Power Electronics Thermal Management

Keystone Project 1

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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

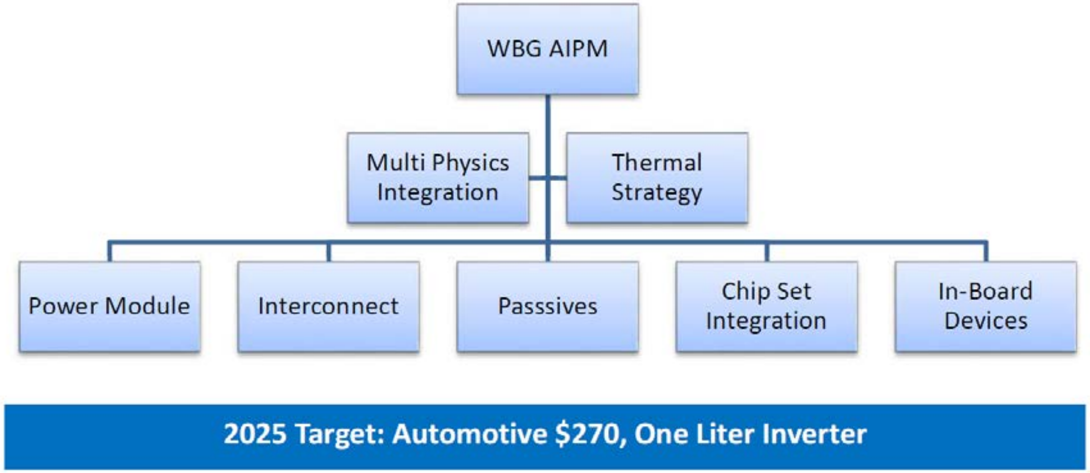
Partners

- 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.

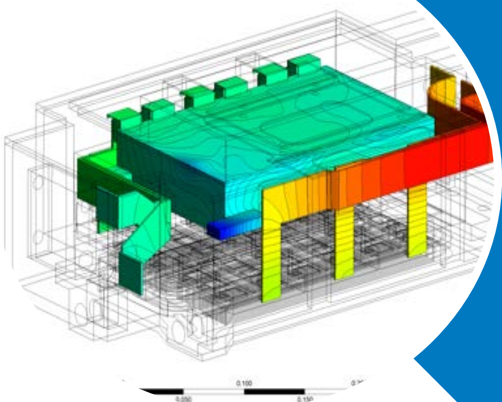
- **Objective:** Develop thermal management techniques to enable achieving the (year 2025) DOE 100 kW/L power density target.
  - Challenge is to create a thermal solution that allows for packaging high temperature (250°C) and high heat flux wide-bandgap (WBG) devices next to capacitors that typically 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)

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.

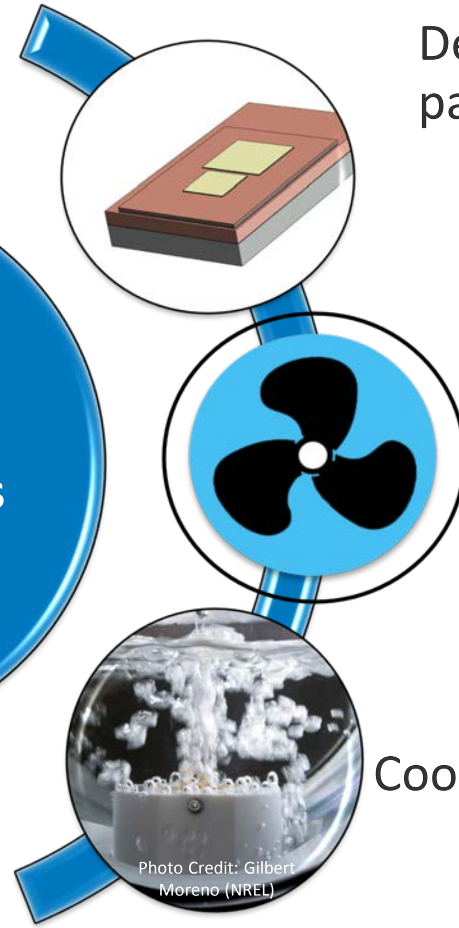
CRADA: cooperative research and development agreement

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



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

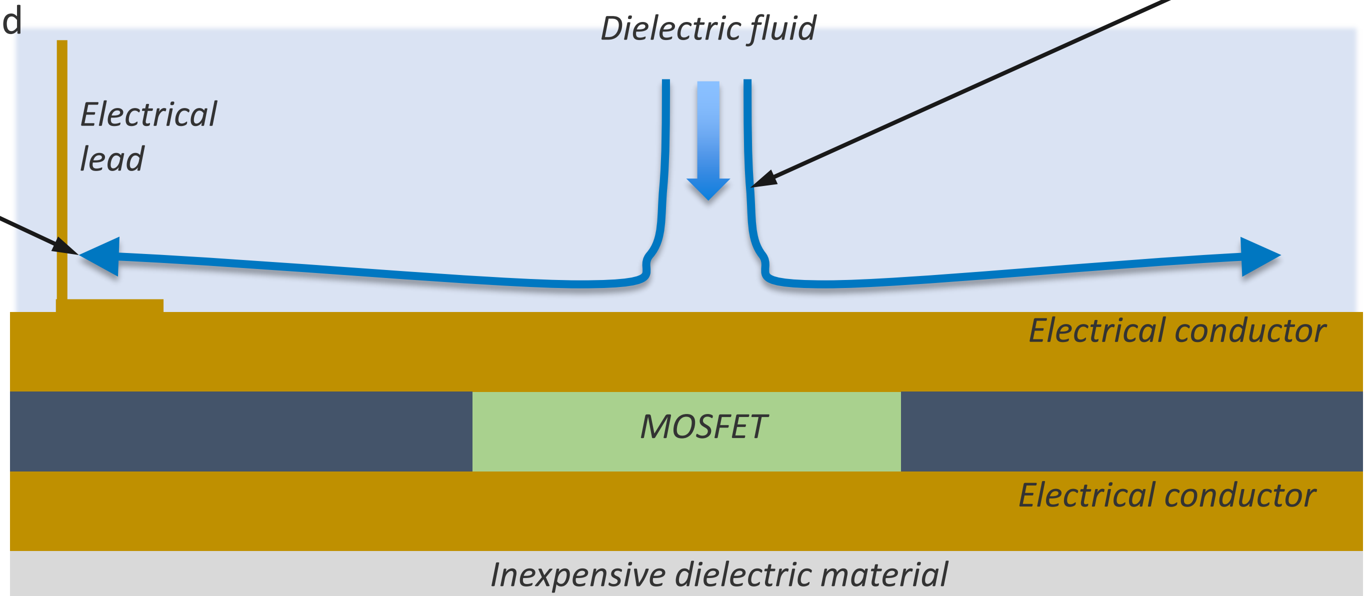
Volumetric thermal resistance target: 21 cm^3-K/W

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)

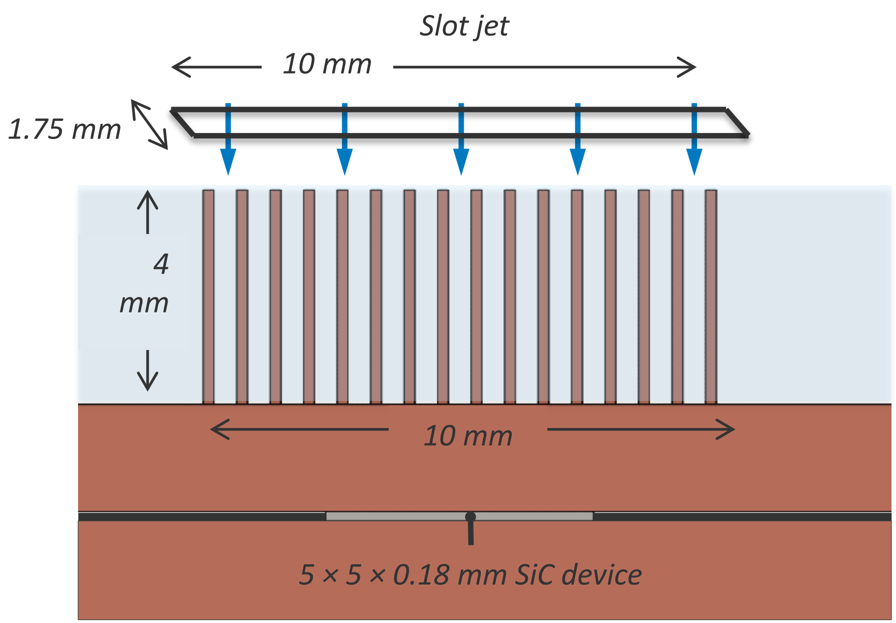
Achieved high thermal performance

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

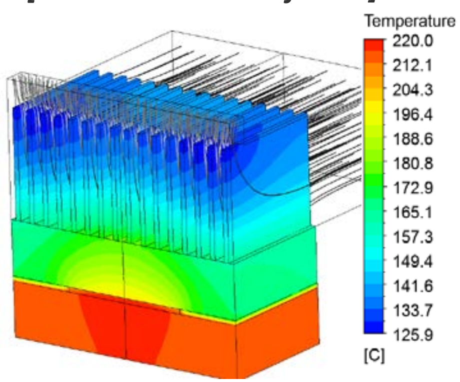
Decreased size

- 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

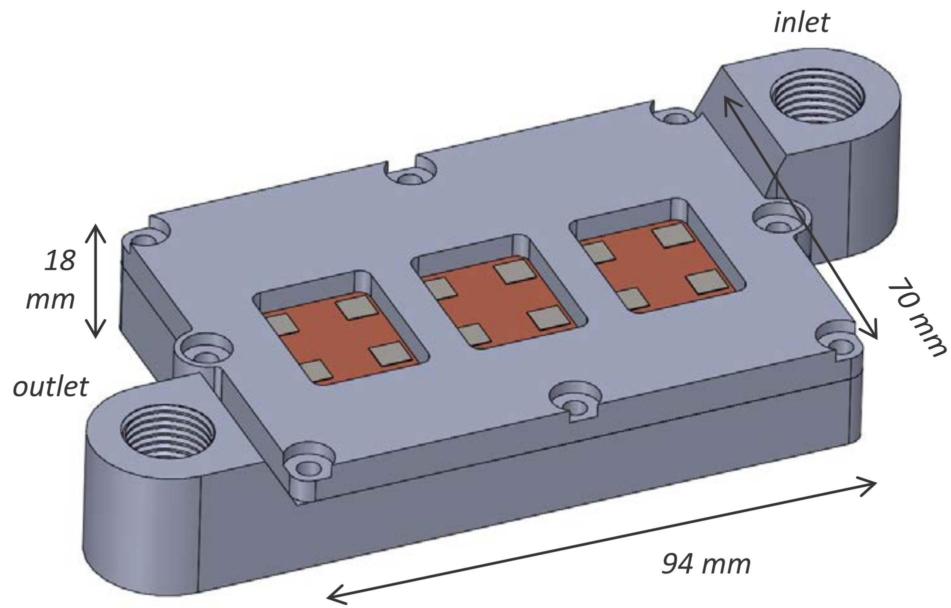
Results using Alpha 6 fluid at T_{inlet} = 65°C

[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

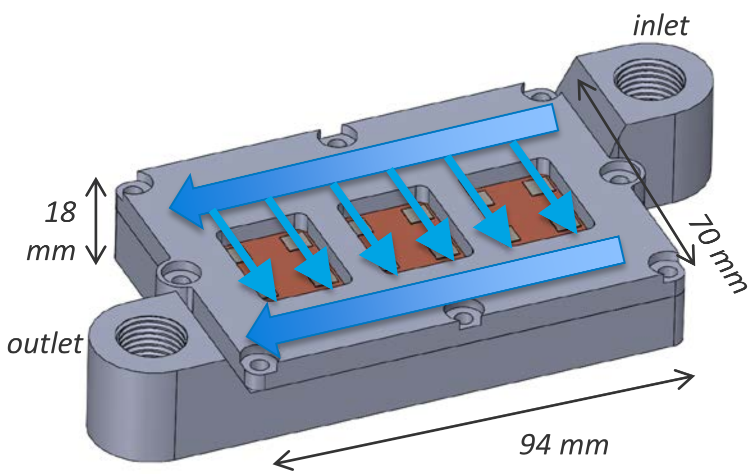
Results using Alpha 6 fluid at T_{inlet} = 65°C

CAD: computer-aided design

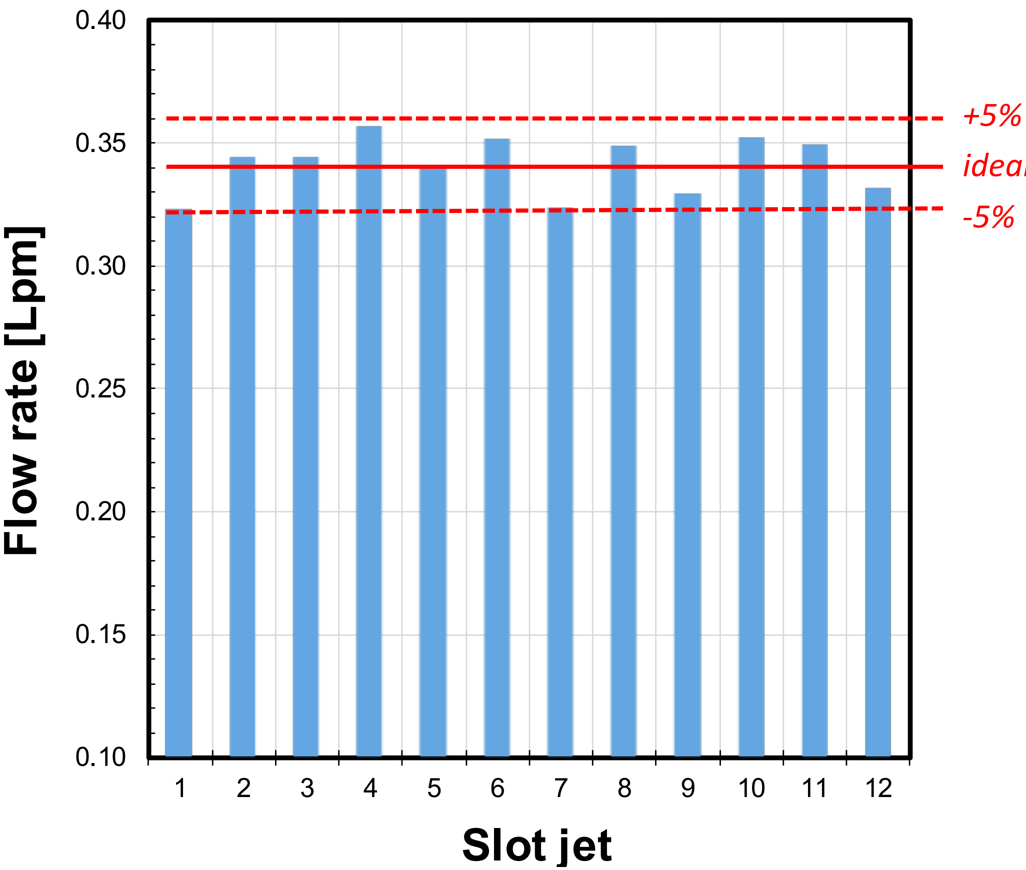
Cooling System Design: Modeling Results

Designed fluid manifold to distribute flow to 12 devices

- Predict +/- 5% flow variation



Manifold flow distribution

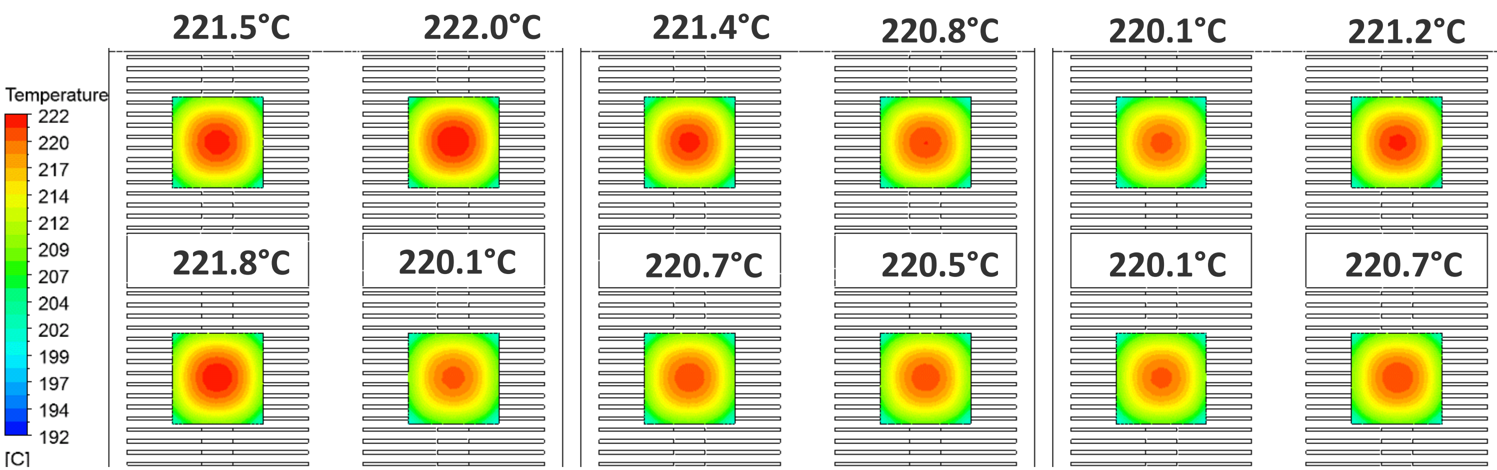


Flow distribution through 12 slot jets

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/cm²), 4.1 Lpm total flow rate



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

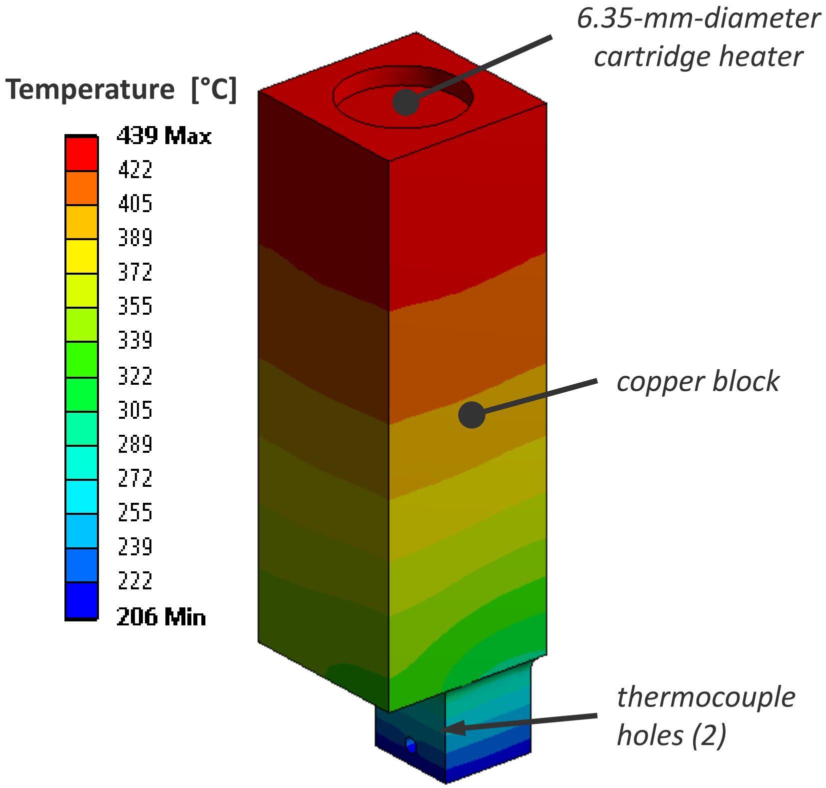
Fluid	$T_{maximum}$ [°C]	Pressure drop [Pa]	Pumping power [W]	Volumetric thermal resistance [cm³-K/W]
Alpha 6	222	2,214	0.16	8.7

- Performed better than the volumetric thermal resistance target of 21 cm³-K/W
- Fluid outlet temperature is 82°C

Experimental Validation

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

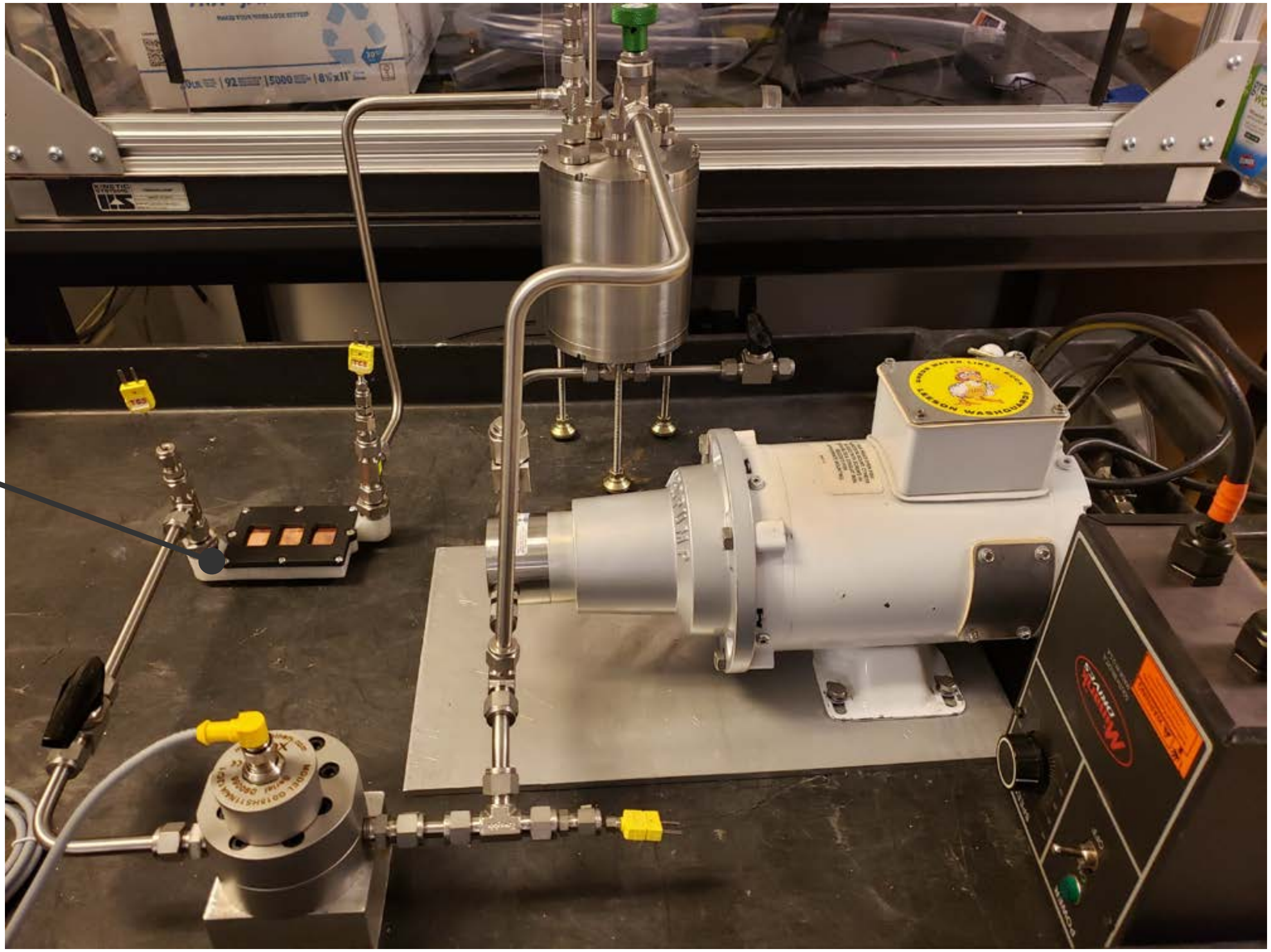
Cold plate size compared to cell phone

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

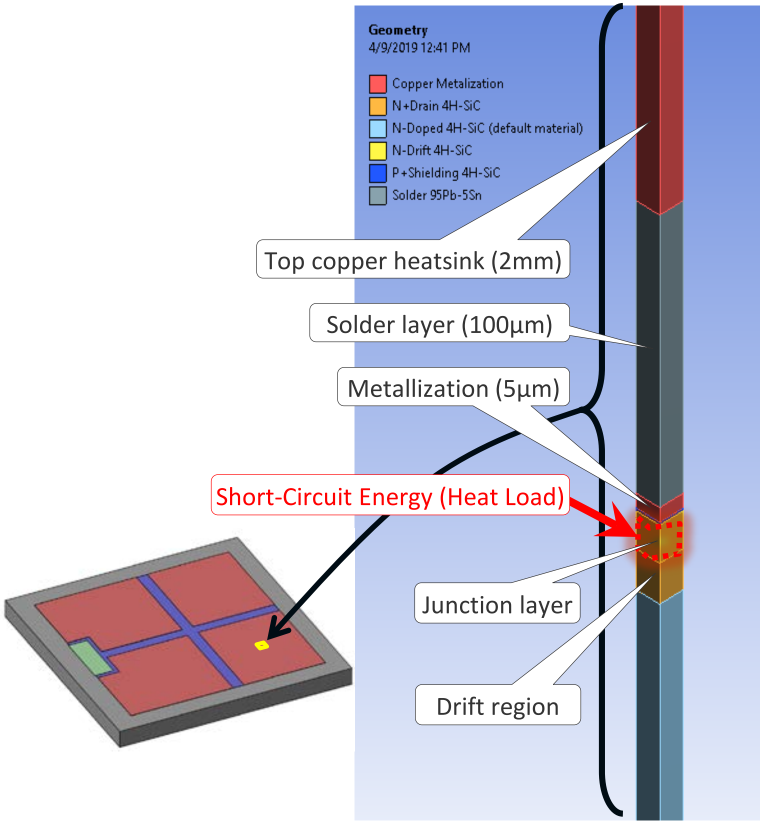


Flow loop to test cold plate thermal performance

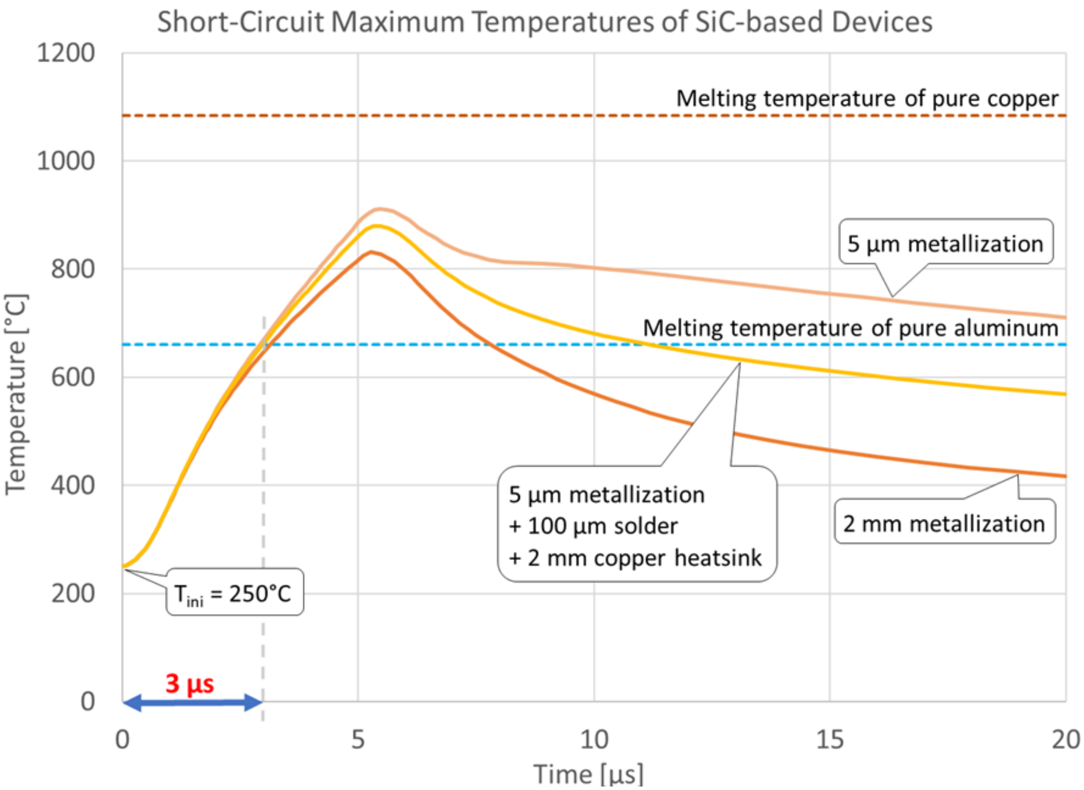
Short-Circuit Behavior of SiC Power Devices

Technical Accomplishments

- 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

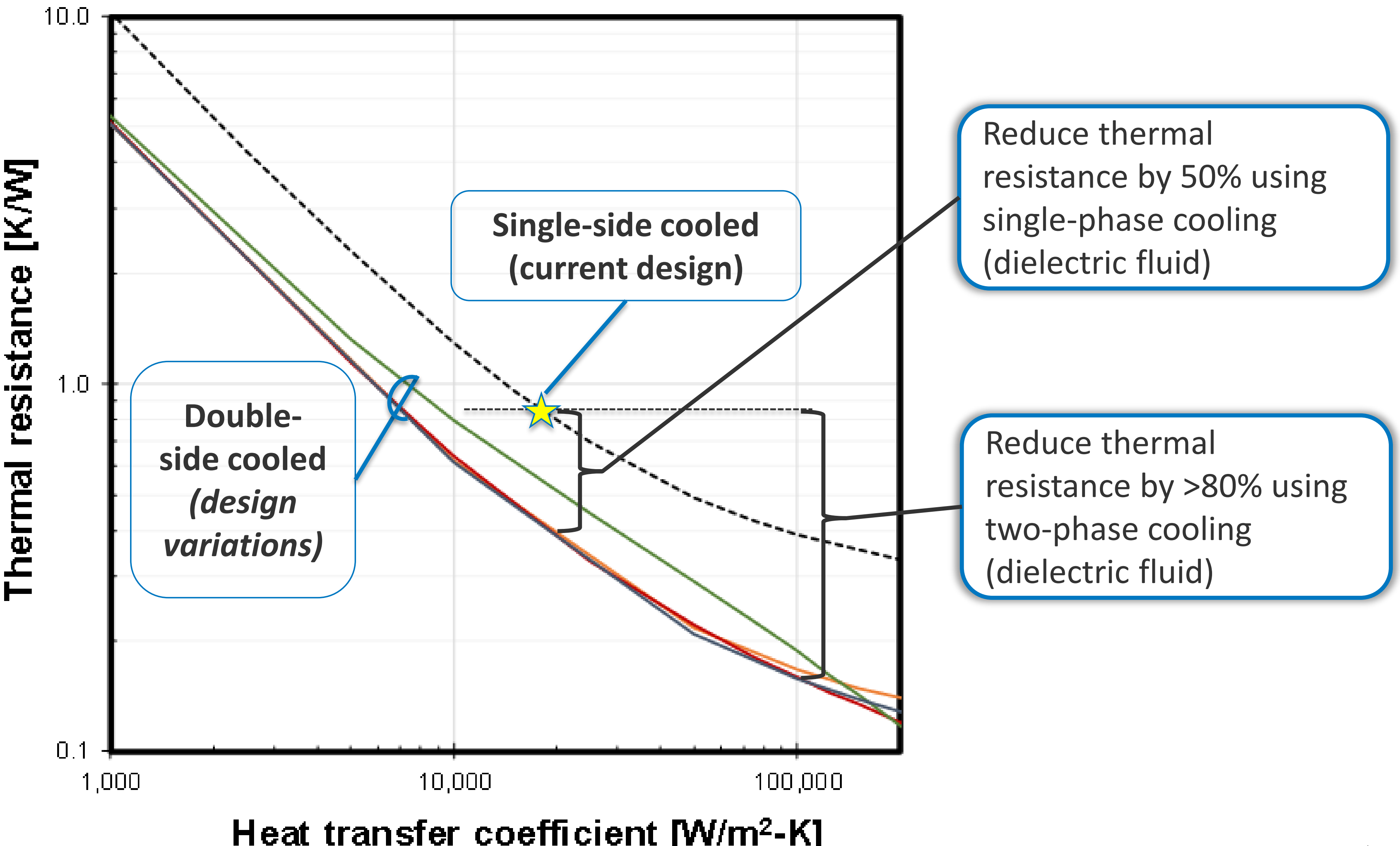


FEA transient results

[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

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Thank You

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