 65°C

Cooling System Design: Modeling Results

Inverter-scale conjugate heat transfer CFD: 2.2 kW total heat (718 W/cm^2), 4.1 Lpm total flow rate



Device temperature contours from CFD. Results using Alpha 6 fluid at T_{inlet} = 65°C

Fluid	$T_{maximum}$ [°C]	Pressure drop [Pa]	Pumping power [W]	Volumetric thermal resistance [cm^3-K/W]
Alpha 6	222	2,214	0.16	8.7

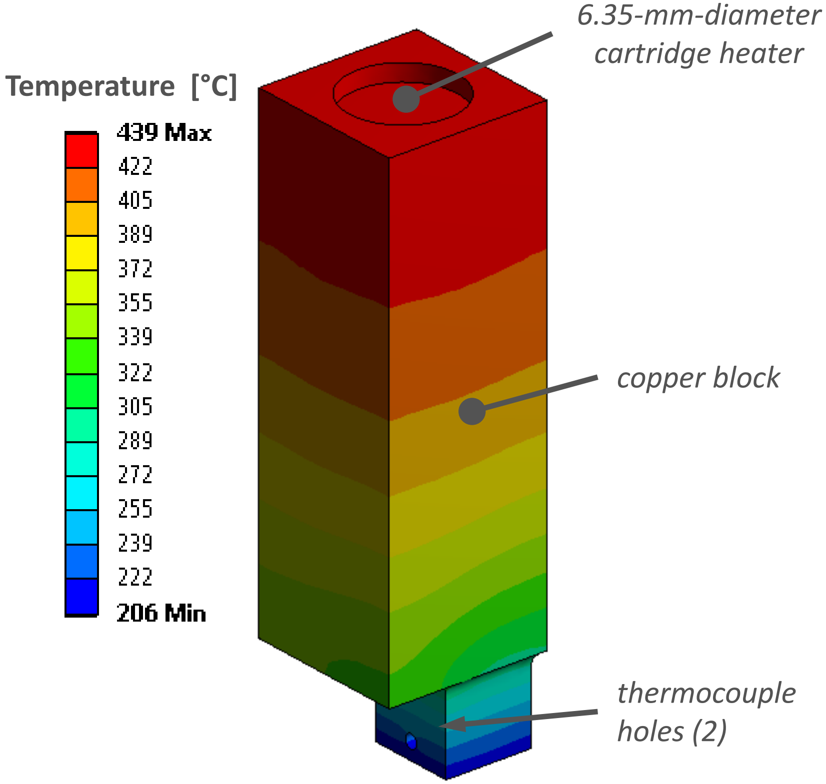
- Performed better than the volumetric thermal resistance target of 21 cm^3-K/W
- Fluid outlet temperature is 82°C

Experimental Validation

Technical Accomplishments

Designed the heaters

✓ To simulate devices and dissipate >700 W/cm^2



Cartridge heater design-temperature contours for the 718 W/cm^2 heat flux condition

Completed cold plate fabrication

✓ 3D printed using inexpensive, lightweight plastic to test prototype

✓ Cold plate can be fabricated using conventional manufacturing methods

Nylon cold plate manifold prototype

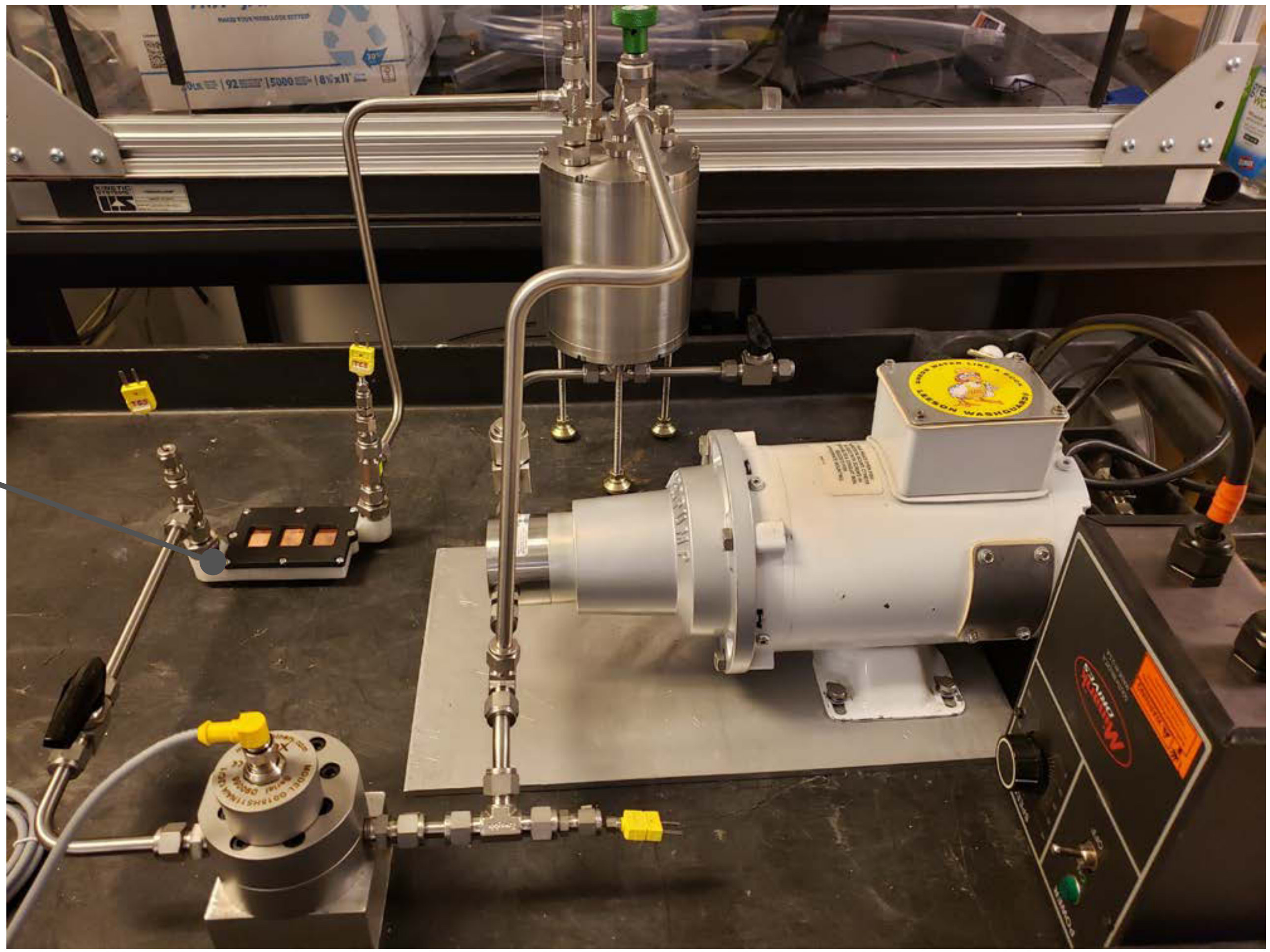
Cold plate size compared to cell phone

Experimental Validation

Fabricated new flow loop

✓ To characterize the thermal performance using different dielectric fluids at various fluid temperatures (-40°–70°C) and flow rates

3D printed cold plate

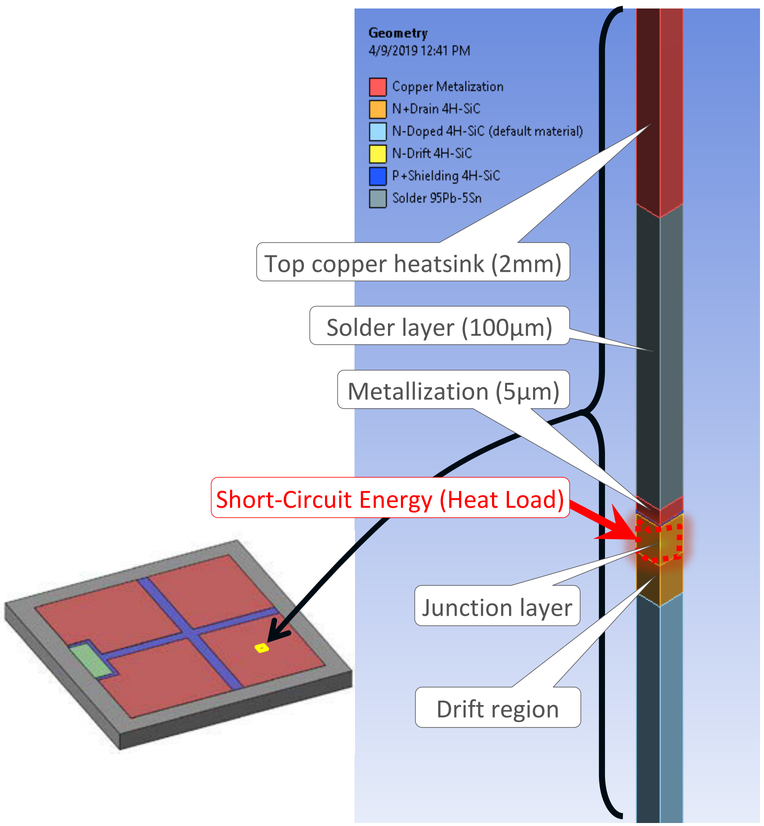


Flow loop to test cold plate thermal performance

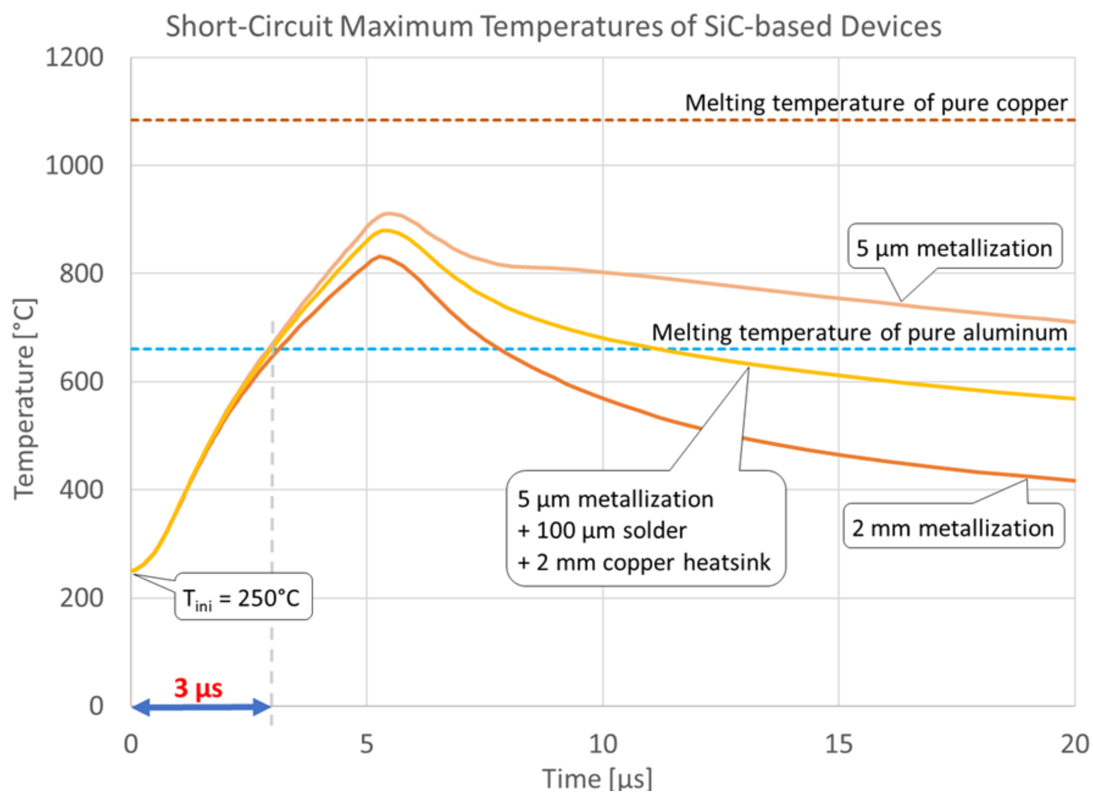
Technical Accomplishments

Short-Circuit Behavior of SiC Power Devices

- Modeled the short-circuit behavior of the cooling concept
- Used temperature-dependent thermal properties for SiC and Cu metallization and applied volumetric heat load to junction layer (from März et al.[1])



FEA model

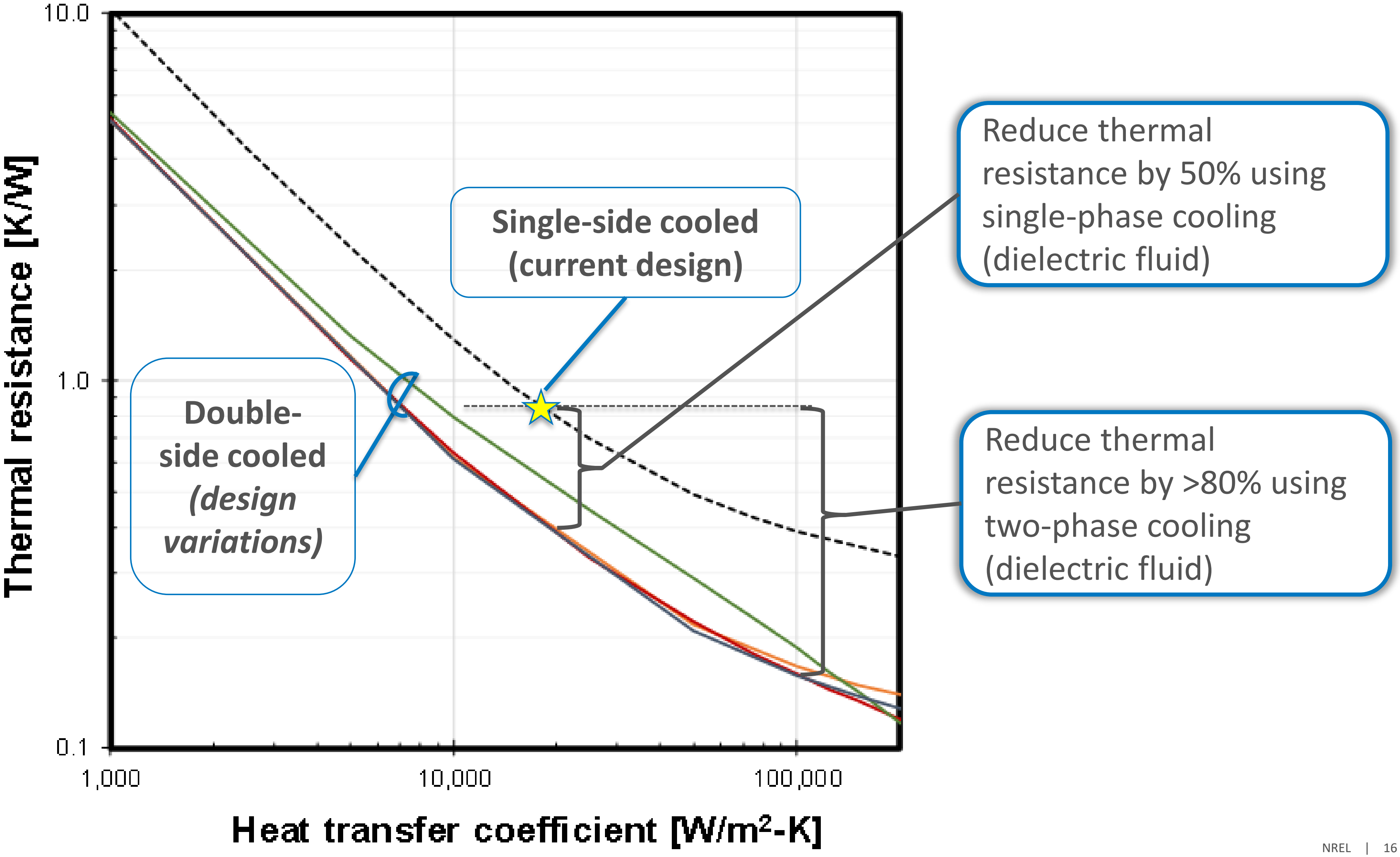


FEA transient results

[1] A. März, T. Bertelshofer, R. Horff, M. Helsper, M.M. Bakran, Explaining the short-circuit capability of SiC MOSFETs by using a simple thermal transmission-line model, in: 2016 18th Eur. Conf. Power Electron. Appl. EPE16 ECCE Eur., 2016: pp. 1–10.

Advanced Packaging/Cooling Concepts

Double-side cooled modules cooled using dielectric fluids



Responses to Previous Year Reviewers' Comments

- This is a new project with no reviewer comments.

Collaboration and Coordination

- John Deere (industry): Two-phase cooling for high-packaging-density planar inverter (CRADA)
- Elementum3D (industry): Provide 3D-printed metal parts to evaluate new heat exchanger concepts
- Dielectric fluid manufacturers
- ORNL

Remaining Challenges and Barriers

- **Creating a reliable, leak-free cooling system:** main challenge is sealing the electrical leads that penetrate through the power module.
- **Fluid compatibility with power electronics materials:** selected fluids should be compatible with electronics materials but experiments should be conducted to verify compatibility.
- **Pumping power requirements** at low temperatures due to higher fluid viscosity.
- **Industry adoption** of new (non-conventional) technology.

Proposed Future Research

FY 2019

- Complete the experiments using Alpha 6, AC-100, and ATF and evaluate the effects of varying the flow rate and fluid temperature.
- Complete the experiments to measure the thermal performance of the John Deere two-phase cooling system (CRADA).

FY 2020 and beyond

- Evaluate and develop new packaging/cooling concepts to further increase power density.
- Work with consortium partners to build an inverter that utilizes the advanced cooling concepts.

Any proposed future work is subject to change based on funding levels

Summary

Relevance

- Effective thermal management is essential to achieve the year 2025 DOE power density (100 kW/L) and cost ($2.7/kW) targets.

Approach/Strategy

- Define a thermal target required to achieve the 100 kW/L power density.
- Evaluate and select the cooling strategies that enable high packaging density.

Technical Accomplishments

- Completed the design of an inverter-scale, dielectric fluid cooling concept that exceeds the volumetric thermal targets and thus enables achieving the 100 kW/L power density target.
- Fabricated a heat exchanger prototype to conduct experiments and measured its thermal performance.
- Fabricated a new flow loop to allow us to characterize the thermal performance of the heat exchanger using various dielectric fluids and evaluate the effects of fluid temperature (-40°–105°C) and flow rate.
- Collaborated with John Deere to develop a two-phase cooling strategy for their inverter.

Collaborations

- John Deere
- Elementum3D
- Dielectric coolant manufacturers
- ORNL

Acknowledgments

Susan Rogers, U.S. Department of Energy

NREL EDT Task Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: 303-275-4062

Team Members

Kevin Bennion (NREL)
Emily Cousineau (NREL)
Xuhui Feng (NREL)
Bidzina Kekelia (NREL)
Ramachandra Kotecha (NREL)

EDT: Electric Drive Technologies

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

For more information, contact

Principal Investigator
Gilbert Moreno
Gilbert.Moreno@nrel.gov
Phone: 303-275-4450

Thank You

www.nrel.gov

NREL/PR-5400-73547

NREL
Transforming ENERGY