Advanced Power Electronics and Electric Machines Packaging, Thermal Management, and Reliability for Electric-Drive Mobility Applications

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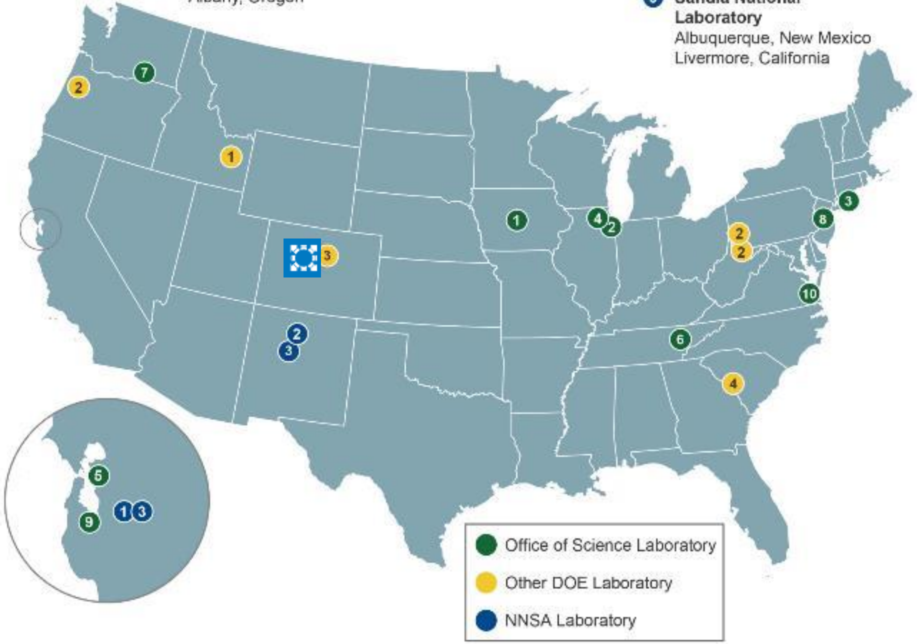


NREL: Sponsored by the Office of Energy Efficiency and Renewable Energy

National Renewable Energy Laboratory

Leading clean energy innovation for 46 years

3,300 employees with world-class facilities

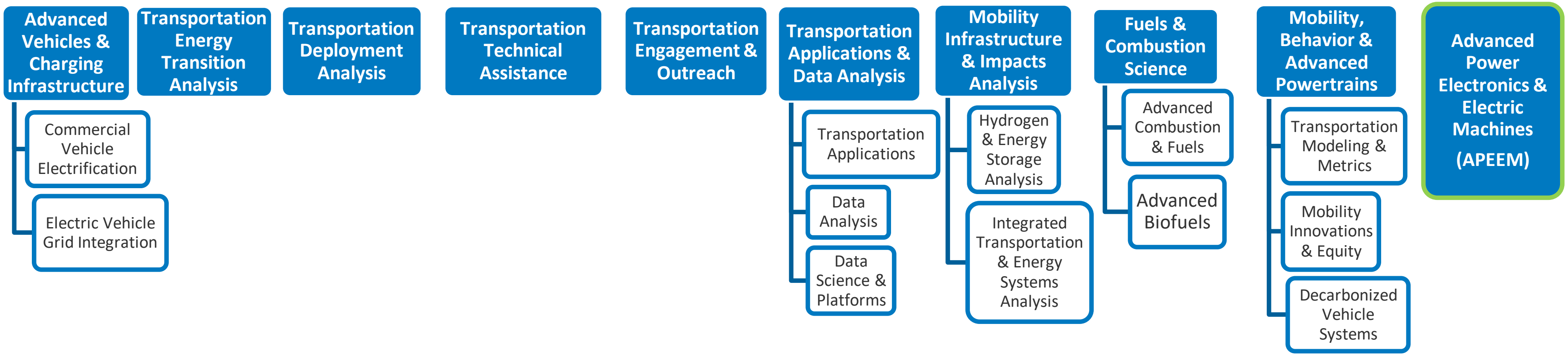
Campus is a living model of sustainable energy

Sponsored by the U.S. Department of Energy

Operated by the Alliance for Sustainable Energy

Scope of NREL's Mission

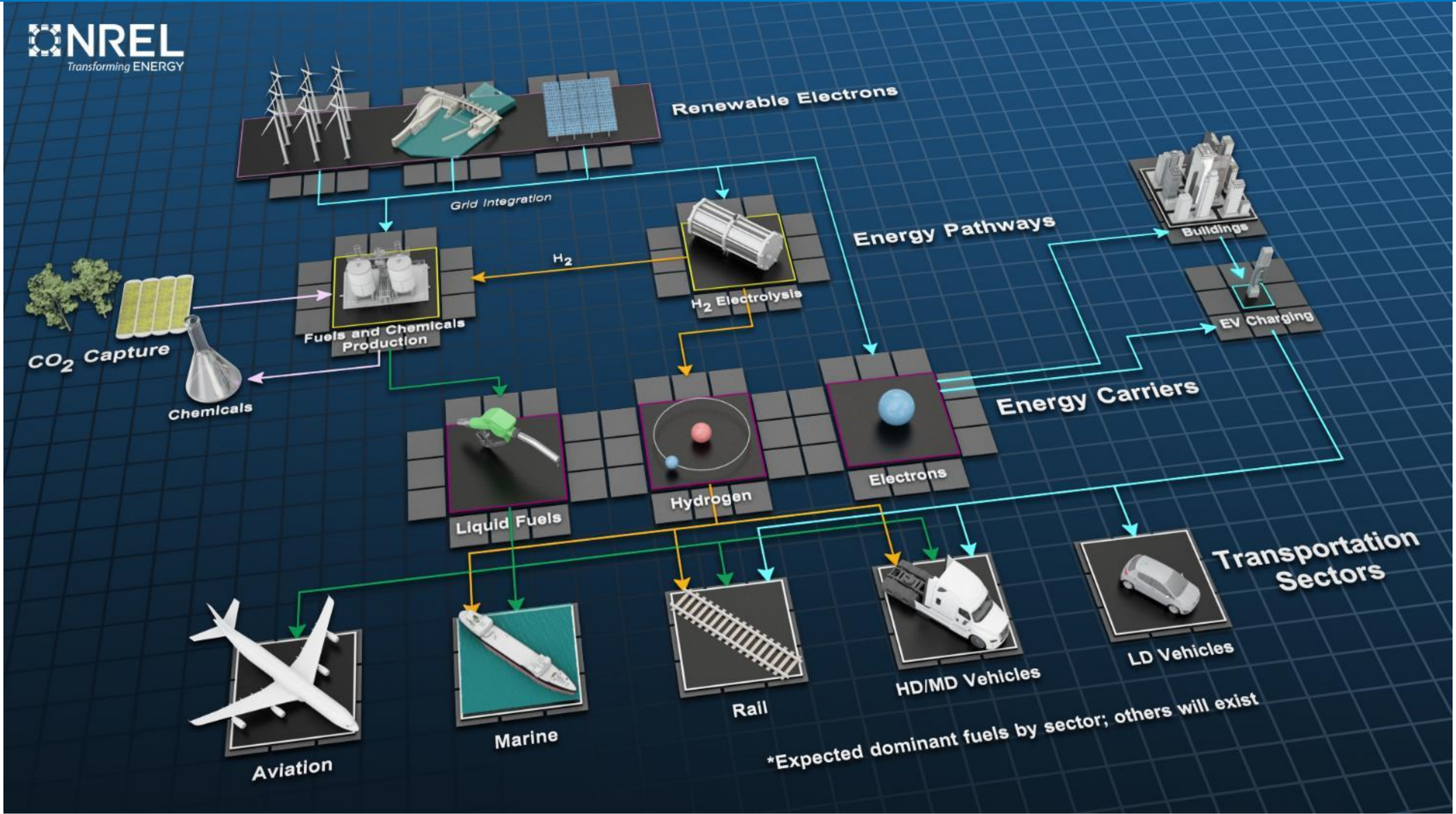
Sustainable Transportation	Energy Productivity	Renewable Electricity	Systems Integration	Partnerships
Vehicle Technologies	Residential Buildings	Solar	Grid Integration of Clean Energy	Private Industry
Hydrogen	Commercial Buildings	Wind	Distributed Energy Systems	Federal Agencies
Biofuels	Manufacturing	Water: Marine Hydrokinetics	Batteries and Thermal Storage	State/Local Government
		Geothermal	Energy Analysis	International

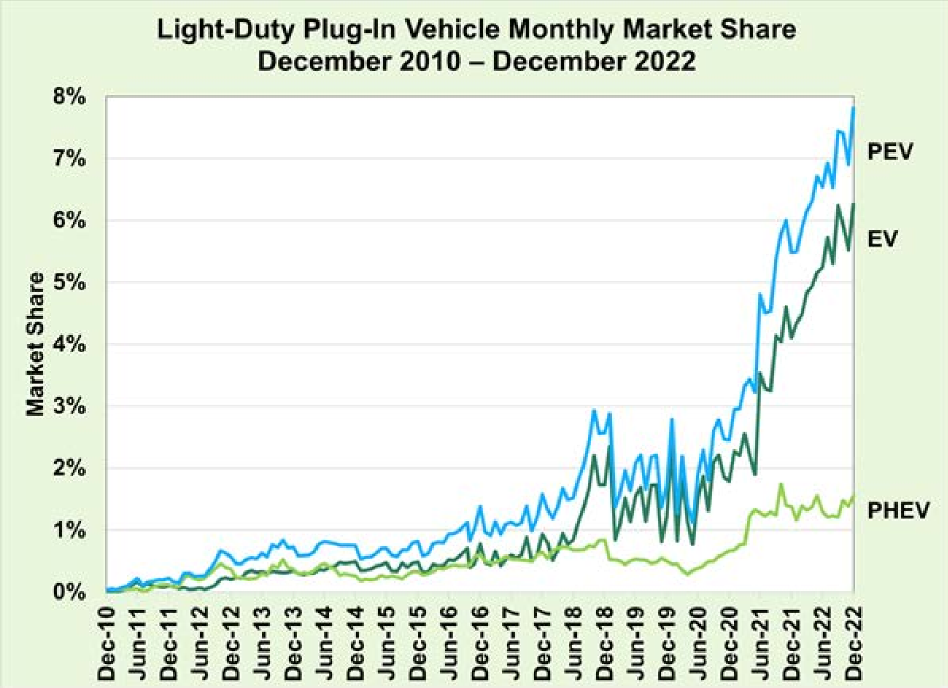


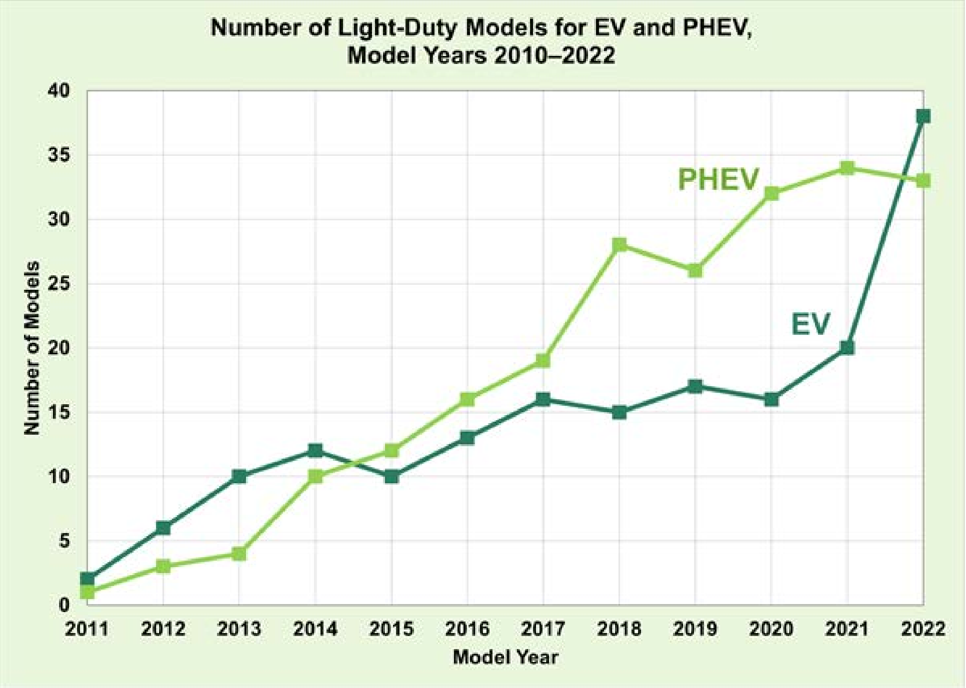
Center for Integrated Mobility Sciences (CIMS)

APEEM group: Fifteen staff members involved in electrothermal, thermal-fluids, thermomechanical, and reliability research activities.

NREL's Vision for Decarbonizing the Transportation Sector





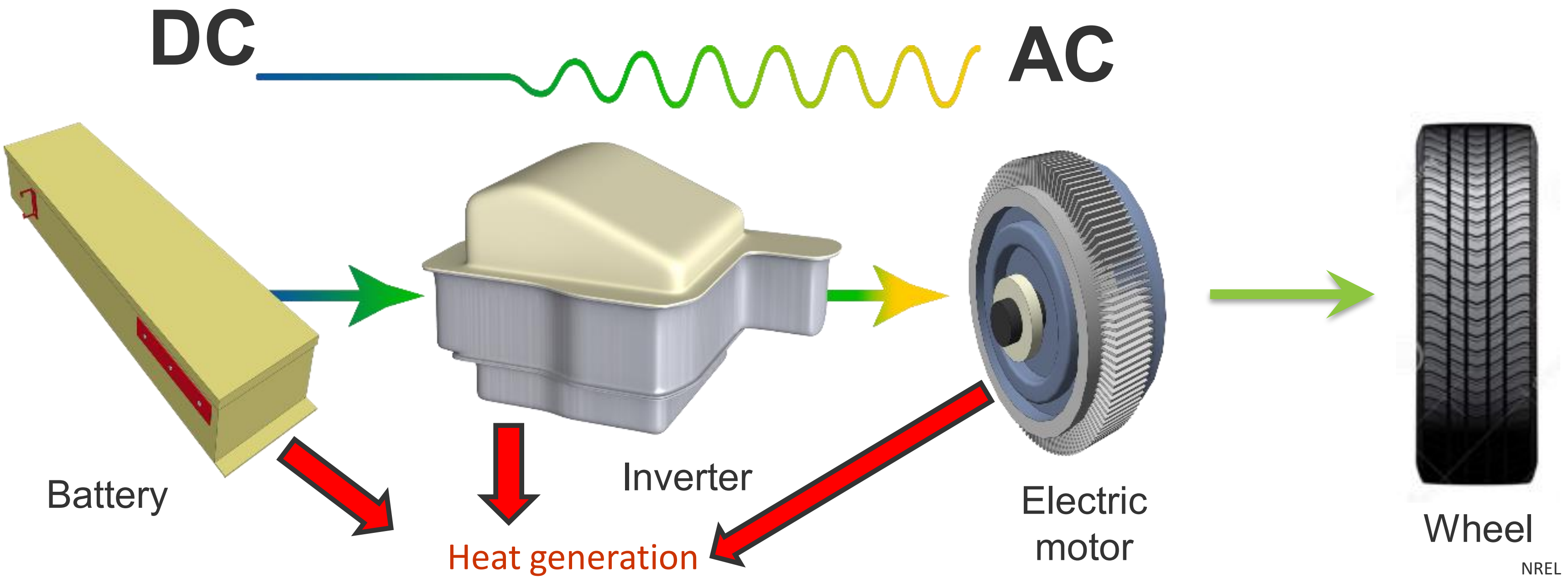


Source: Argonne National Laboratory. 2022. "Light-Duty Electric Drive Vehicles Monthly Sales Updates, December 2022." https://www.anl.gov/esia/light-duty-electric-drive-vehicles-monthly-sales-updates.

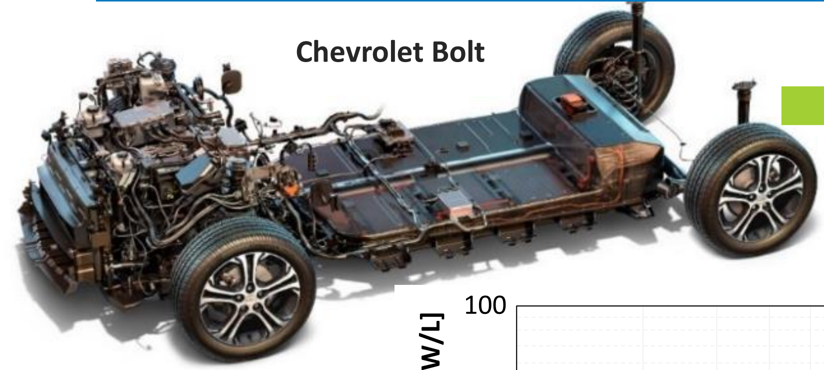
Source: U.S. Department of Energy and U.S. Environmental Protection Agency. 2023. "Fuel Economy data." Accessed Jan. 24, 2023. https://www.fueleconomy.gov/feg/download.shtml.

Electric Traction Drive – Basic Functionality

- Inverter: Converts direct current (DC) from the battery to alternating current (AC) for the electric motor.
- Electric motor: Power to the wheels.

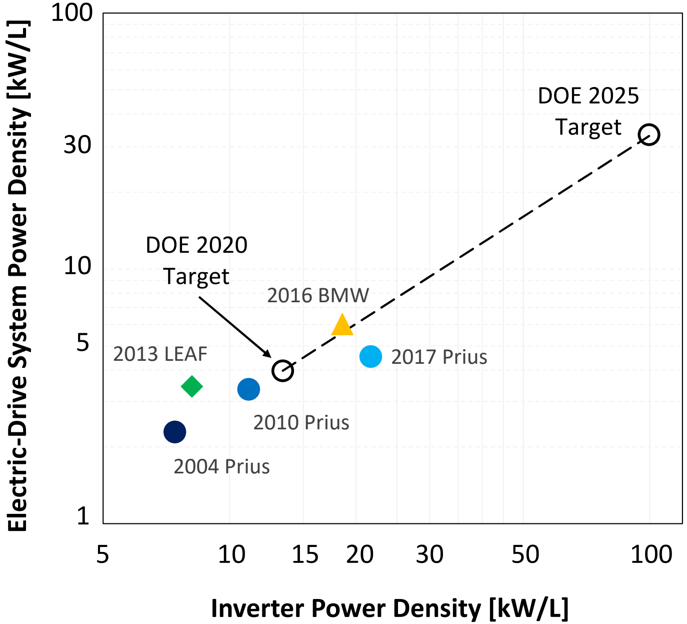


Vehicle Technologies Office EDT Research Pathway for Electric-Drive Vehicle Electrification



Chevrolet Bolt

Future mobility design concept



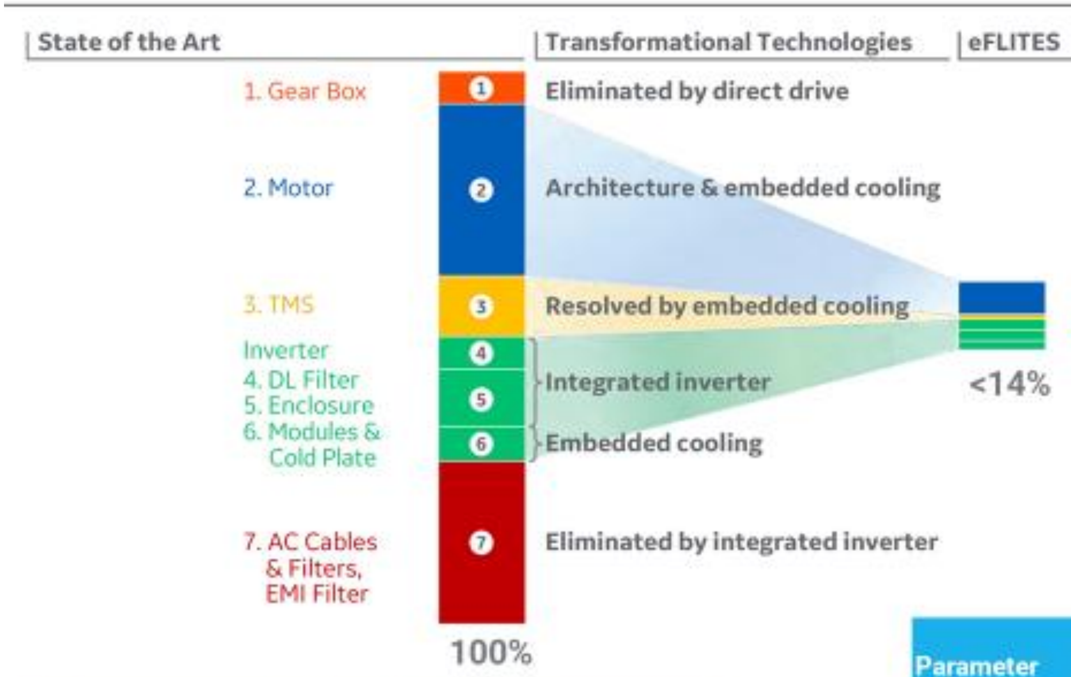
2025 Electric Traction Drive System Targets	
Cost	**$6/kW (50% reduction)**
Power Density	**33 kW/L (850% increase)**
Power Level	**100 kW**
Reliability/Lifetime	**300,000 miles (100% increase)**

EDT: electric-drive technologies

Source: M. Muratori, M. Alexander, D. Arent, M. Bazilian, E. Dede, J. Farrell, C. Gearhart, et al. 2021. “The Rise of Electric Vehicles – 2020 Status and Future Expectations.” *Progress in Energy* 3 (2), 022002.

Source: 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.

Integrated Electric Drive and Thermal Management for Aviation

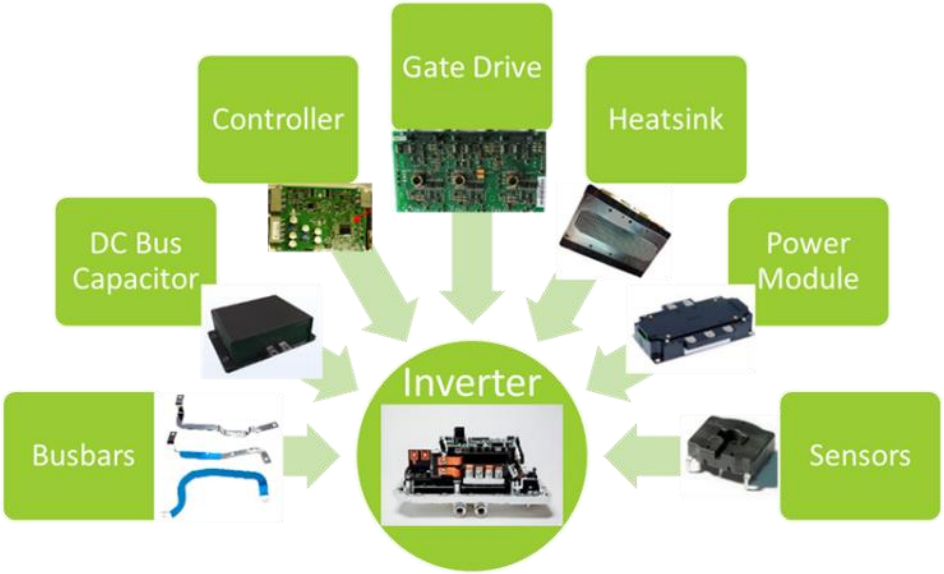


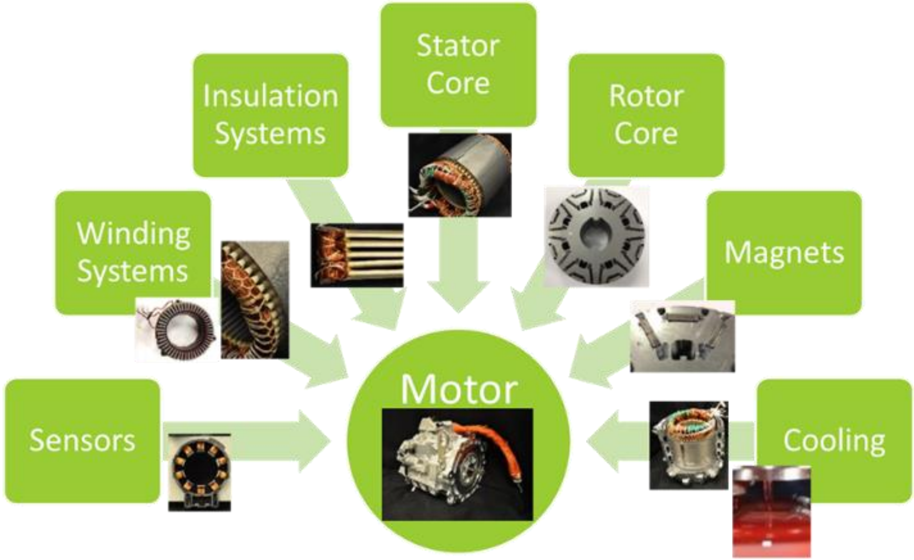
Co-design / Integration & Cooling Technologies vital to power density increase

Parameter	Performance Metric	
	State-of-the-Art	eFLITES
Power Density [kW/kg]	~1.5	>10
Take-off & Climb Efficiency [%]	87+	94

Image credit: John Yagielski, GE Global Research Center

Inverter and Electric Motor – Constituents

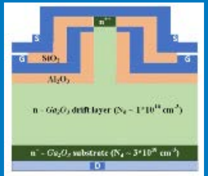
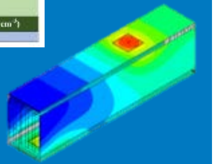


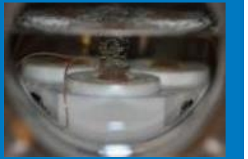


Source: Susan Rogers. 2019. "Electric Drive Technologies Program Overview." DOE Annual Merit Review, June 2019.

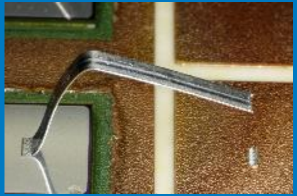
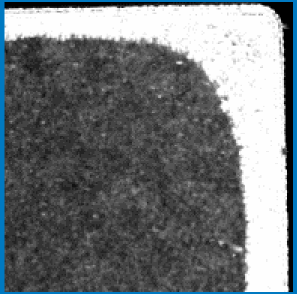
NREL APEEM Group Research Focus Areas

Power Electronics

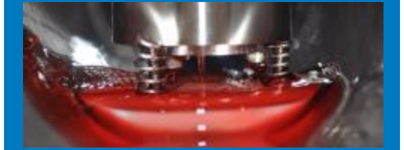
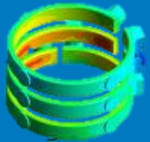





Advanced Packaging Reliability

Electric Motors

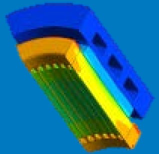
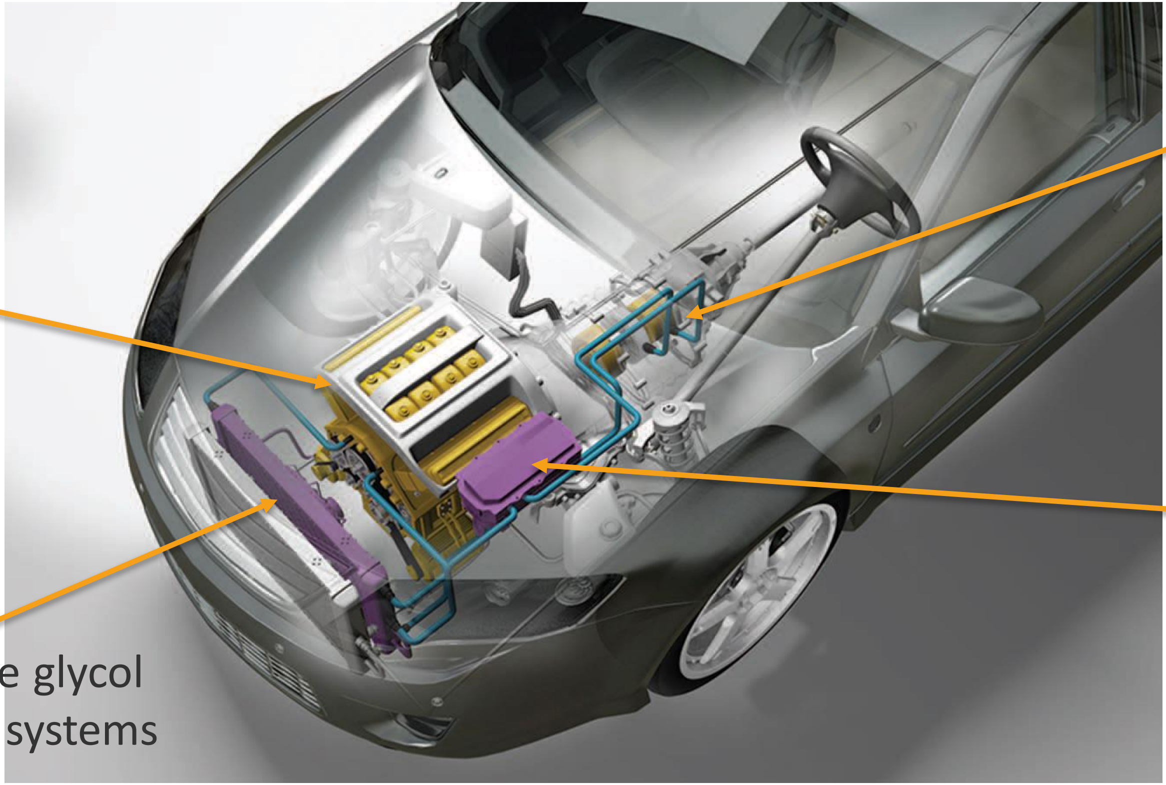


Photo credits: Mark Mihalic, Sreekant Narumanchi, Gilbert Moreno, Doug DeVoto, Bidzina Kekelia, and Kevin Bennion, NREL

Power Electronics
Thermal Management

Electric-Drive Vehicle Coolant Systems

Hybrid electric vehicle



Power electronics

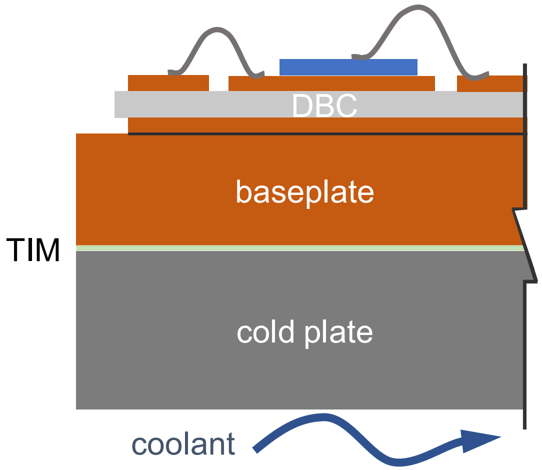
Image credit: Xuhui Feng, NREL

G. Moreno, S. Narumanchi, K. Bennion, S. Waye, and D. DeVoto. 2014. "Gaining Traction: Thermal Management and Reliability of Automotive Electric Traction-Drive Systems." *Electrification Magazine* 2 (2): 42–49. doi: 10.1109/MELE.2014.2314501.

Typical Power Module Packaging Configurations

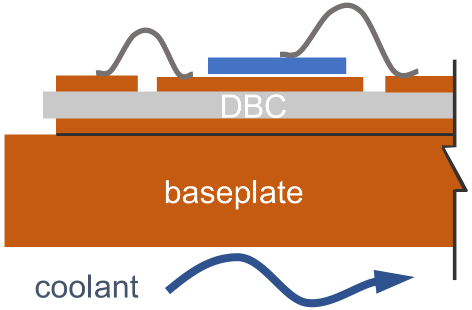
Single-side cooled

Cold plate cooled



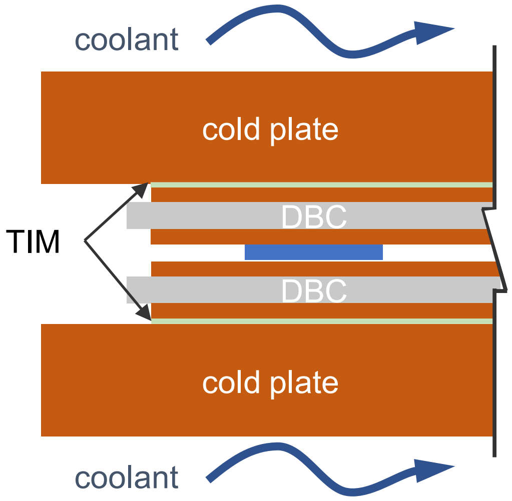
Examples:
2007 Camry HEV
2012 LEAF EV

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

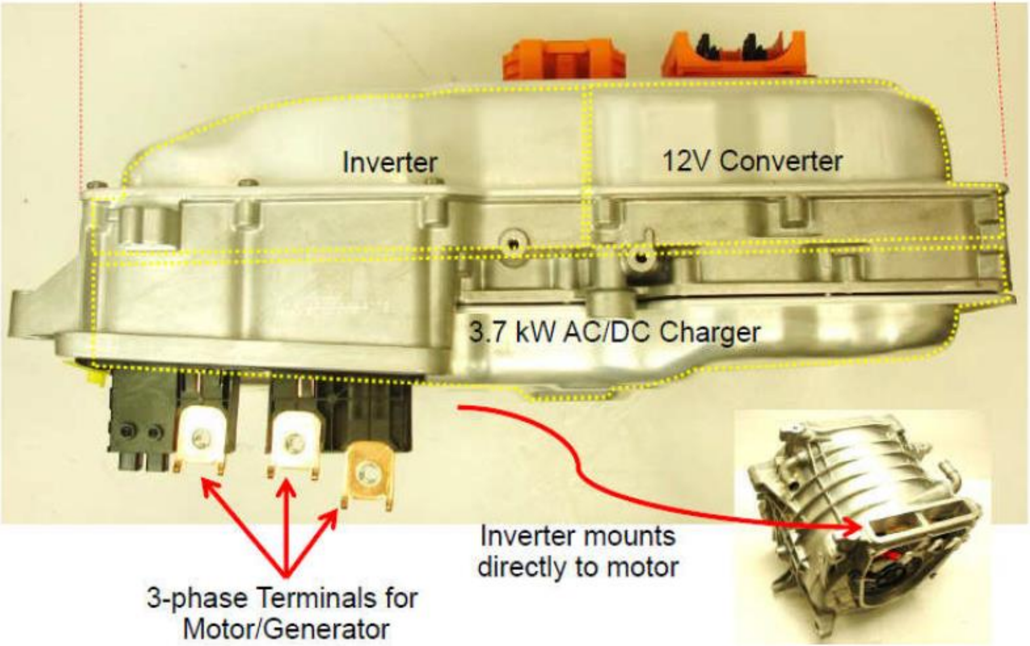
Automotive power electronics cooling trend

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: 125 kW

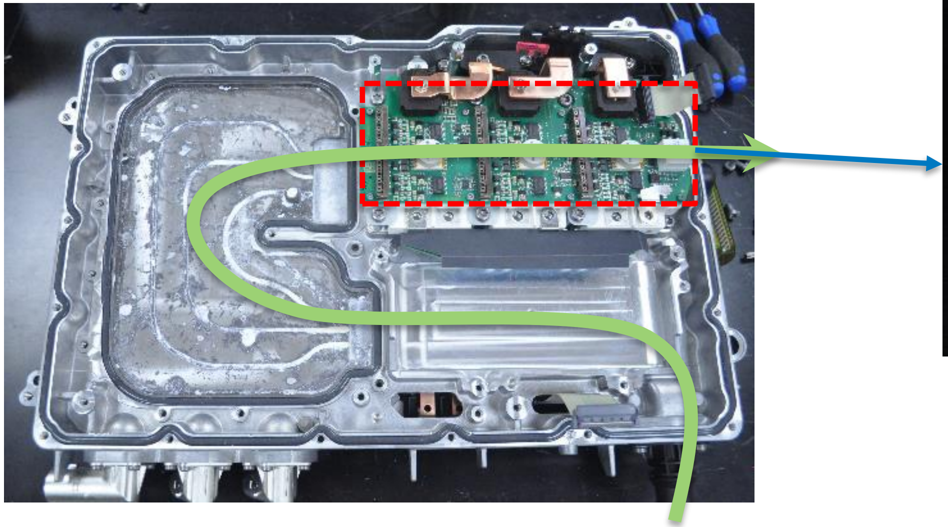
Baseplate-cooled system

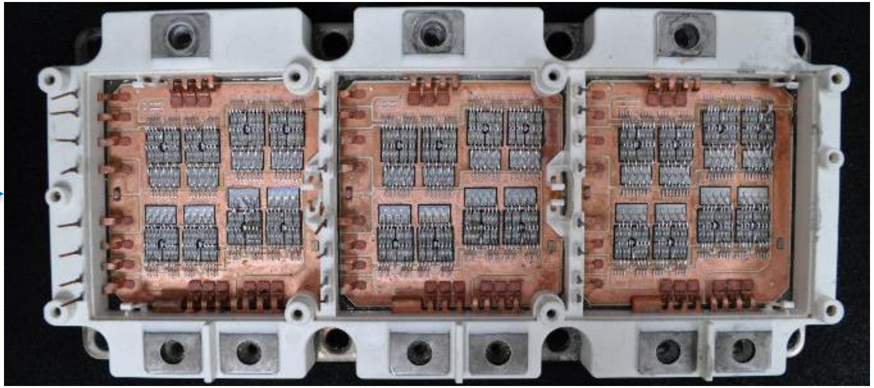


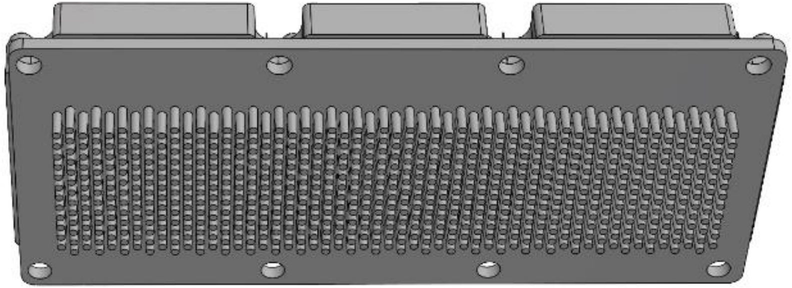
Includes traction inverter, 12-V converter, AC-DC charger

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 Heat Exchanger







Pin fins: diameter = 2.5 mm, height = 8 mm, pitch = 4.2 mm, gap between fins = 1.8 mm

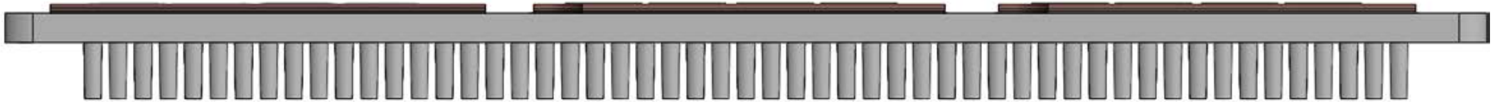
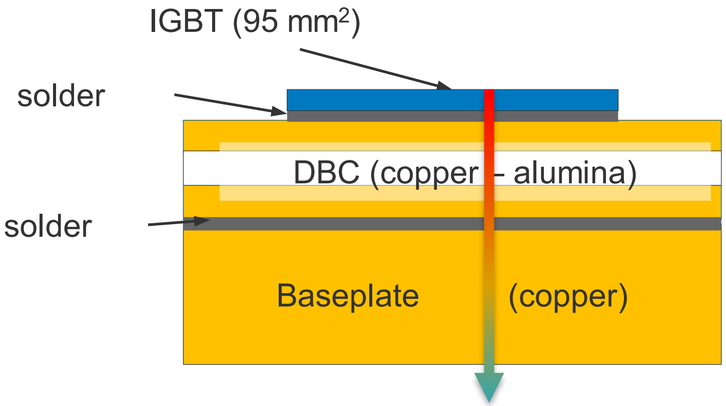
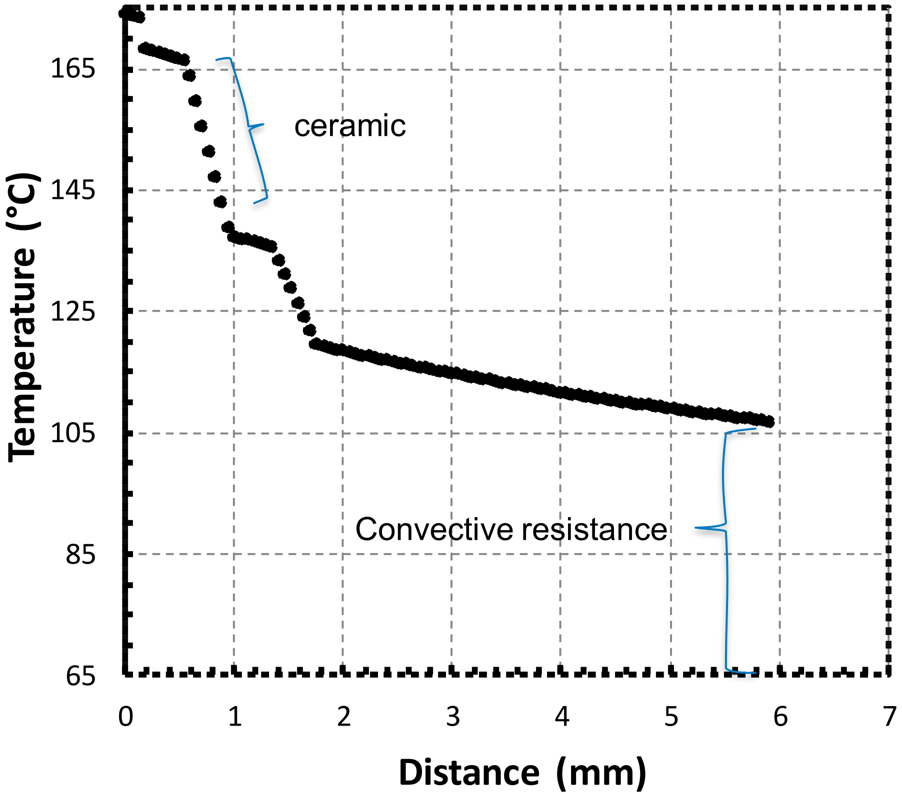


Image credits: Xuhui Feng, NREL

2015 BMW i3 EV (Baseplate Cooled)

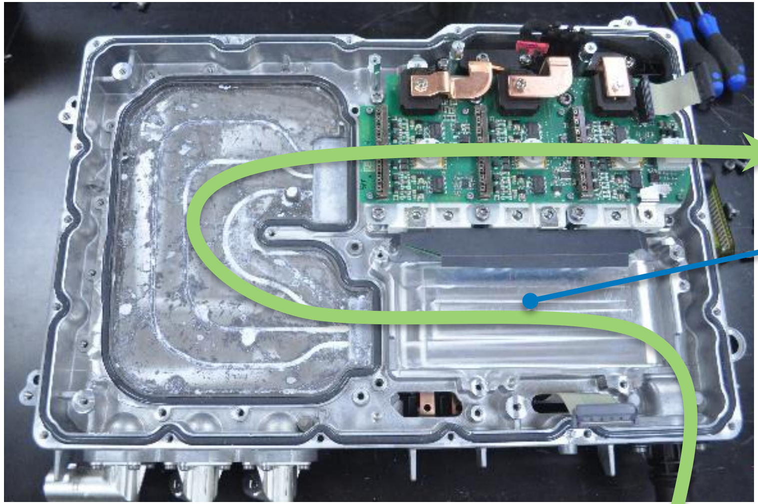


- Package conduction resistance is about 64% of the total thermal resistance.
- Ceramic makes up the largest thermal resistance within the package.
- Predicted to provide a 49-mm^2·K/W thermal resistance performance.



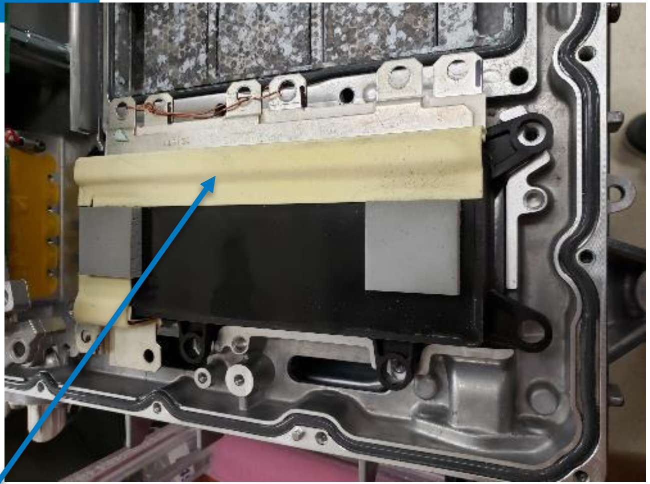
IGBT: insulated-gate bipolar transistor

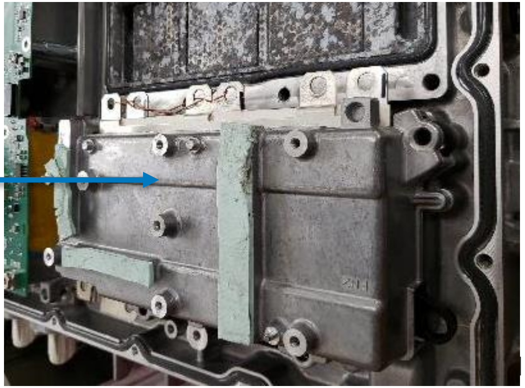
2015 BMW i3 Heat Exchanger



Fluid path

Capacitors are mounted to the liquid-cooled aluminum surface. No thermal grease is used.





DC bus bars cooled via contact to the aluminum housing and thermal interface pads

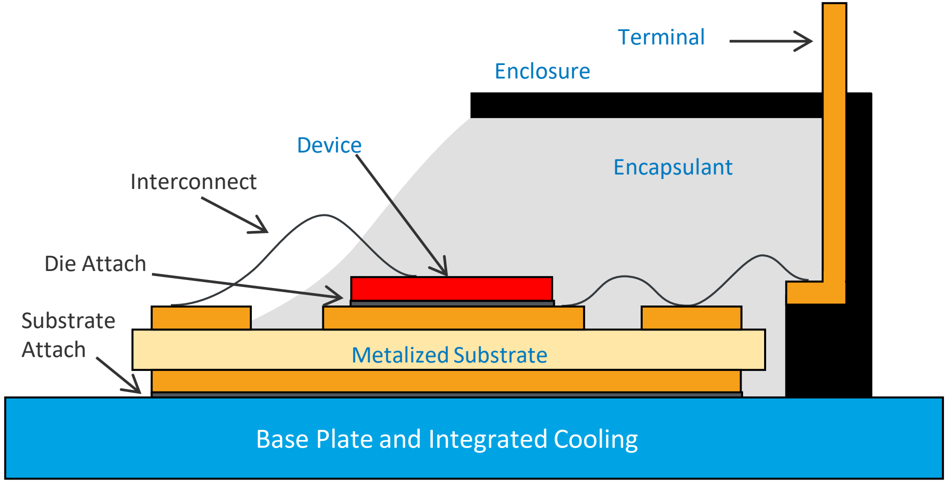
Image credits: Xuhui Feng, NREL

Advanced Cooling Technologies

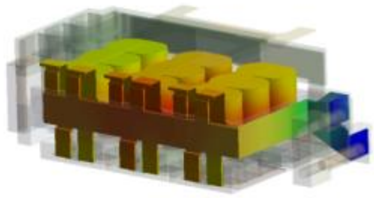
Objective: Develop thermal management strategies to reach the DOE 2025 power density target of 100 kW/L

Power Electronics Thermal-Fluids Research Pathway

- Compact, power-dense wide-bandgap (WBG)-device-based power electronics
  - Higher-temperature-rated devices, components and materials
  - Advanced heat transfer technologies
    - Single-phase WEG
    - Single-phase dielectric fluids
    - Two-phase with dielectrics and refrigerants
  - System-level thermal management.



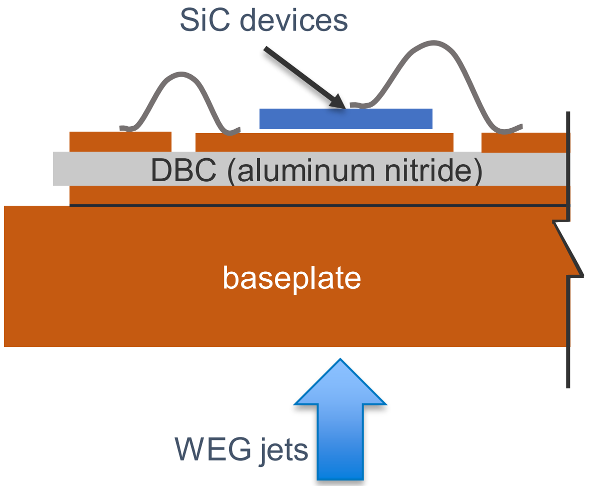
Advanced Cooling



Component-level and system-level heat transfer

Jet Impingement With WEG

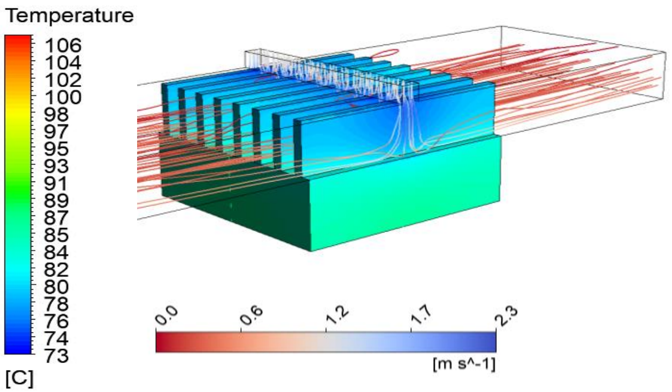
- Created a silicon carbide (SiC)-based, half-bridge module.
- Used a jet-impingement-on-module-baseplate cooling approach.
- Complied with automotive guidelines (≥1-mm channels), minimized erosion-corrosion effects, and fabricated using in-house fabrication methods (CNC milling, SLA 3D printing, and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

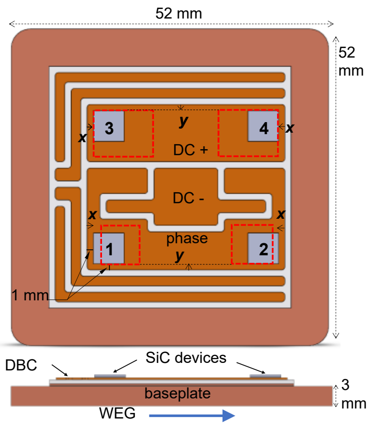


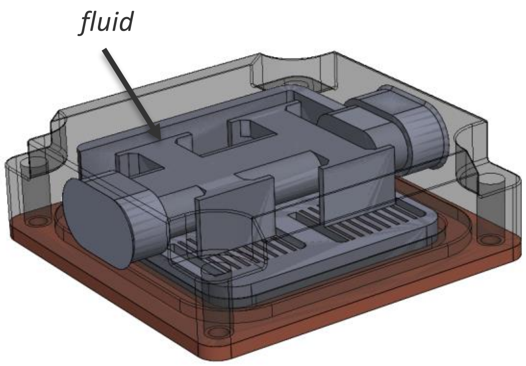
SLA: stereolithography

Jet Impingement With WEG

- 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

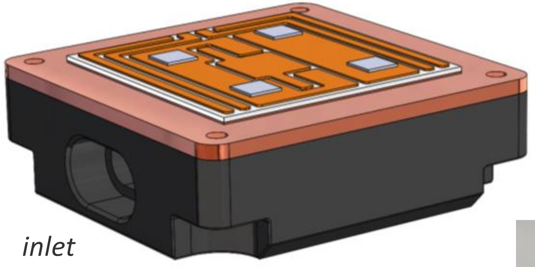
package dimensions

CFD: computational fluid dynamics, FEA: finite element analysis, HTC: heat transfer coefficient

Jet Impingement With WEG

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



inlet

SLA-printed manifold

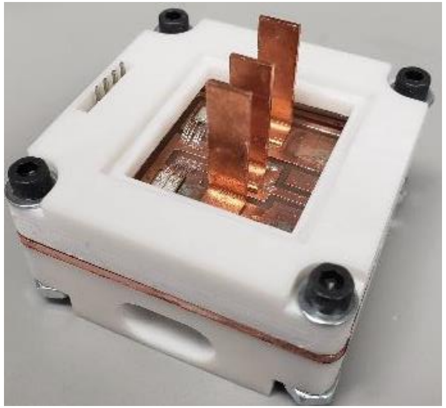
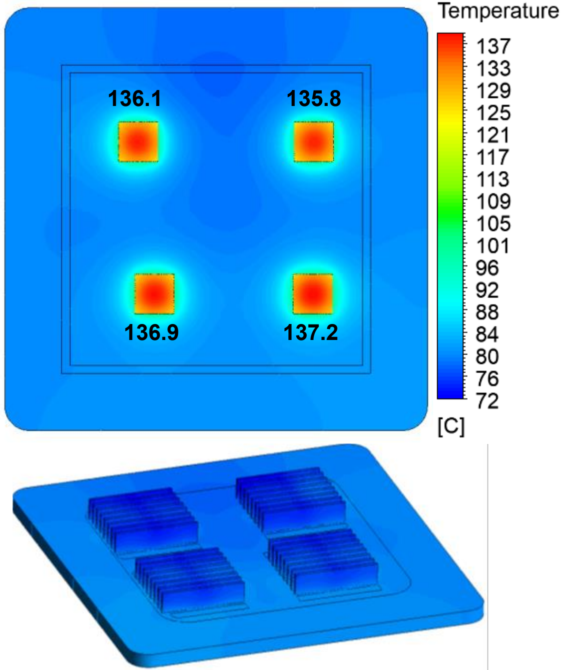


Image credit: Josh Major (NREL)

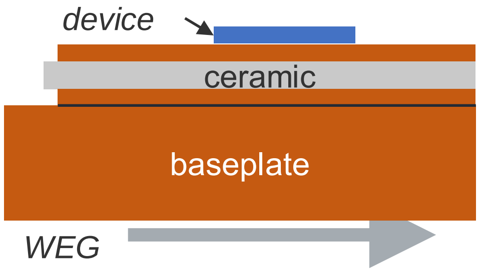


CFD-computed temperatures for 65°C fluid inlet temperature and a 433-W/cm² device heat flux

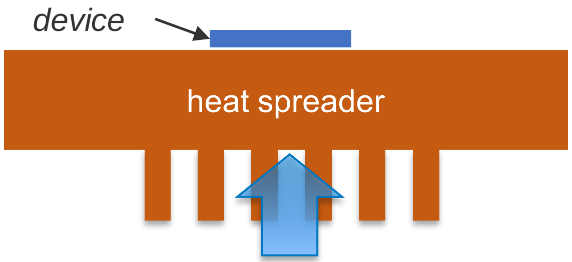
CAD: computer-aided drawing

Dielectric Fluid Cooling Concept

Conventional DBC-based module



Dielectric fluid module



dielectric fluid jets

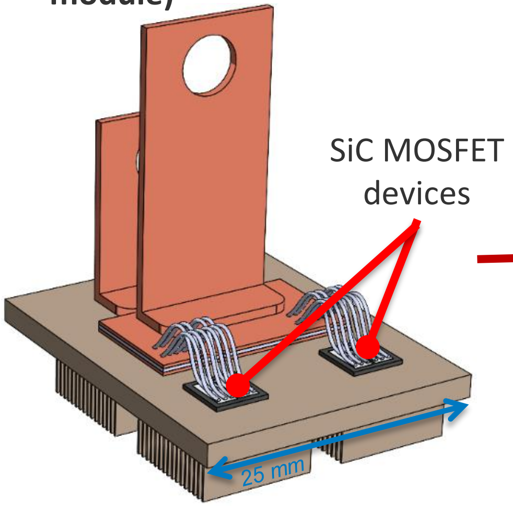
- Eliminate thermally resistive and failure-prone ceramic component.
- Reduce package resistance by 18%–43%.
- Use single-phase heat transfer.
- Developed single- and double-side-cooled configurations.

Dielectric fluid cooling may enable:

- Cooling other components (e.g., capacitors)
- Using fluids found in vehicle
- Integrating inverter with the motor

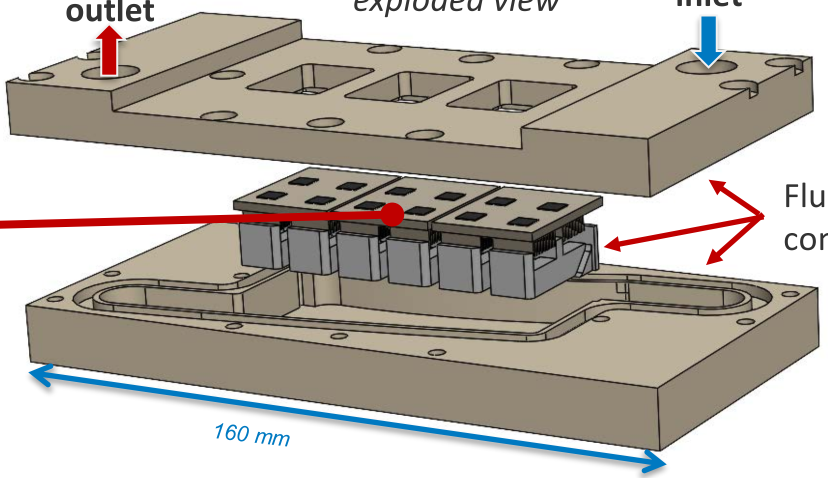
Dielectric Fluid Cooling Demonstration Using a SiC Module

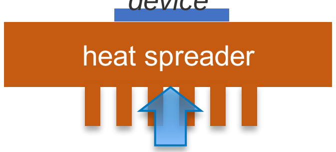
Fabricated a SiC-based module (thermal demonstration module)



cold plate/heat spreader (nickel-plated)

Installed module within dielectric fluid manifold/heat exchanger



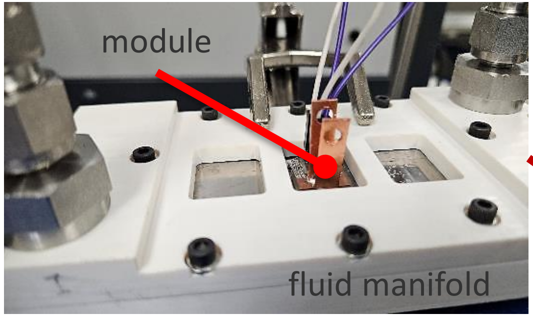


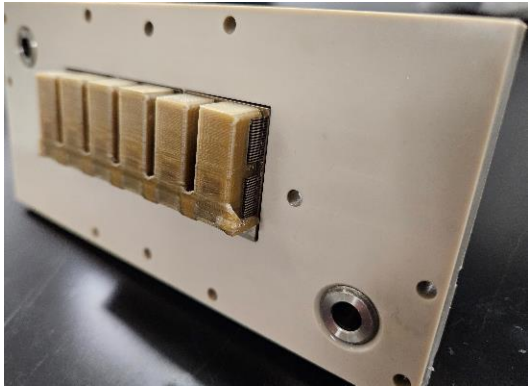
MOSFET: metal–oxide–semiconductor field-effect transistor

G. Moreno, S. V. J. Narumanchi, K. S. Bennion, R. M. Kotecha, P. P. Paret, and F. Xuhui. 2020. "Jet Impingement Manifolds for Cooling Power Electronics Modules." Non-Provisional Patent Application 17/084,236, filed October 2020.

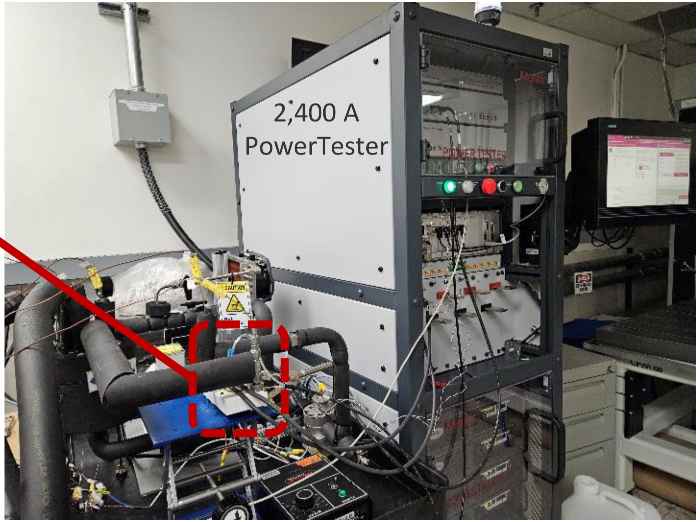
Dielectric Fluid Cooling Demonstration Using a SiC Module

Module and heat exchanger





Dielectric fluid loop and PowerTester



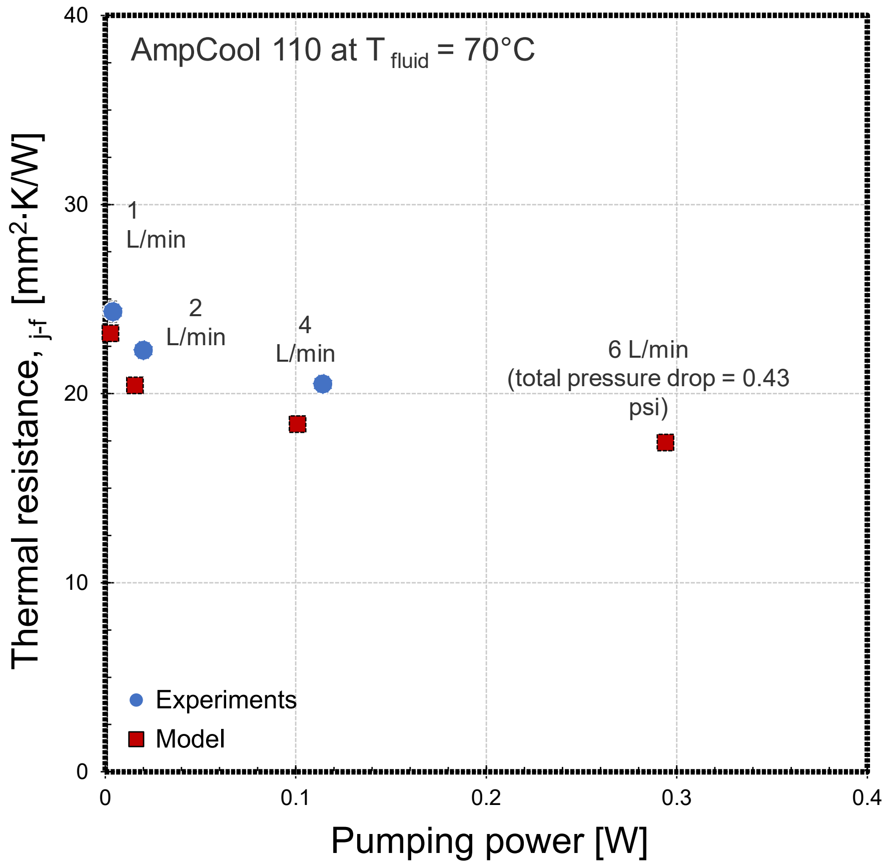
Dielectric fluid loop circulating AmpCool 110

Process:

1. Calibrate to obtain temperature versus body-diode voltage drop correlation using small-sense current.
2. Apply power pulse to devices to steady-state conditions.
3. Turn off the power pulse and measure device temperatures via voltage measurements.
4. Repeat process for various test conditions (e.g., flow rates).

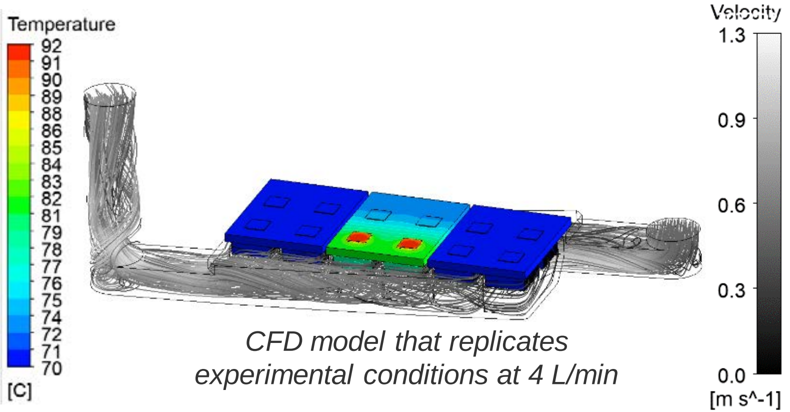
Image credit: Gilbert Moreno (NREL)

Dielectric Fluid Cooling Demonstration Using a SiC Module



Experimental results and comparisons to model predictions

- Applied 116-W/cm^2 heat flux for both devices using 75 amps.
- Model predictions in agreement with experimental results
  - Maximum deviation is ~10% for the thermal resistance.

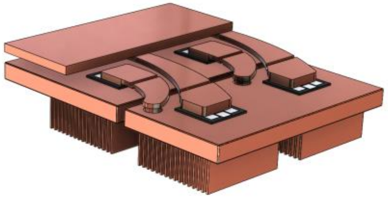


CFD model that replicates experimental conditions at 4 L/min

j–f: junction-to-fluid

Dielectric Fluids (Single Phase)

Single-side cooled



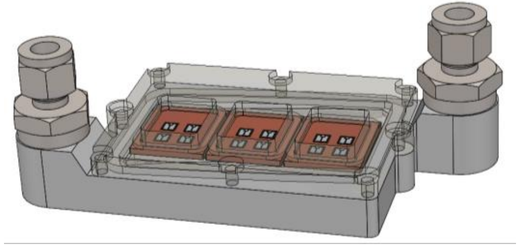
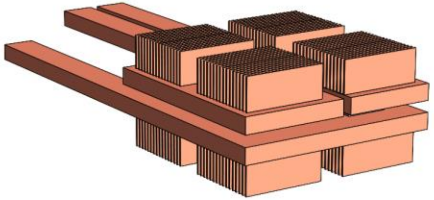
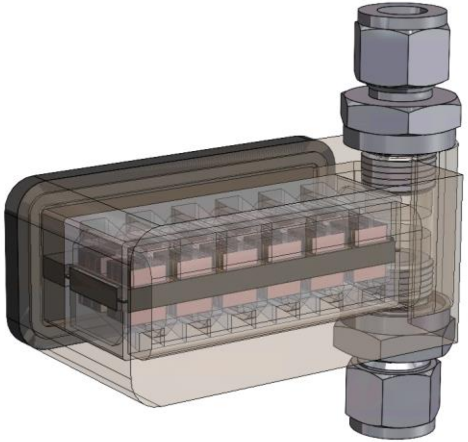


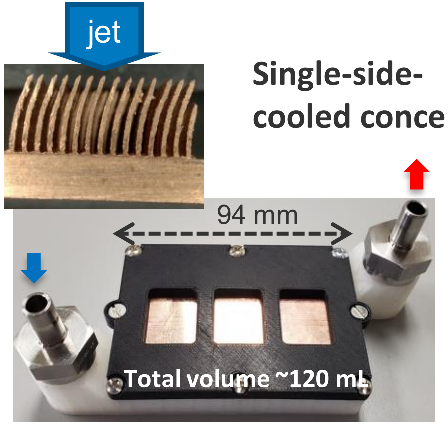
Image credit: Gilbert Moreno, NREL

Double-side cooled



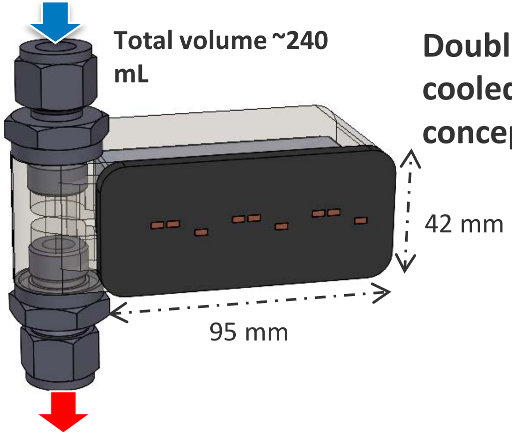


Dielectric Fluids (Single Phase)



Single-side-cooled concept

Image credit: Gilbert Moreno, NREL



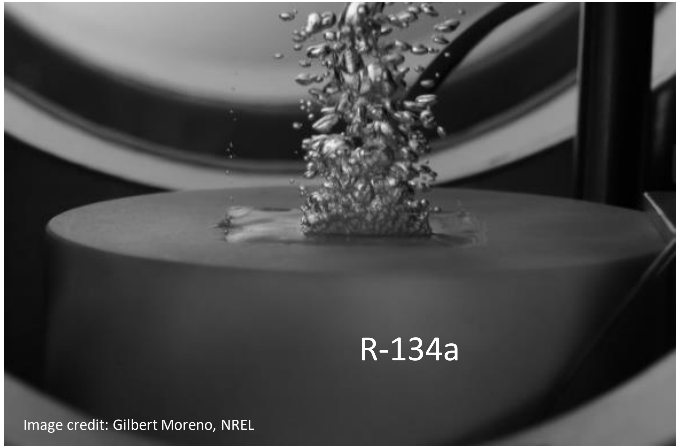
Double-side-cooled concept

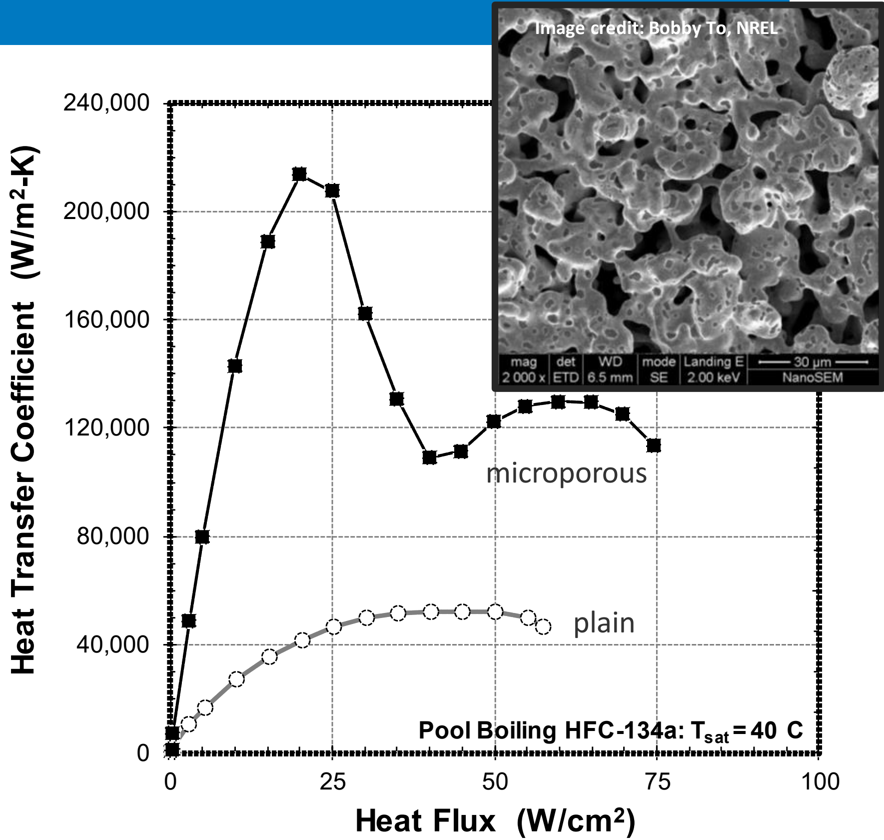
* Estimates assuming T_{fluid} = 70°C

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/m²·K on smooth (and no fins) surfaces.
- Measured HTCs >200,000 W/m²·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.

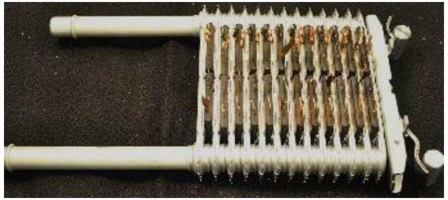




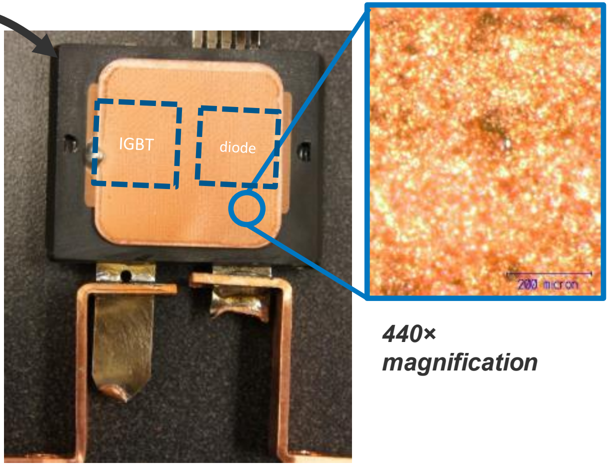
CHF: critical heat flux

Two-Phase Cooling: Immersion Cooling of a Module

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

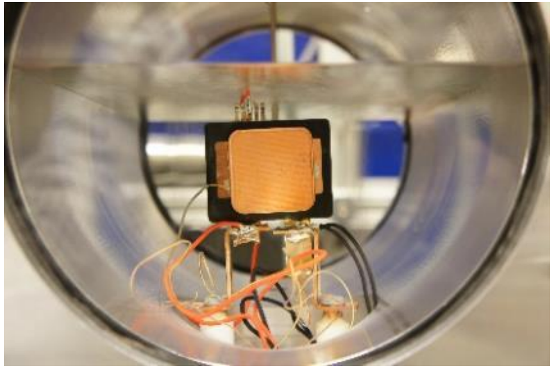


Used a module from the 2008 Lexus



440× magnification

Applied microporous coating to the module

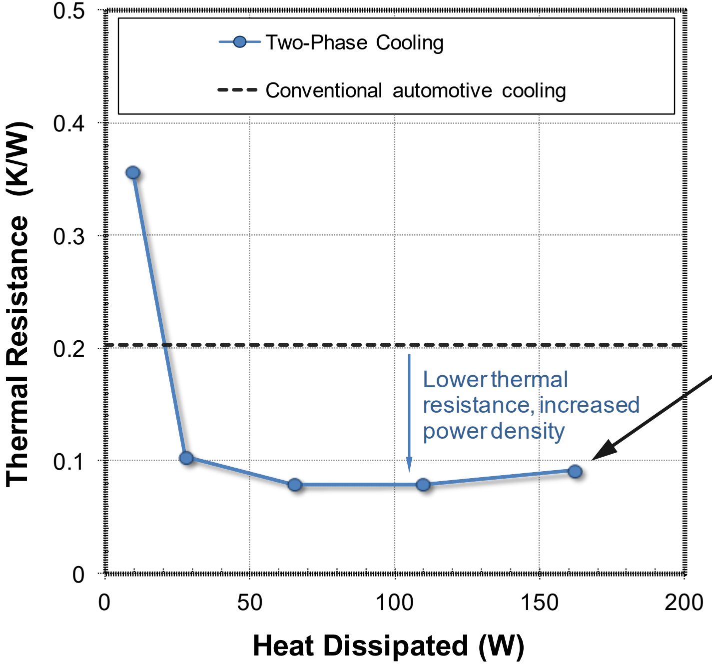


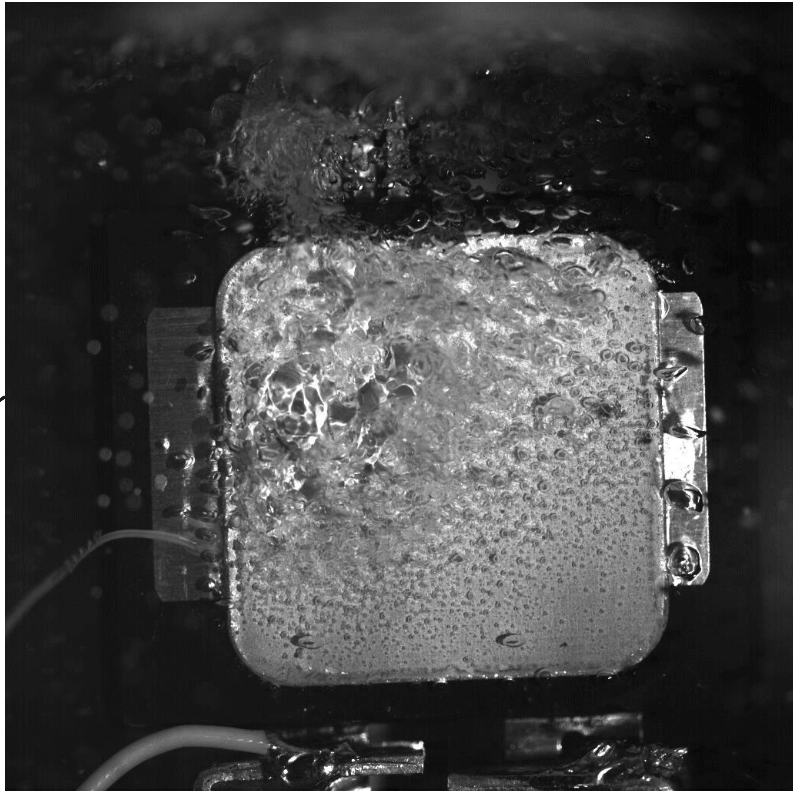
Immersed the module in HFE-7100 fluid

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.



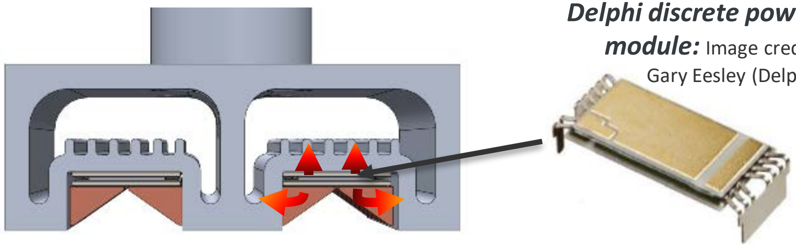


Immersion cooling: HFE-7100 refrigerant

Image credits: Gilbert Moreno, NREL

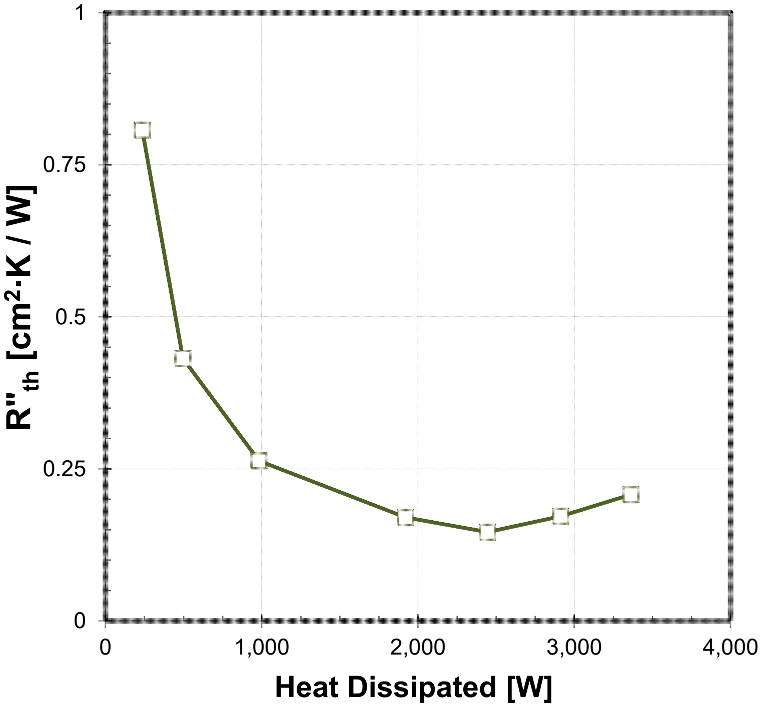
Two-Phase Cooling: Indirect Cooling Concept

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



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

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



- 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.

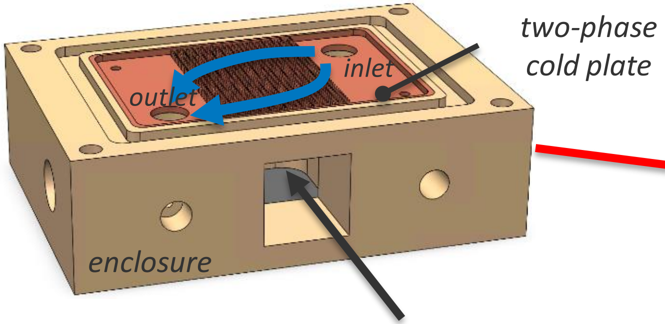
Collaborating With Georgia Tech To Evaluate Two-Phase Cooling Strategies

Georgia Tech (Dr. Yogendra Joshi) is developing two-phase-based power electronics cooling systems

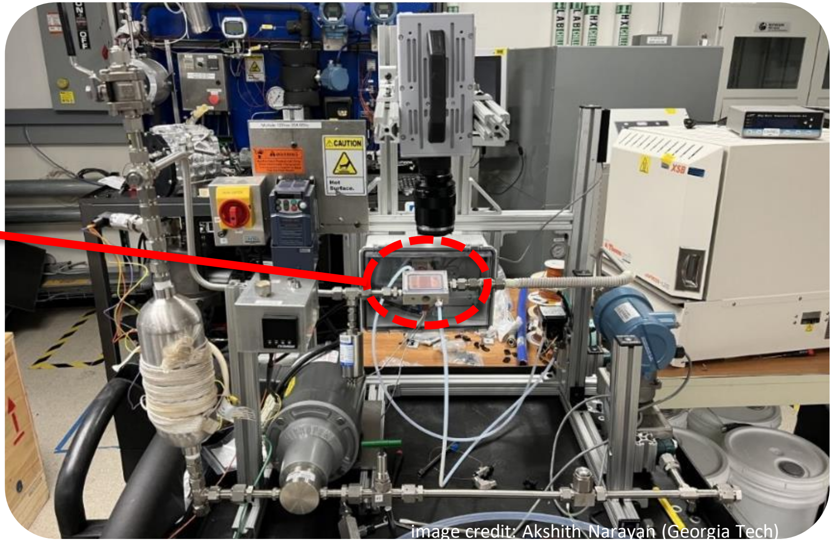
- Two-phase HTC can be >100,000 W/m^2·K.

NREL helped design and fabricate the experimental apparatus used for the experimental demonstration

- Georgia Tech graduate intern at NREL conducted experiments.

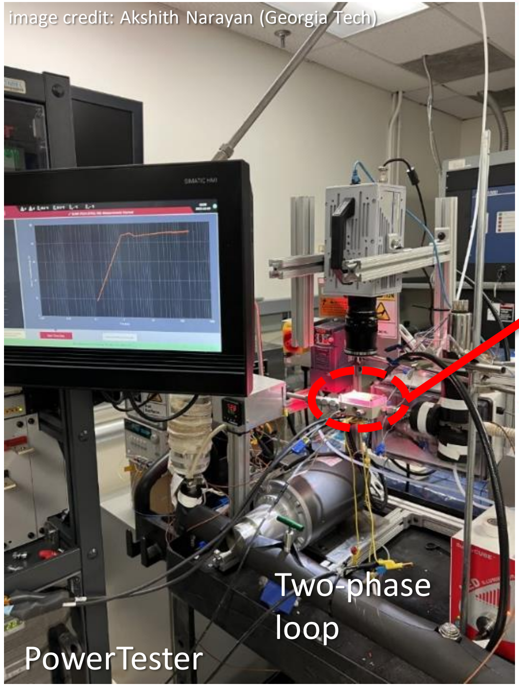


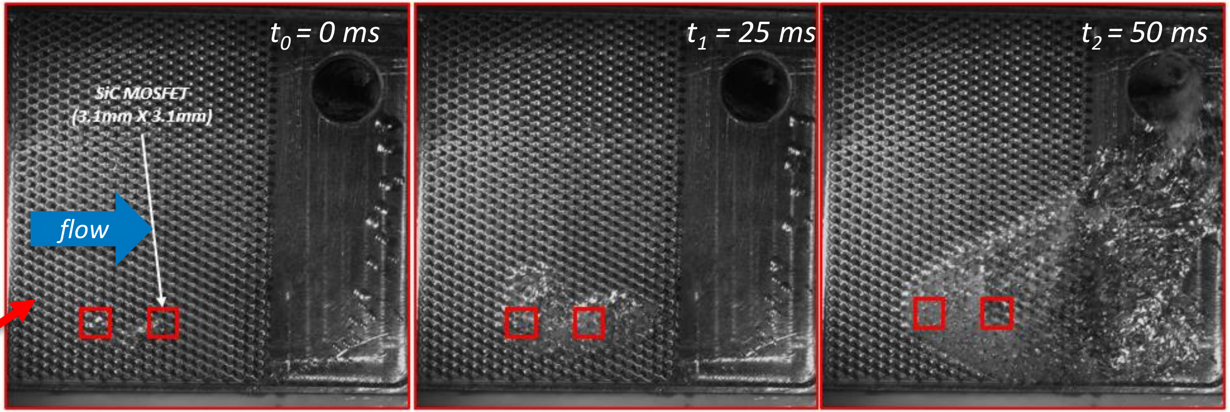
1. Cartridge heaters
2. SUNY Polytechnic Institute SiC MOSFET devices



Two-phase fluid loop with HFE-7200

Collaborating With Georgia Tech To Evaluate Two-Phase Cooling Strategies





Visualization of incipience boiling of HFE7200 over pin-fins at 635-W/cm² device heat flux

- Completed experiments with both resistive heaters and SiC devices.
- Achieved:
  - Heat fluxes as high as 934 W/cm^2.
  - Thermal resistance values as low as 12.8 $mm^2{\cdot}K/W$.
  - Pumping power of 0.08 W (1 L/min at 0.7 psi).

Power Electronics Materials and Component Reliability

Advanced Power Electronics Packaging Performance and Reliability – Research Pathway

- Improve reliability of new (high-temperature/wide-bandgap) technologies.
- Develop predictive and remaining lifetime models.
- Package parametric modeling—design for reliability.

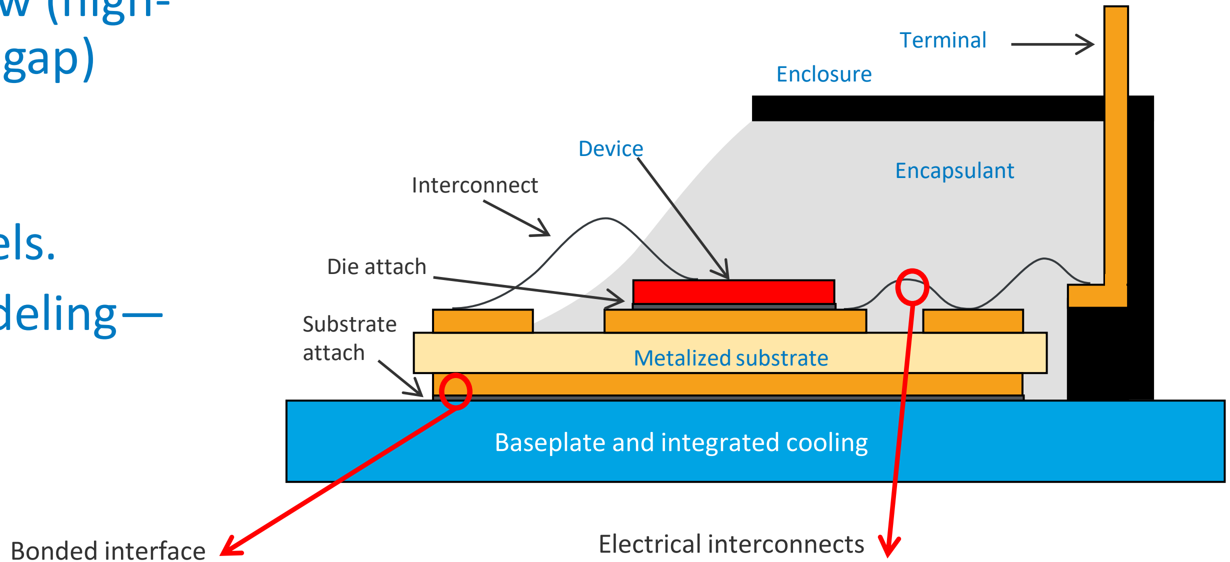


Photo credit: Paul Paret, NREL

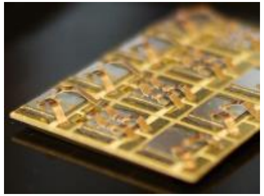
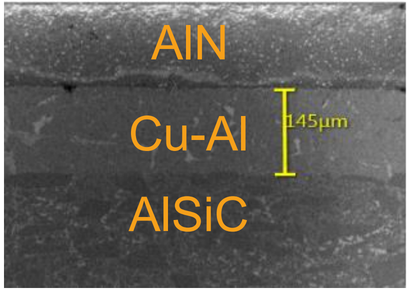


Photo credit: Doug DeVoto, NREL

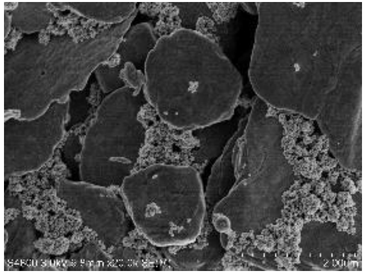
Materials, Bonded Interfaces

High-temperature bonded material

- Georgia Tech
  - Cu/Al, Cu/Sn
- Virginia Tech
  - Sintered silver
    - Pressureless
    - Low-pressure-assisted
      - 3 MPa
      - 10 MPa
- Institute for Innovative Mobility
  - Sintered copper
- NREL
  - Sintered silver (industry)
    - Pressureless
- ADA Technologies
  - HM3/HM4



Cu-Al bond—scanning electron microscope image. *Image credit: Darshan Pahinkar*

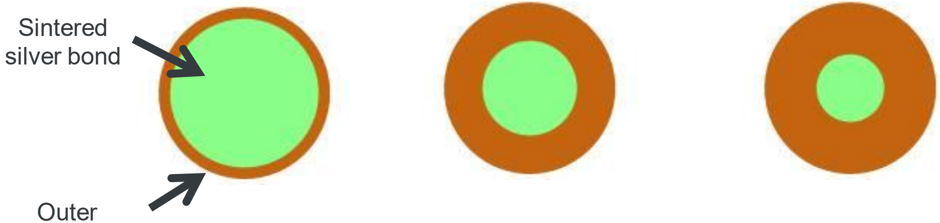


Hybrid-silver—scanning electron microscope image. *Image credit: Yansong Tan*

Approach – Reliability Evaluation of Bonded Interfaces

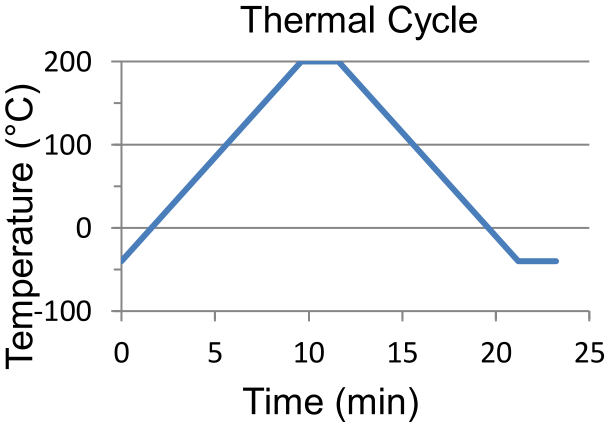
1-inch-diameter copper and Invar coupons: non-plated (top), plated with 4-μm-thick silver (bottom)

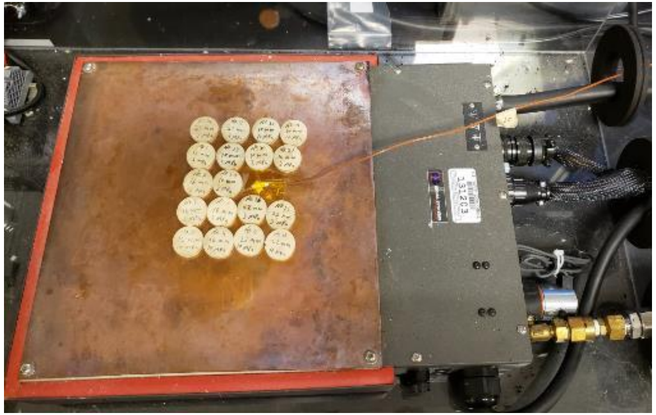
Sample structure



Samples with three different bond diameters were fabricated: 22 mm (left), 16 mm (center), and 10 mm (right)

Accelerated thermal cycling





Samples placed on thermal platform for thermal cycling; C-mode scanning acoustic microscope images of these samples are taken periodically.

Photo credits: Paul Paret, Josh Major, Doug DeVoto, NREL

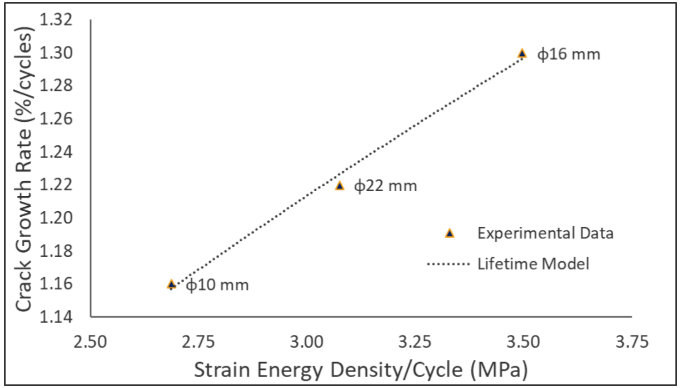
Lifetime Model of Sintered Silver

- Sintered silver exhibited predominantly adhesive fracture under thermal cycling experiments.
- Correlated the crack growth rate measurements with the modeling results of strain energy density per cycle.
  - Formulated the lifetime prediction model.
- The lifetime prediction model incorporates the thermomechanical degradation of sintered silver at 200°C.

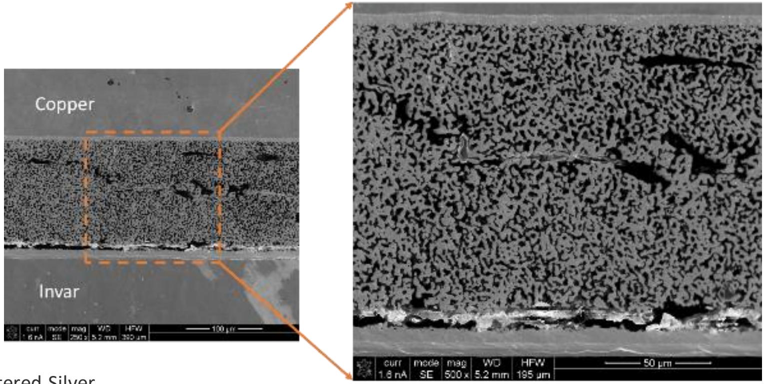
$$\frac{dA}{dN} = 0.76\, \Delta W^{0.431}$$

$\frac{dA}{dN}$ = crack growth rate, ΔW = strain energy density/cycle

- Power electronics packaging design engineers can use the lifetime model to estimate and improve the reliability of high-temperature packages.



Lifetime prediction model



Source: P. Paret, J. Major, D. DeVoto, S. Narumanchi, C. Ding, and G.-Q. Lu. 2021. "Reliability and Lifetime Prediction Model of Sintered Silver under High-Temperature Cycling." *IEEE Journal of Emerging and Selected Topics in Power Electronics.* DOI: 10.1109/JESTPE.2021.3121195.

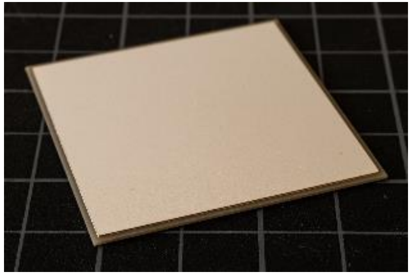
Failure mechanisms in sintered silver

Substrates Research

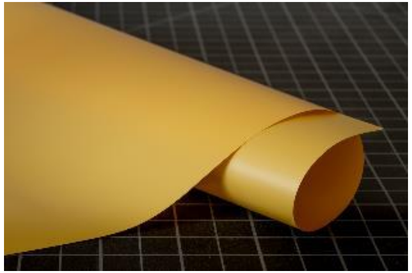
- **Alternative electrically insulated substrate designs are required to enable reliable packages that operate with higher power densities and higher temperatures.**

- Traditional metalized ceramic substrate technologies:
  - DBC.
  - Active metal bonding.

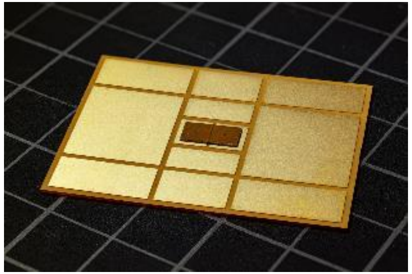
- Organic direct-bond copper (ODBC)
  - A polyimide dielectric is bonded with metal through elevated temperature and pressure.
  - No limitations in metal material or metallization thickness.



Traditional substrate



DuPont Temprion polyimide film



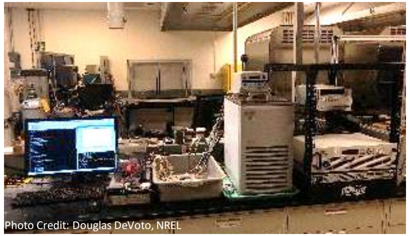
DuPont ODBC substrate

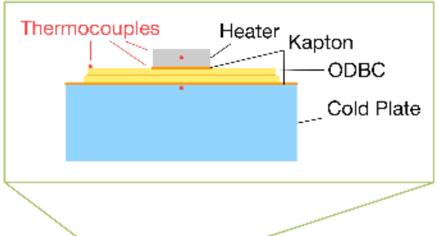
Photo credits: Doug DeVoto, NREL

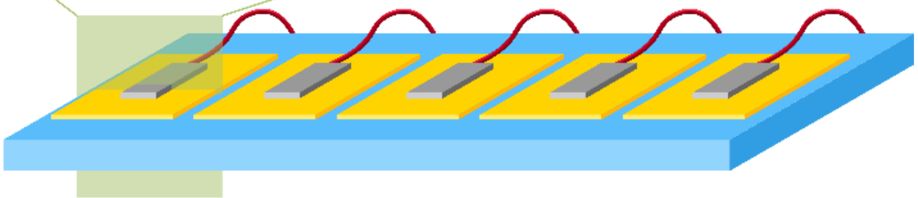
ODBC Reliability

- Thermal shock: −40°C to 200°C, 5-minute dwells.
- Thermal aging: 175°C.
- Power cycling: 40°C to 200°C.
- ODBC substrates reached 5,000 thermal shock cycles, 1,900 thermal aging hours, and 2,200 power cycles.
- No significant decrease in electrical or thermal performance was observed.

Substrates undergoing aging





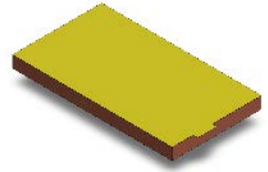


Power cycling test setup

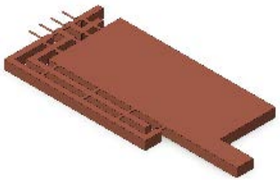
Advanced Power Electronics Packaging Concepts

Advanced Packaging Incorporating ODBC

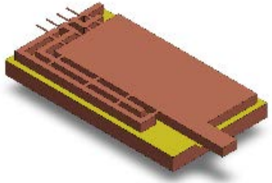
- Simplified packaging process has been envisioned with ODBC substrates in a double-side-cooled module.



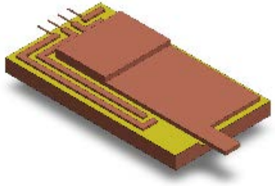
1. *Bond lower Temprion layer to lower cold plate.*



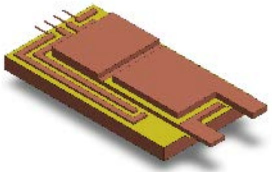
2. *Etch bottom face of drain busbar and traces.*



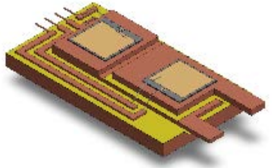
3. *Bond drain busbar and traces to lower Temprion layer.*



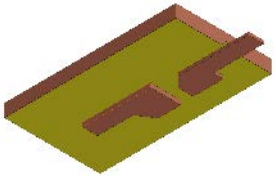
4. *Etch top face of drain busbar and traces.*



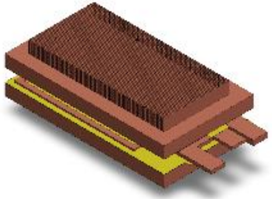
5. *Bond middle Temprion layer and output 2 busbar.*



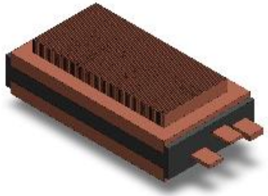
6. *Sinter and wire bond devices.*



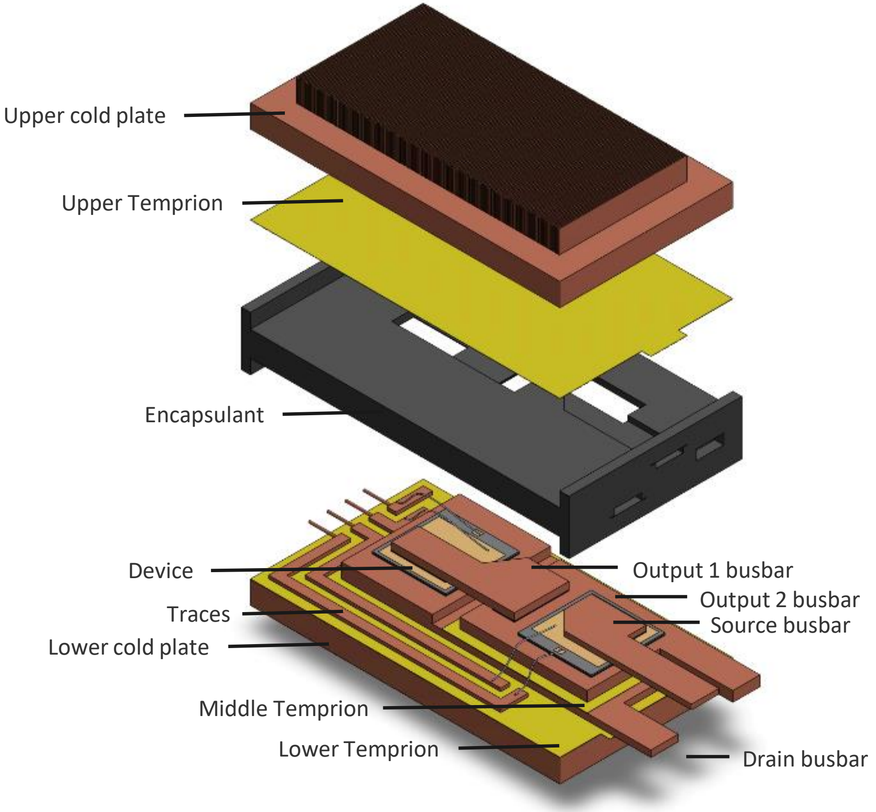
7. *Bond output 1 and source busbars to upper Temprion and upper cold plate.*



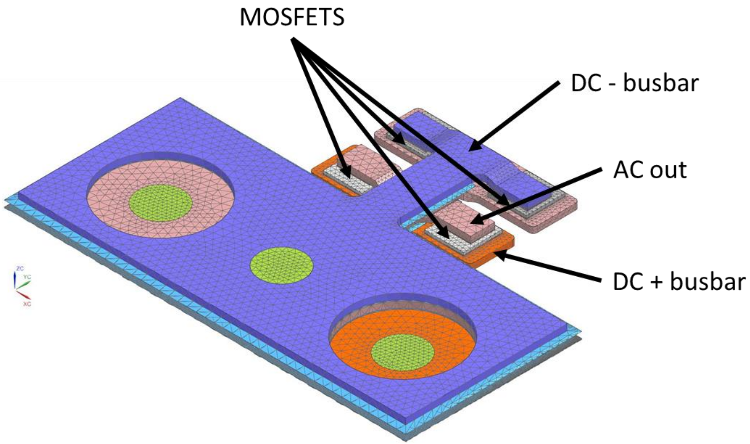
8. *Sinter previous assembly to devices.*



9. *Fill cavity with encapsulant.*



Advanced Packaging Incorporating ODBC



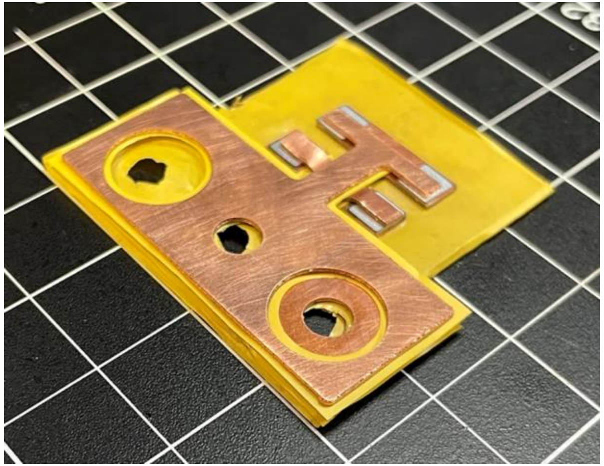
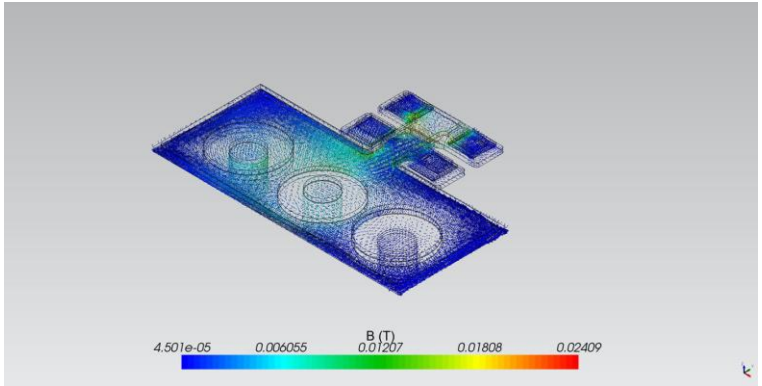
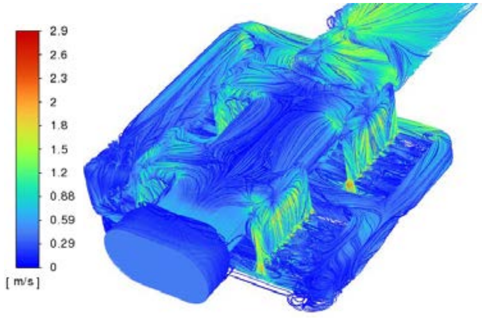


Photo credit: Joshua Major

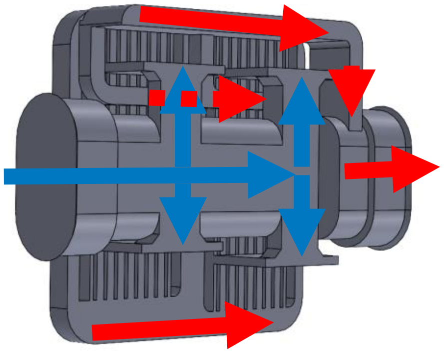


Intelligent Power Module Development

We have fabricated a proof-of-concept half-bridge SiC MOSFET protype capable of working at 650V and 236A continuous current. We have used bare SiC dies obtained from ROHM.

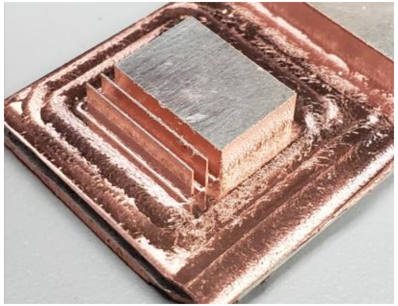


CFD-computed velocity streamlines

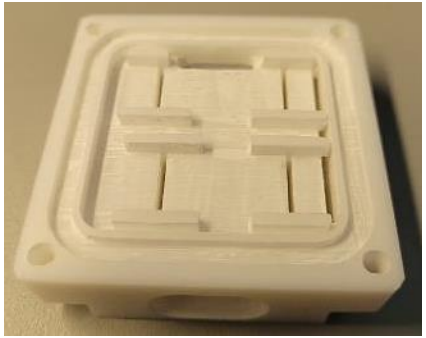


Coolant manifold

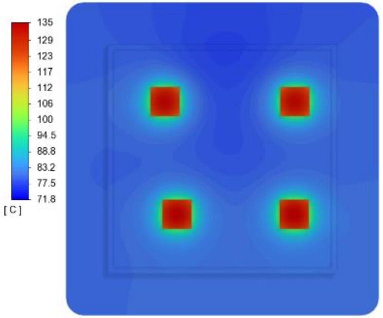
In-house heatsink design



In-house 3D printed casing

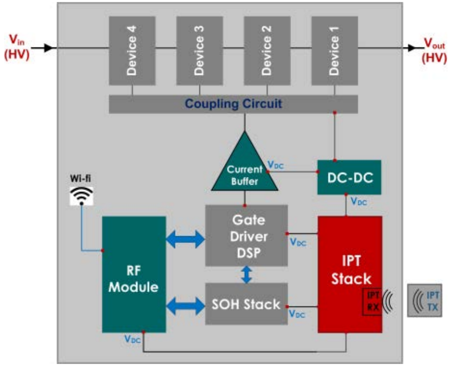


Optimized device placement

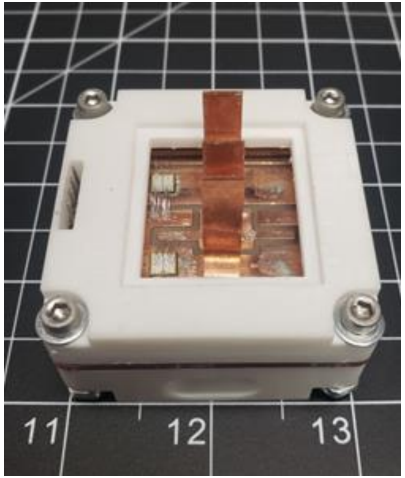


G. Moreno, J. Major, D. DeVoto, F. Khan, S. Narumanchi, X. Feng, and P. Paret, **"THERMAL OPTIMIZATION OF A SILICON CARBIDE, HALF-BRIDGE POWER MODULE," Proceedings of the ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems InterPACK2022**

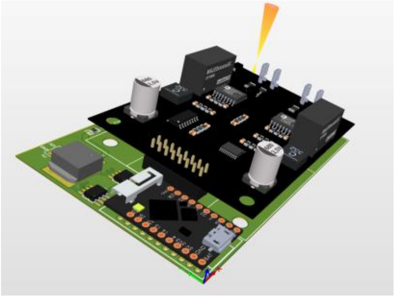
Intelligent Power Module Development (Cont.)

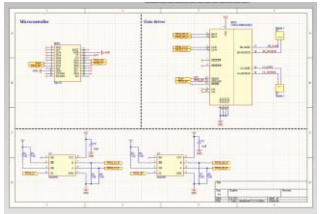


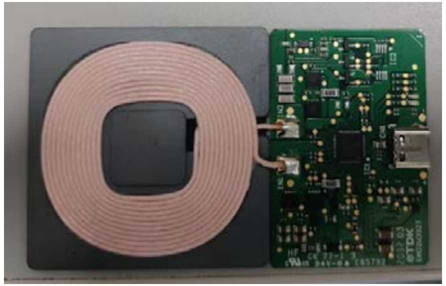
The module has been tested for basic device characteristics, PWM over wi-fi and WPT power architecture.



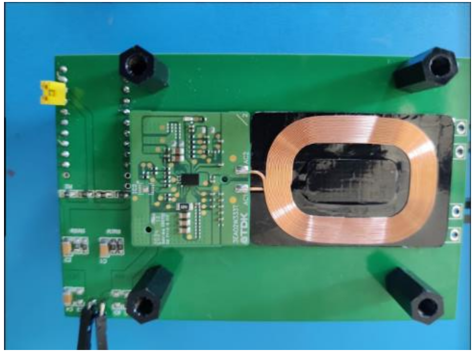
Completed power module



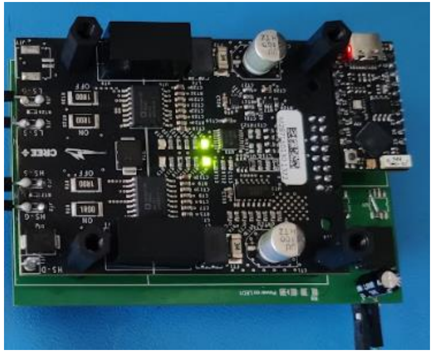




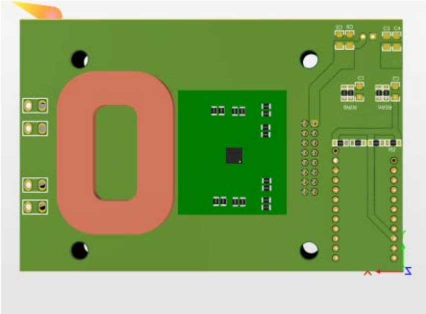
WPT transmitter module



In-house designed motherboard and WPT module



Working prototype



Board layout and schematic

Thermal Management of Electric Motors and Integrated Electric (Traction) Drive Systems

Electric Motor Thermal Management – Research Pathway

- Understand and evaluate material and interface properties as a function of temperature.
- Develop and evaluate advanced fluid-based cooling strategies.
- Use modeling to guide advanced motor design and development.

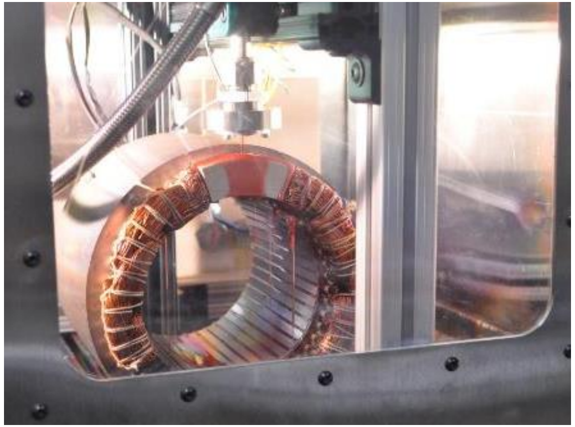
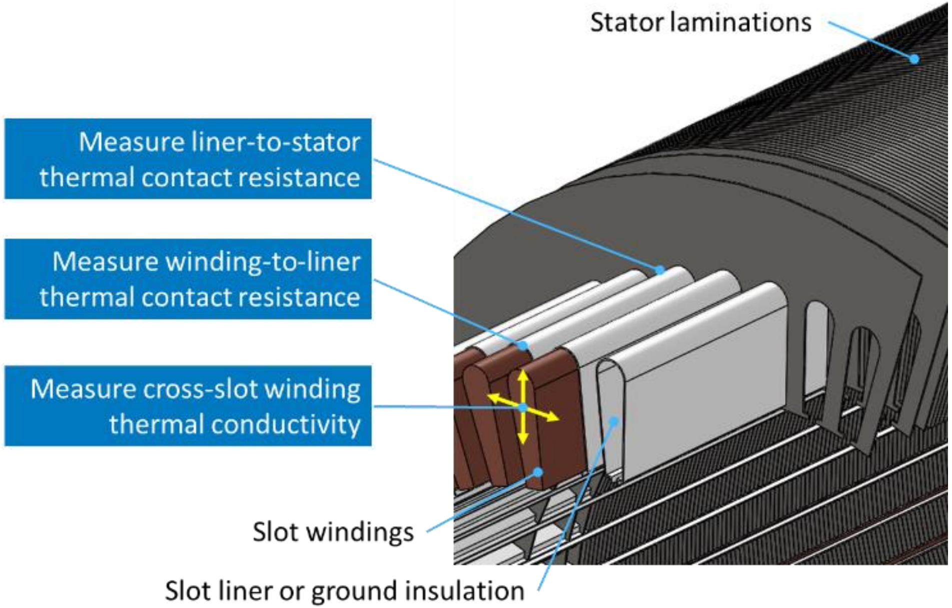
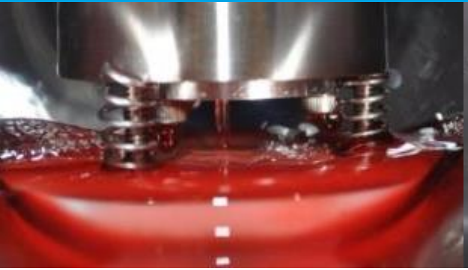


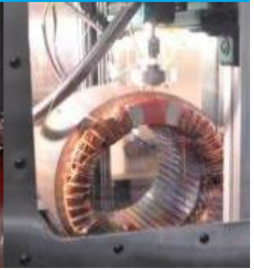
Photo credit: Bidzina Kekelia, NREL

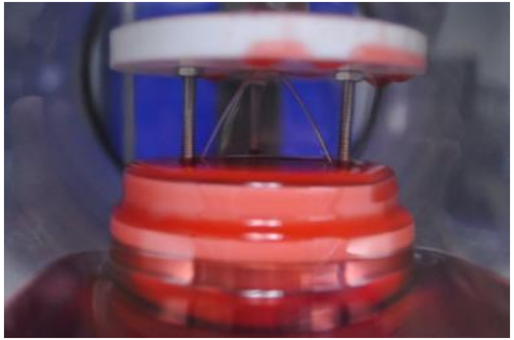


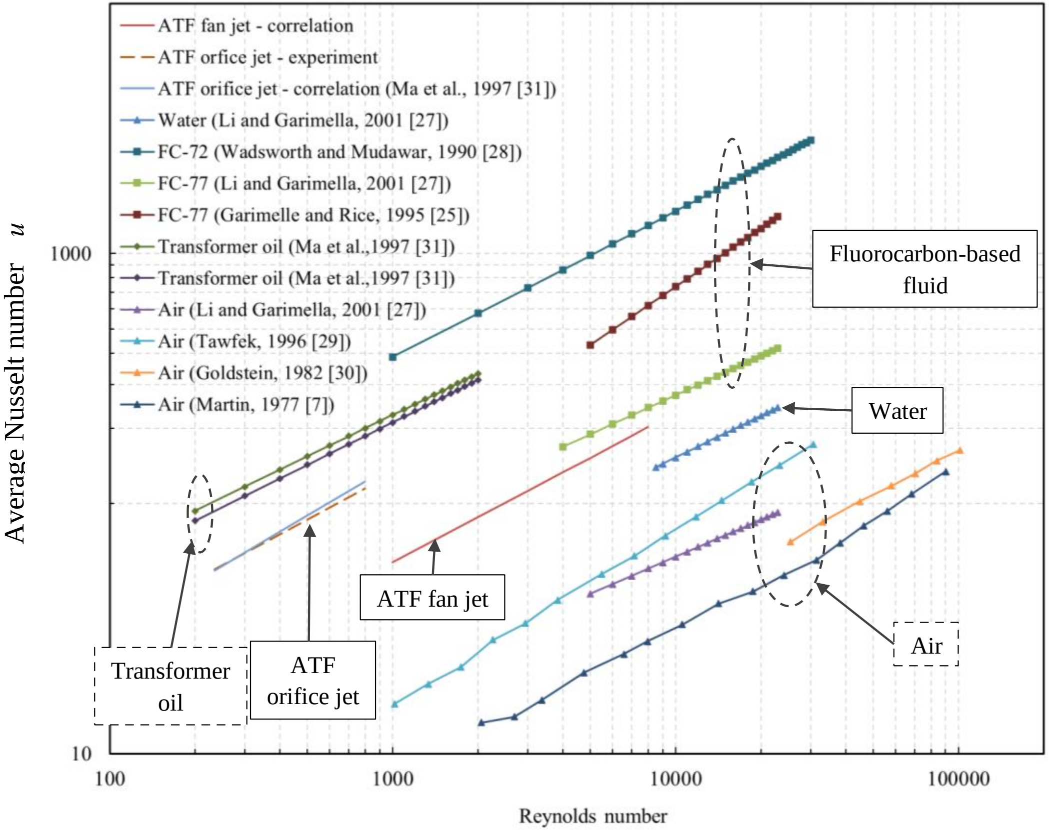
Automatic Transmission Fluid (ATF) Jet Impingement

Direct impingement cooling for motor windings



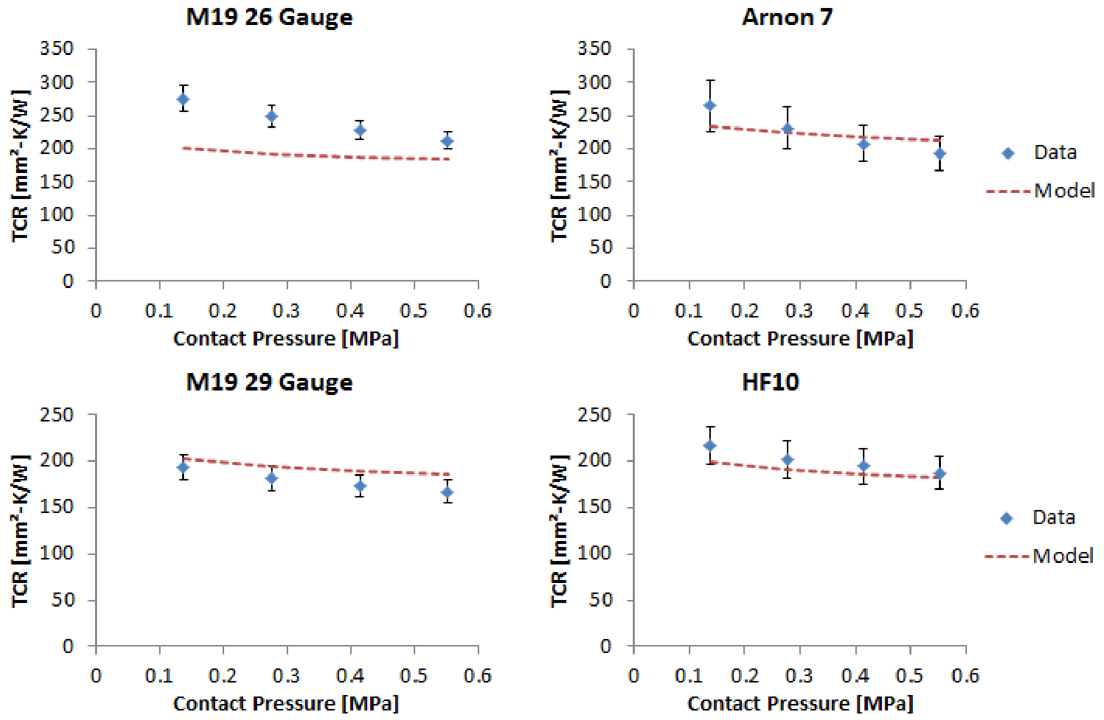






Source: X. Feng, E. Cousineau, K. Bennion, G. Moreno, K. Kekelia, and S. Narumanchi. 2021. "Experimental and numerical study of heat transfer characteristics of single-phase free-surface fan jet impingement with automatic transmission fluid." *International Journal of Heat and Mass Transfer* 166: 120731.

Motor Lamination Thermal Contact Resistance



- Validated model with experimental data using multiple materials.
- $R_{air} = \delta / k_{air}$
  $\delta = 1.53\sigma_{RMS}(P/H)^{-0.097}$
  $R_C = (\delta + t_{C5})/k_{air}$

TCR: thermal contact resistance

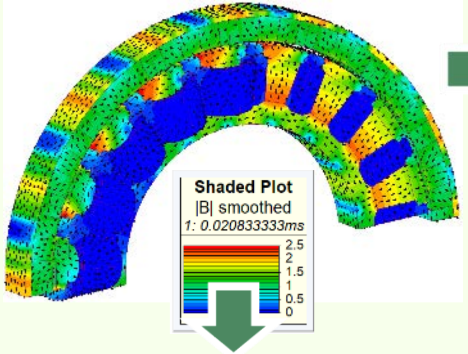
Source: J. E. Cousineau, K. Bennion, D. DeVoto, and S. Narumanchi. 2019. "Experimental Characterization and Modeling of Thermal Resistance of Electric Machine Lamination Stacks." *International Journal of Heat and Mass Transfer* 129: 152–159.

Electric Motor Modeling and Design

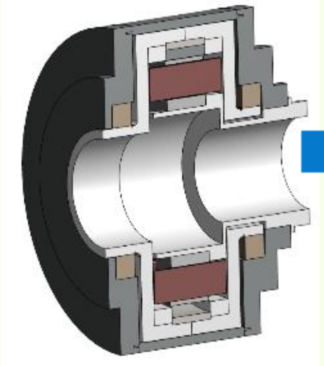
Electromagnetic, mechanical, and thermal design

Oak Ridge National Laboratory (ORNL)

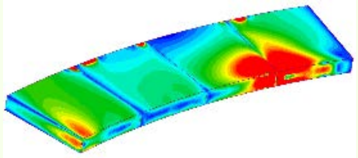
Electromagnetic design



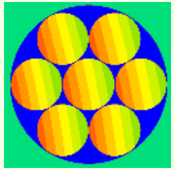
Mechanical assembly design



Loss evaluation



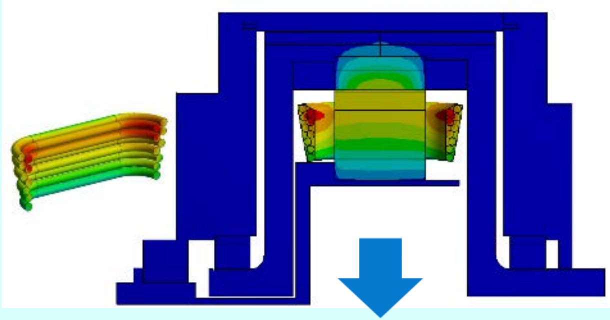
Permanent magnet eddy current loss



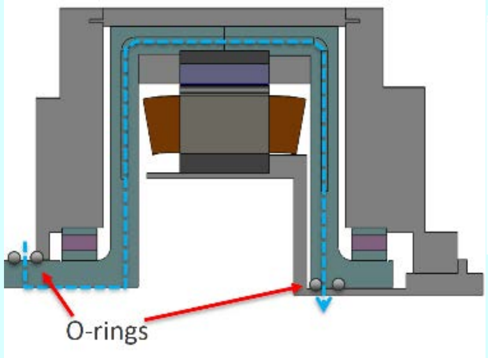
AC loss in Litz wire winding

NREL and Georgia Tech

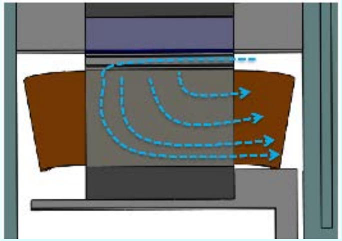
Thermal modeling



Cooling design



Rotor cooling

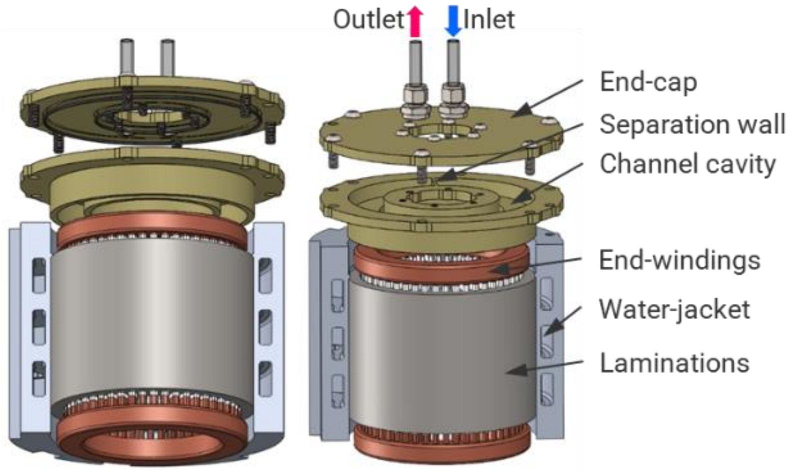


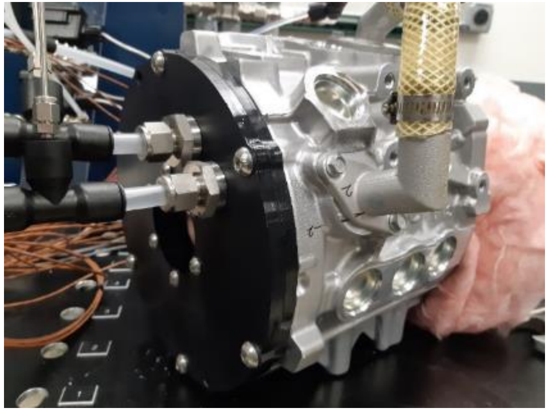
Slot heat exchanger

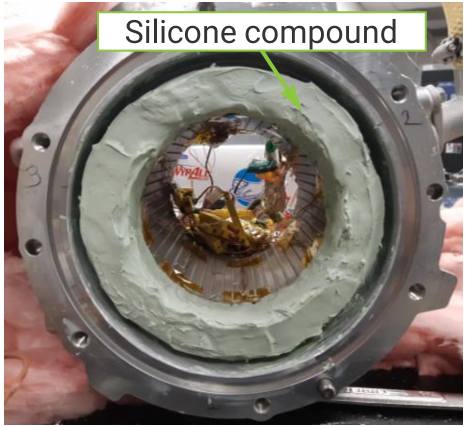
Experimental Validation of Motor Cooling Concept

- Advanced thermal management designs are critical to enable increased motor power density to meet DOE targets (50 kW/L).
- Collaboration between Georgia Tech and NREL.
- Cooling technology demonstrated a 30%–45% decrease in motor end-winding temperatures relative to the baseline commercial electric vehicle motor.

Section view of proposed motor end-winding cooling concept with WEG (50%–50% mixture by volume).





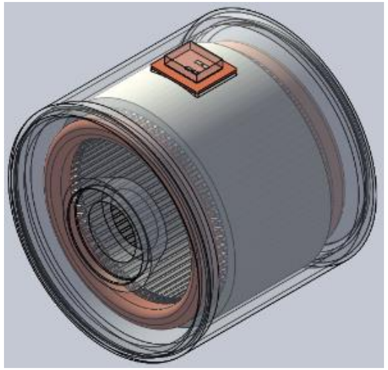


Assembled motor end-winding cooler at NREL (Photo credit: Sebastien Sequeira, Georgia Tech and NREL).

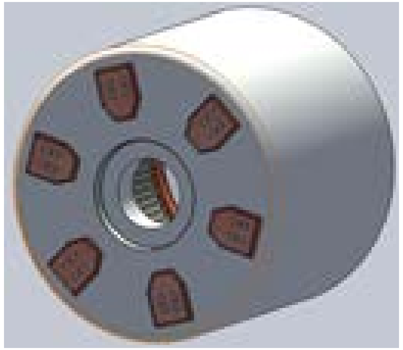
Integrated Traction Drive System

Different integration techniques

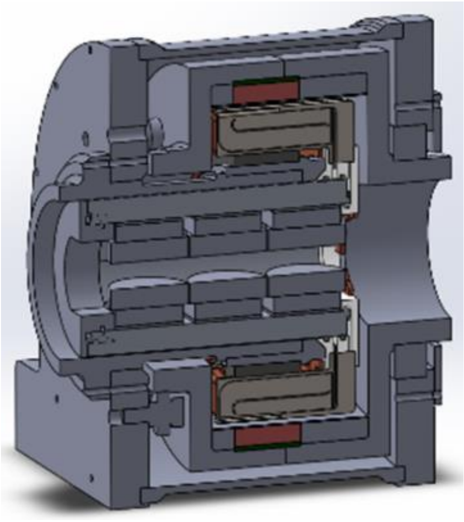
Separate enclosures



Radial integration



Axial integration

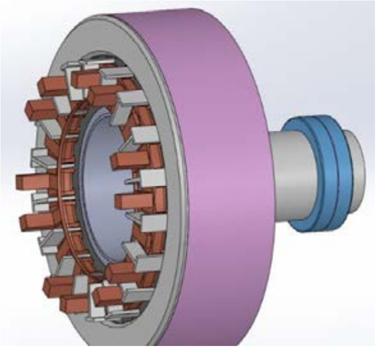


Inside motor

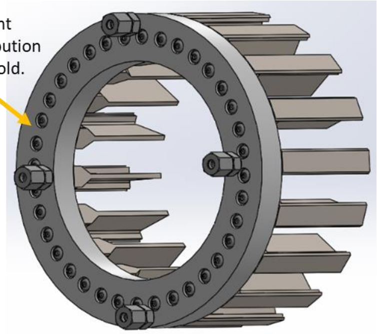
Integrated Traction Drive Thermal Management

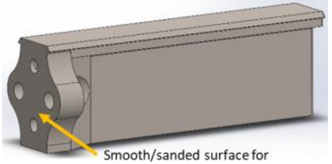
ORNL and NREL integrated drive:

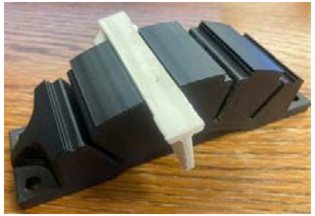
- Designed cooling system components to accommodate change in the drive design-shift to cantilever suspension of the outer rotor.
- First samples of in-slot heat exchangers have been 3D-printed from alumina (Al_2O_3). Working with the manufacturer on optimal fit in stator laminations.
- Coolant distribution manifold redesign is underway. Manufacturing options are being evaluated (3D printing versus machining).
- With new power module/inverter assembly being finalized by ORNL, work on inverter's cylindrical housing has been renewed. Working on redesign of the internal channels and coolant inlet/outlet and flow return endcaps (see following slide).



Cantilever suspension of outer rotor of ORNL's integrated drive.

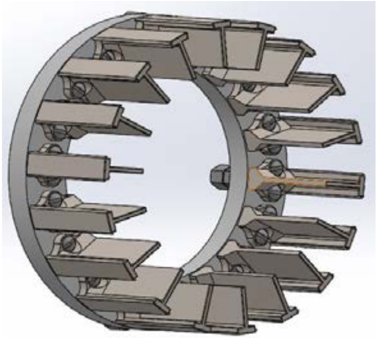






T-shape in-slot heat exchanger.

Photo Credit: Bidzina Kekelia, NREL

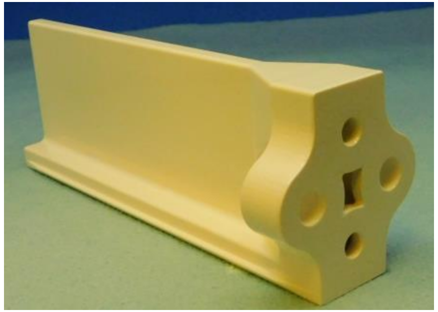


Stator cooling assembly with 18 T-shape in-slot heat exchangers attached to coolant distribution manifold.

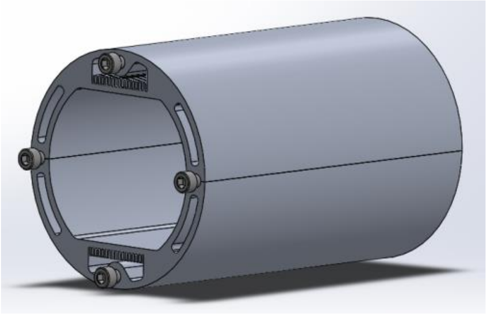
Integrated Traction Drive Thermal Management – Future Work

Next Steps:

- Finalize design, manufacture, and leak-test coolant distribution manifold.
- Experimentally evaluate T-shape in-slot heat exchanger 3D-printed from Al_2O_3.
- Finalize cylindrical inverter housing redesign and perform thermal modeling.



T-shape in-slot heat exchanger 3D printed from ceramics.



Cylindrical inverter housing for 6-phase inverter.

More Information

Acknowledgments:

- **Electric Drive Technologies Program, Vehicle Technologies Office**
- **Advanced Manufacturing Office**
- **ARPA-E**
- **U.S. Department of Energy**
- **NREL**

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