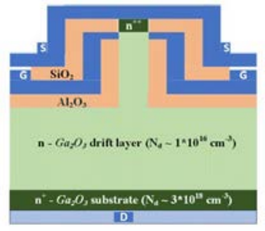
Automotive Power Electronics Cooling Technology Research at NREL

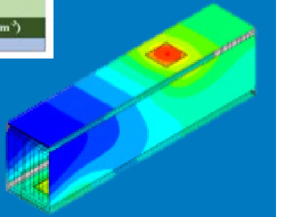
2022 Electronics Packaging Symposium
Sept 7-8, 2022

Gilbert Moreno

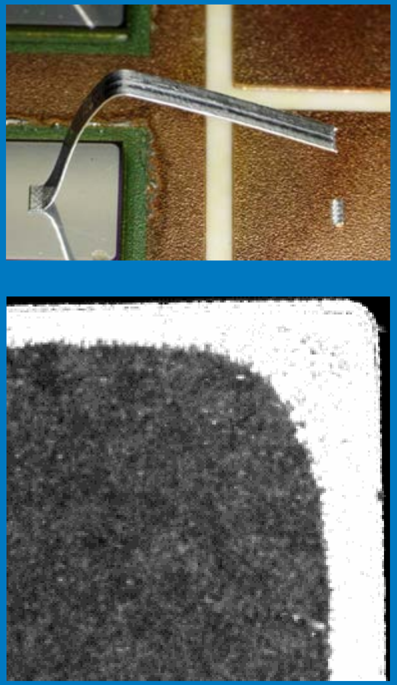
NREL APEEM Group Research Focus Areas

Power Electronics Thermal and Electro-Thermal

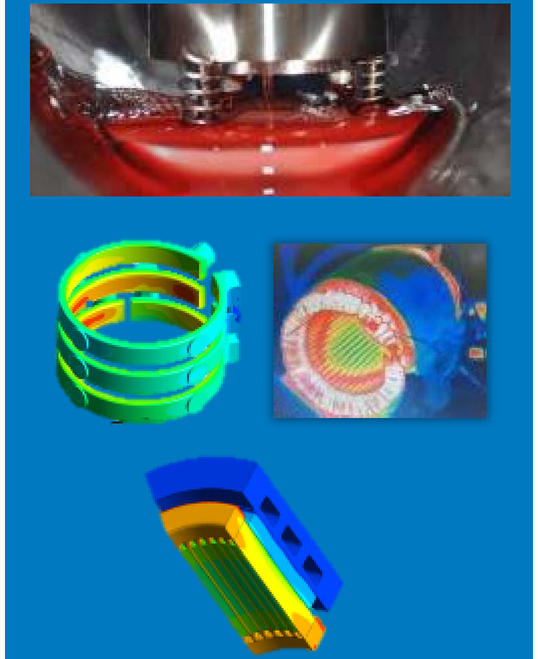




Advanced Packaging Designs and Reliability



Electric Motor Thermal Management

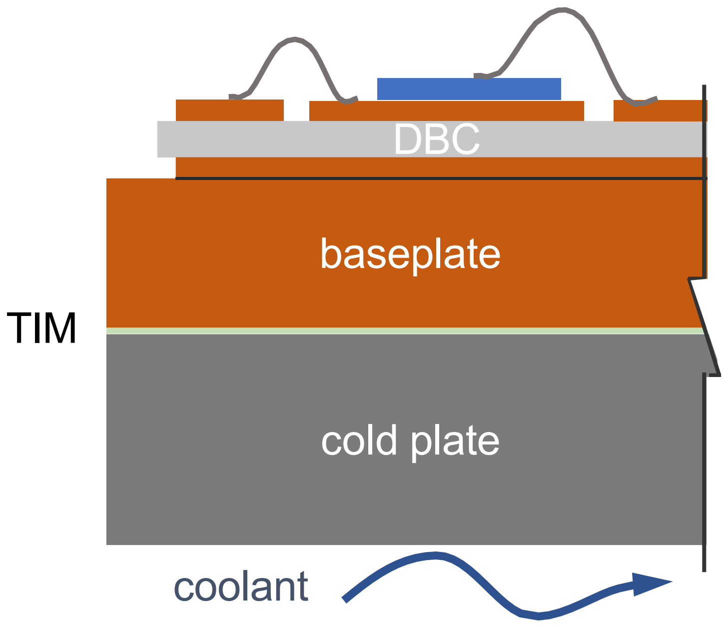


APEEM: advanced power electronics and electric machines

Typical Power Module Packaging Configurations

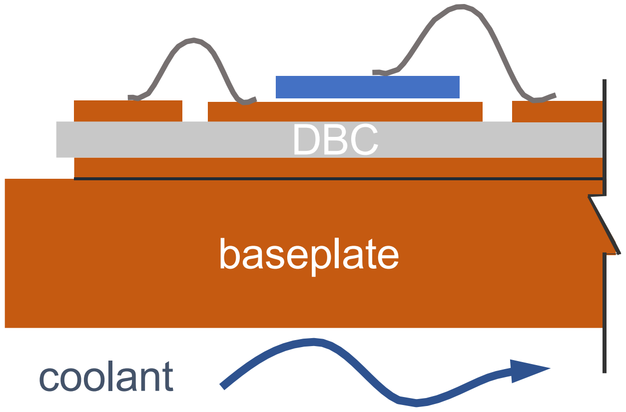
Single-side cooled

Cold plate cooled



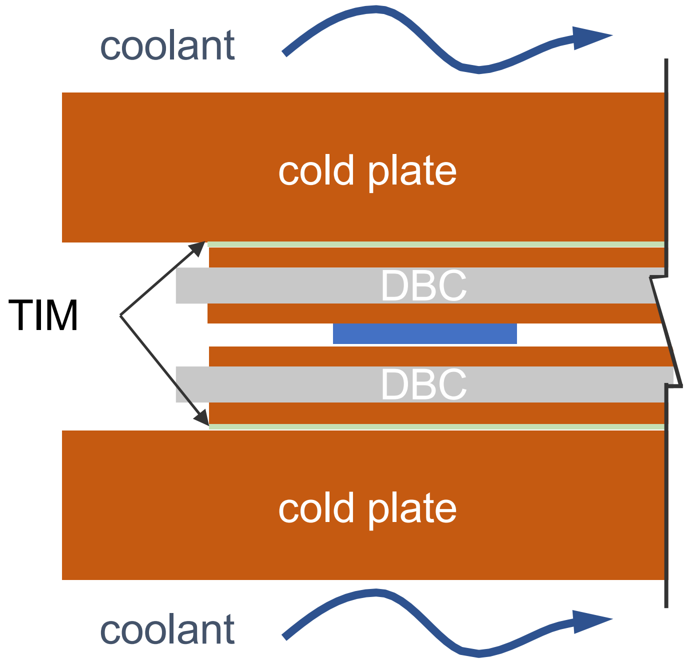
Examples:
2007 Camry HEV
2012 LEAF EV

Baseplate cooled



Examples:
2010 Prius HEV
2014 Accord HEV
2015 BMW i3 EV
2018 Tesla Model 3 EV

Double-side cooled



Examples:
2008 Lexus LS HEV
2014 Camry HEV
2016 Volt HEV
2017 Cadillac CT6 HEV

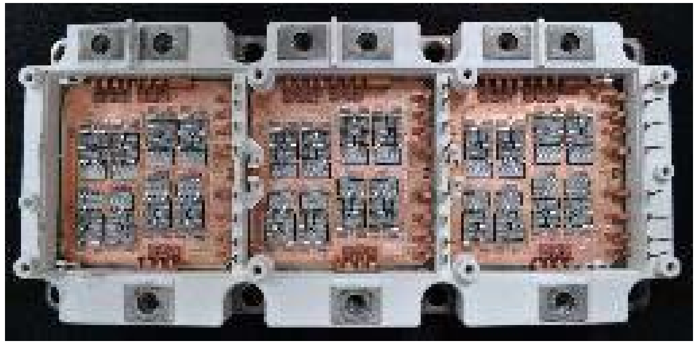
Automotive power electronics cooling trend

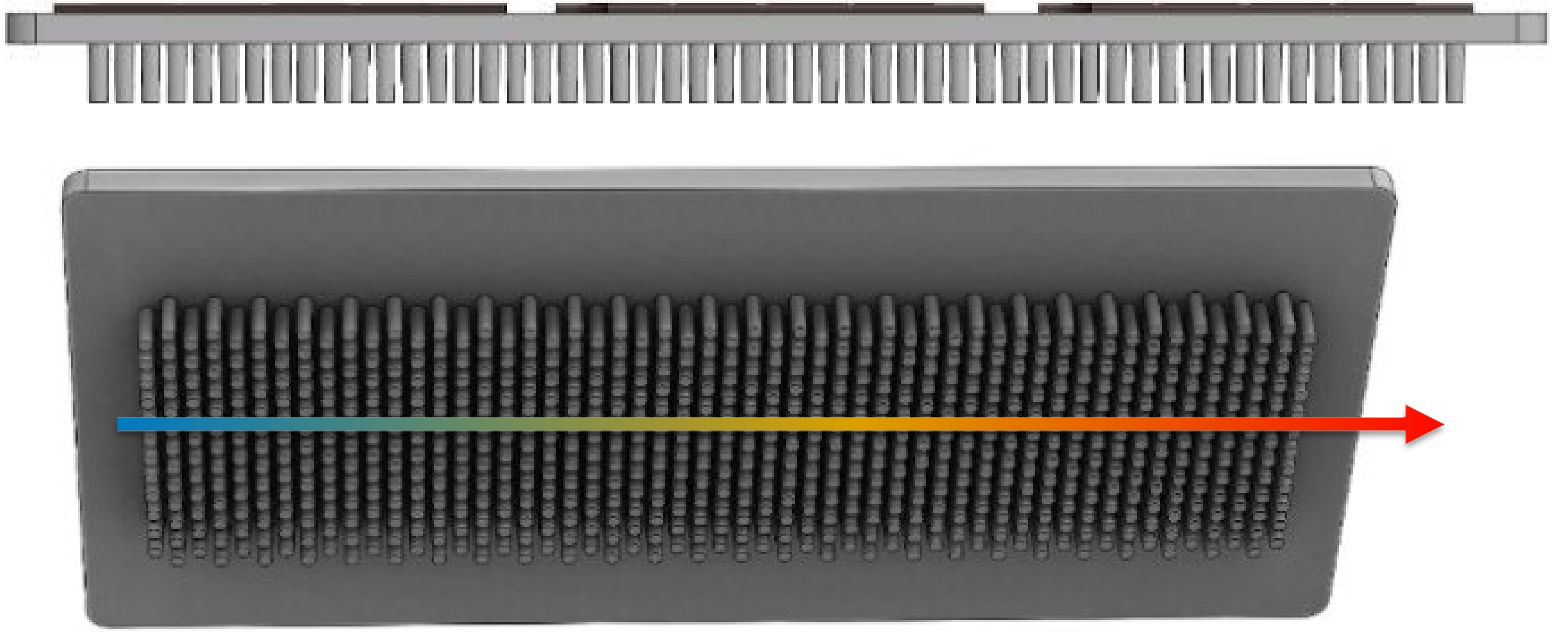
variations for each cooling configuration exist

DBC: direct-bond copper, EV: electric vehicle, HEV: hybrid electric vehicle, TIM: thermal interface material

2015 BMW i3 EV (Baseplate Cooled)


Image credit: Xuhui Feng (NREL)

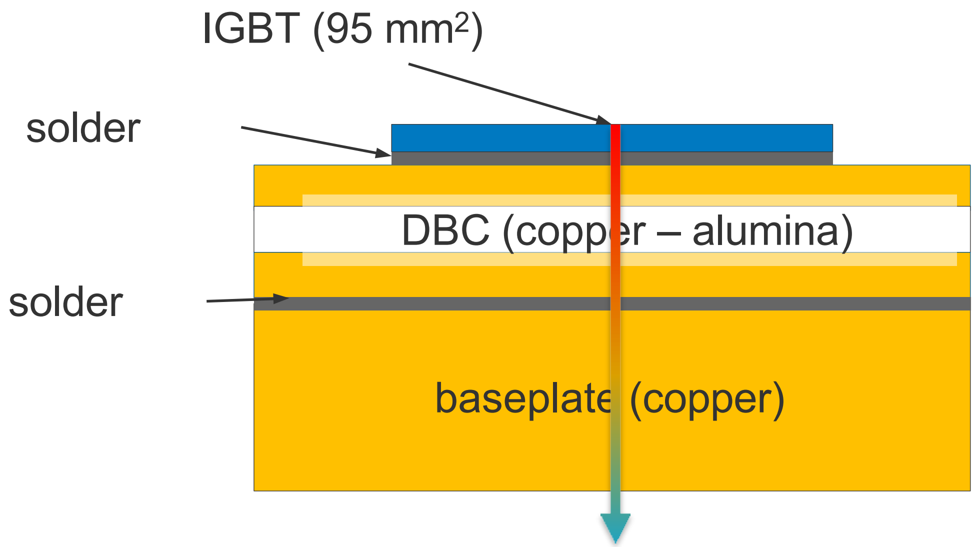



Copper heat exchanger; pin fins: diameter ≈ 2.5 mm, height ≈ 8 mm, gap between fins ≈ 1.8 mm

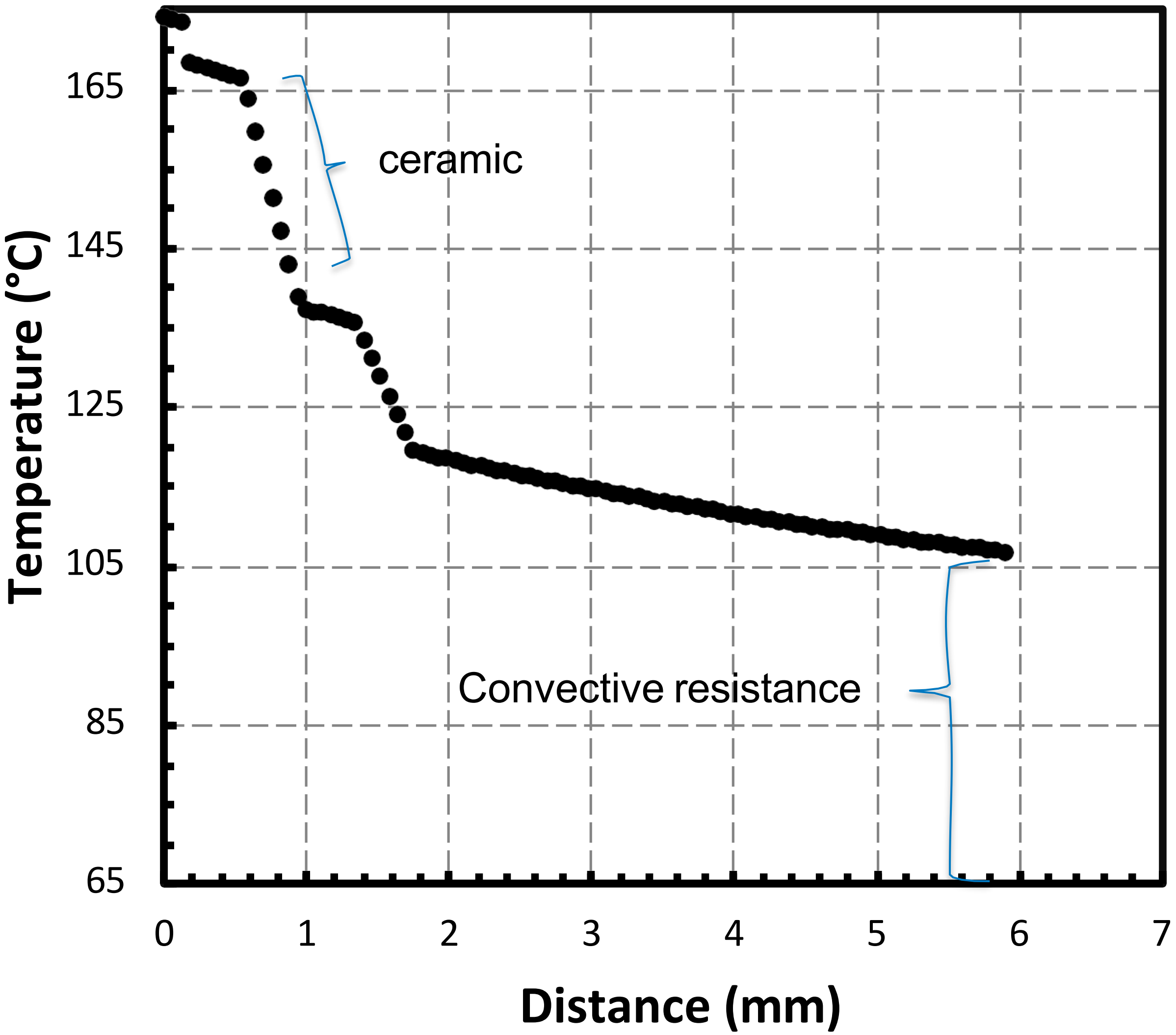
Power density: 18.5 kW/L *

*U.S. DRIVE. 2017. *Electrical and Electronics Technical Team Roadmap*. https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf.

2015 BMW i3 EV (Baseplate Cooled)



- Package conduction resistance is about 64% of the total thermal resistance
- Ceramic makes up the largest thermal resistance within the package.
- Predicted to provide a 49 mm² ·K/W thermal resistance performance

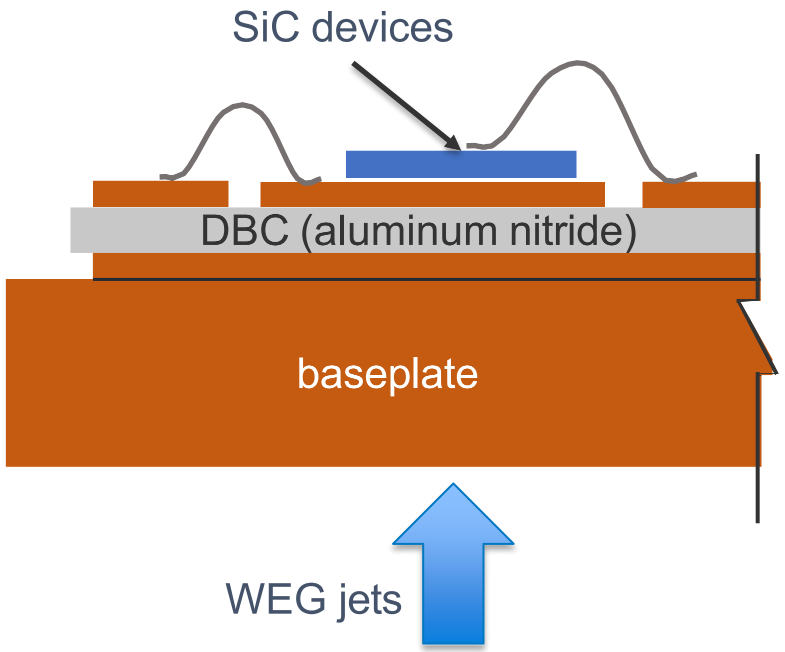


Advanced Cooling Technologies

Objective: Develop thermal management strategies to reach the U.S. Department of Energy power density target of 100 kW/L

Jet Impingement with Water-Ethylene Glycol (WEG)

- Created a silicon carbide (SiC)-based, half-bridge module
- Used a jet-impingement-on-module-baseplate cooling approach
- Complied with automotive guidelines (≥1 mm channels), minimized erosion-corrosion effects, and fabricated using in-house fabrication methods (CNC milling, SLA 3D printing, and wire bonding)

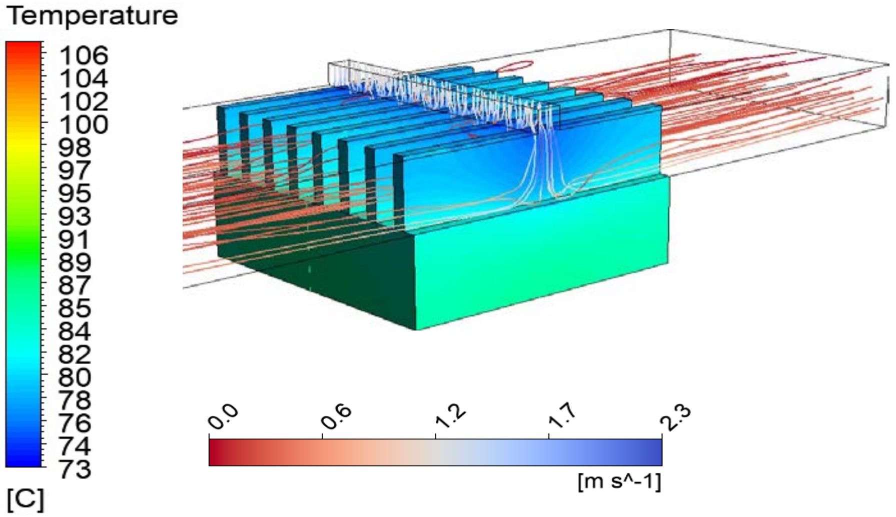


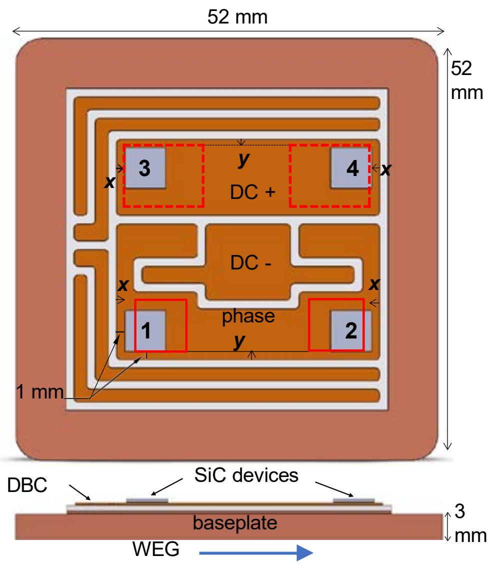
Jet Impingement with Water-Ethylene Glycol

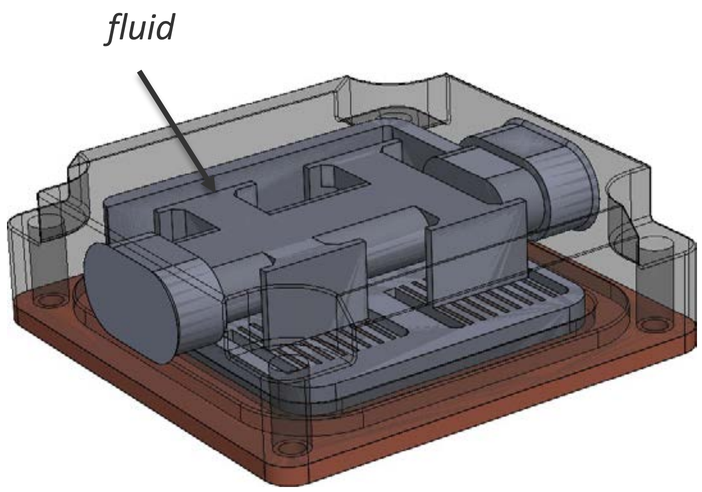
Computed effective HTCs using device-scale CFD model

Optimized package dimensions to maximize thermal performance using FEA

Optimized fluid manifold dimensions to minimize thermal resistance and pumping power







HTC boundary condition

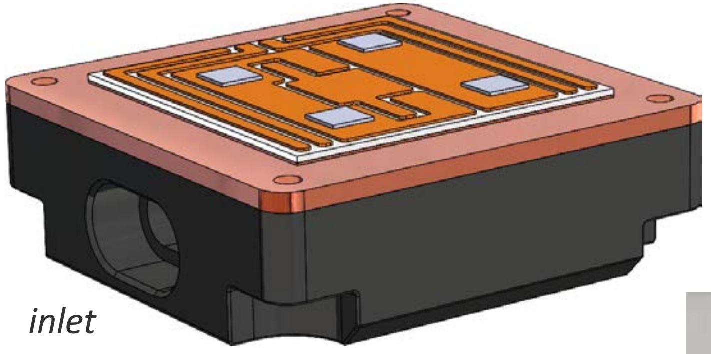
package dimensions

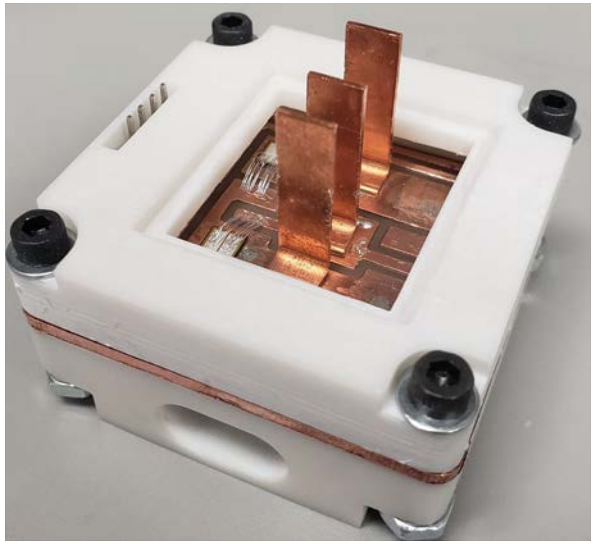
CFD: computational fluid dynamics, FEA: finite element analysis

Jet Impingement with Water-Ethylene Glycol

Predict a junction-to-fluid thermal resistance of 17 mm²·K/W and 1.4°C device temperature variation at 0.8 psi pressure drop

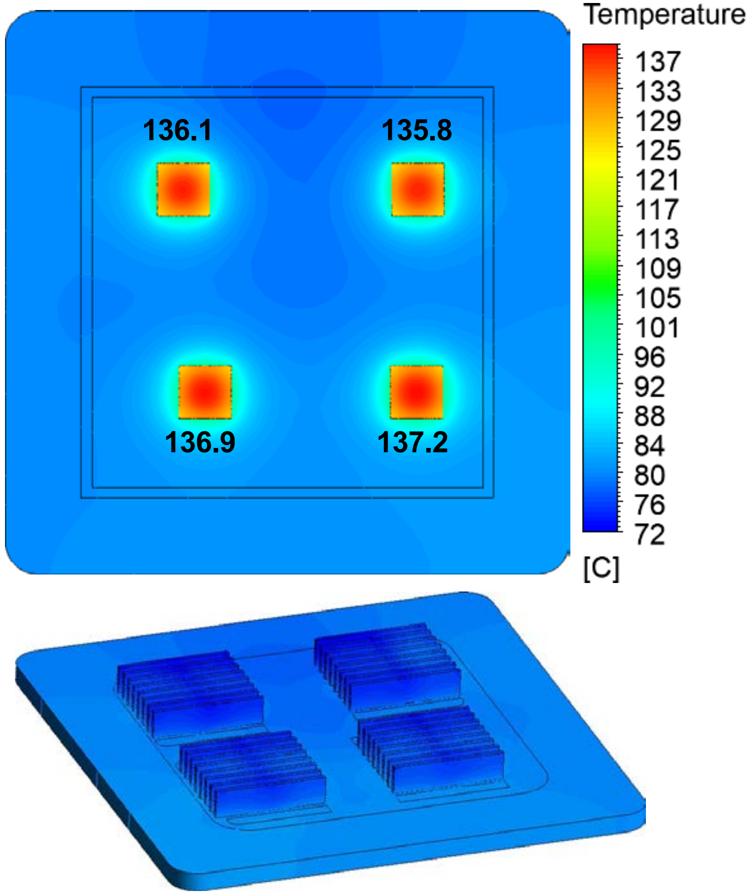
CAD of module on manifold





SLA printed manifold

Image credit: Josh Major (NREL)



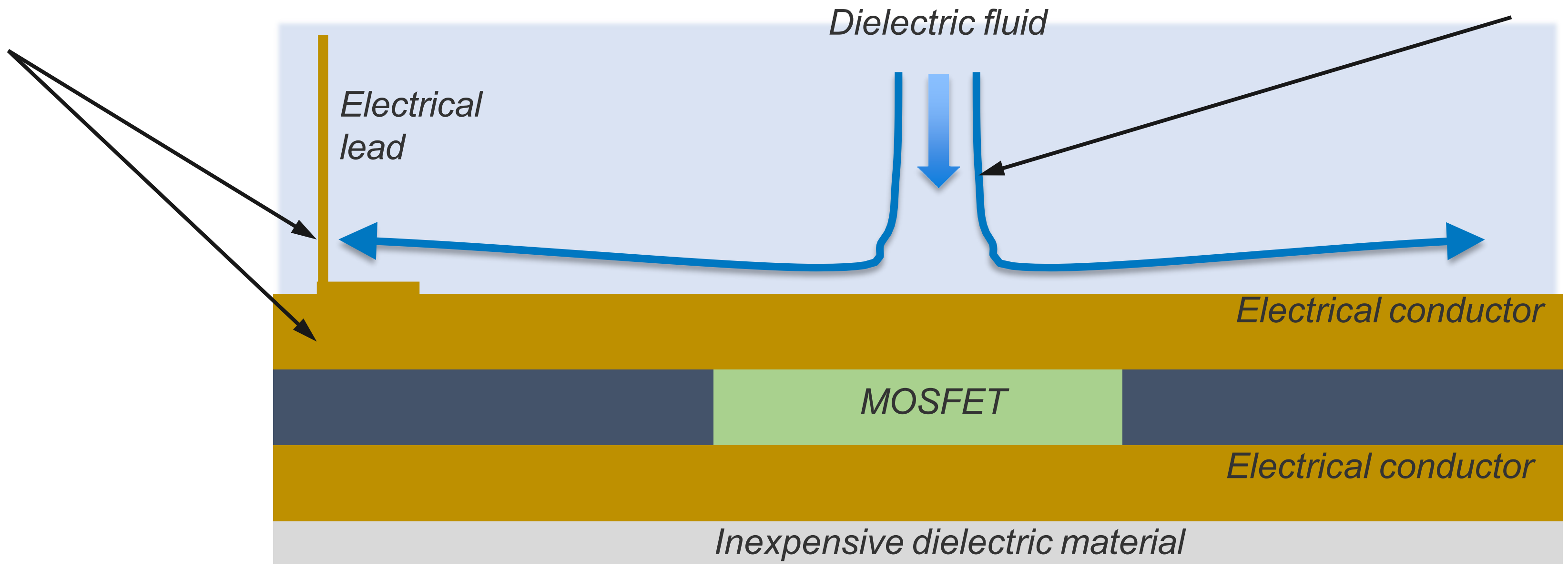
CFD-computed temperatures for 65°C fluid inlet temperature and a 433 W/cm² device heat flux

CAD: computer-aided drawing, SLA: stereolithography

Dielectric Fluid Cooling Concept (Single Phase)

Allows for cooling of the bus bars/electrical interconnects to lower capacitor and gate driver temperatures

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



Eliminates expensive ceramic materials

Improves thermal performance over conventional DBC-based designs

- Reduced package/conduction resistance to 33% of total thermal resistance using a relatively high convection coefficient (17,300 W/[$m^2 \cdot K$])
- Designed single-side and double-side dielectric fluid cooling concepts.

MOSFET*:* metal–oxide–semiconductor field-effect transistor

Dielectric Fluids (Single Phase)

- 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.

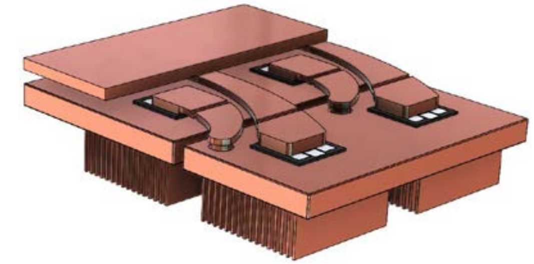
[3] Alshamani, Kaisar. 2003. "Equations for Physical Properties of Automotive Coolants." SAE Technical Paper.

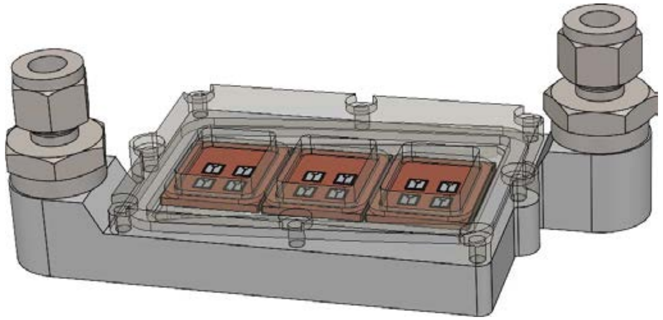
[4] Valvoline. 2019. "Safety Data Sheet ZEREX HD Nitrile Free Extended Life 50/50 Antifreeze Coolant." Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.

[5] Valvoline. 2021. "Product Information: Valvoline ZEREX G05 Antifreeze Coolant." https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

Dielectric Fluids (Single Phase)

Single-side cooled





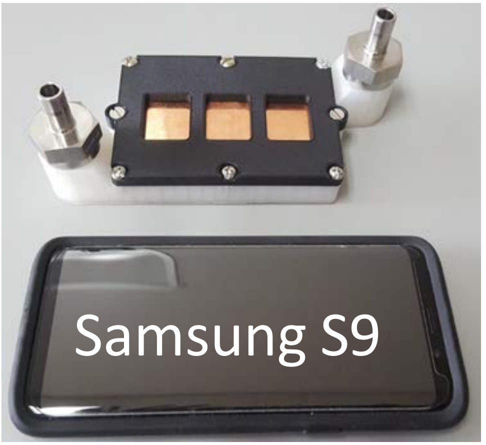
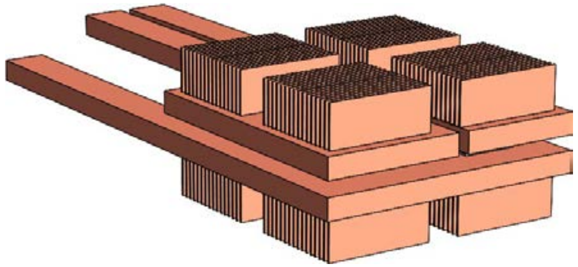
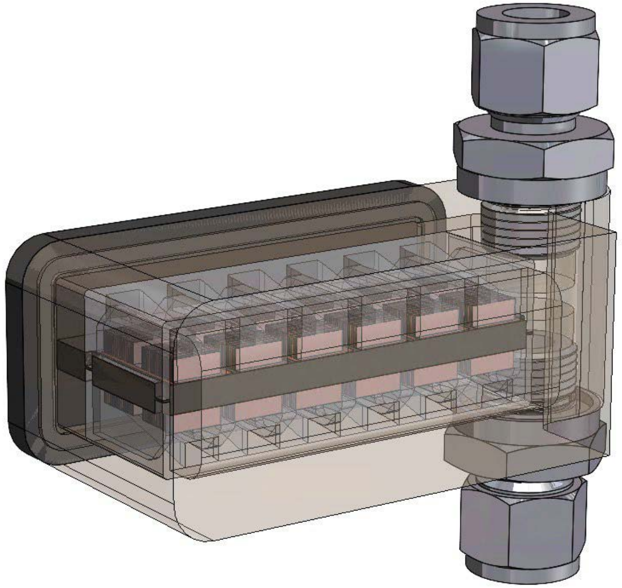


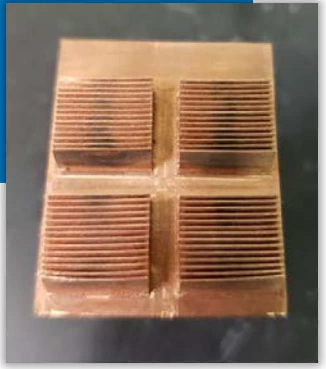
Image credit: Gilbert Moreno, NREL

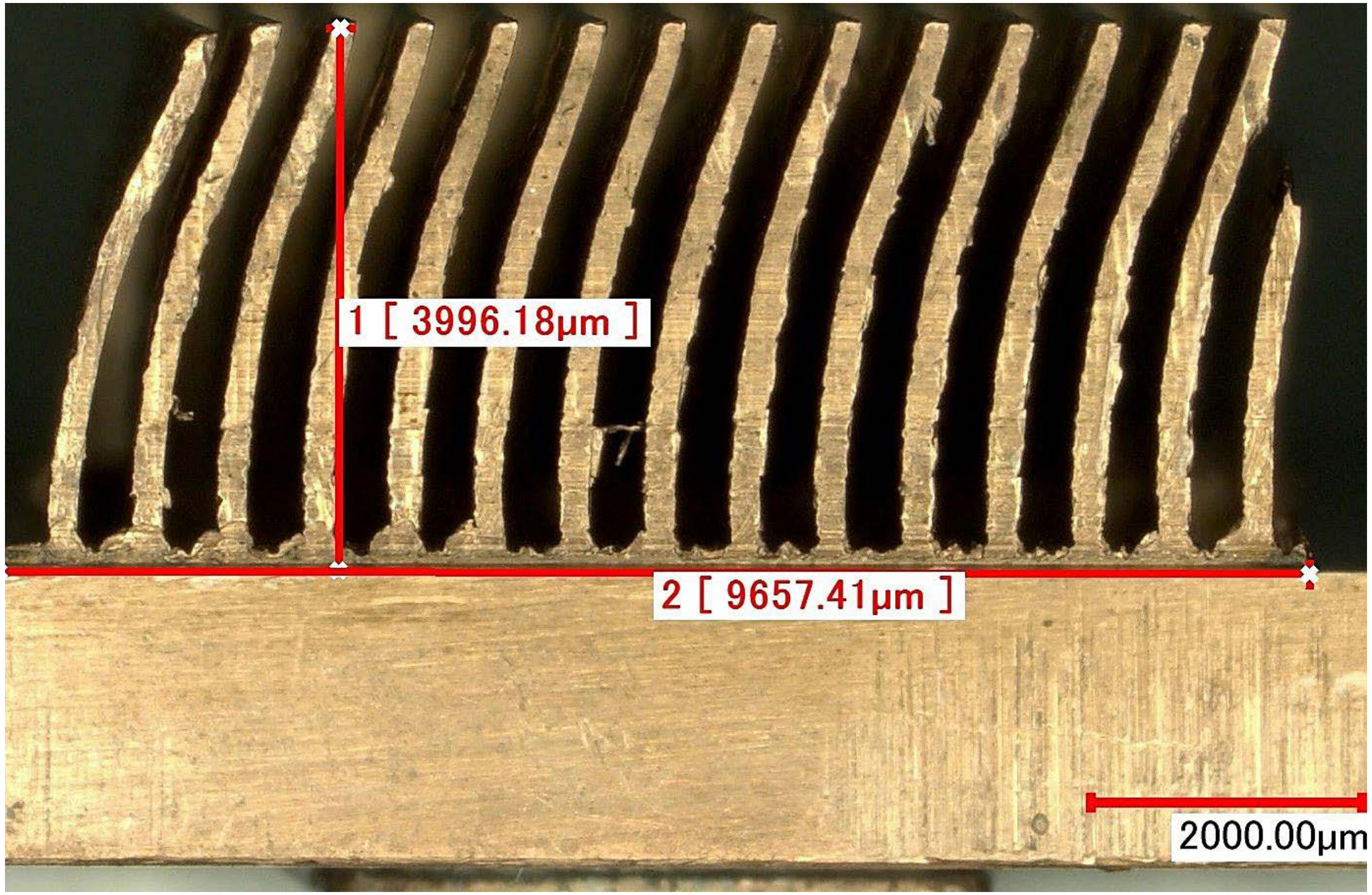
Double-side cooled





Dielectric Fluids (Single Phase)





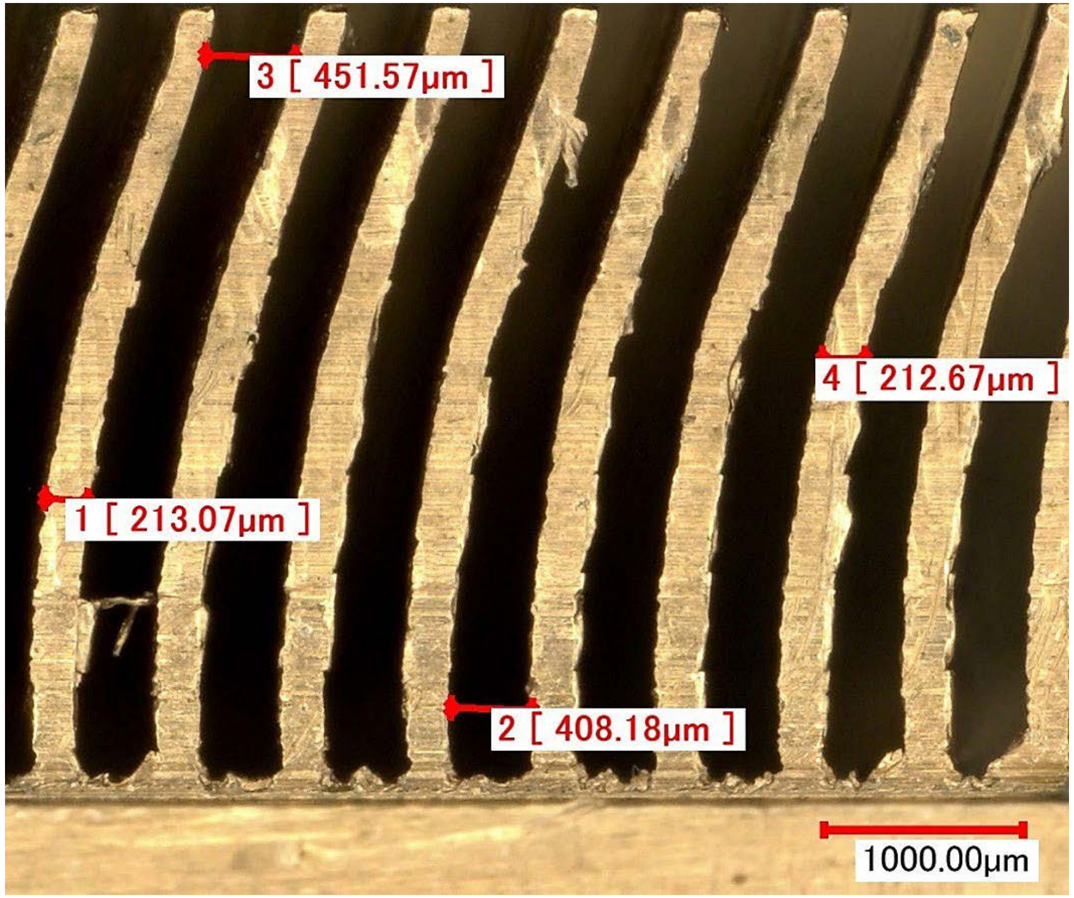
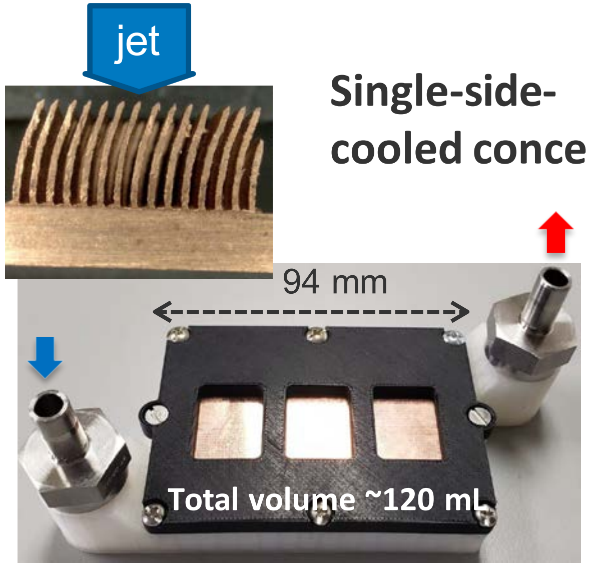


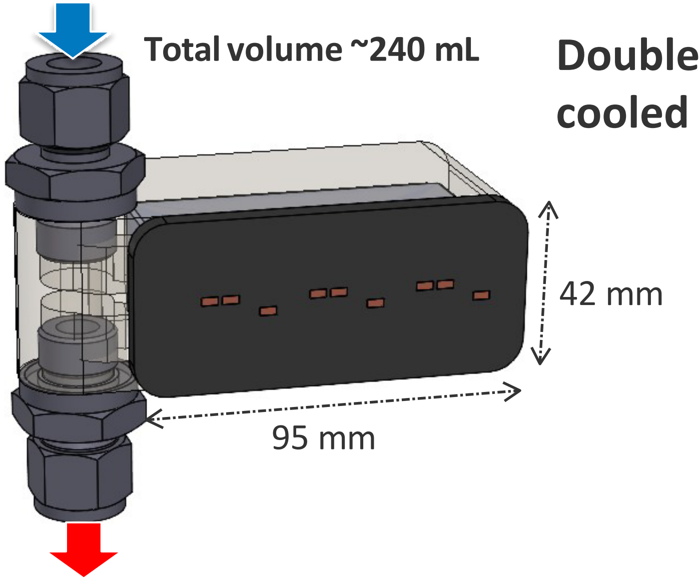
Image credits: Gilbert Moreno, NREL

Dielectric Fluids (Single Phase)



Single-side-cooled concept

Image credit: Gilbert Moreno, NREL



Double-side-cooled concept

* Estimates assuming T_{fluid} = 70°C

System	Thermal Resistance (junction-to-fluid)	Flow Rate	Pressure Drop	T_j Maximum	Device Heat Flux*	Total Volume (power modules and cold plate)
	mm²·K/W	*L/min*	*psi [kPa]*	*°C*	*W/cm²*	*mL*
2015 BMW i3, (WEG cooled)	49	10	1.4 [9.6]	175	214	900
Single-side-cooled dielectric fluid	**20**	**4.1**	**0.2 [1.4]**	**175**	**525**	**120**
Double-side-cooled dielectric fluid	**11**	**4.1**	**0.6 [4.1]**	**175**	**875**	**240**

Two-Phase Cooling

- Measured boiling heat transfer performance on 10 × 10-mm heated surfaces and evaluated the following:
  - Refrigerants: R-245fa, R-134a, HFO-1234yf, HFE-7100
  - Enhanced surface: microporous coating, nanostructures
- Achieved HTCs ~50,000 $W/m^2 \cdot K$ on smooth (and no fins) surfaces
- Measured HTCs >200,000 $W/m^2 \cdot K$ within small heat flux range
- CHF is one of the major limitations of boiling heat transfer—requires enhanced surfaces to increase CHF and/or limit the heat flux on the boiling surfaces.

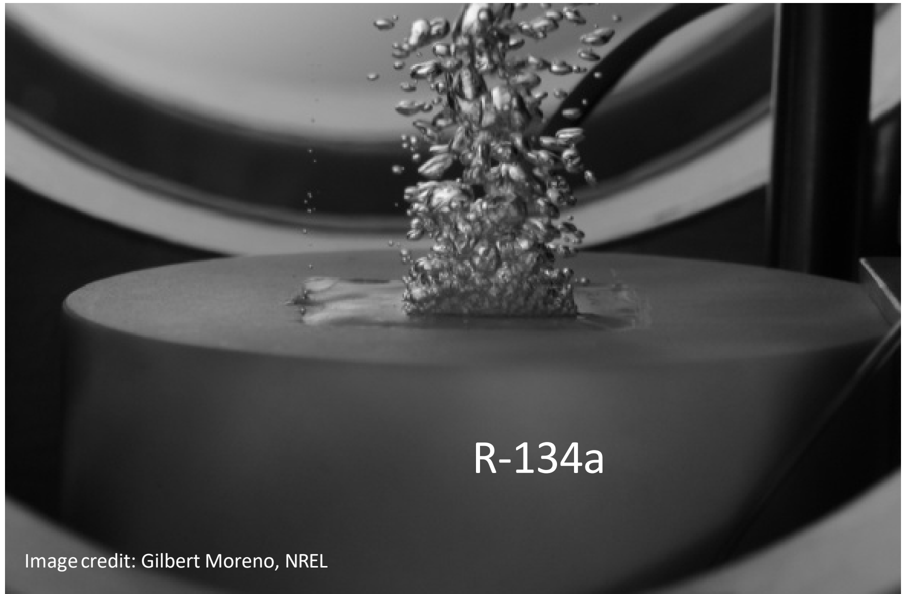


Image credit: Gilbert Moreno, NREL

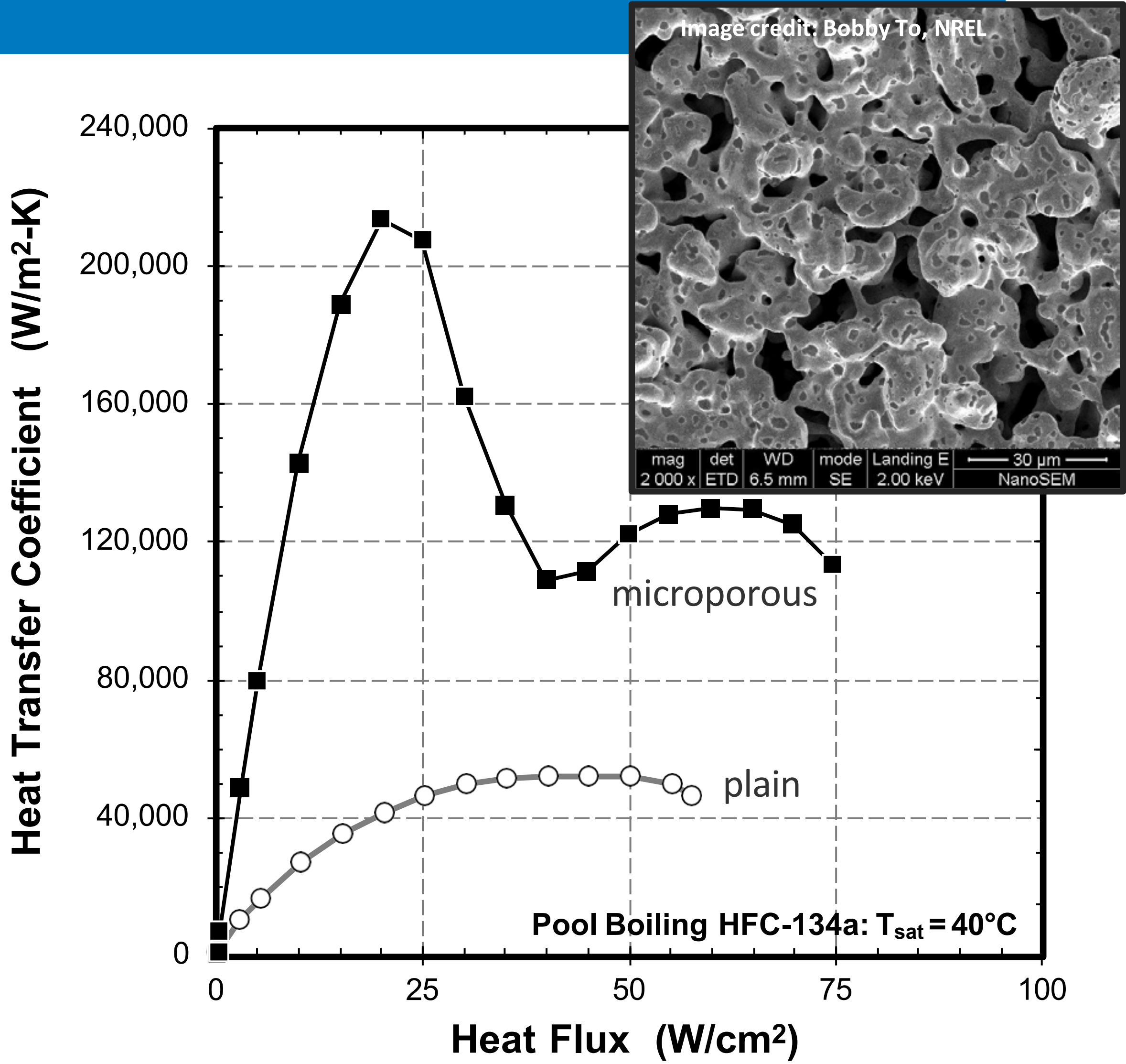
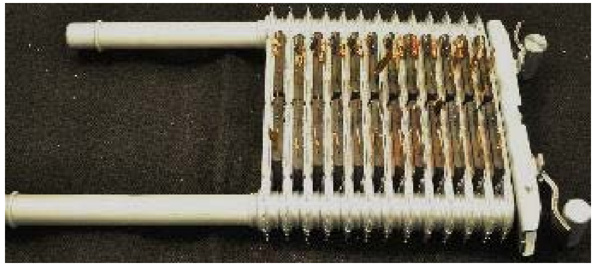


Image credit: Bobby To, NREL

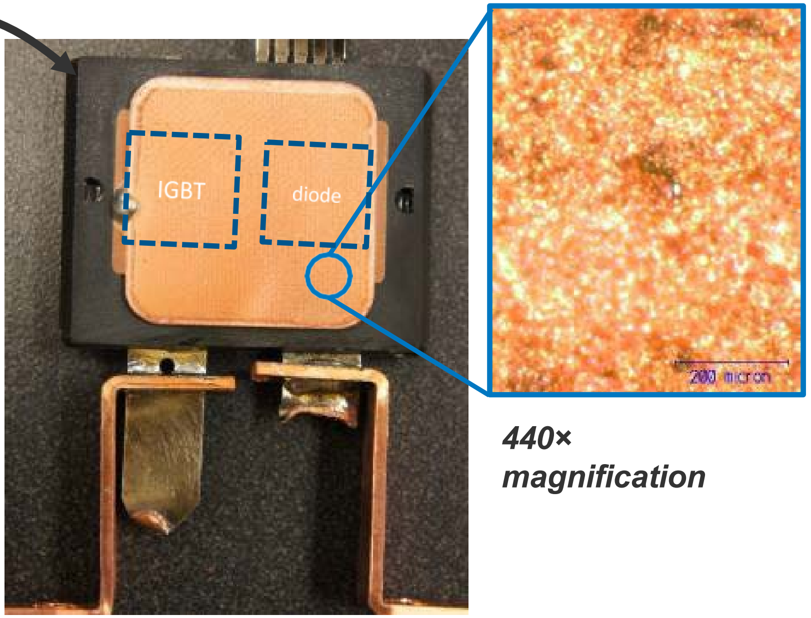
CHF: critical heat flux, HTC: heat transfer coefficient

Two-Phase Cooling: Immersion Cooling of a Module

Immersion cooling two-phase (boiling) cooling of an automotive power module (2008 Lexus HEV)

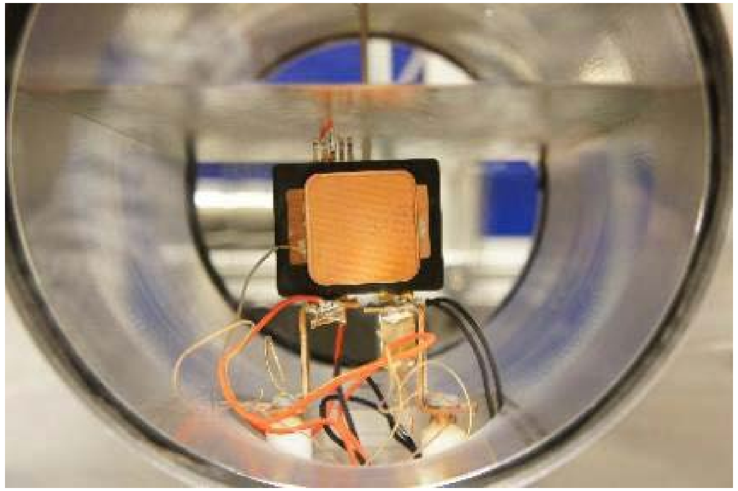


Used a module from the 2008 Lexus



440× magnification

Applied microporous coating to the module

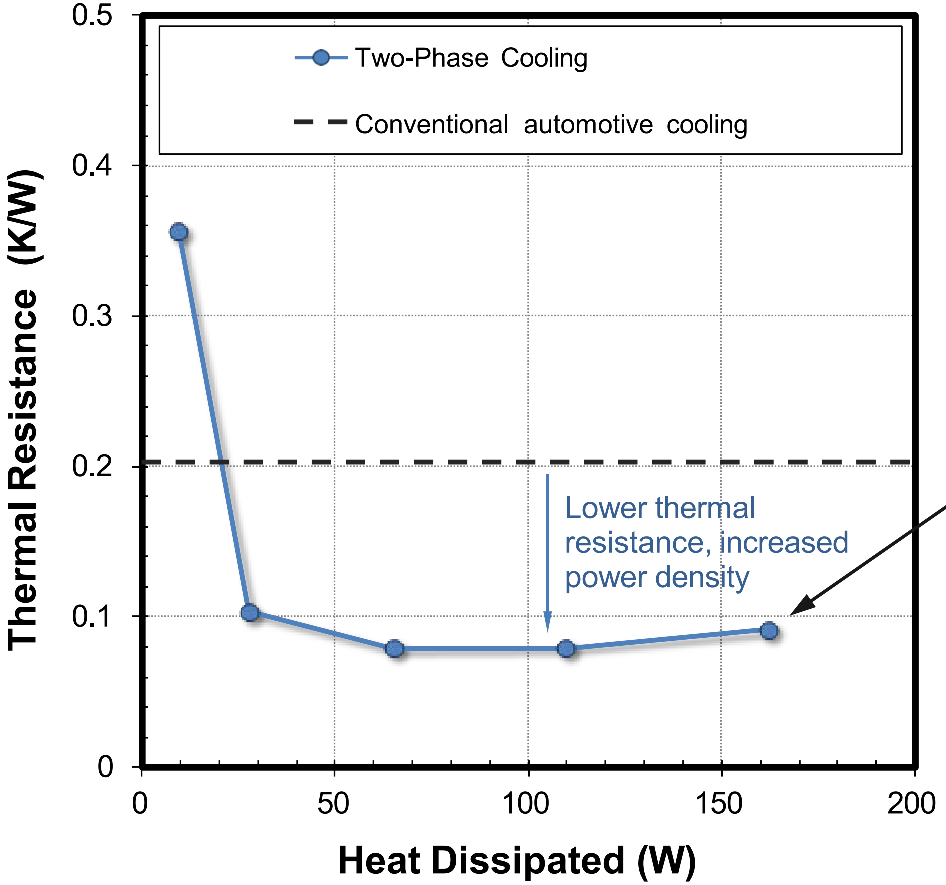


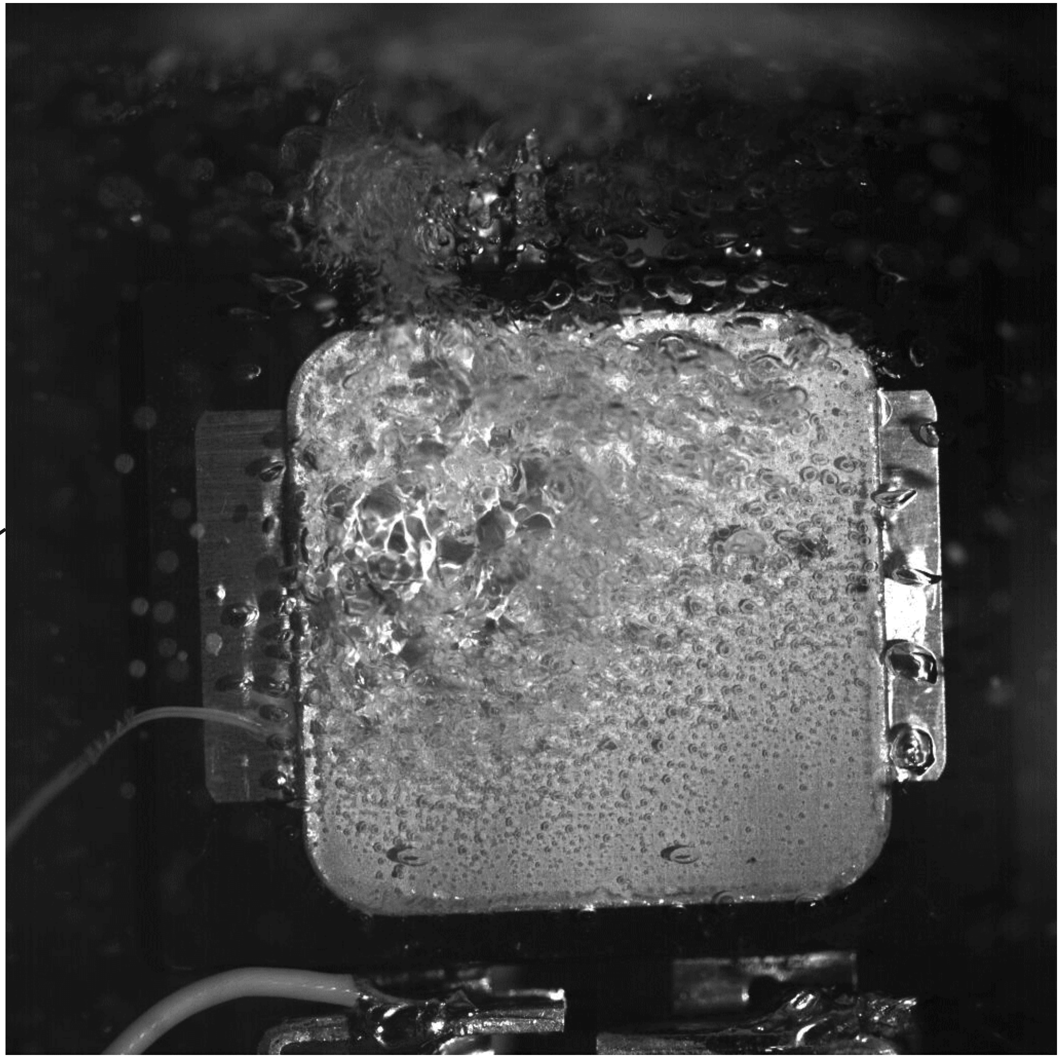
Immersed the module in HFE-7100 fluid

Image credits: Gilbert Moreno, NREL

Two-Phase Cooling: Immersion Cooling of a Module

Two-phase cooling with microporous coating reduced thermal resistance by over 60% as compared with the 2008 Lexus system—better performance with no pump required.



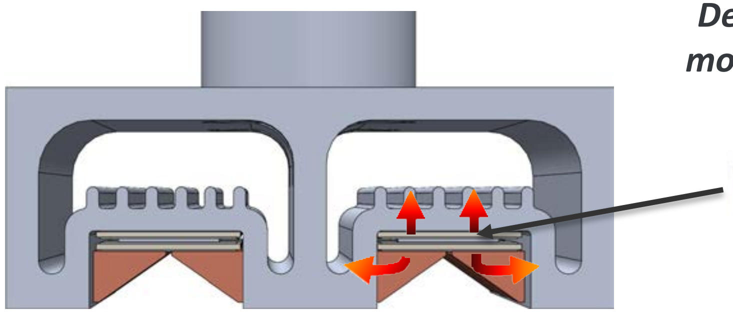


Immersion cooling: HFE-7100 refrigerant

Image credits: Gilbert Moreno, NREL

Two-phase Cooling: Indirect Cooling Concept

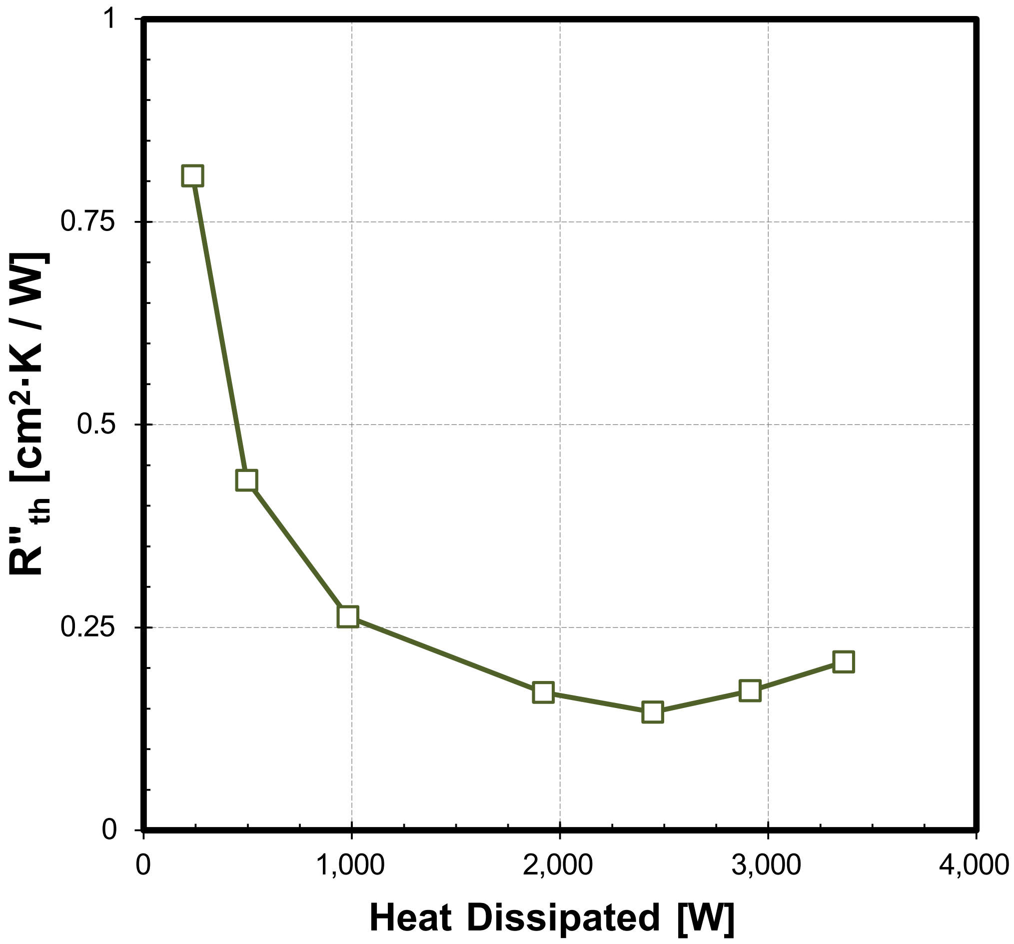
Designed a passive, indirect two-phase cooling system to cool six Delphi power modules



Heat conduction path from backside of the electronic device to the evaporator surface

Delphi discrete power module: Image credit: Gary Eesley (Delphi)

- Fabricated from low-cost materials (aluminum) using low-cost manufacturing techniques
- Reduced refrigerant requirements to 180 mL, (HFO-1234yf = 200 g, R-245fa = 240 g)
    - Comparison: 2010 Toyota Camry air-conditioning system uses 510 g of R-134a
- Dissipated 3.5 kW of heat with only 180 mL of R-245fa

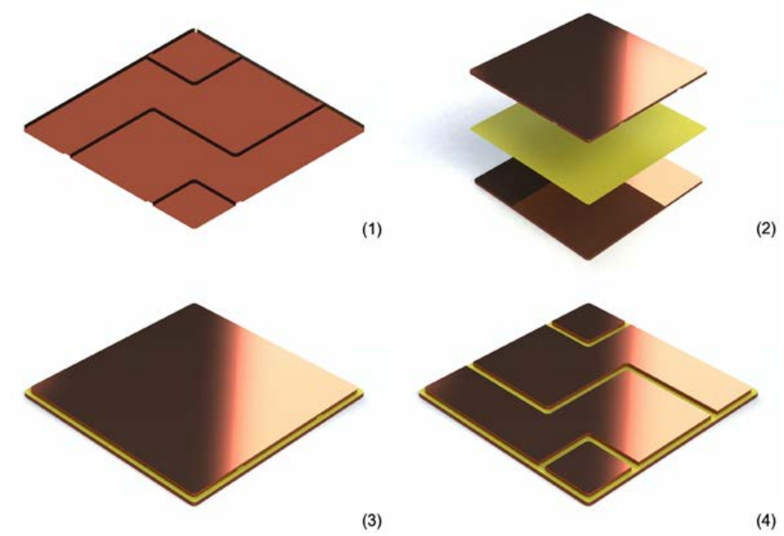


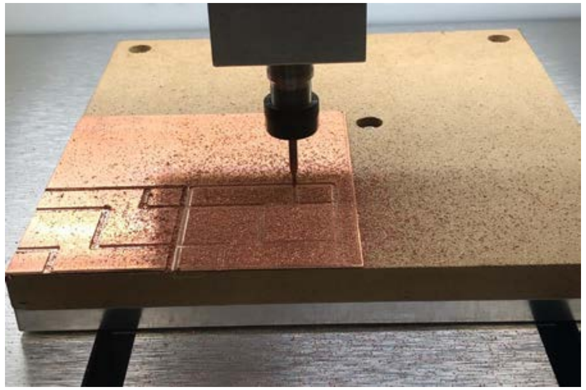
Alternate Substrates: ODBC Substrates

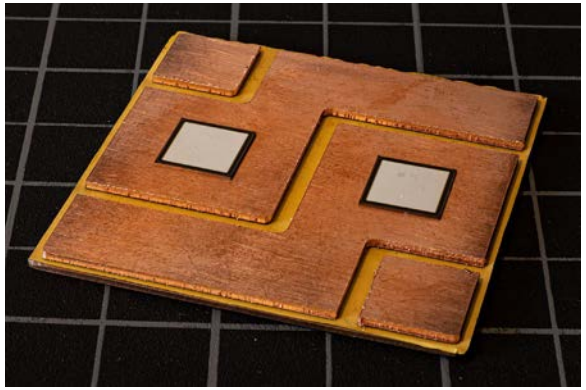
- Organic direct bond copper (ODBC) substrates
  - A polyimide dielectric is bonded with metal through elevated temperature and pressure
  - No limitations in metal material or metallization thickness
- The ability to bond thick copper metallization layers (1–1.5 mm) improves heat spreading directly below devices and lowers their junction temperatures
- Mechanical etching allows for fine width spacing (<1 mm) between conductor traces through thick metallization layers.

Substrate assembly process

1. *Mechanically etch bottom face of top metallization layer.*
2. *Assemble Temprion and metallization layers.*
3. *Apply temperature and pressure to substrate stack.*
4. *Mechanically etch top face of top metallization layer.*




Machining process


NREL prototype substrate

Acknowledgments

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Thank You

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