Advanced Power Electronics and Electric Machines

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Advanced Power Electronics and Electric Machines Group
Center for Integrated Mobility Sciences
National Renewable Energy Laboratory

Lecture at the University of Toronto
April 6, 2022

Seminar/Lecture Outline

- **4:15 – 4:45 p.m. Eastern**: Overview of Advanced Power Electronics and Electric Machines Electro-thermal, Thermal-Fluids, Thermo-mechanical, and Reliability Research at NREL (Sreekant)
- **4:45 - 5:05 p.m**.: Thermal Management of Power Electronics (Gilbert)
- **5:05 -5:15 p.m.:** Break
- **5:15 – 5:55 p.m.:** Thermal Management of Power Electronics (Gilbert) - continued
- **5:55 – 6:10 p.m.:** Power Electronics Materials and Component Reliability (Sreekant)
- **6:10 – 6:20 p.m.:** Break
- **6:20 – 6:35 p.m.:** Thermal Management of Electric Machines and Integrated Electric Drive Systems (Sreekant)

Overview of Advanced Power Electronics and Electric Machines Electro-thermal, Thermal-Fluids, Thermo-mechanical, and Reliability Research at NREL

Sreekant Narumanchi

Group/Center Members: Kevin Bennion, Diane Bock, Emily Cousineau, Doug DeVoto, Xuhui Feng, Bidzina Kekelia, Brian Kelly, Faisal Khan, Ram Kotecha, Josh Major, Gilbert Moreno, Paul Paret, Jeff Tomerlin

U.S. Department of Energy Laboratories

Office of Science Laboratories

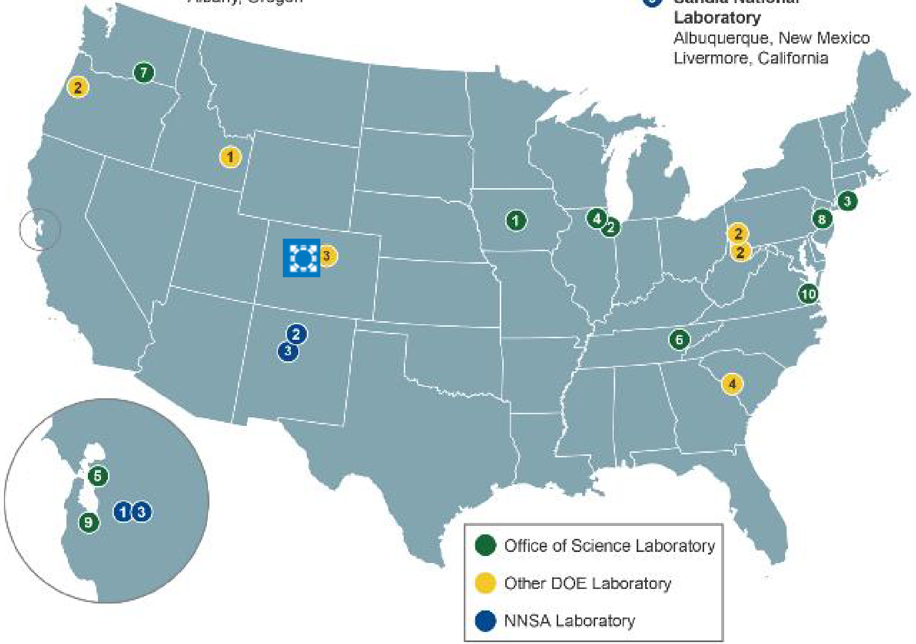
1. **Ames Laboratory**
   Ames, Iowa
2. **Argonne National Laboratory**
   Argonne, Illinois
3. **Brookhaven National Laboratory**
   Upton, New York
4. **Fermi National Accelerator Laboratory**
   Batavia, Illinois
5. **Lawrence Berkeley National Laboratory**
   Berkeley, California
6. **Oak Ridge National Laboratory**
   Oak Ridge, Tennessee
7. **Pacific Northwest National Laboratory**
   Richland, Washington
8. **Princeton Plasma Physics Laboratory**
   Princeton, New Jersey
9. **SLAC National Accelerator Laboratory**
   Menlo Park, California
10. **Thomas Jefferson National Accelerator Facility**
    Newport News, Virginia

Other DOE Laboratories

1. **Idaho National Laboratory**
   Idaho Falls, Idaho
2. **National Energy Technology Laboratory**
   Morgantown, West Virginia
   Pittsburgh, Pennsylvania
   Albany, Oregon
3. **National Renewable Energy Laboratory**
   Golden, Colorado
4. **Savannah River National Laboratory**
   Aiken, South Carolina

NNSA Laboratories

1. **Lawrence Livermore National Laboratory**
   Livermore, California
2. **Los Alamos National Laboratory**
   Los Alamos, New Mexico
3. **Sandia National Laboratory**
   Albuquerque, New Mexico
   Livermore, California



NREL - owned by the Office of Energy Efficiency and Renewable Energy

National Renewable Energy Laboratory

Leading clean energy innovation for 45 years

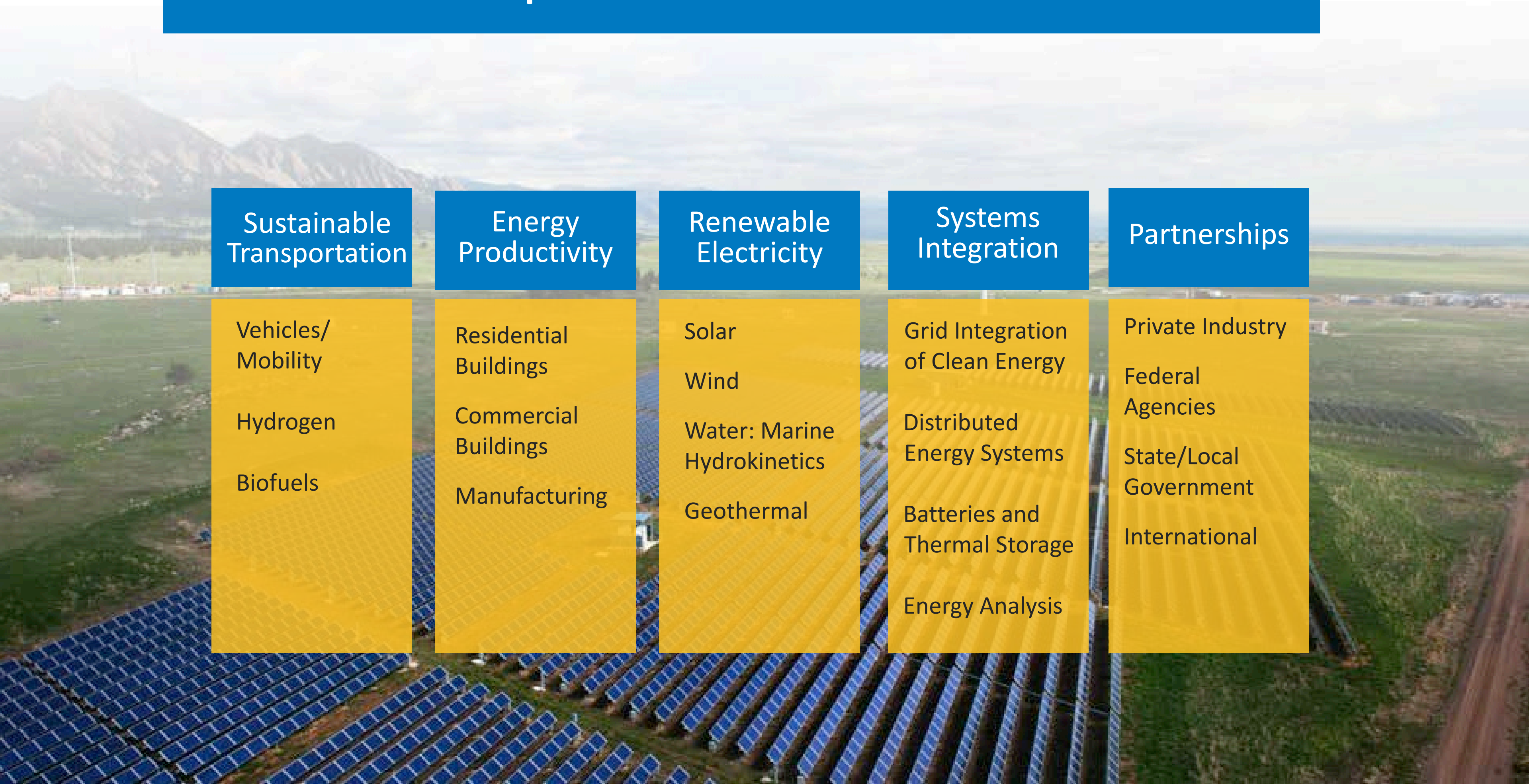
3,000 employees with world-class facilities

Campus is a living model of sustainable energy

Owned by the U.S. Department of Energy (DOE)

Operated by the Alliance for Sustainable Energy

Scope of NREL’s Mission



Sustainable Transportation

- Vehicles/ Mobility
- Hydrogen
- Biofuels

Energy Productivity

- Residential Buildings
- Commercial Buildings
- Manufacturing

Renewable Electricity

- Solar
- Wind
- Water: Marine Hydrokinetics
- Geothermal

Systems Integration

- Grid Integration of Clean Energy
- Distributed Energy Systems
- Batteries and Thermal Storage
- Energy Analysis

Partnerships

- Private Industry
- Federal Agencies
- State/Local Government
- International

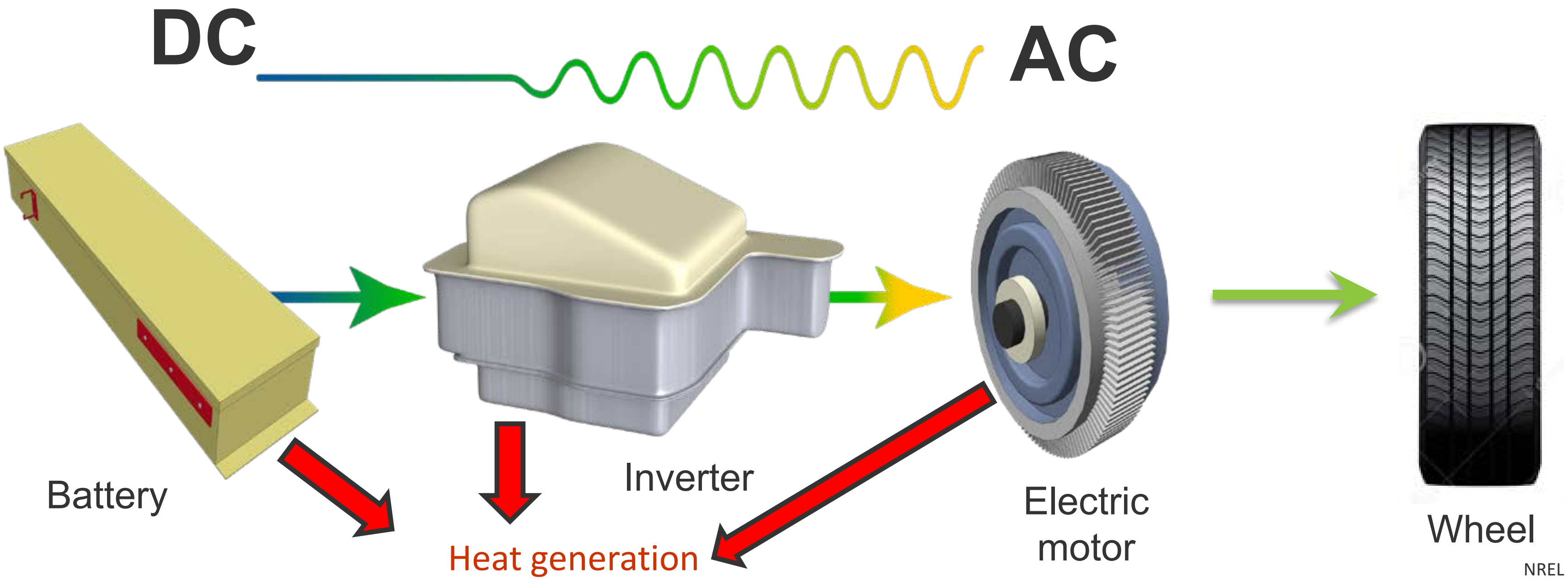
- Advanced Vehicles & Charging Infrastructure
  - Commercial Vehicle Technologies
  - Electric Vehicle Grid Integration
- Sustainable Transportation Integration
  - Technology Integration
  - Regulatory Programs
- Transportation Applications & Data Analysis
  - Transportation Applications
  - Data Analysis
- Transportation Energy Storage Infrastructure & Analysis
  - Hydrogen & Energy Storage Analysis
  - Integrated Transportation Energy Systems & Analysis
- Fuels & Combustion Science
  - Advanced Combustion & Fuels
  - Advanced Biofuels
- Mobility, Behavior & Advanced Powertrains
  - Vehicle Systems
  - Mobility Systems
- Advanced Power Electronics & Electric Machines (APEEM)

Center for Integrated Mobility Sciences (CIMS)

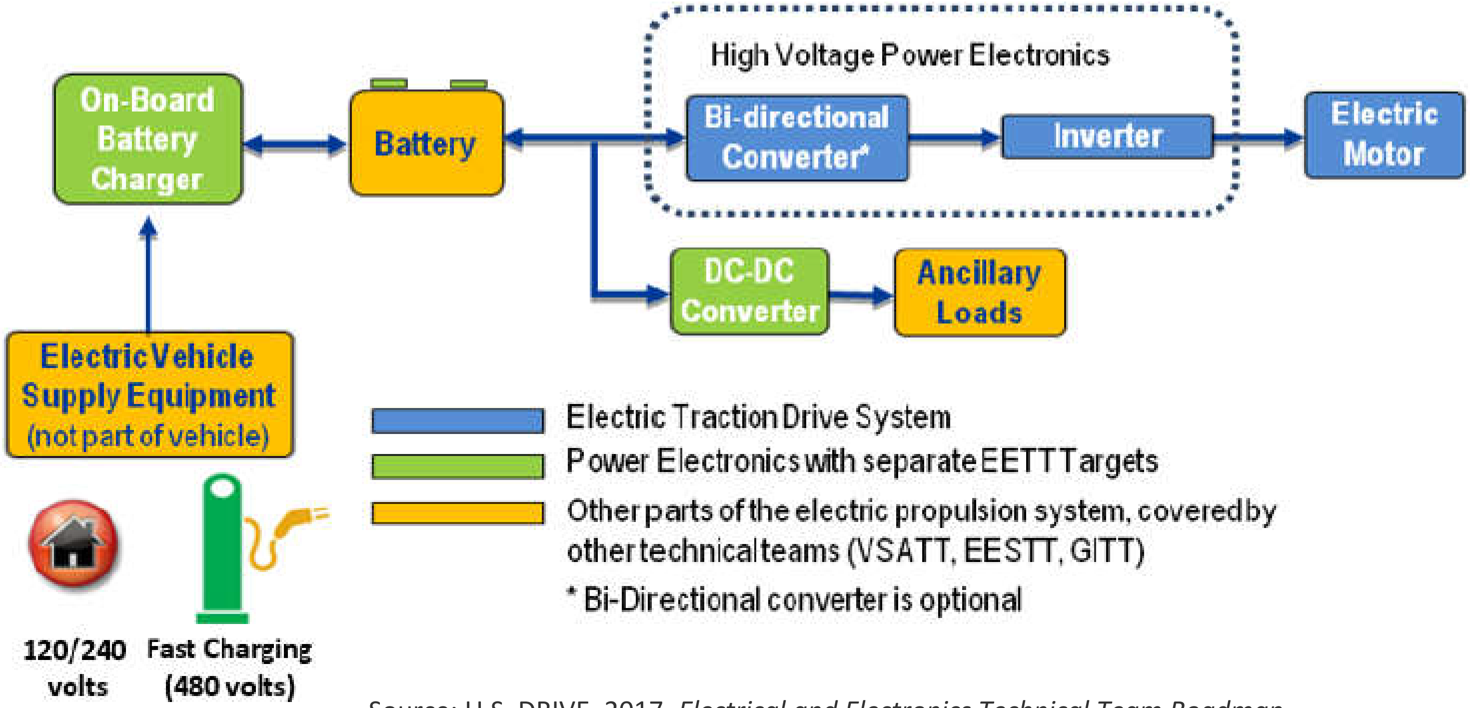
APEEM Group: Twelve (12) staff members involved in electro-thermal, thermal-fluids, thermo-mechanical, and reliability research activities.

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.

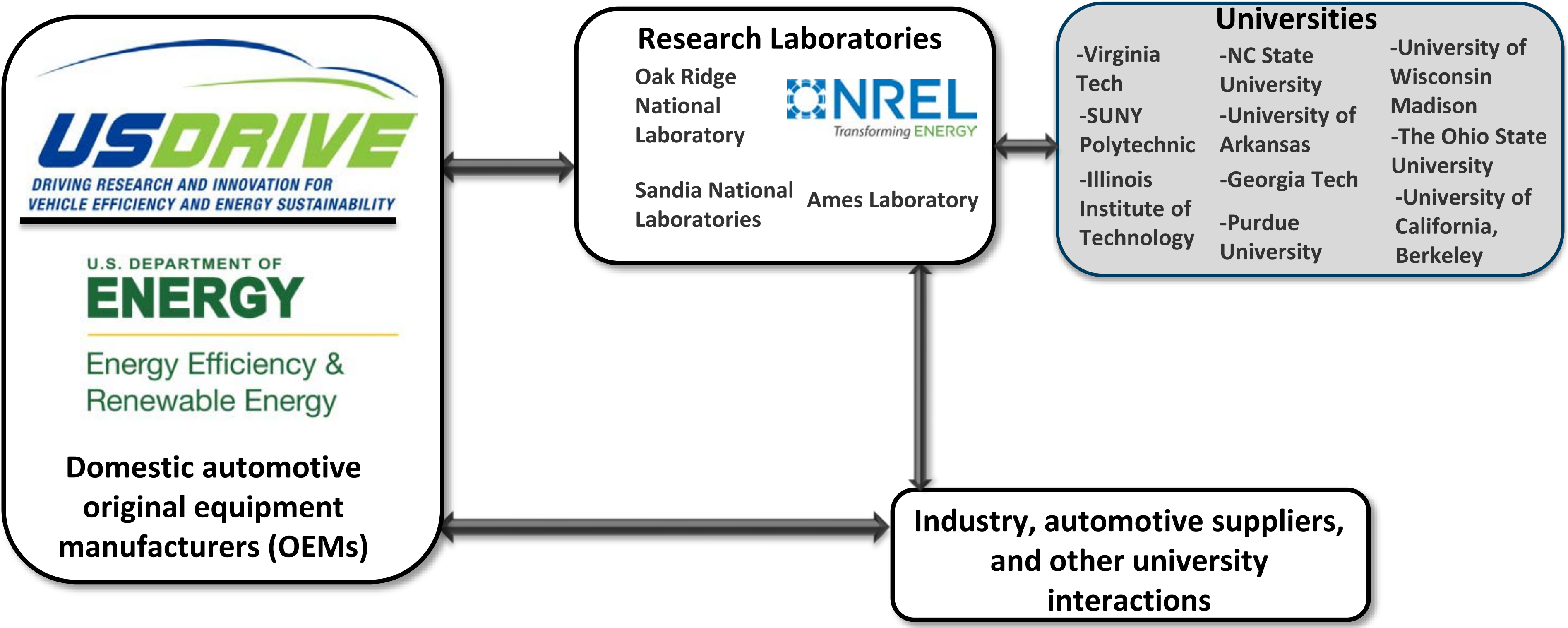


Electric Traction Drive System



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.

DOE Vehicle Technologies Office (VTO) Electric Drive Technologies (EDT) Program



USDRIVE

DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

Domestic automotive original equipment manufacturers (OEMs)

Research Laboratories

Oak Ridge National Laboratory

NREL Transforming ENERGY

Sandia National Laboratories

Ames Laboratory

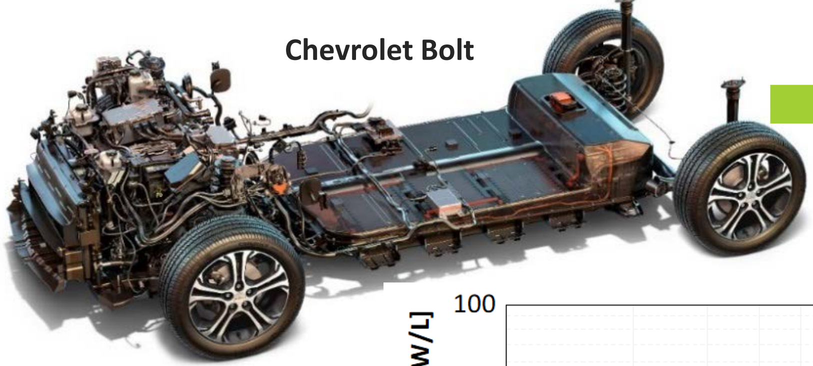
Universities

- -Virginia Tech
- -SUNY Polytechnic
- -Illinois Institute of Technology
- -NC State University
- -University of Arkansas
- -Georgia Tech
- -Purdue University
- -University of Wisconsin Madison
- -The Ohio State University
- -University of California, Berkeley

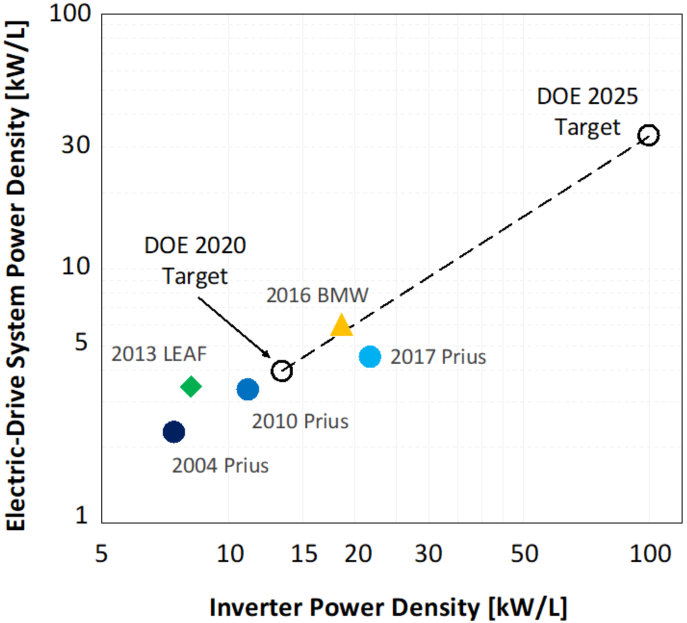
Industry, automotive suppliers, and other university interactions

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.

VTO EDT Research Pathway for Electric-Drive Vehicle Electrification



Chevrolet Bolt



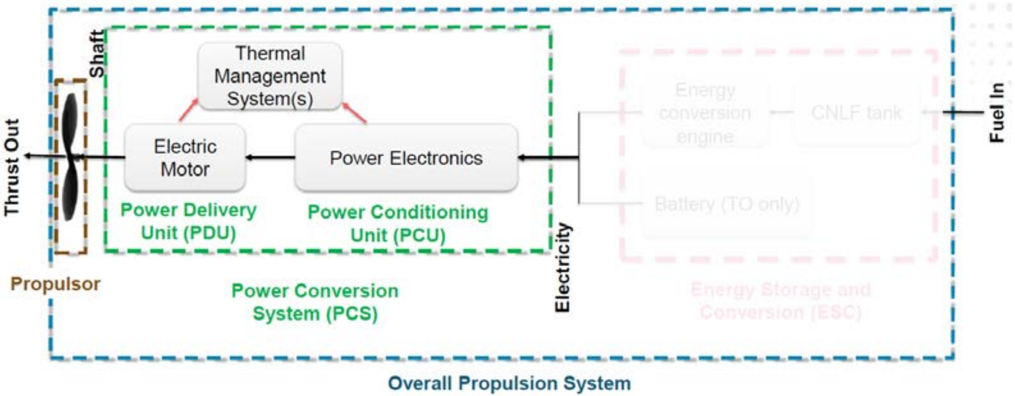
Source: M. Muratori, M. Alexander, D. Arent, M. Bazilian, E. Dede, J. Farrell, C. Gearhart, et al. 2021. “The Rise of Electric Vehicles – 2020 Status and Future Expectations.” *Progress in Energy* 3 (2), 022002.

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)

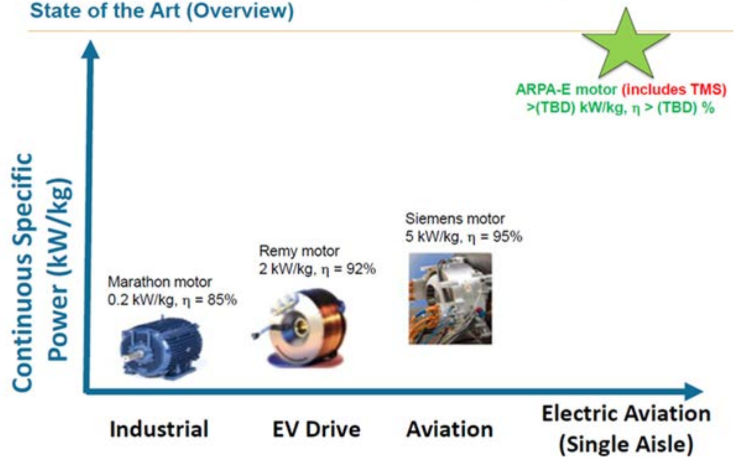
Source: U.S. DRIVE. 2017. *Electrical and Electronics Technical Team Roadmap.* https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf.

Advanced Research Projects Agency – Energy (ARPA-E) Electric Drive Efforts



ASCEND Solicitation

Source: Overview Presentation by Michael Ohadi at the ARPA-E Workshop on Electrified Aviation, August 2019, Arlington, VA.




LEAP-1B - Boeing 737 MAX

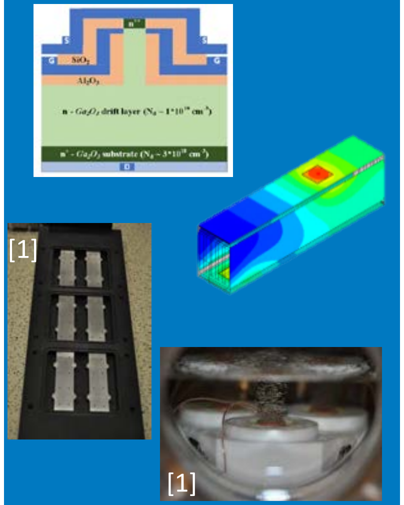
23,000 – 28,000 pounds thrust

Boeing B737-MAX 8
Range: 6,570 km
MTOW: 82,191 kg
Take-off thrust: 130.4 kN

Single-aisle (narrow-body): 100 – 200 passengers

NREL APEEM Group Research Focus Areas

Power Electronics Thermal and Electrothermal



Advanced Packaging Designs and Reliability

Electric Motor Thermal Management

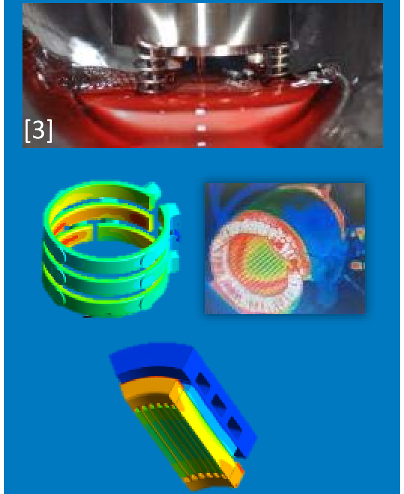
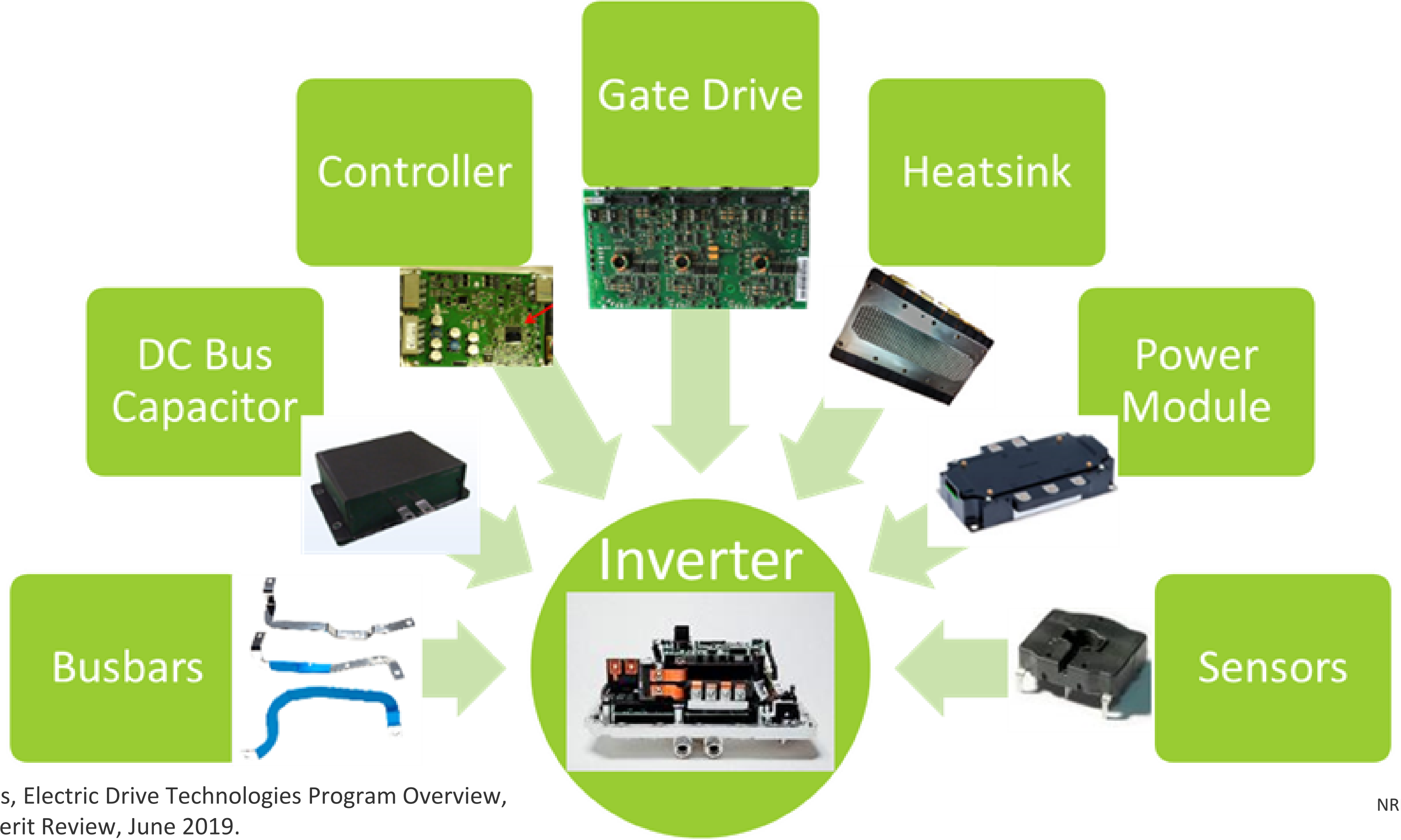


Image credits: [1] Gilbert Moreno, NREL, [2] Doug DeVoto, NREL, [3] Emily Cousineau, NREL

Inverter – Constituents



Controller

Gate Drive

Heatsink

DC Bus Capacitor

Power Module

Busbars

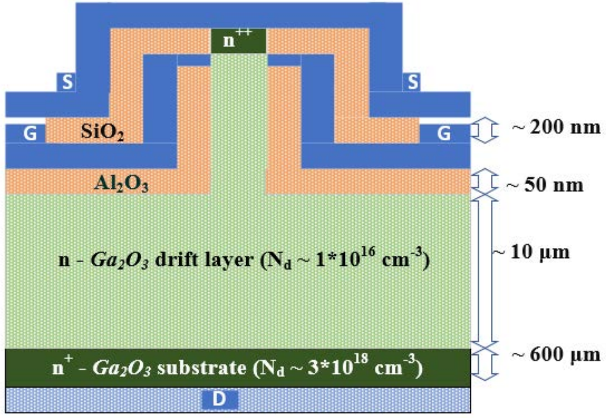
Inverter

Sensors

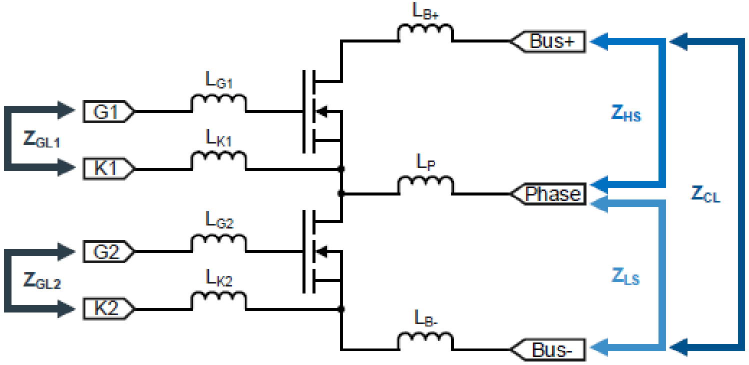
Source: Susan Rogers, Electric Drive Technologies Program Overview, 2019 DOE Annual Merit Review, June 2019.

Power Electronics: Semiconductor Device and Package Research

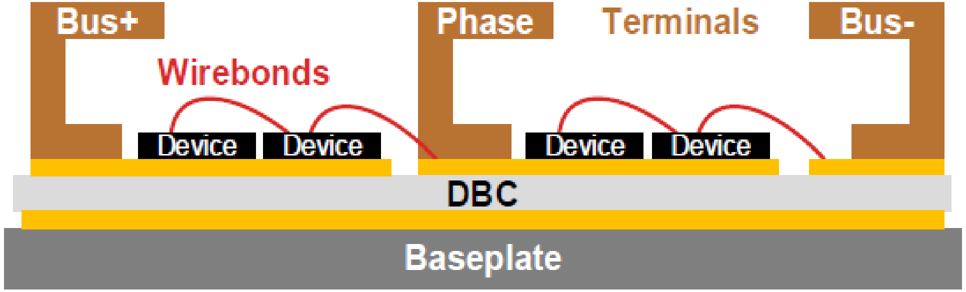
- Semiconductor modeling research for wide-bandgap (WBG) and ultrawide-bandgap (UWBG) devices.
- Electrical and electromagnetic design for power electronics packages.



Micro-nanoscale device modeling



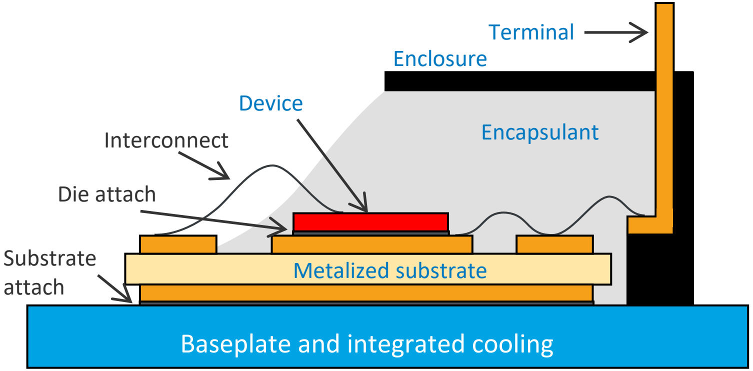
Equivalent circuit of extracted package



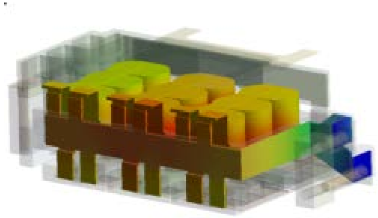
Multi-chip power module

Power Electronics Thermal and Electrothermal Research Pathway

- Compact, power-dense WBG-device-based power electronics
    - Higher-temperature-rated devices, components, and materials
    - Advanced heat transfer technologies
    - System-level thermal management.

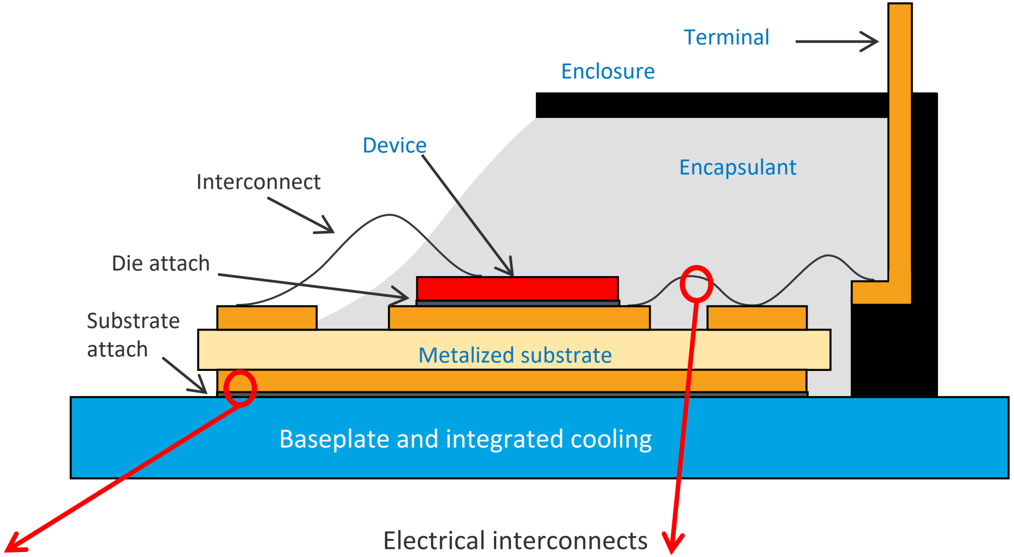



Advanced cooling


Component-level and system-level heat transfer

Advanced Power Electronics Packaging Performance and Reliability – Research Pathway

- Improve reliability of new (high-temperature/WBG) technologies
- Develop predictive and remaining lifetime models
- Package parametric modeling



Bonded interface

Electrical interconnects

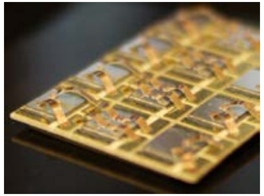
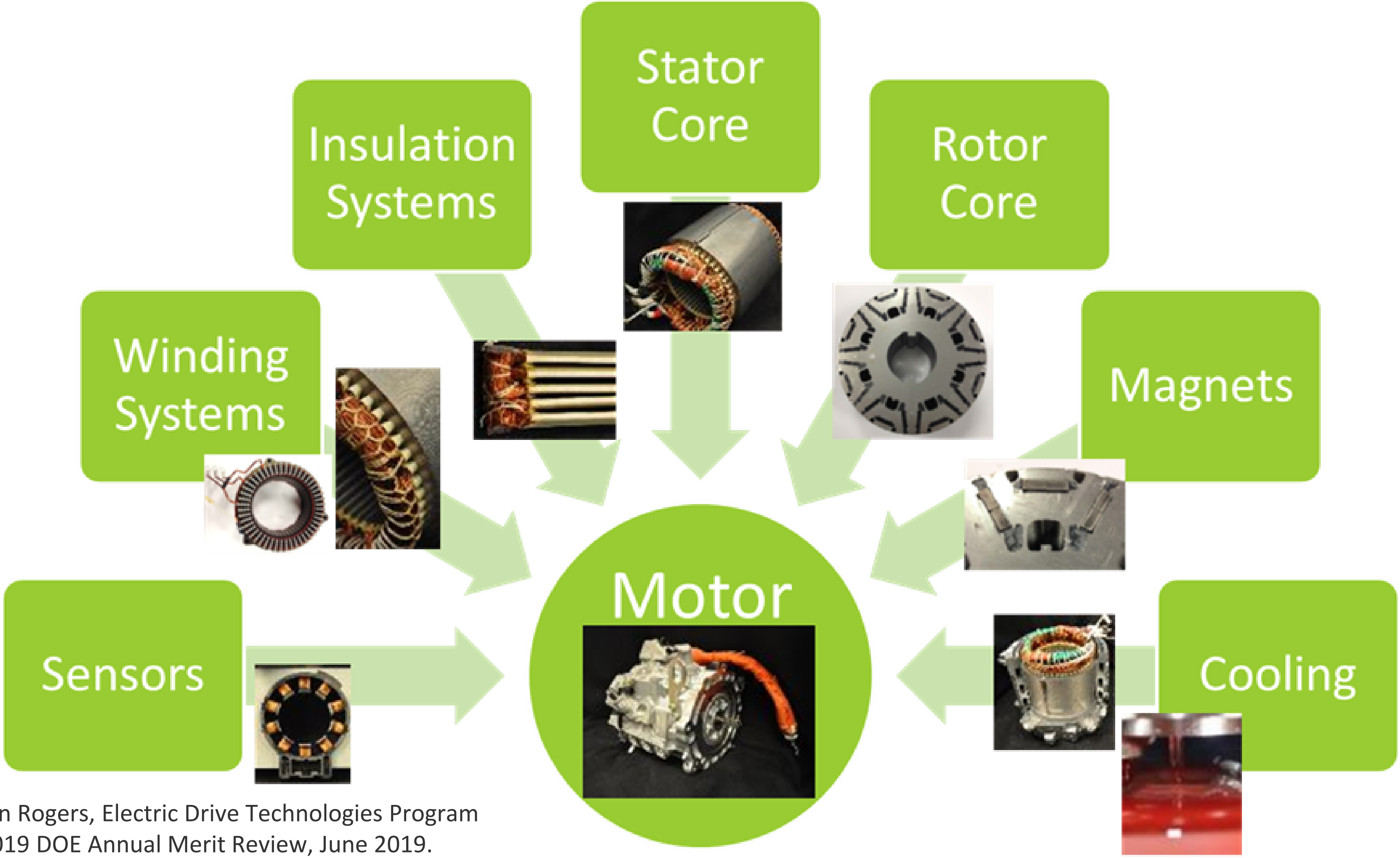


Image credits: Paul Paret, NREL

Electric Motor – Constituents



Stator Core

Insulation Systems

Rotor Core

Winding Systems

Magnets

Sensors

Motor

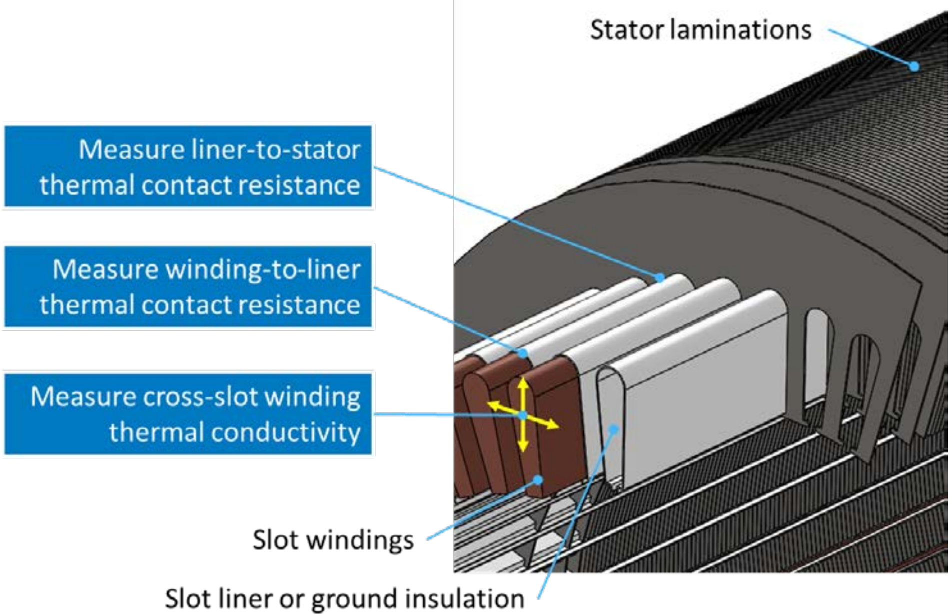
Cooling

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

Electric Motor Thermal Management – Research Pathway

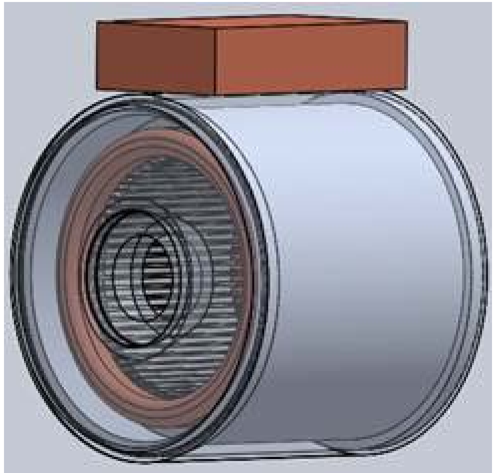
- Understand and evaluate material and interface properties as a function of temperature.
- Develop and evaluate advanced fluid-based cooling strategies.
- Use modeling to guide advanced motor design and development.

Image credit: Bidzina Kekelia (NREL)

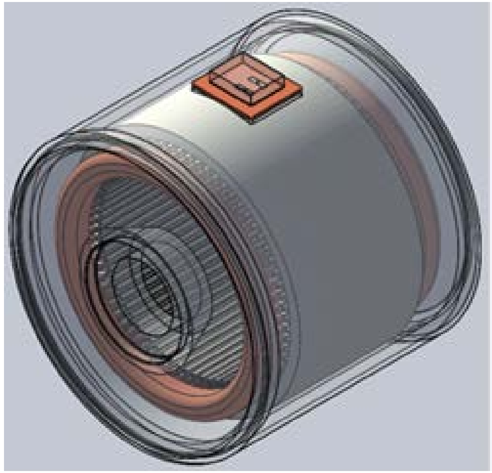


Integrated Traction Drive System

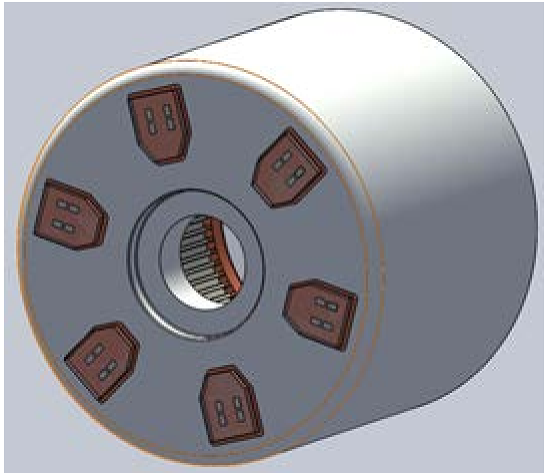
Different integration techniques



Separate enclosures



Radial integration

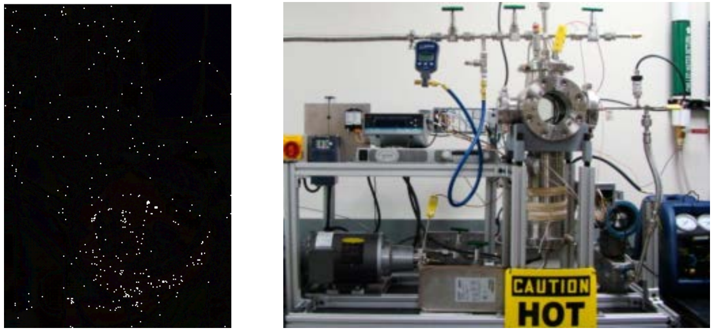


Axial integration

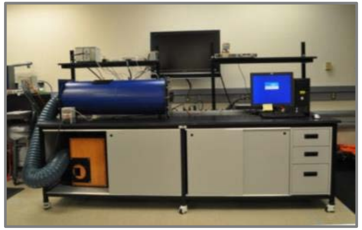
Thermal-fluids and Electro-thermal Capabilities

Laboratory Resources

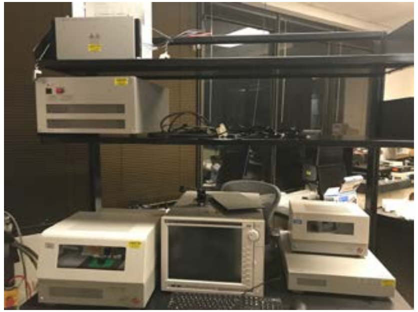
Single-phase liquid loops



Two-phase liquid loops

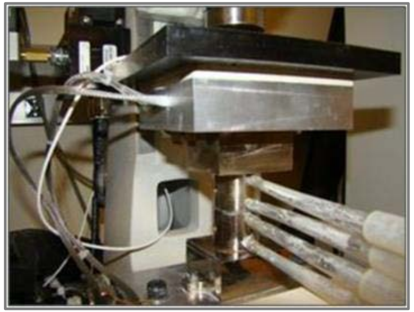


Air cooling loops



Power device analyzer

Transient thermal tester

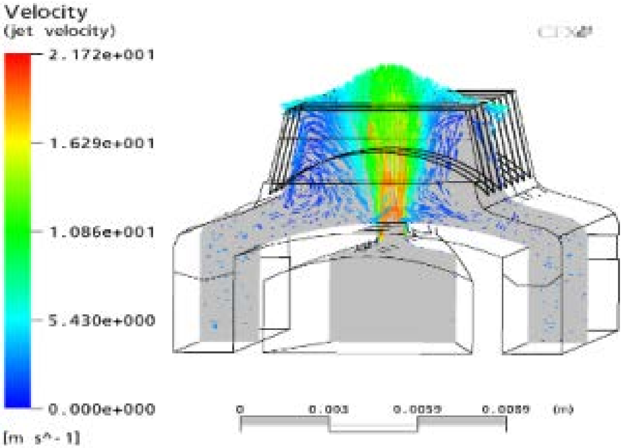


Material thermal resistance characterization

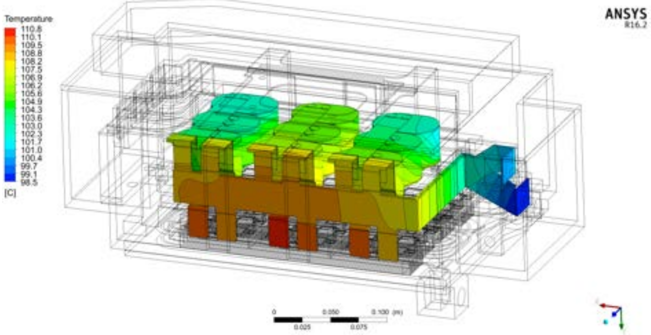
Image credits: Doug DeVoto and Sreekant Narumanchi (NREL)

Thermal-fluids and Electro-thermal Capabilities

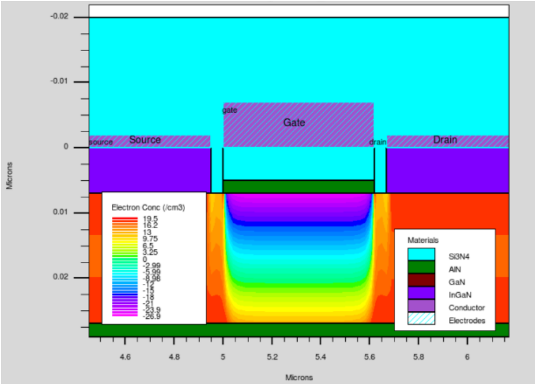
Modeling Capabilities



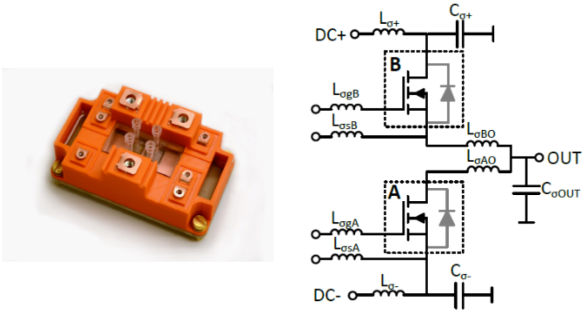
Single-phase computational fluid dynamics



Thermal finite element analysis



Power device electrothermal finite element analysis



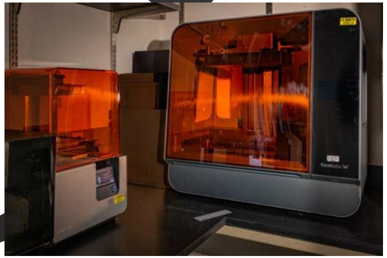
Module parasitics extraction and modeling

Prototype Fabrication Capabilities

CNC router

Waterjet cutter

SLA printer



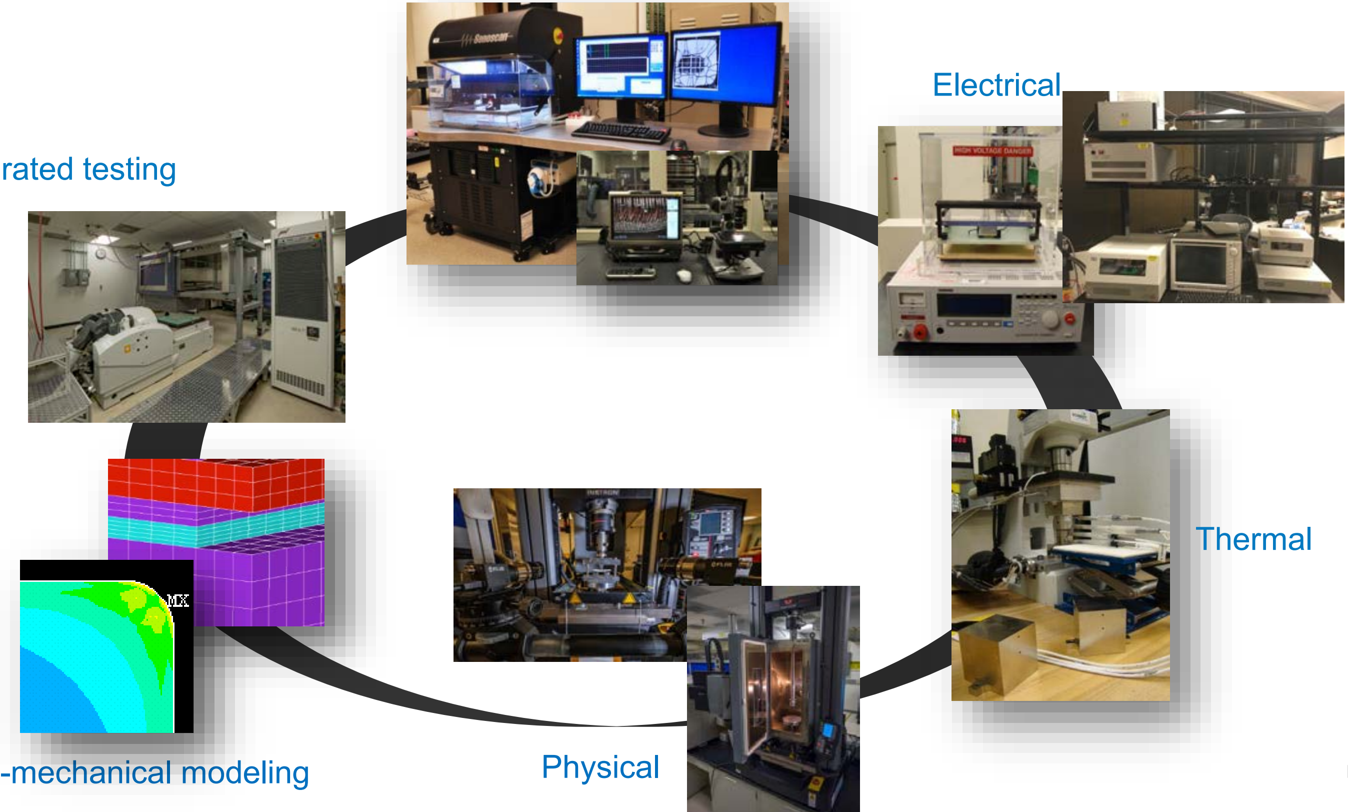
Wire bonder

Synthesis of bonded interfaces

Image credits: Doug DeVoto, NREL

Computer numerical control (CNC), Stereolithography (SLA)

Thermo-mechanical Reliability Capabilities



Nondestructive imaging

Electrical

Thermal

Physical

Thermo-mechanical modeling

Accelerated testing

Image credits: Doug DeVoto and Sreekant Narumanchi (NREL)

How To Work With NREL

Visit: https://www.nrel.gov/workingwithus/technology-partnership-agreements.html

- Shared resources collaborations (DOE EDT projects)

- Cooperative research and development agreements (CRADAs)
    - Shared resources
    - Funds-in agreements

- Technology partnership projects
    - Interagency agreement
    - Funds-in agreement
    - Technical services agreement

- Teaming in response to lab calls, solicitations, and calls for proposals

More Information

Acknowledgments:

- U.S. Department of Energy (DOE)
- EDT Program, DOE Vehicle Technologies Office
- DOE Advanced Manufacturing Office
- ARPA-E

For more information, contact:

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sreekant.narumanchi@nrel.gov
Phone: (303) 275-4062

Industry and Research Partners and Collaborators	
Industry OEMs	Ford, GM, John Deere, Toyota, Caterpillar. Cummins, Daimler
Suppliers/other industry	3M, NBETech, Curamik, DuPont, General Electric (Global Research Center, GE Aviation), Semikron, Kyocera, Sapa, Delphi, BorgWarner, ADA Technologies, Heraeus, Henkel, Wolverine Tube Inc., Wolfspeed, Indiana IC, Momentive, Kulicke & Soffa, UQM Technologies, nGimat LLC, Synteris, Packet Digital
Agencies	DARPA, U.S. Army
National/government laboratories	Oak Ridge National Laboratory, Ames Laboratory, Argonne National Laboratory, Sandia National Laboratories, U.S. Army Research Laboratory
Universities	Virginia Tech, University of Colorado Boulder, University of Wisconsin, Carnegie Mellon University, Texas A&M University, North Carolina State University, The Ohio State University, Florida State University, Georgia Tech, University of Missouri Kansas City, North Dakota State University, University of Arkansas, University of Maryland, University of Tennessee, Stanford University

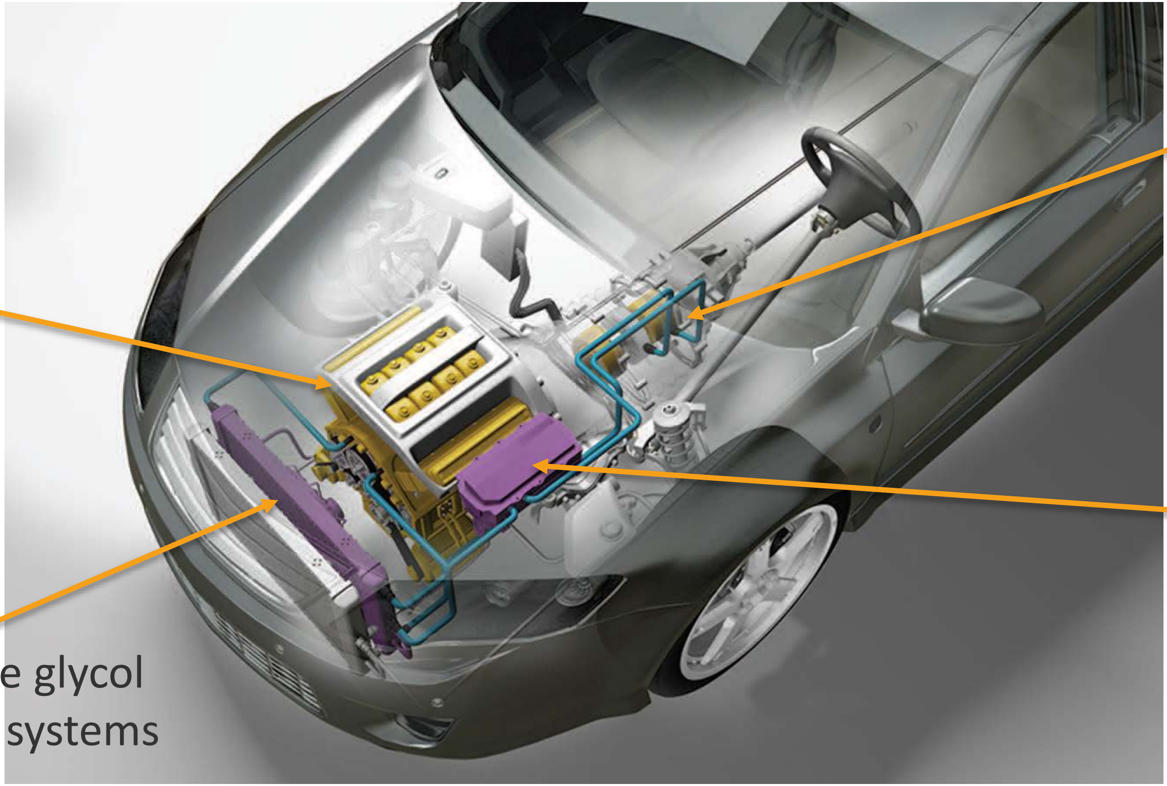
Thermal Management of Power Electronics

Gilbert Moreno

Automotive Power Electronics Cooling Roadmap: Current Status

Electric-Drive Vehicle Coolant Systems

Hybrid electric vehicle



Internal combustion engine

Electric motor(s)

Water-ethylene glycol (WEG) cooling systems

Power electronics

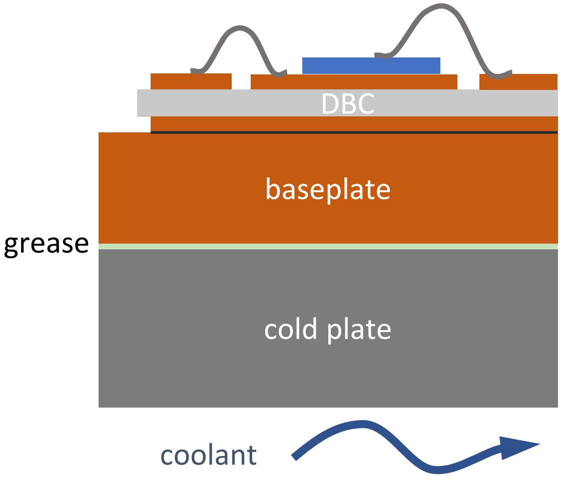
Image credit: Xuhui Feng, NREL

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](https://doi.org/10.1109/MELE.2014.2314501).

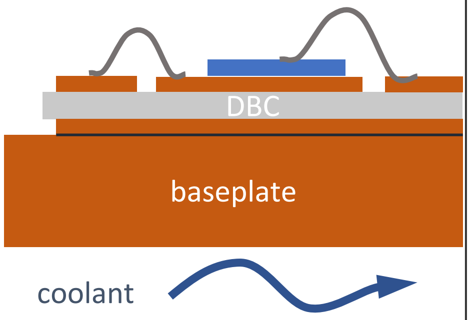
Typical Power Module Configurations

Single-side cooled

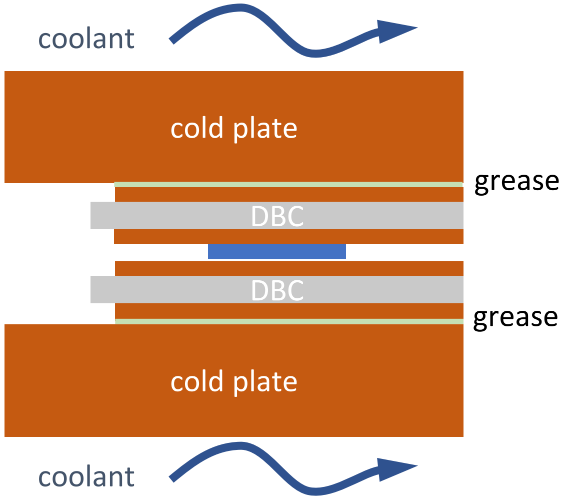
Cold plate cooled



Baseplate cooled



Double-side cooled



Automotive power electronics cooling trend

Variations for each cooling configuration exist

DBC: direct-bond copper

Typical Power Module Configurations

Single-side cooled

Cold plate cooled

2012 LEAF EV

Baseplate cooled

2014 Accord HEV

2015 BMW i3 EV

Double-side cooled

2008 Lexus LS HEV

2014 Camry HEV

2017 Volt HEV

EV: electric vehicle; HEV: hybrid electric vehicle

2012 LEAF Inverter: 80 kW

Cold-plate-cooled system

Includes one inverter

Image credit: Scott Waye, NREL

2012 LEAF Power Module Description

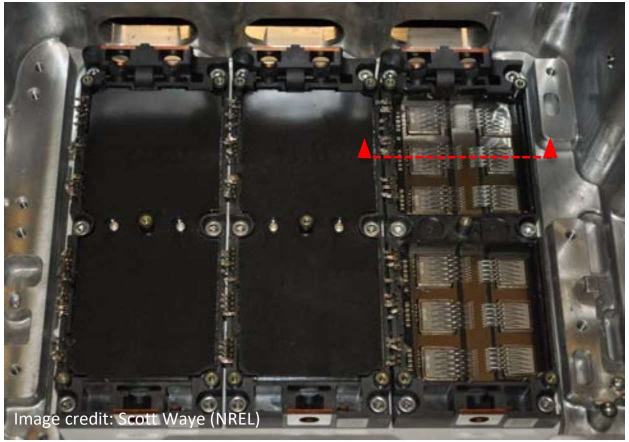


Image credit: Scott Waye (NREL)

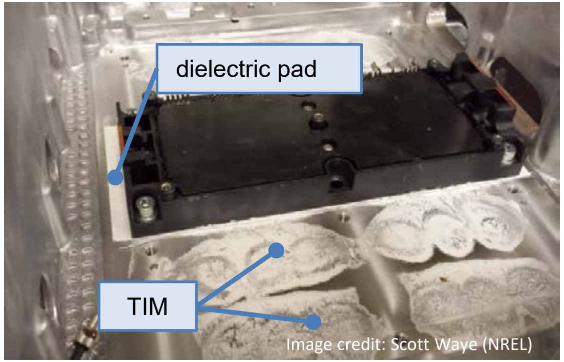
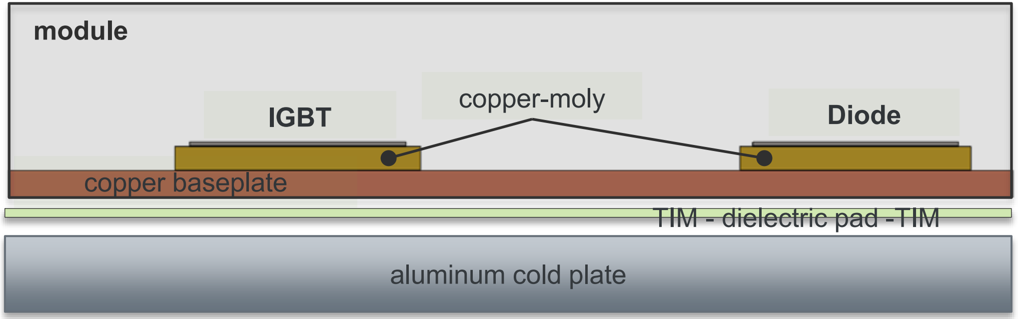


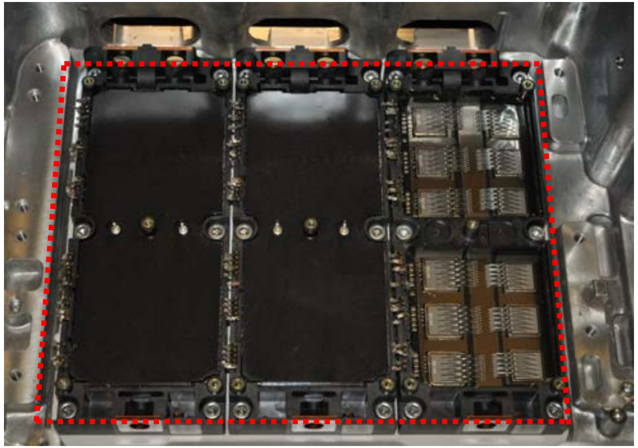
Image credit: Scott Waye (NREL)

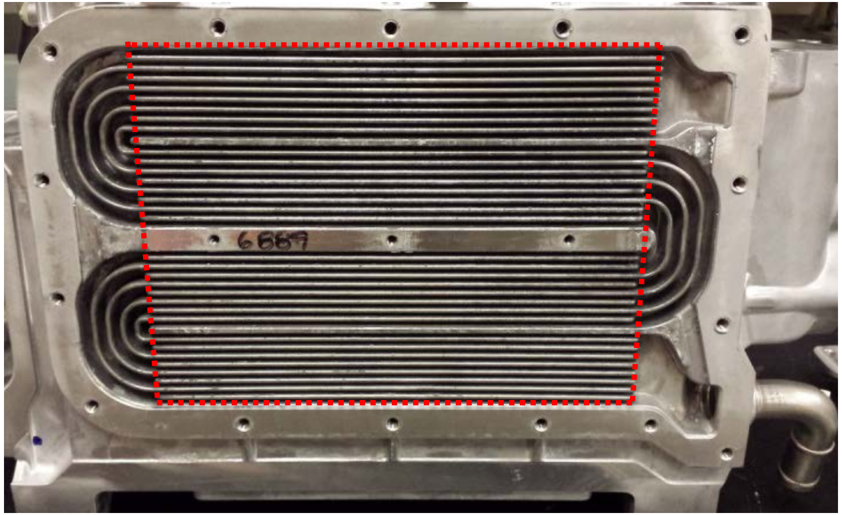


- LEAF modules do not use a metalized-ceramic substrate. Instead, they use a dielectric pad for electrical isolation
- Copper Moly plate beneath the devices for CTE matching
- TIM is provided on both sides of the dielectric pad to reduce the thermal resistance

Insulated-gate bipolar transistor (IGBT), thermal interface material (TIM), coefficient of thermal expansion (CTE)

2012 LEAF Heat Exchanger



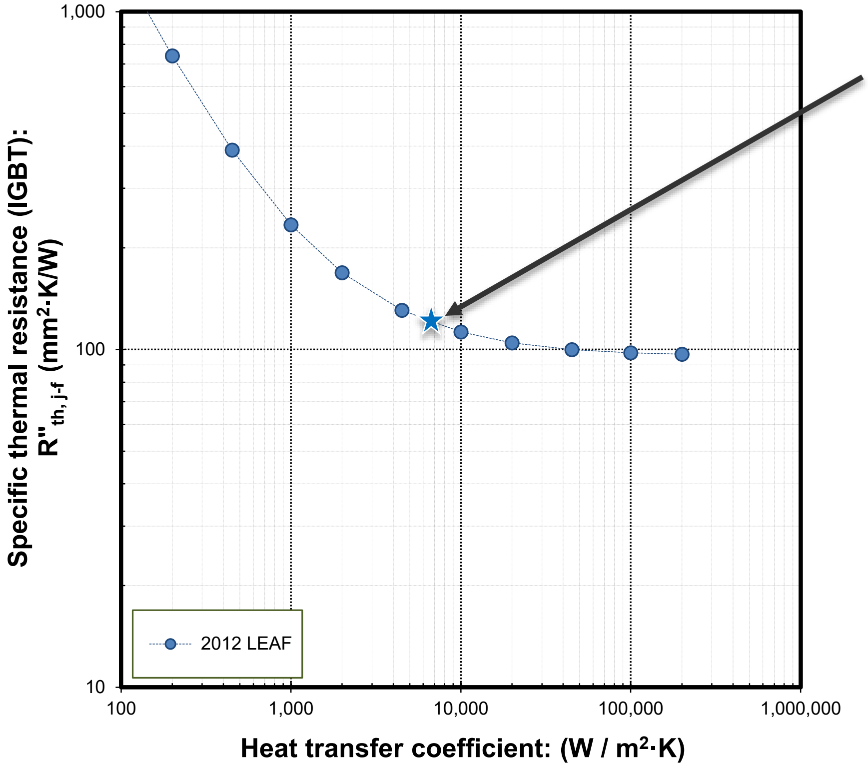


Cast aluminum cold plate

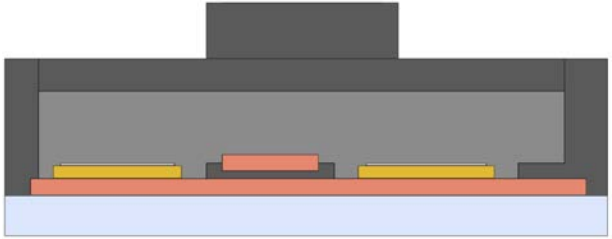
~2-mm-thick fins and channels
~11.5-mm-tall fins

Image credits: Scott Waye, NREL

2012 LEAF Thermal Resistance



Estimated cold plate performance at 10 L/min

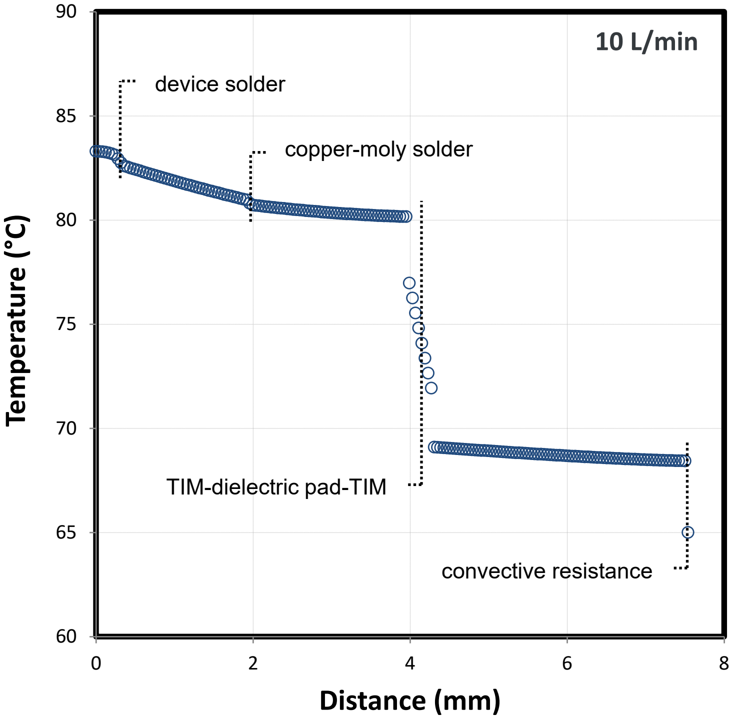


Not much to be gained from increasing convective performance

G. Moreno, K. Bennion, C. King, and S. Narumanchi. 2016. “Evaluation of Performance and Opportunities for Improvements in Automotive Power Electronics Systems.” In *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 185–92. https://doi.org/10.1109/ITHERM.2016.7517548.

2012 LEAF Junction-to-Coolant Temperature Profile

- Passive stack is about 83% of the total thermal resistance.
- Dielectric pad and associated TIM layers are the largest resistance (~60% of the total temperature drop).
- LEAF design may reduce cost.



G. Moreno, K. Bennion, C. King, and S. Narumanchi. 2016. "Evaluation of Performance and Opportunities for Improvements in Automotive Power Electronics Systems." In *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 185–92. https://doi.org/10.1109/ITHERM.2016.7517548.

2014 Honda Accord HEV: 118 kW

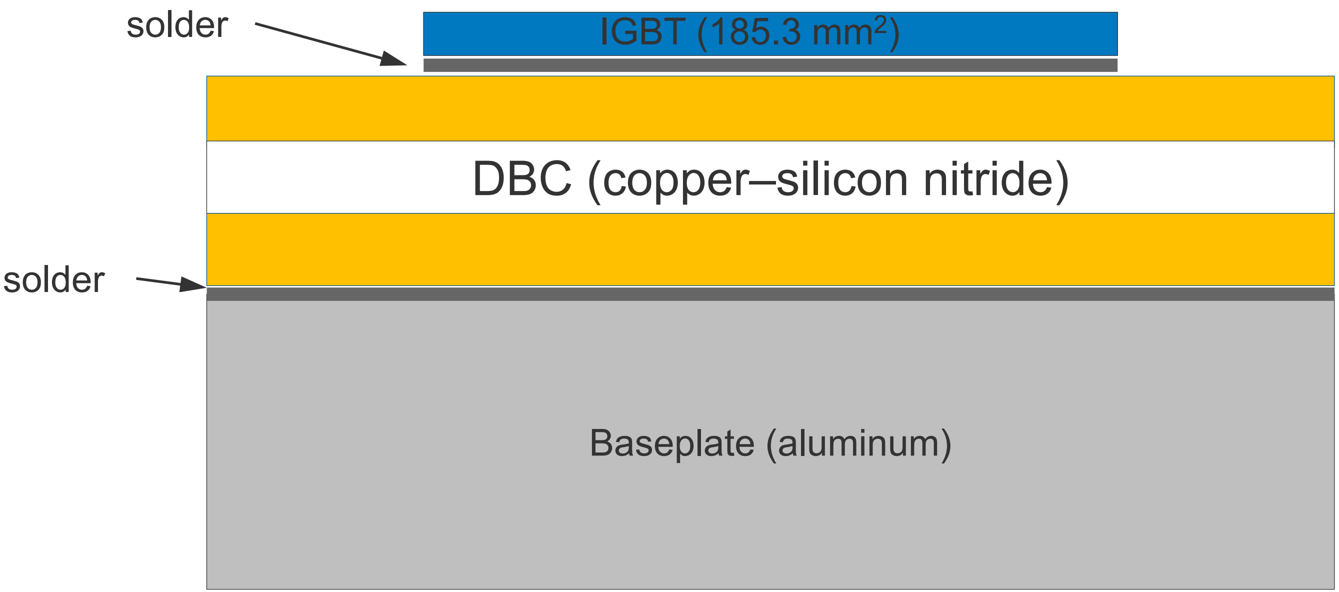
Baseplate-cooled system

Includes two inverters and one boost converter

Image credit: Gilbert Moreno, NREL

2014 Accord Module Description

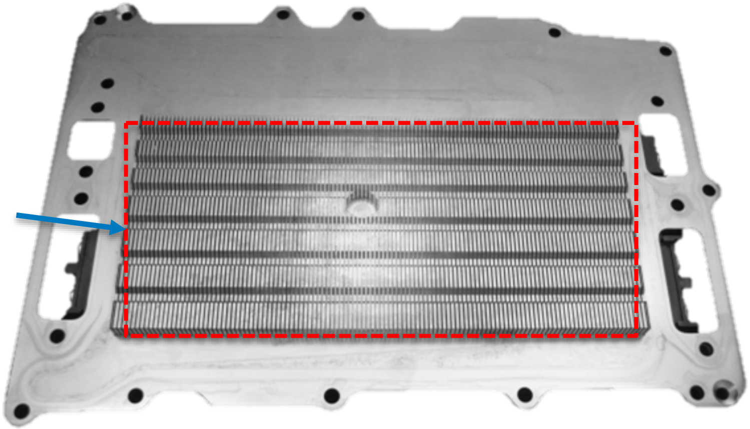
Power module stack-up



Silicon nitride likely used to improve mechanical performance due to the large CTE discrepancy between aluminum baseplate and Si devices.

2014 Accord Heat Exchanger

Machined aluminum cold plate (baseplate) with nickel plating
~1-mm-wide channels, 1.2-mm-thick and 10-mm-tall fins



Power module footprint

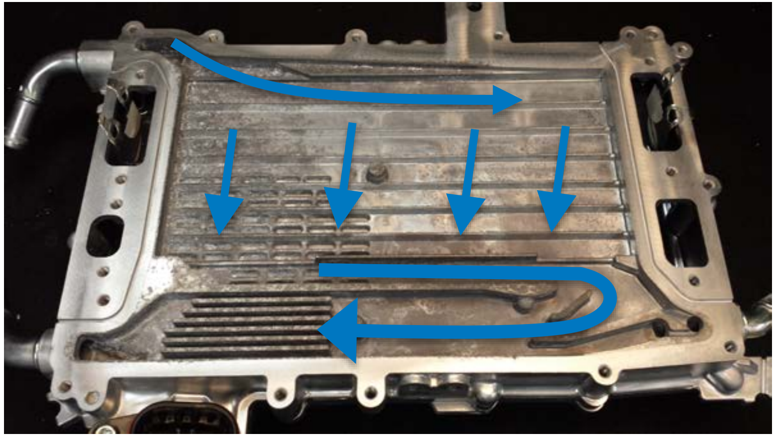
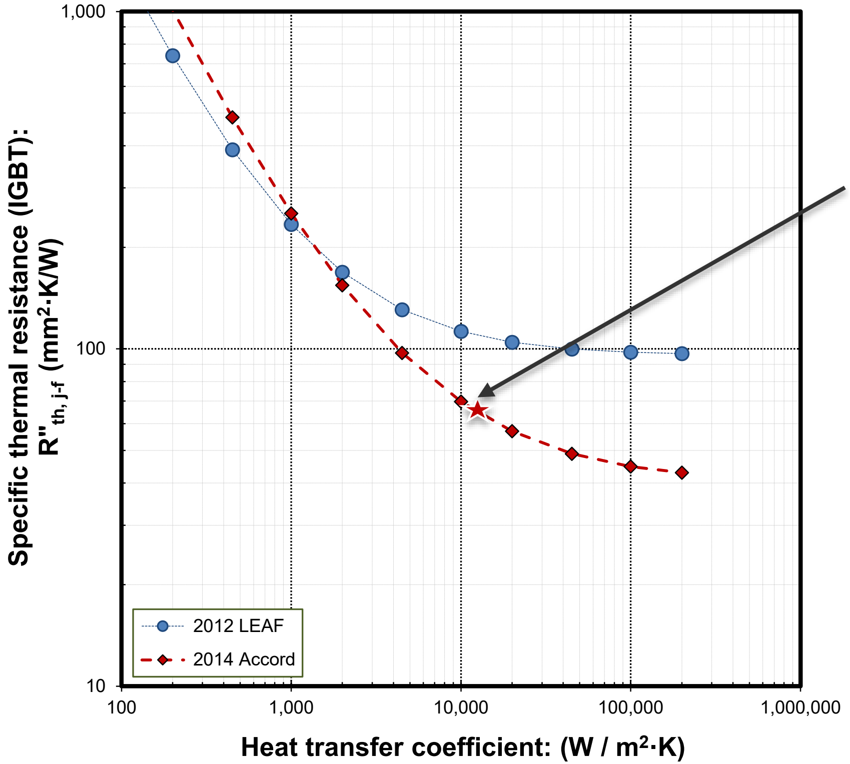


Image credits: Gilbert Moreno, NREL

2014 Accord Thermal Resistance



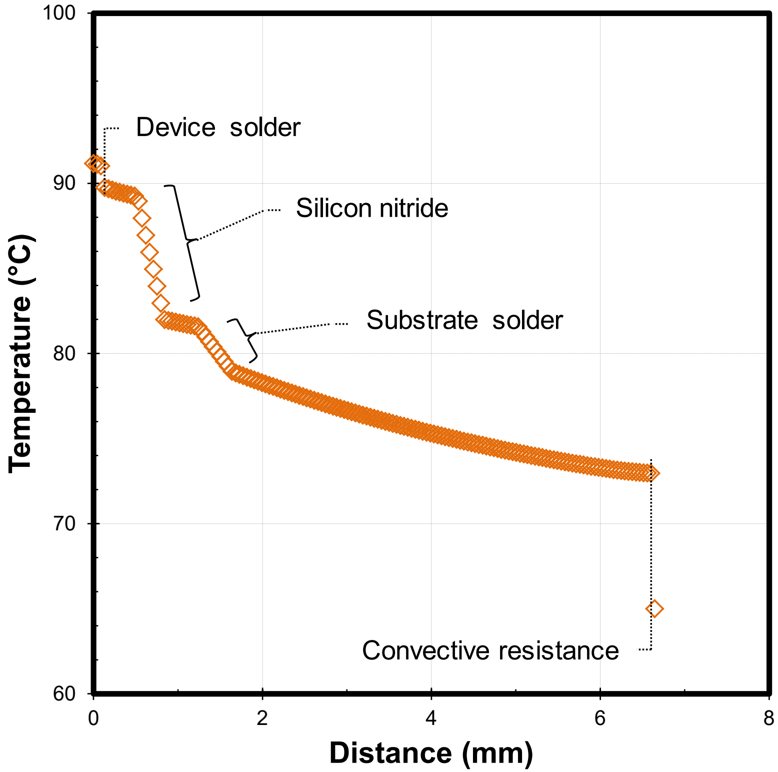
Estimated cold plate performance at 10 L/min

Significant improvement compared to 2012 LEAF thermal performance

G. Moreno, K. Bennion, C. King, and S. Narumanchi. 2016. "Evaluation of Performance and Opportunities for Improvements in Automotive Power Electronics Systems." In *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 185–92. https://doi.org/10.1109/ITHERM.2016.7517548.

2014 Accord Junction-to-Coolant Temperature Profile

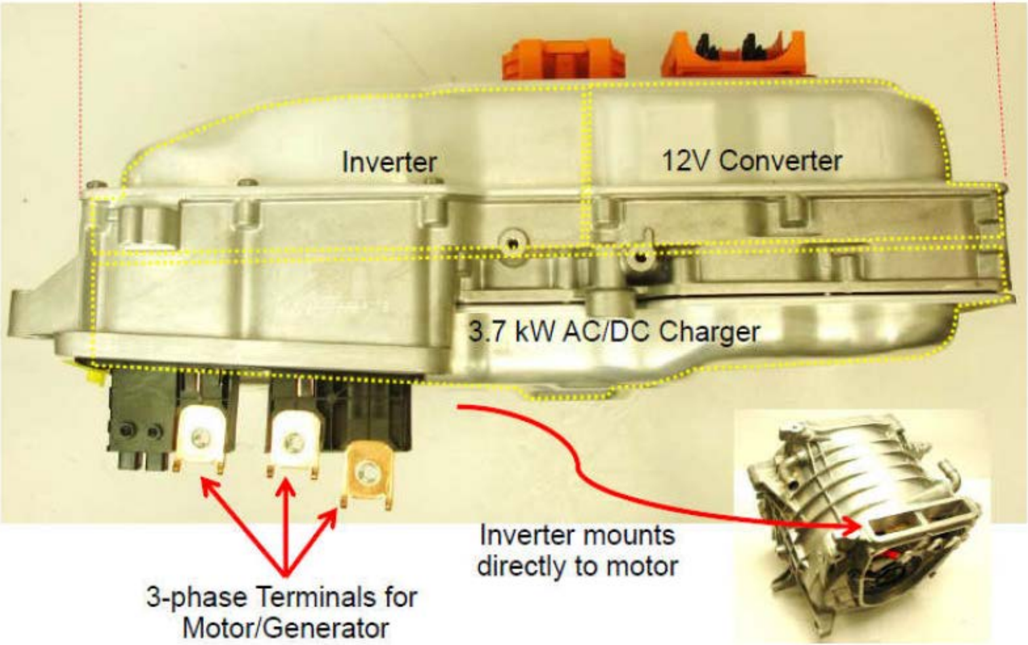
- Passive stack is about 70% of the total thermal resistance.
- Ceramic makes up the largest thermal resistance within the package.



G. Moreno, K. Bennion, C. King, and S. Narumanchi. 2016. "Evaluation of Performance and Opportunities for Improvements in Automotive Power Electronics Systems." In *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 185–92. https://doi.org/10.1109/ITHERM.2016.7517548.

2015 BWMi3 EV: 125 kW, 6.8 L

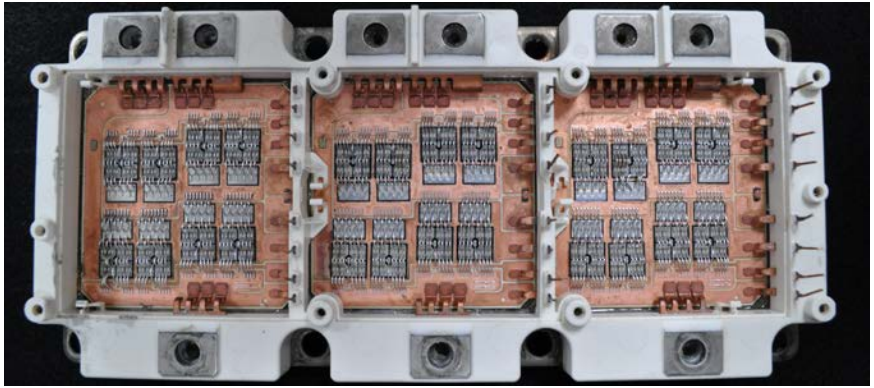
Baseplate-cooled system



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 BWM i3 Module Description



Uses the Infineon HybridPACK2

Materials
Silicon (area IGBT = 95 mm^2, diode = 45 mm^2)
Die solder
DBC (copper)
DBC (alumina)
DBC solder
Baseplate (copper)

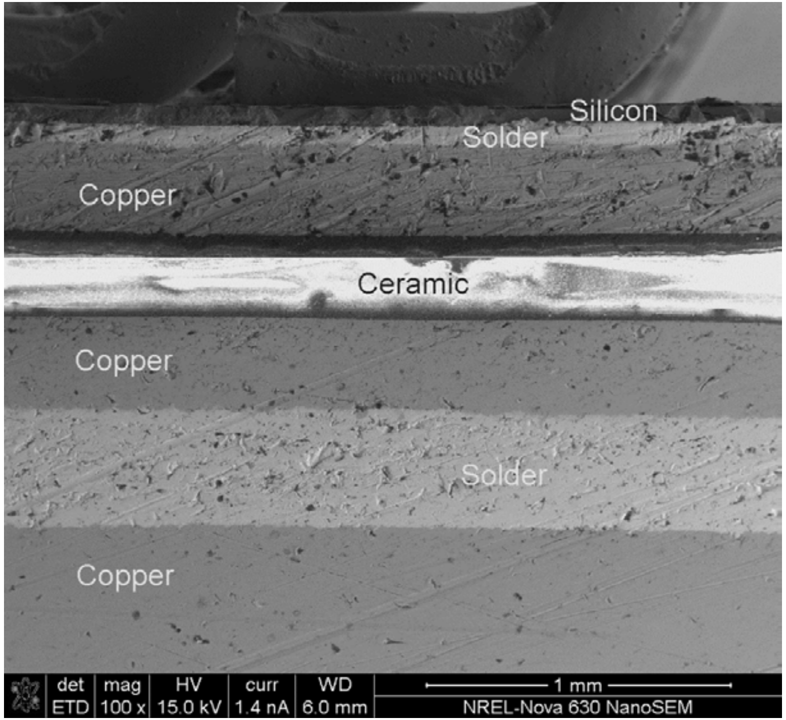
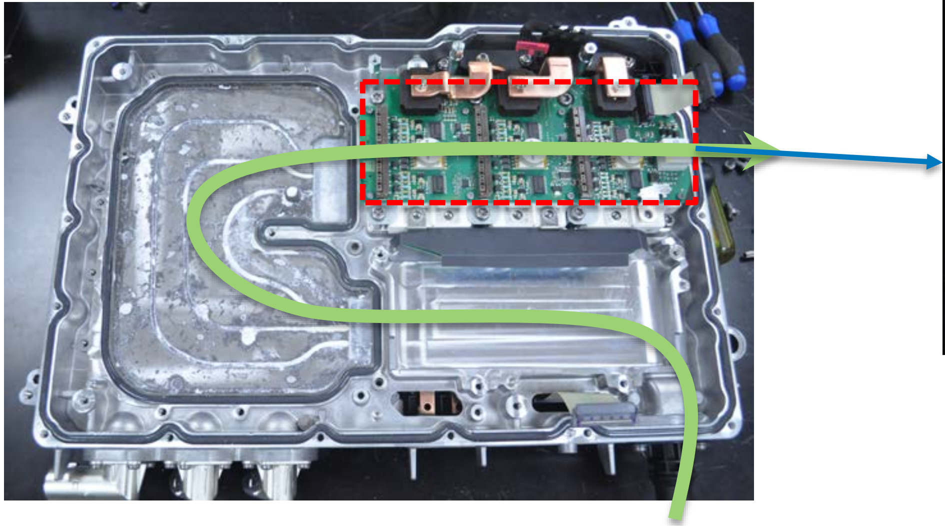
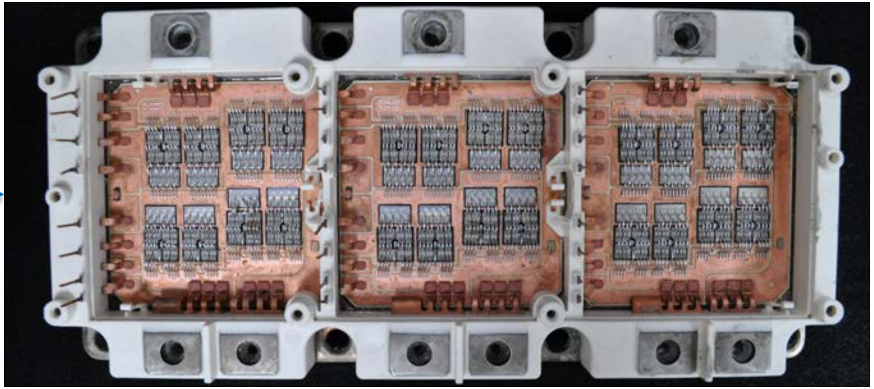


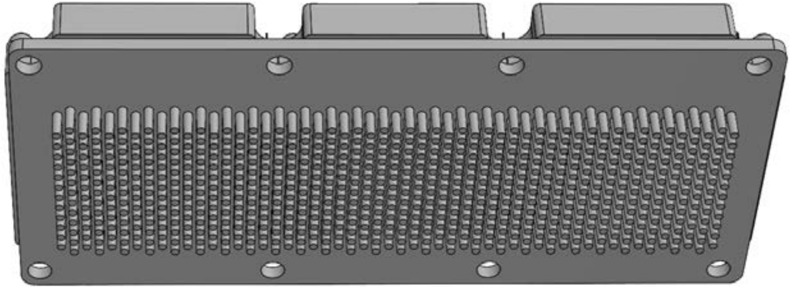
Image credits: Xuhui Feng (NREL)

2015 BWM i3 Heat Exchanger



Fluid path





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

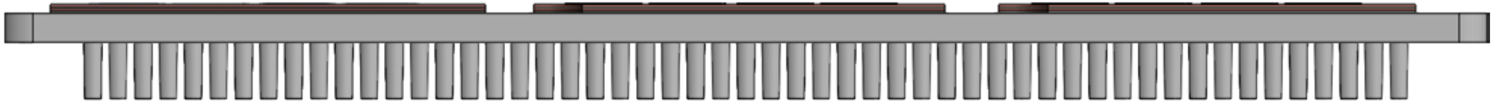
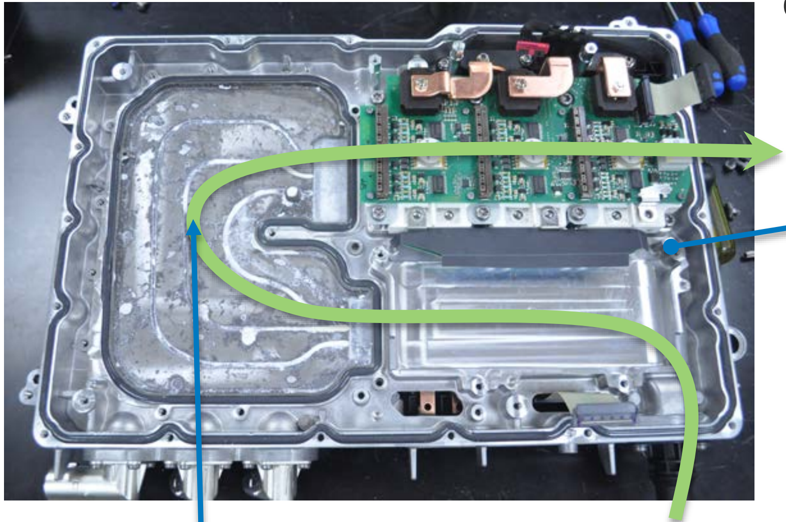
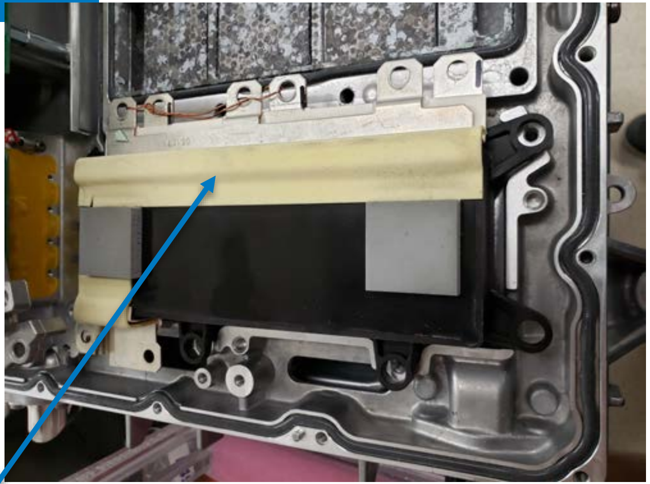


Image credits: Xuhui Feng, NREL

2015 BWM i3 Heat Exchanger

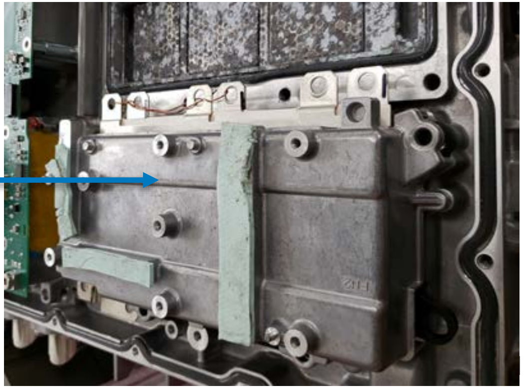


Capacitors are mounted to the liquid-cooled aluminum surface. No thermal grease used.



Fluid path

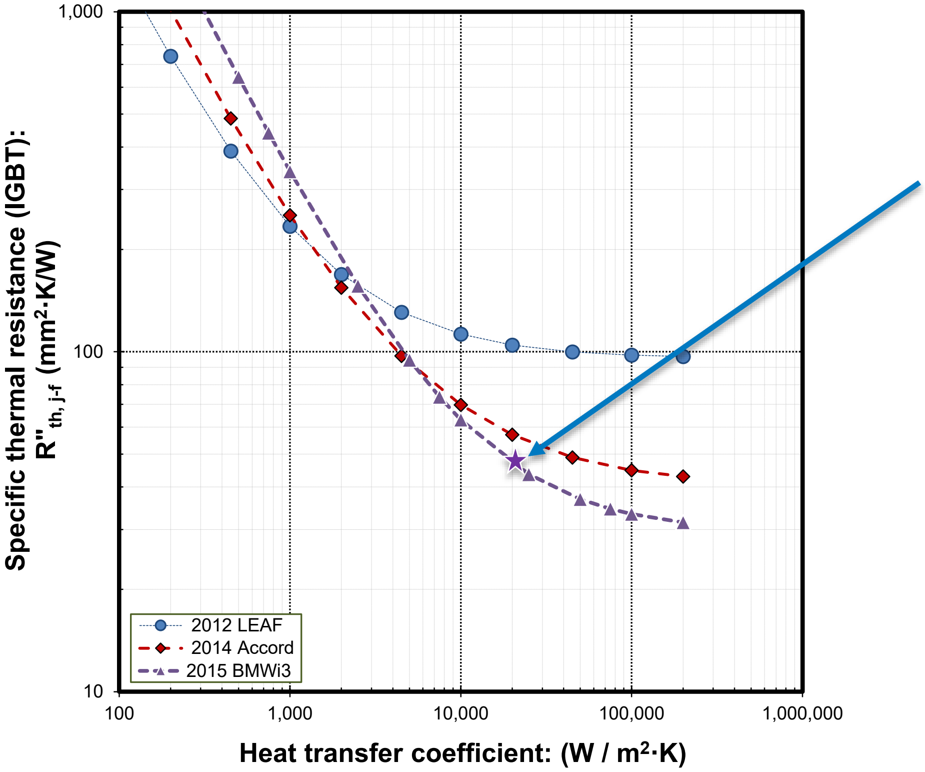
Charger and DC-DC converter cooled via coolant path



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

Image credits: Xuhui Feng, NREL

2015 BMW i3 Thermal Resistance

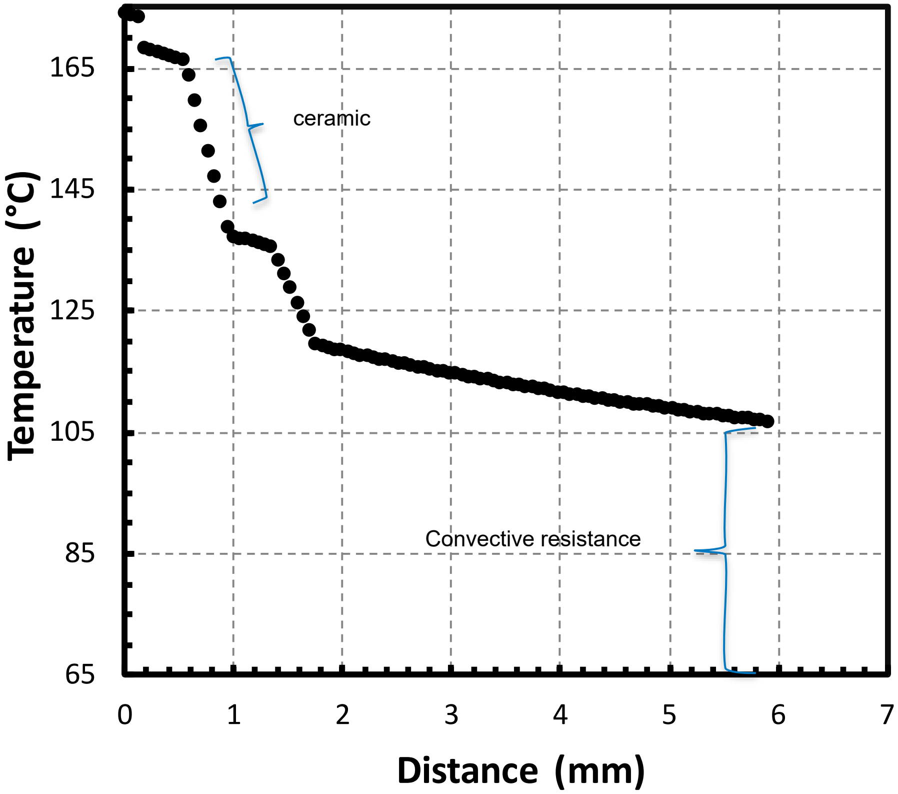


Estimated cold plate performance at 10 L/min

BMW i3 has lower thermal resistance compared to Accord due to higher thermally conductive materials (copper baseplate)

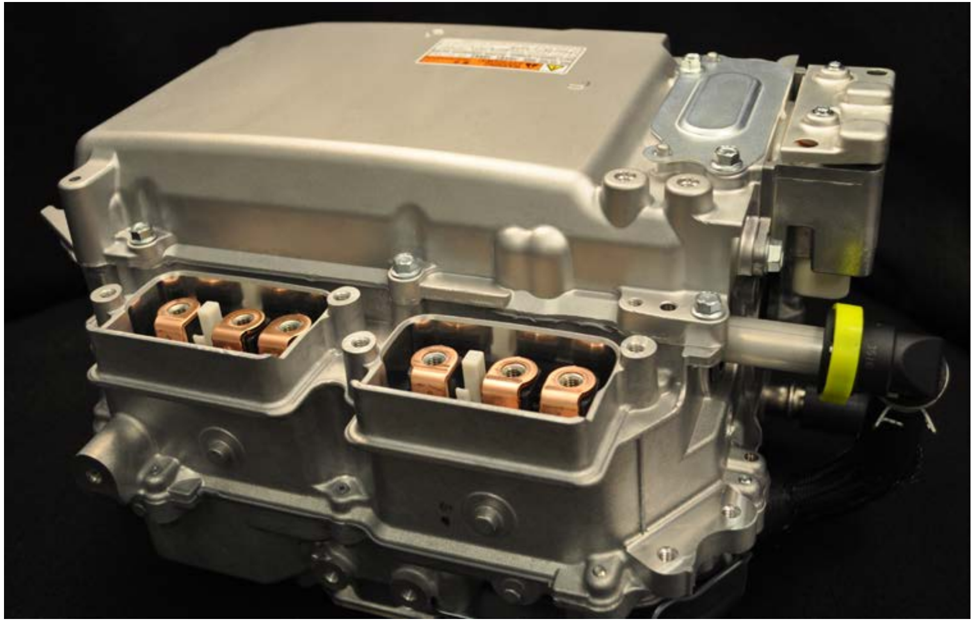
2015 BMW i3 Temperature Profile

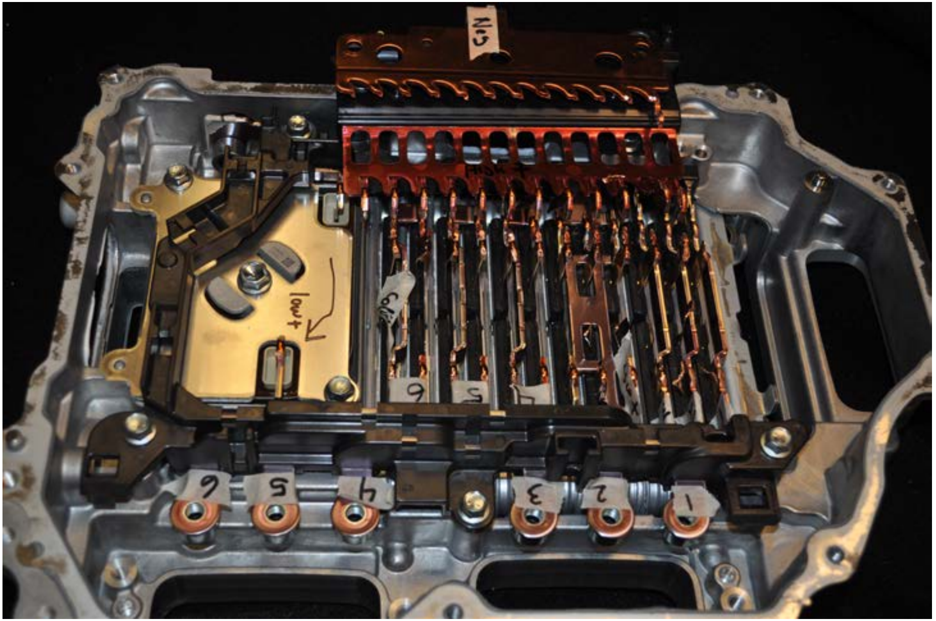
- Passive stack is about 64% of the total thermal resistance.
- Ceramic makes up the largest thermal resistance within the package.



2014 Camry HEV: 105 kW

Double-side-cooled system

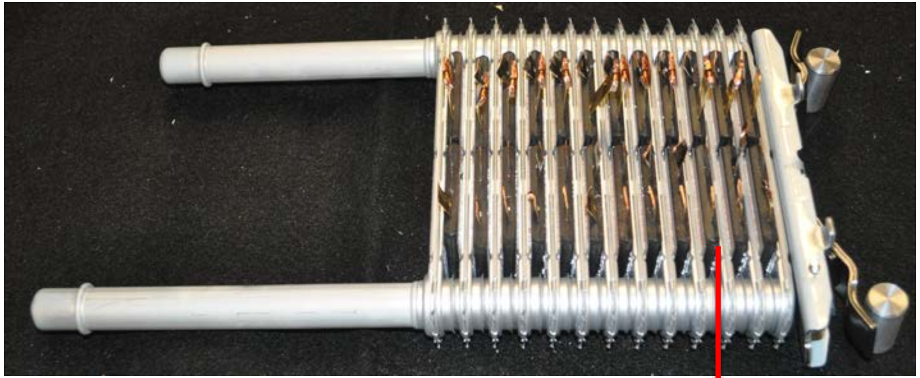




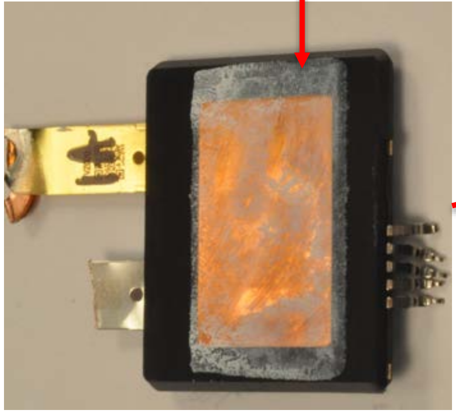
Includes two inverters, DC boost converter, and 12-V converter

Image credits: Gilbert Moreno, NREL

2014 Camry HEV



Power module heat exchanger



Power module

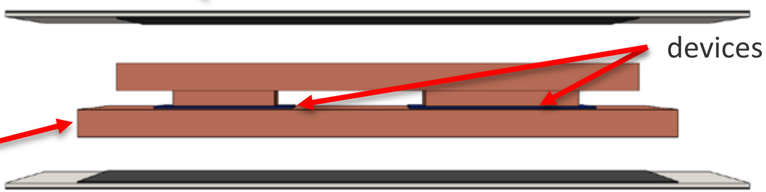
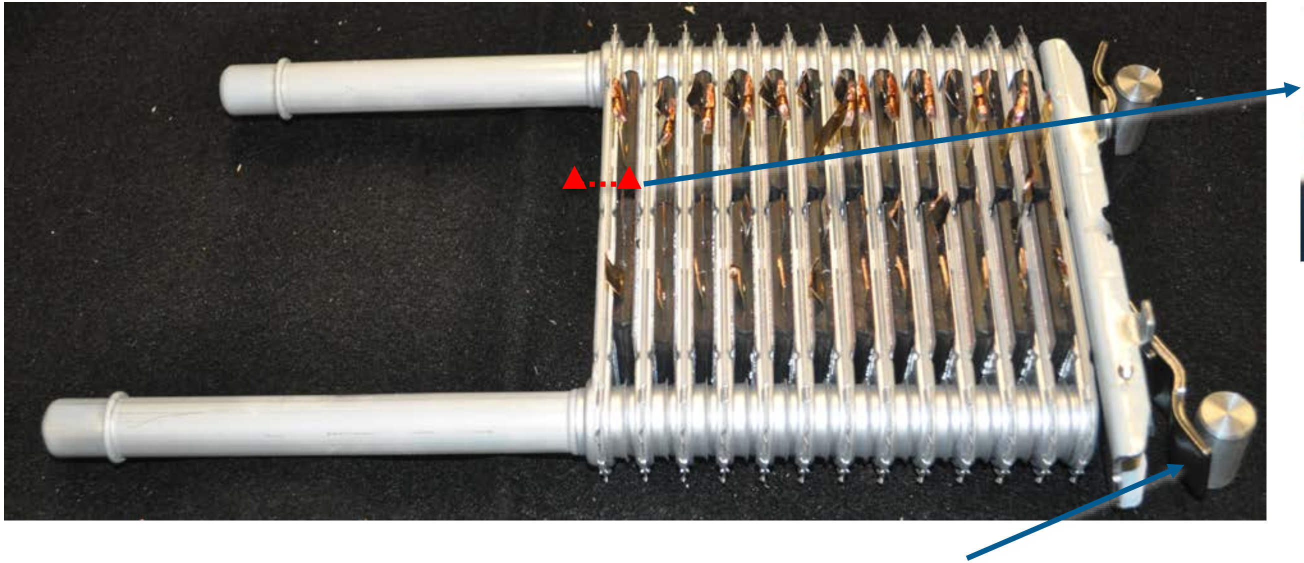
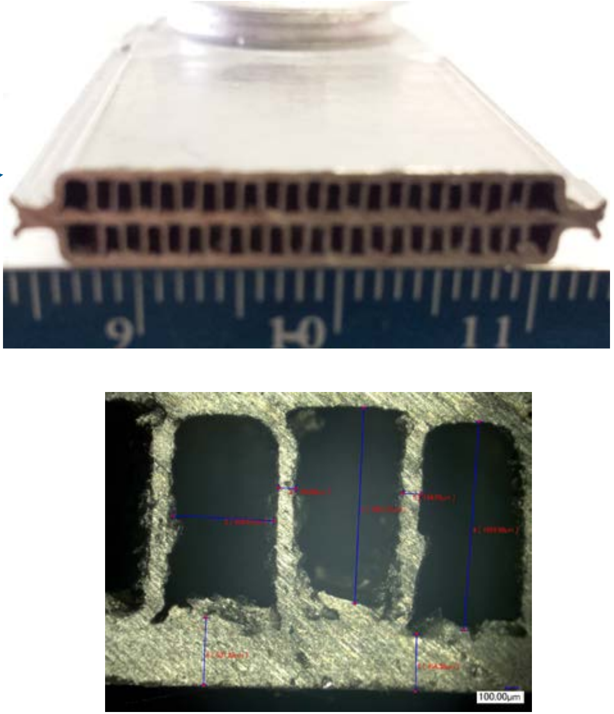


Image credits: Gilbert Moreno (NREL)

2014 Camry HEV



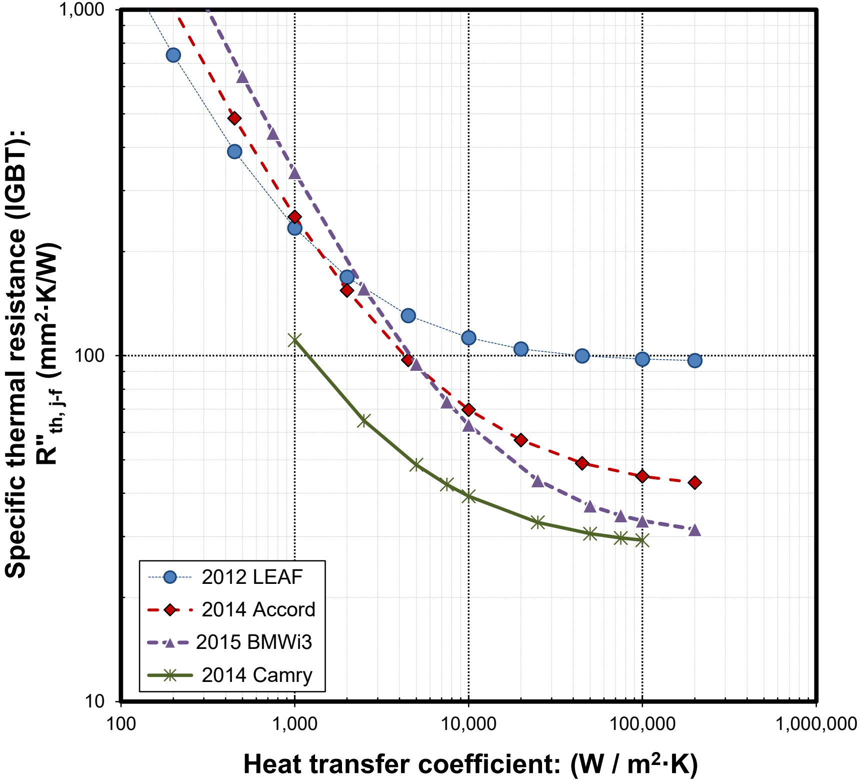
Spring mechanism to minimize thermal contact



Channels: folded fin ~1 x 1.5-mm channels

Image credits: Gilbert Moreno (NREL)

2014 Camry HEV Thermal Resistance

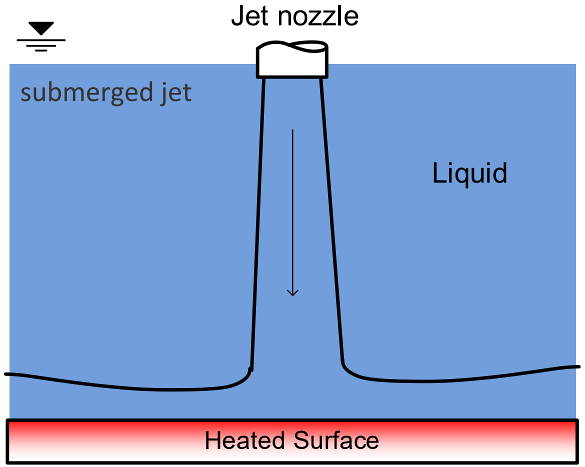


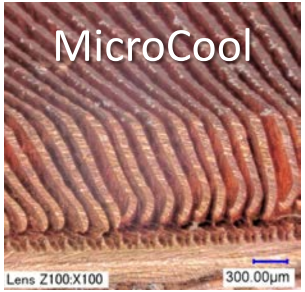
- Lowest thermal resistance values from the double-side-cooled strategy.
- Thermal performance levels off at relatively low heat transfer coefficient (HTC) values—a result of the thermal grease layers.

Advanced Cooling Technologies Developed at NREL

Jet Impingement: Fundamental Study

- Evaluated both free and submerged water jets on enhanced surfaces.
- Measured HTCs of 30,000 W/m²·K at 2 m/s. Higher HTCs at higher velocities.





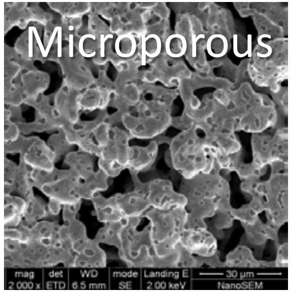
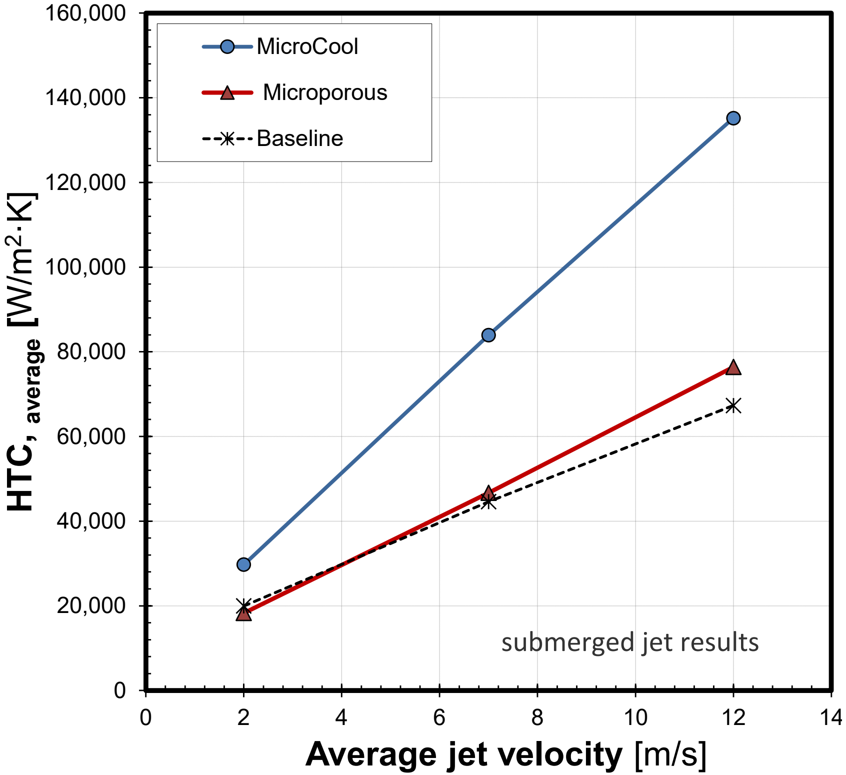


Image credits: Bobby To, NREL

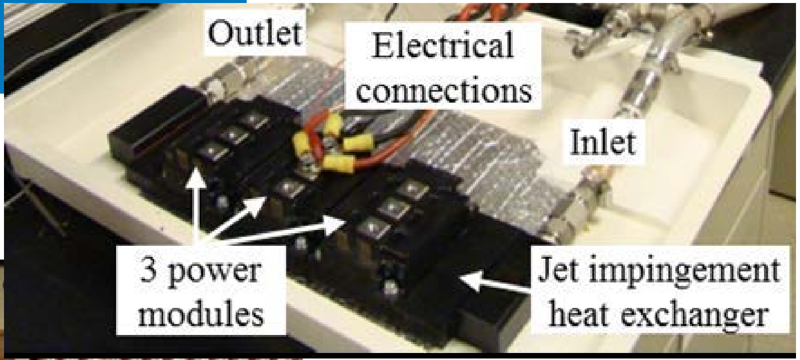


G. Moreno, S. Narumanchi, T. Venson, and K. Bennion. 2013. “Microstructured Surfaces for Single-Phase Jet Impingement Heat Transfer Enhancement.” *Journal of Thermal Science and Engineering Applications* 5 (3): 031004–031004. doi: 10.1115/1.4023308.

Jet Impingement: Implementation with WEG

- Used plastic (lightweight and inexpensive) manifold to distribute fluid to the 1.4-mm-diameter jets centered directly behind the devices.
- Used WEG at 10 L/min.
- Reduced thermal resistance by 17% with jets on MicroCool surface compared to baseline case with equivalent pumping power.

Image credits: Mark Mihalic, NREL



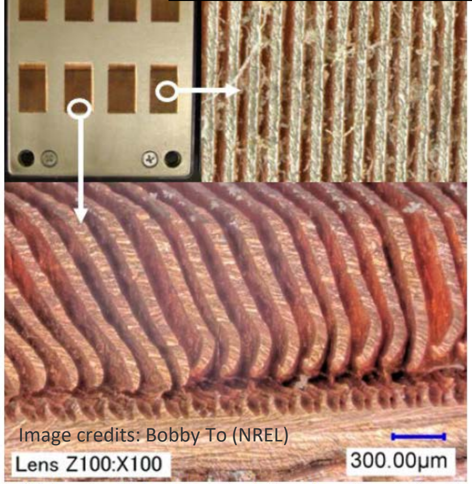


Image credits: Bobby To (NREL)

Fig. 3 Wolverine Tube MicroCool finned surface technology on module (top left) and close-up (top right and bottom).

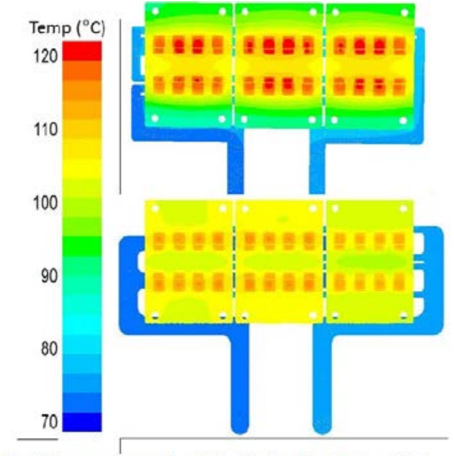
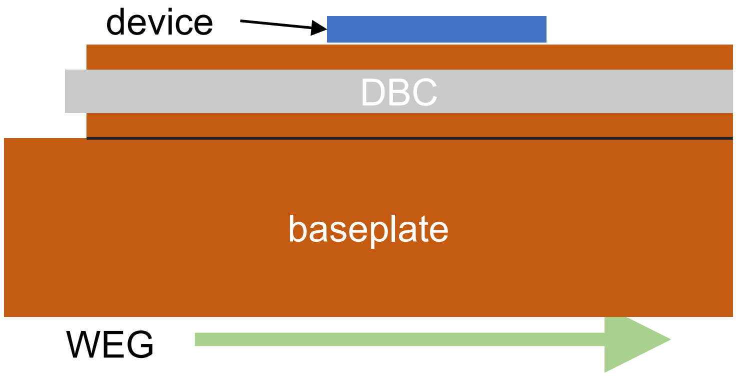
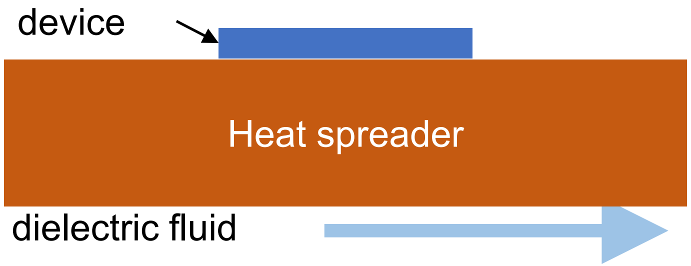


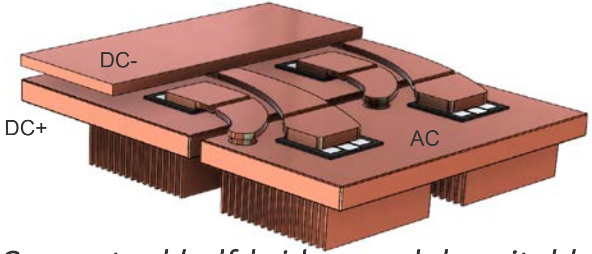
Fig. 9 Temperatures of modules for baseline (top) and jet impingement on the plain surface for the first prototype (bottom). The second prototype has similar thermal performance.

S. K. Waye, S. Narumanchi, M. Mihalic, G. Moreno, K. Bennion, and J. Jeffers. 2014. "Advanced Liquid Cooling for a Traction Drive Inverter Using Jet Impingement and Microfinned Enhanced Surfaces." In *Fourteenth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 1064–73. https://doi.org/10.1109/ITHERM.2014.6892399.

Jet Impingement: Implementation with Dielectric Fluids (Single-Phase)







Conceptual half-bridge module suitable for dielectric fluid cooling

Dielectric fluids can eliminate layers in the package to reduce thermal resistance, allow for direct cooling of the bus bars, and allow for the potential to use driveline fluids as coolants.

Jet Impingement: Implementation with 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 WEG.

Fluid *(properties at 70°C)*	**Thermal conductivity [W/m-K]**	**Specific heat [J/kg-K]**	**Density [kg/m^3]**	**Viscosity [Pa-s]**	**Flash point [°C]**	**Pour point [°C]**	**Breakdown voltage (ASTM D1816) [kV]**	**Dielectric constant (ASTM D924)**
Alpha 6 [1]	0.14	2,308	792	0.0091	246	-57	58	?
AC-100 [1]	0.13	2,326	761	0.0025	180	-55	>60	2.3
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 (freeze point)* [5]	-	-

[1] Communications with vendor (DSI Ventures or Engineered Fluids)

[2] S. P. Kemp and James L. Linden. 1990. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." SAE Technical paper.

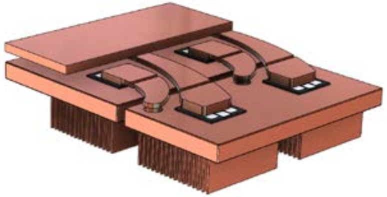
[3] K. Alshamani. 2003. "Equations for Physical Properties of Automotive Coolants." SAE Technical Paper.

[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. https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

Jet Impingement: Implementation with Dielectric Fluids (Single-Phase)

Single-side cooled



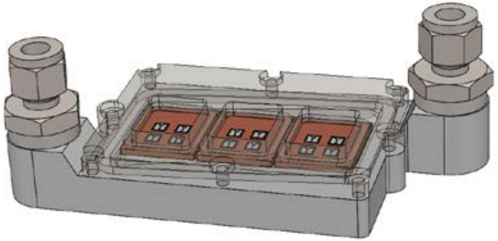
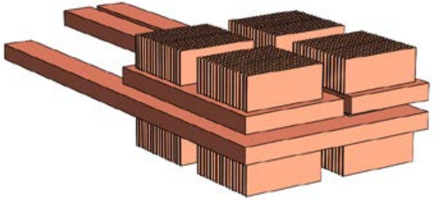
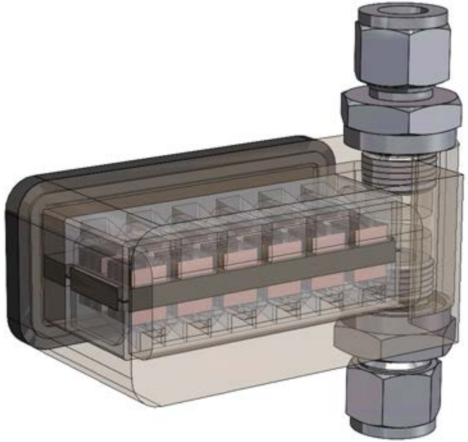


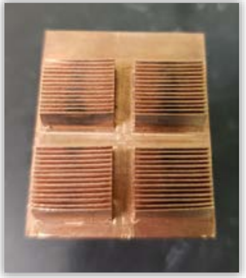
Image credit: Gilbert Moreno, NREL

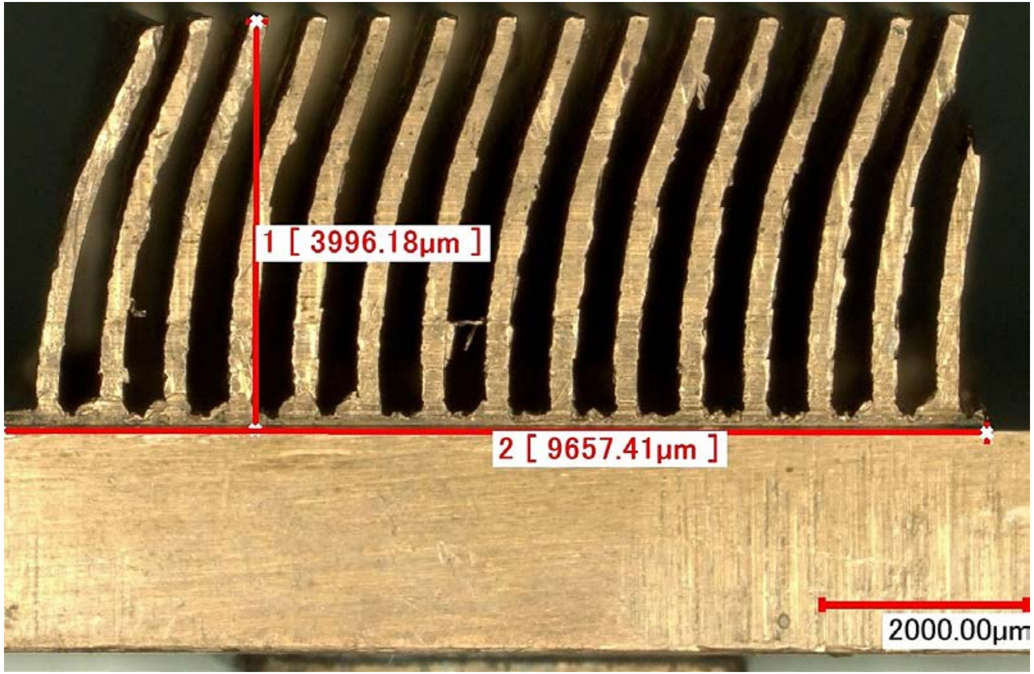
Double-side cooled





Jet Impingement: Implementation with Dielectric Fluids (Single-Phase)





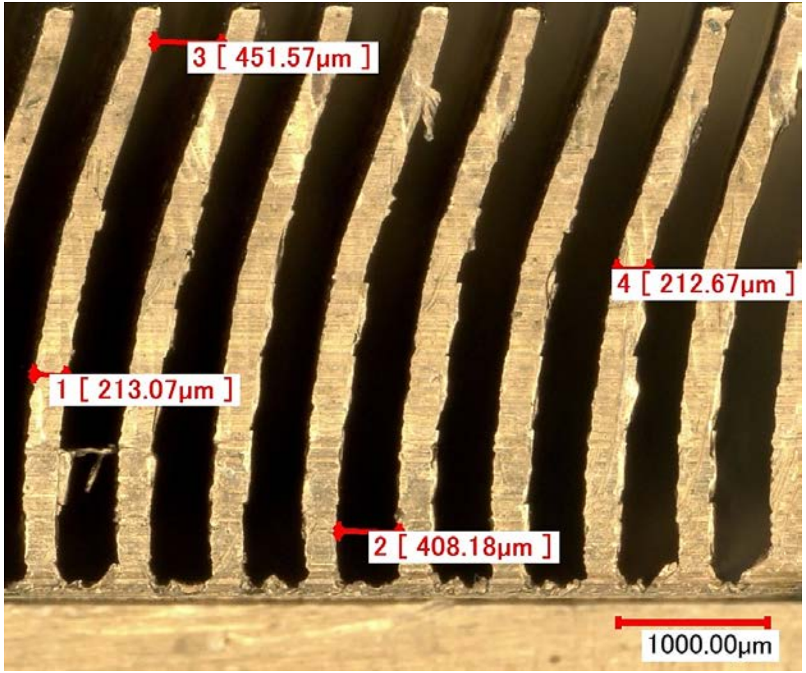
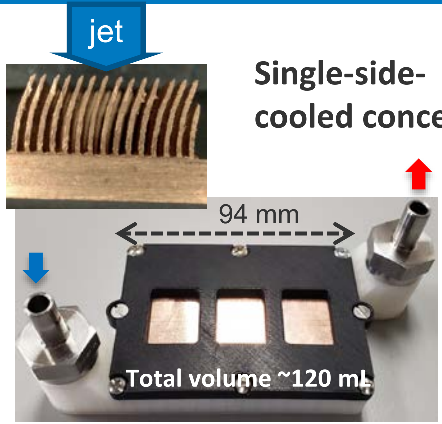


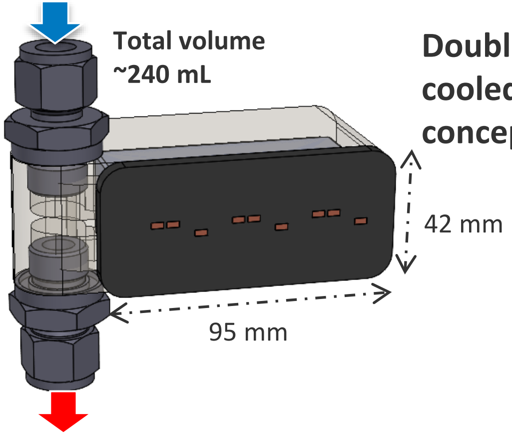
Image credits: Gilbert Moreno, NREL

Jet Impingement: Implementation with 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 Evaluated the following:
  - Refrigerants: R-245fa, R-134a, HFO-1234yf, HFE-7100
  - Enhanced surface: Microporous Coating, nanostructures
- Achieved HTCs ~50,000 W/m^2-K on smooth (and no fins) surfaces
- Measured HTCs > 200,000 W/m^2-K within small heat flux range
- CHF is a 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

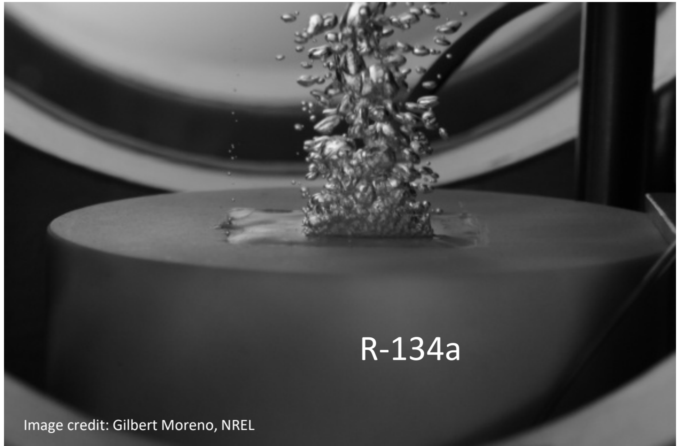
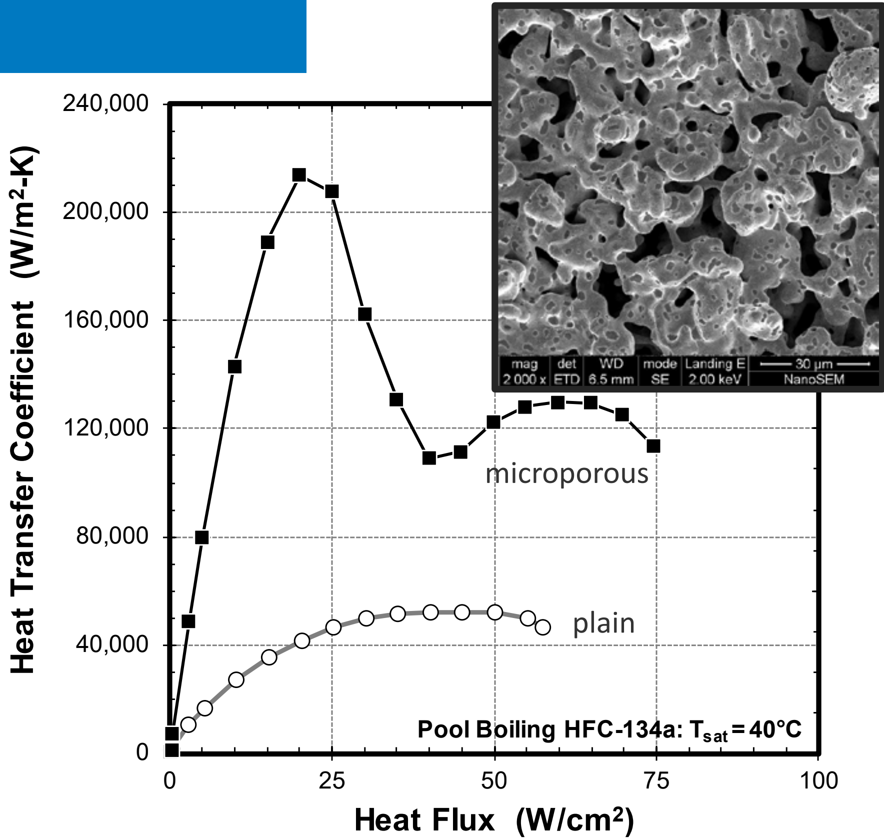


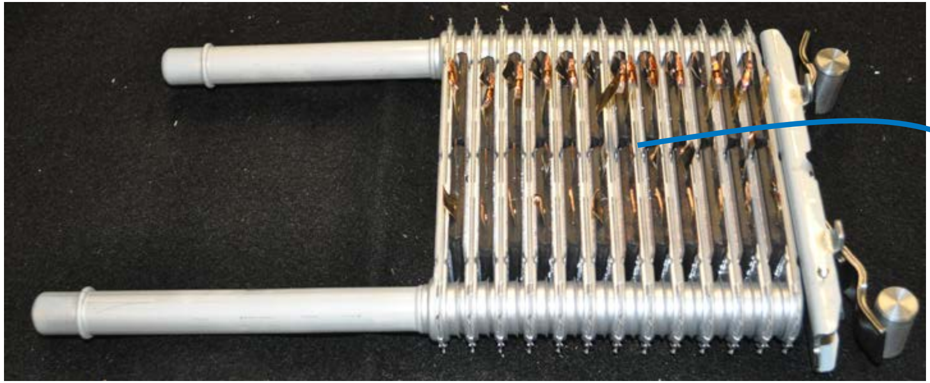
Image credit: Gilbert Moreno, NREL

Image credit: Bobby To, NREL



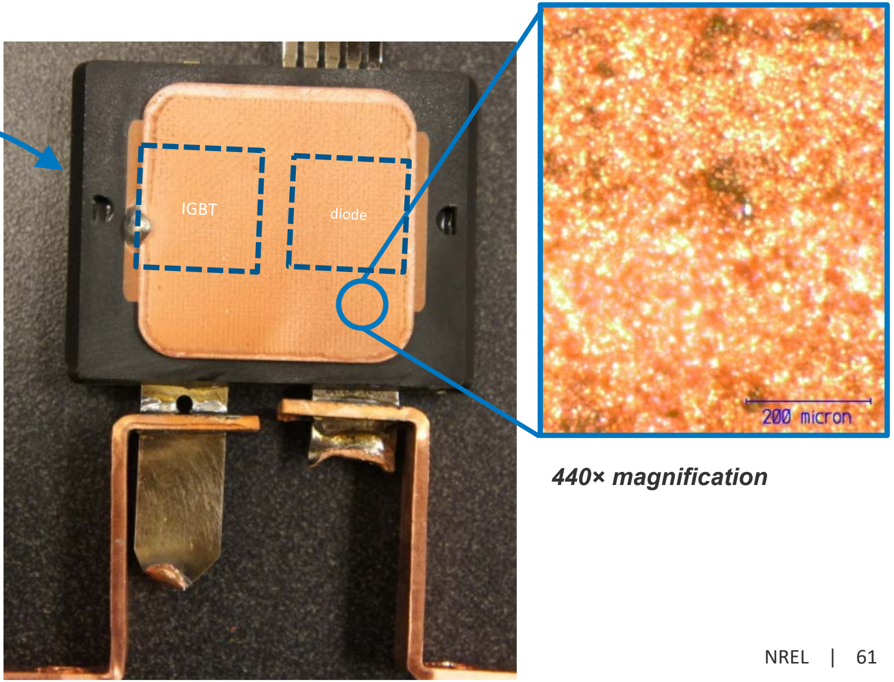
Passive Two-Phase: Module-Scale Demonstration

Demonstrated two-phase cooling (immersion cooling) on an automotive power module (2008 Lexus Hybrid)



Manufacturer’s cooling system: double-side cooling

Power module coated with 3M microporous coating

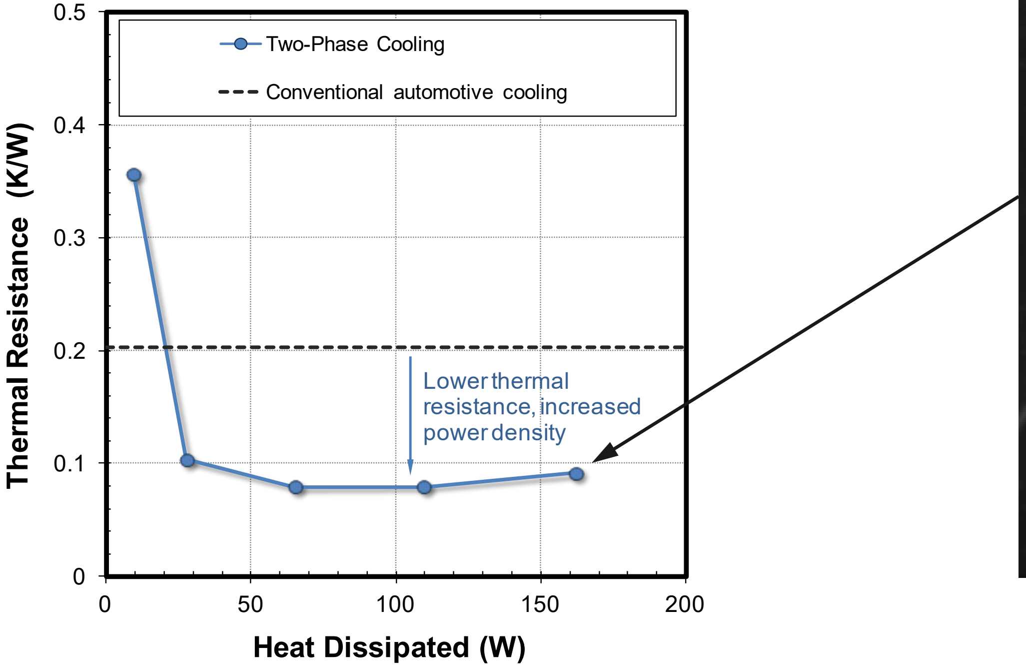


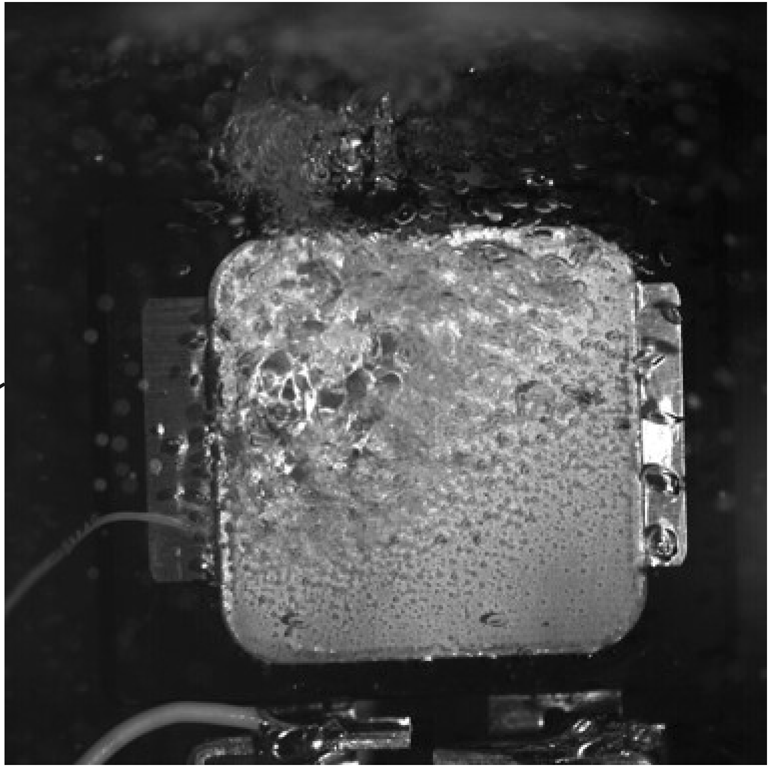
440× magnification

Image credit: Gilbert Moreno, NREL

Passive Two-Phase: Module-Scale Demonstration

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.



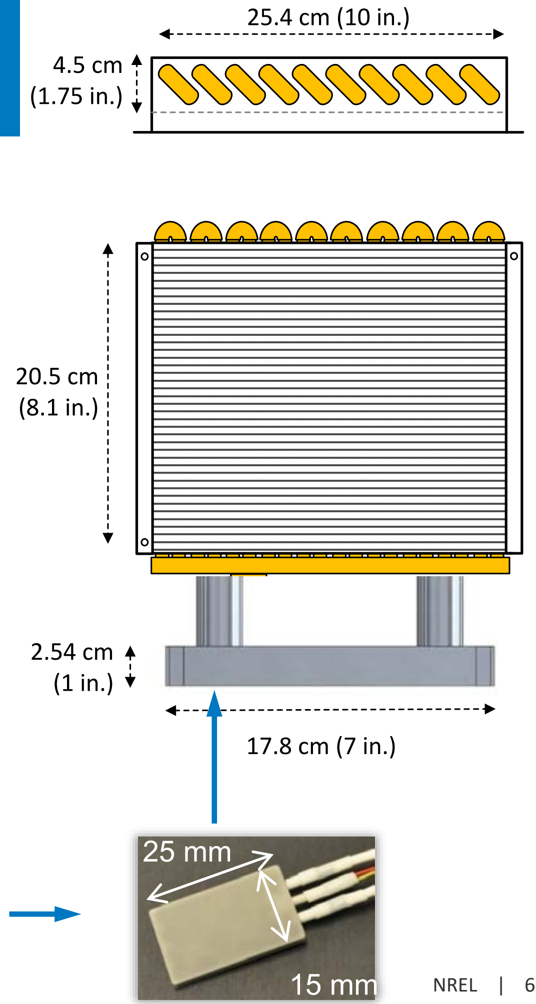


Immersion cooling: HFE-7100 refrigerant

Image credits: Gilbert Moreno, NREL

Passive Two-Phase: Inverter-Scale Demonstration

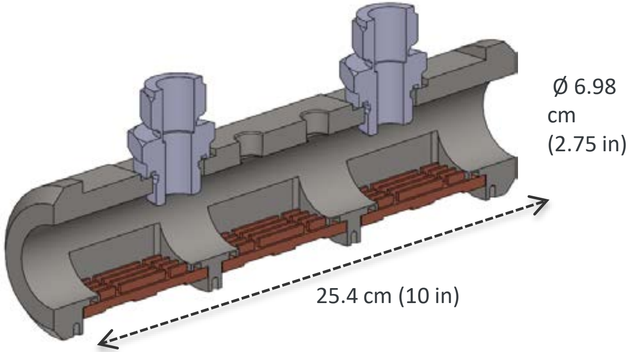
- Cools six Delphi power modules
- Used ceramic heaters as a substitute for the Delphi modules
- Finned-tube condenser with a 38-W axial fan (7-in diameter)
- Two evaporator concepts were tested.



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

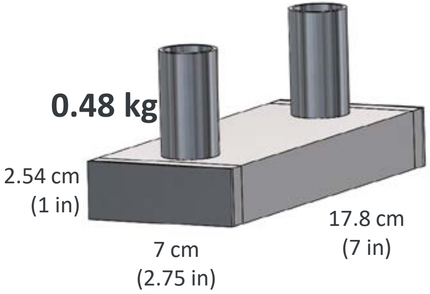
Passive Two-Phase: Inverter-Scale Demonstration

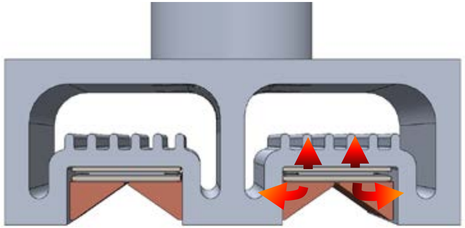
Copper cold plate design



- Interchangeable cold plate design
- Charged with 250 mL of refrigerant

Advanced all-aluminum design



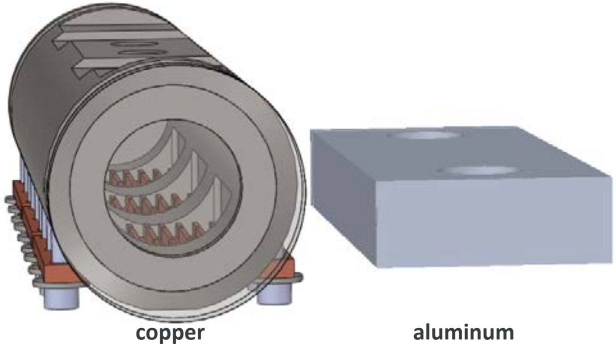


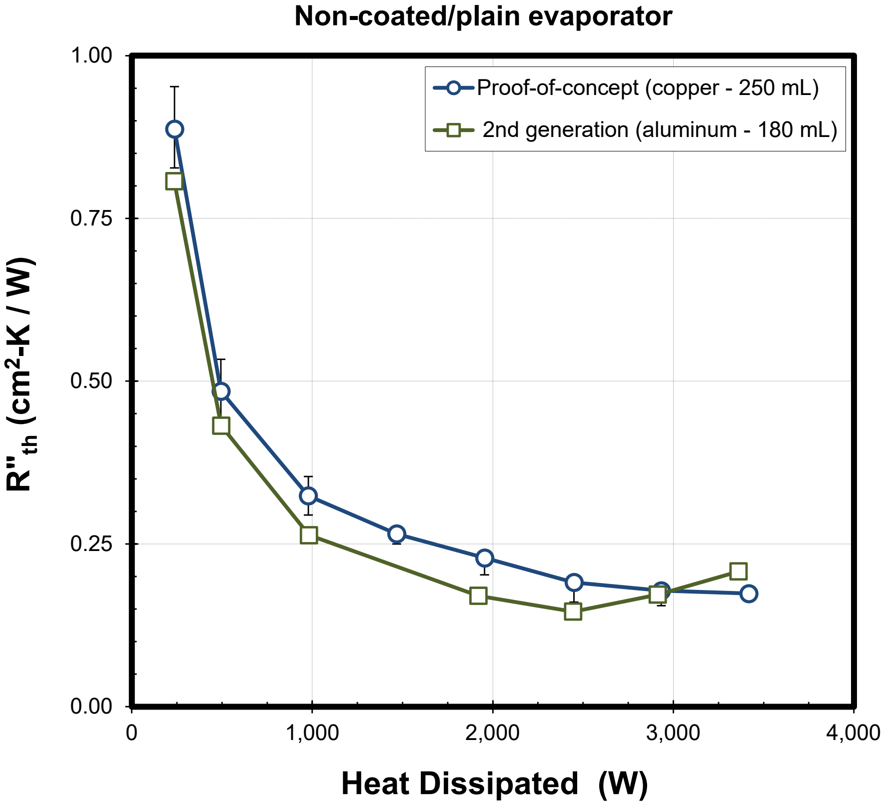
Heat conduction path from backside of the electronic device to the evaporator surface

- 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.

Passive Two-Phase: Inverter-Scale Demonstration

- Dissipated 3.5 kW of heat with only 180 mL of R-245fa



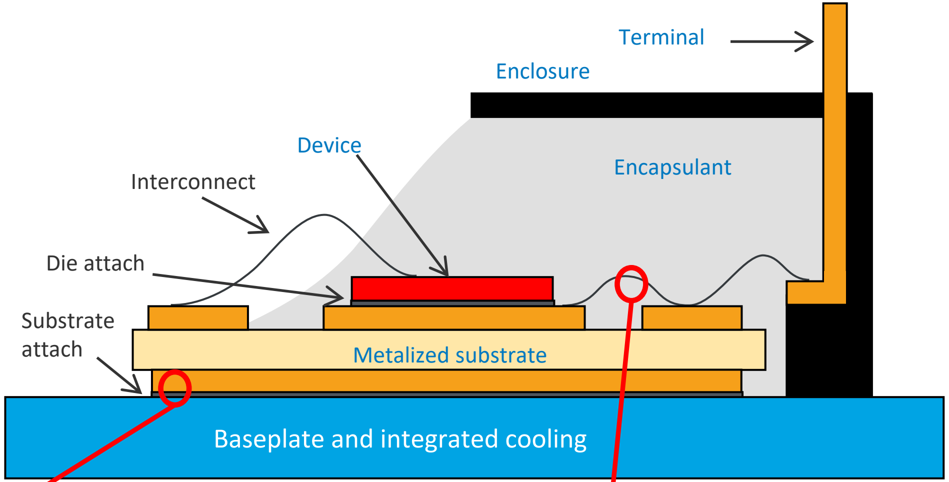


Power Electronics Materials and Component Reliability

Sreekant Narumanchi

Advanced Power Electronics Packaging Performance and Reliability

- Improve reliability of new (high-temperature/WBG) technologies
- Develop predictive and remaining lifetime models
- Package parametric modeling.



Bonded interface

Electrical interconnects

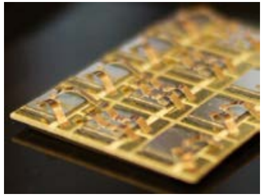
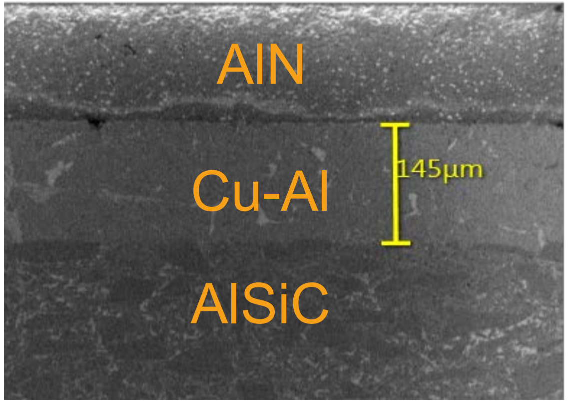


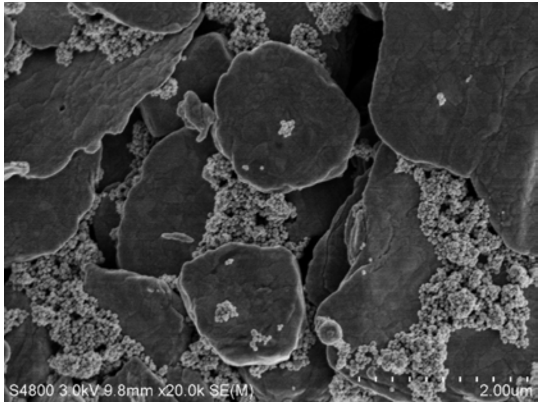
Image credits: Paul Paret and Doug DeVoto (NREL)

Approach – 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
  - NREL
    - Sintered silver (industry)
      - Pressureless



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



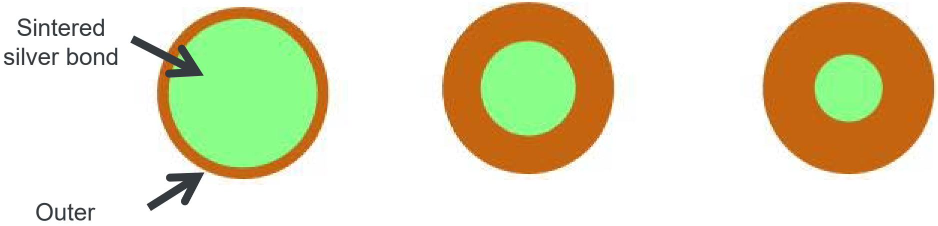
Hybrid-silver—scanning electron microscope image. *Image credit: Yansong Tan*

Approach – Reliability Evaluation


Image credit: Douglas DeVoto

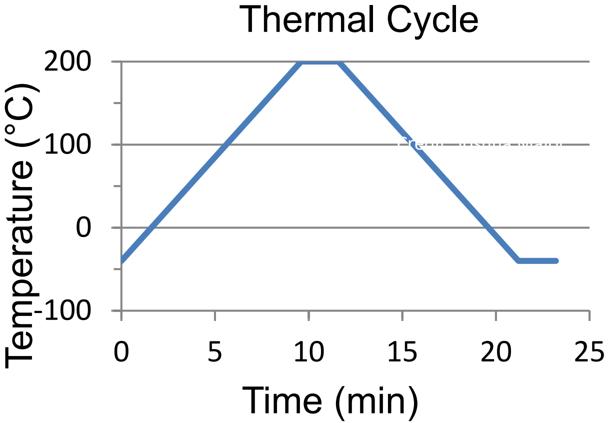
1-inch-diameter copper and Invar coupons: non-plated (top), plated with 4-µm-thick silver (bottom)

Sample structure



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

Accelerated thermal cycling



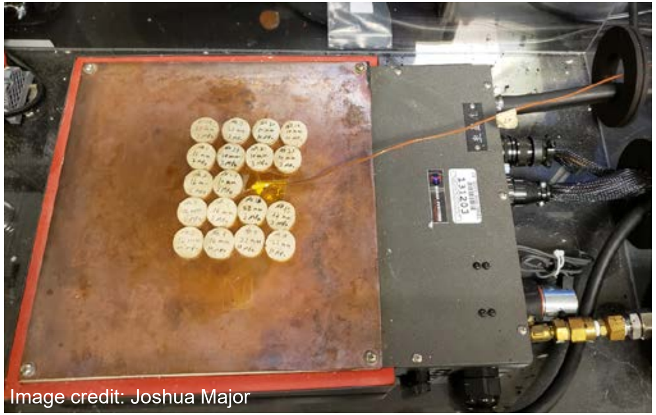


Image credit: Joshua Major

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

Lifetime Model of Sintered Silver Will Guide Advanced Power Electronics Module Design

- Sintered silver exhibited predominantly adhesive fracture under thermal cycling experiments.

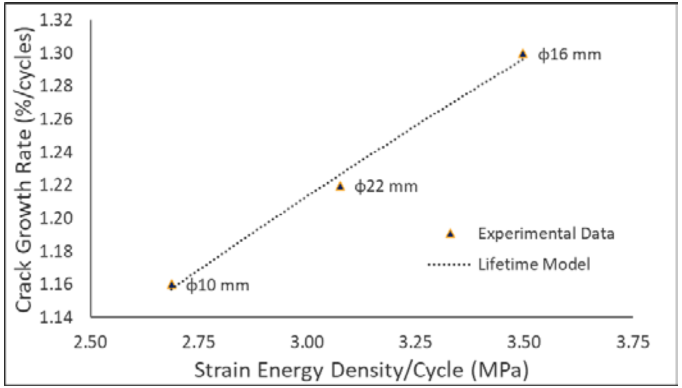
- We correlated the crack growth rate measurements with the strain energy density per cycle modeling results to formulate the lifetime prediction model.

- The lifetime prediction model (equation given below) is the first in the literature that incorporates the thermomechanical degradation of sintered silver at 200°C.

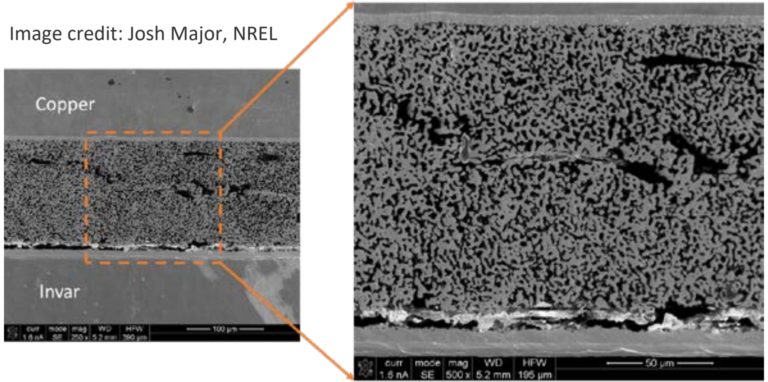
$$\frac{dA}{dN} = 0.76\,\Delta W^{0.431}$$

$\frac{dA}{dN}$ = 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 their high-temperature packages with sintered silver as the bonded interface.



Lifetime prediction model



Failure mechanisms in sintered silver

Substrate Alternatives Research

- DBC
  - Oxidation of Cu foils during bonding lowers melt temperature from 1,083°C to 1,065°C
  - Maximum metallization thickness of 1 mm
  - Must have metallization layers on both sides of ceramic
- Active metal bonding
  - Brazing process with Ag-Cu alloy between Cu and ceramic at 850°C in vacuum
  - Requires more process steps and is more expensive than DBC
- Organic direct-bond copper (ODBC)
  - A polyimide dielectric is bonded with metal
  - No limitations in metal material or metallization thickness.

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.


Photo by Douglas DeVoto, NREL

Substrates undergoing aging

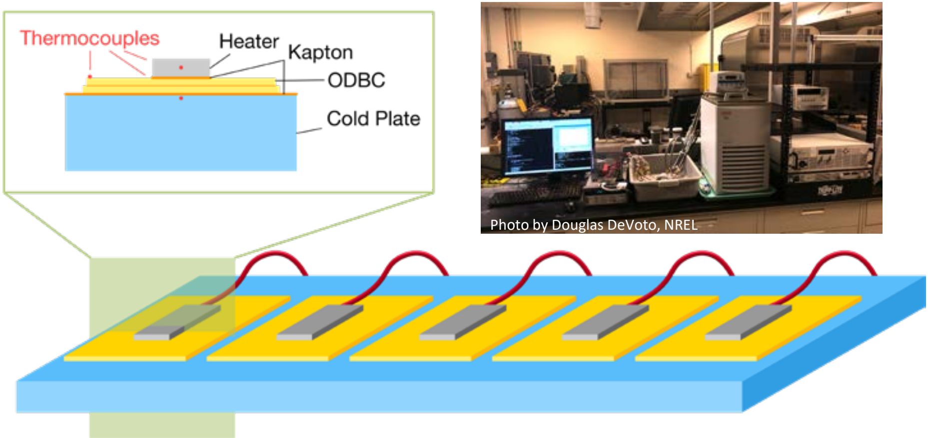


Photo by Douglas DeVoto, NREL

Power cycling test setup

Electrical Interconnect Research

- Alternative interconnect designs are required as devices are reduced in size and spacing between devices is minimized.
- Traditional wire interconnects or etched substrates for topside electrical connections can be replaced with direct chip-to-chip connection.

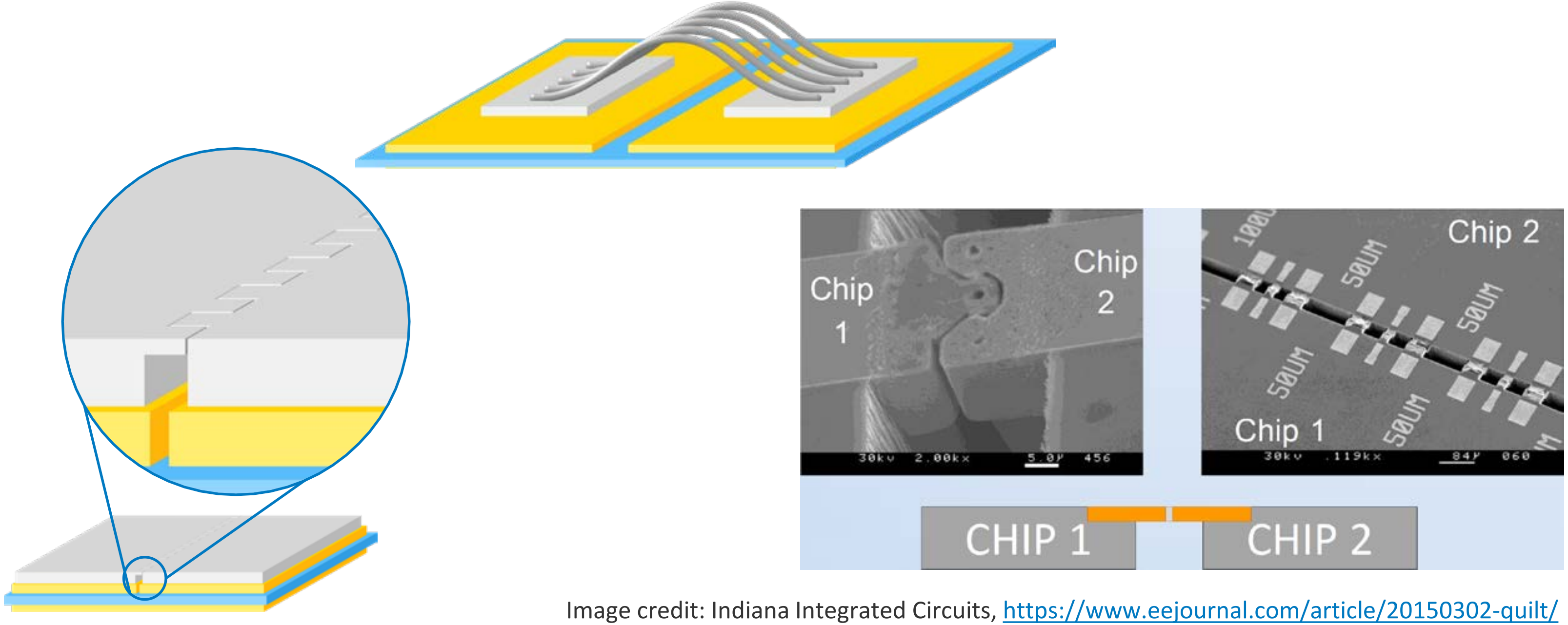


Image credit: Indiana Integrated Circuits, https://www.eejournal.com/article/20150302-quilt/

Quilt Packaging Reliability Experimental Evaluation

- Evaluated quilt packaging samples under thermal cycling and vibration experiments
  - *Sinusoidal vibration:* 20-Hz to 1,000-Hz sweep, 5-g acceleration, 2-hour duration (IEC 60068-2-6)
  - *Mechanical shock:* half-sine pulse, 30-g acceleration, 18-ms duration, repeating three times (IEC 60068-2-27)
  - *Thermal cycling:* –40°C to 150°C, 10°C/min ramp rate, 15-min soak, 1,000 cycles (JESD22-A104D).
- Electrical resistance measurements increased significantly for all samples subjected to mechanical shock and thermal cycling tests.

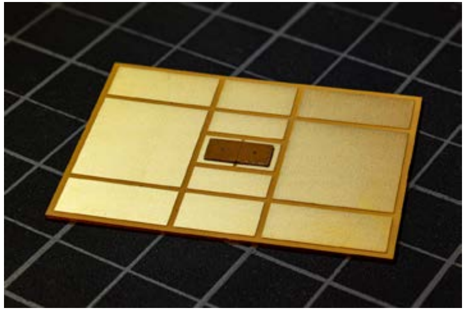
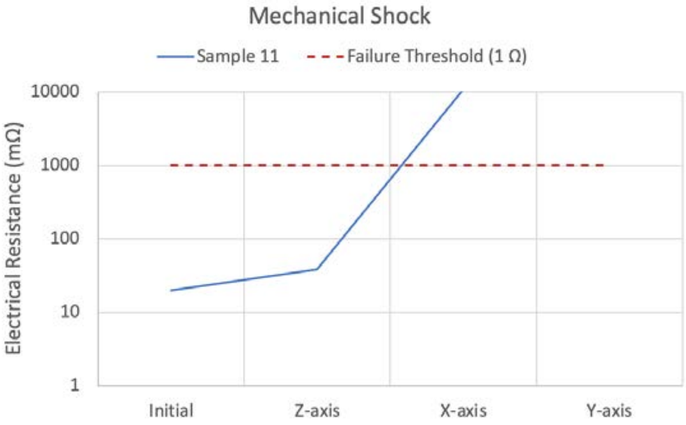
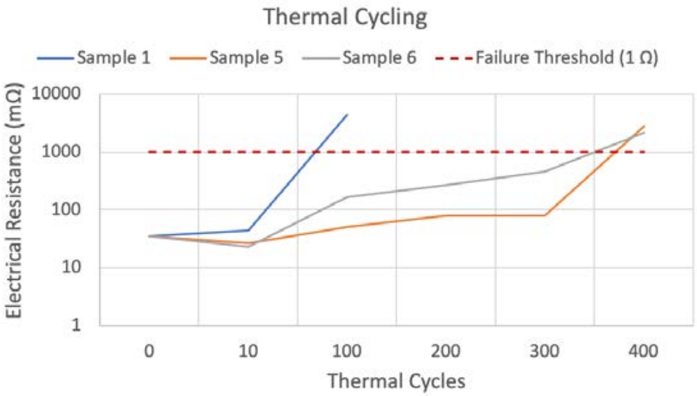


Image credit: Doug DeVoto

Indiana Integrated Circuits package on Dupont ODBC substrate

Nodule electrical resistance



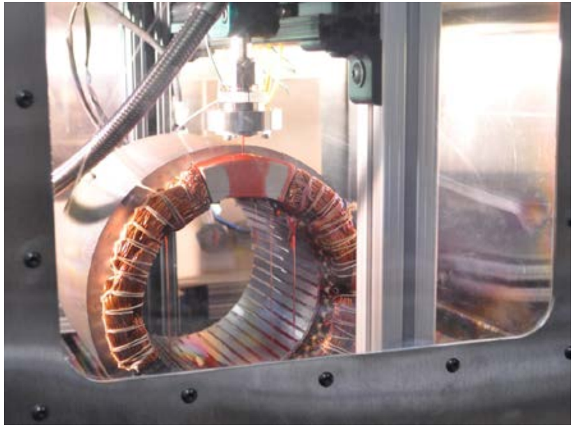


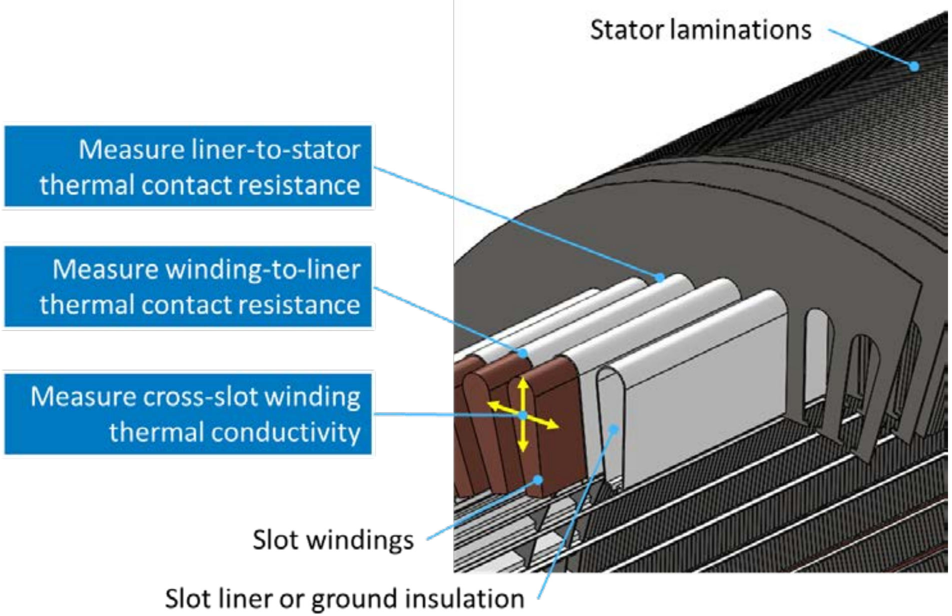
Thermal Management of Electric Machines and Integrated Electric Drive Systems

Sreekant Narumanchi

Electric Motor Thermal Management

- 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.





Measure liner-to-stator thermal contact resistance

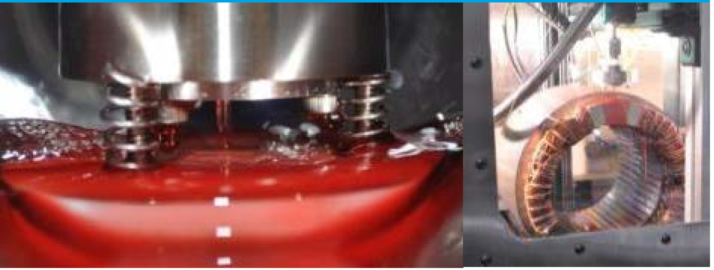
Measure winding-to-liner thermal contact resistance

Measure cross-slot winding thermal conductivity

Image credits: Bidzina Kekelia, NREL

Automatic Transmission Fluid Jet Impingement

Direct impingement cooling for motor windings



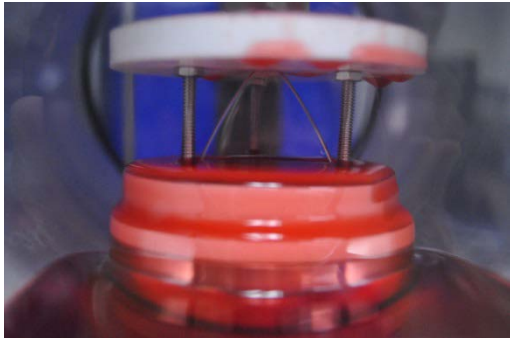
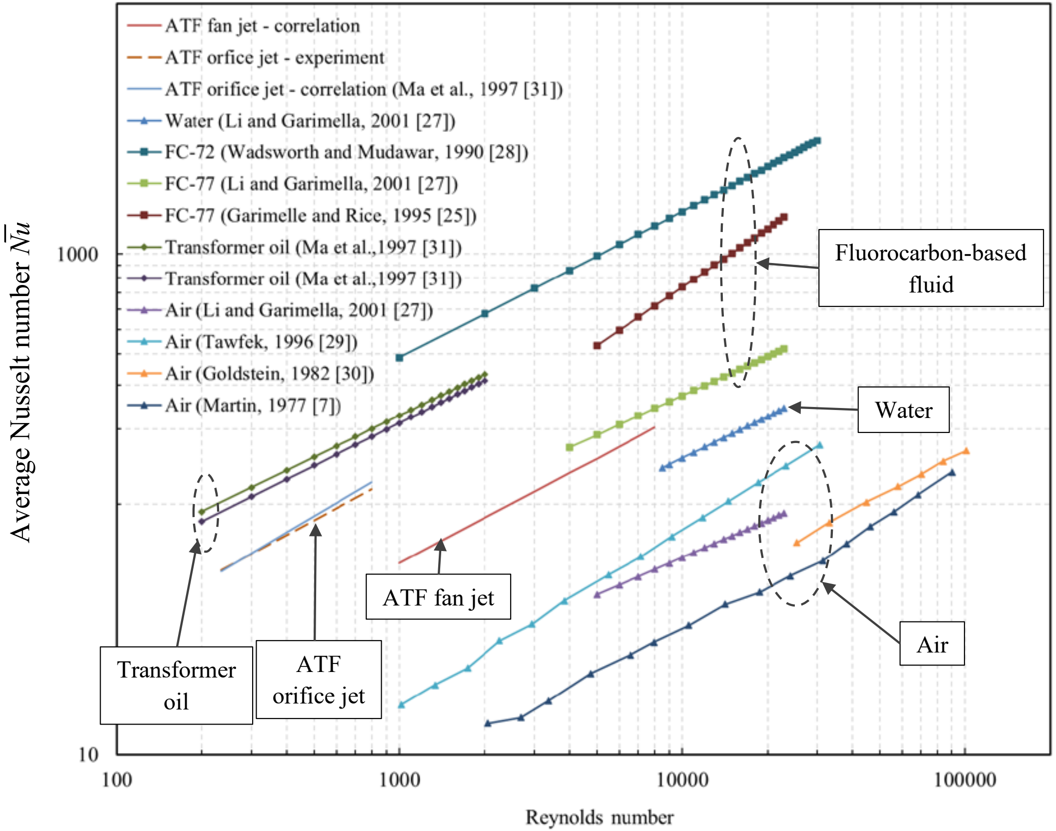
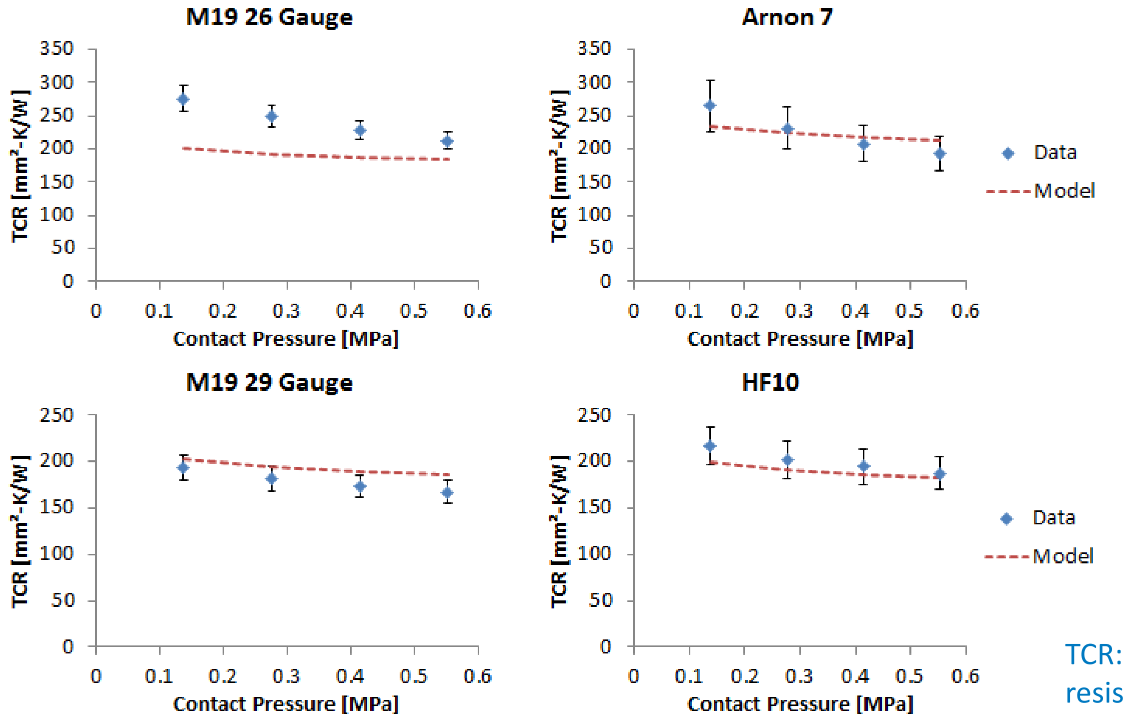


Image credits: Bidzina Kekelia and Xuhui Feng (NREL)



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

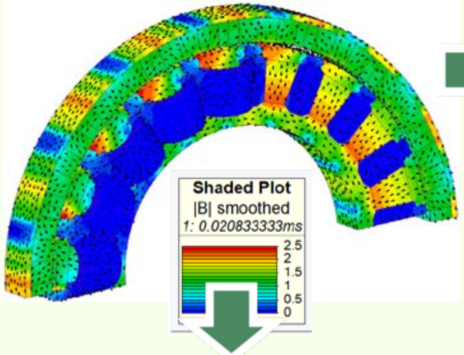
Source: J. E. Cousineau, K. Bennion, D. DeVoto, and S. Narumanchi. 2019. “Experimental Characterization and Modeling of Thermal Resistance of Electric Machine Lamination Stacks.” *International Journal of Heat and Mass Transfer* 129: 152–159.

Electric Motor Modeling and Design

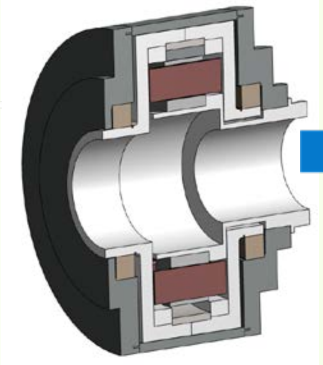
Electromagnetic, mechanical, and thermal design

Oak Ridge National Laboratory (ORNL)

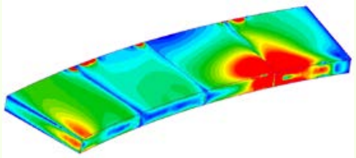
Electromagnetic design



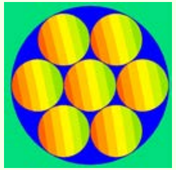
Mechanical assembly design



Loss evaluation



PM eddy current loss

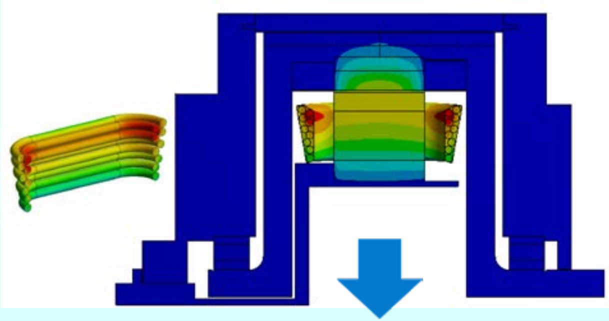


AC loss in Litz wire winding

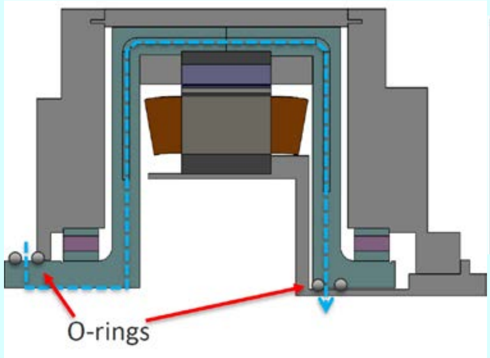
PM: permanent magnet

NREL and Georgia Tech

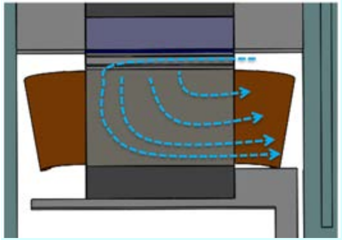
Thermal modeling



Cooling design



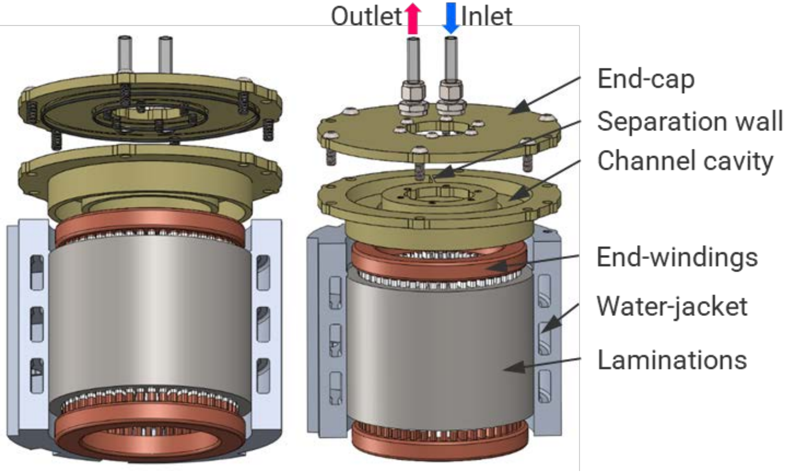
Rotor cooling



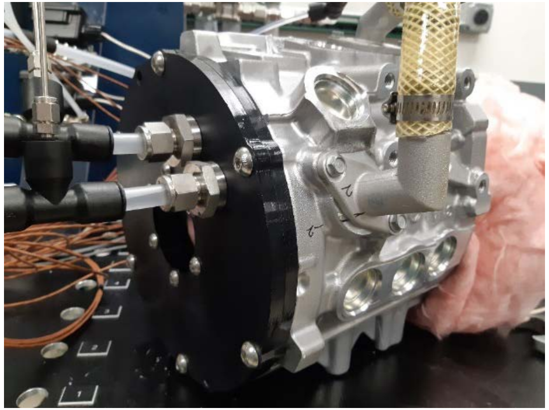
Slot heat exchanger

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.

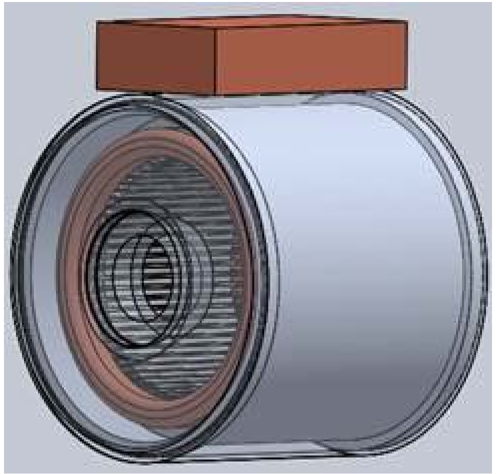


Assembled motor end-winding cooler at NREL (Photo credit: Sebastien Sequeira, Georgia Tech and NREL).

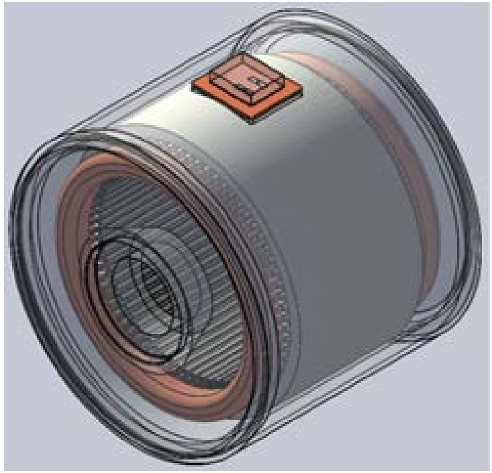
Integrated Electric Drive Thermal Management

Integrated Traction Drive System

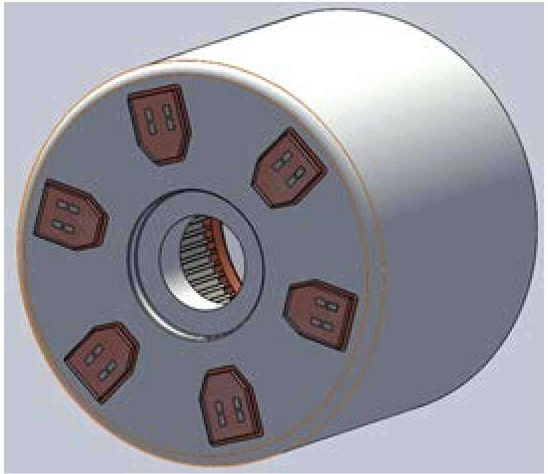
Different integration techniques



Separate enclosures



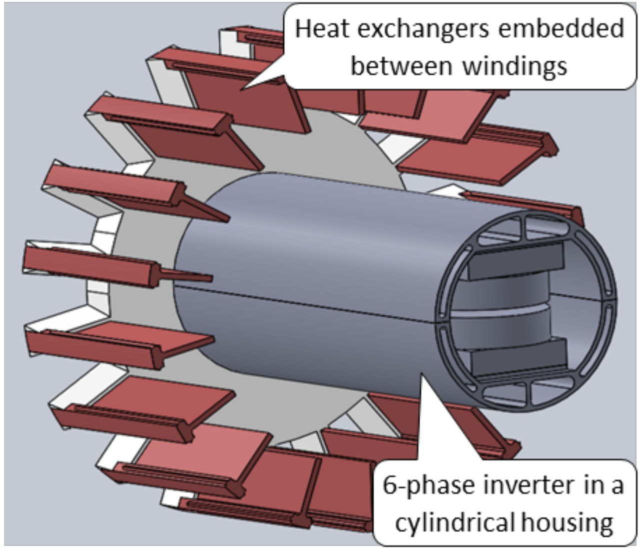
Radial integration



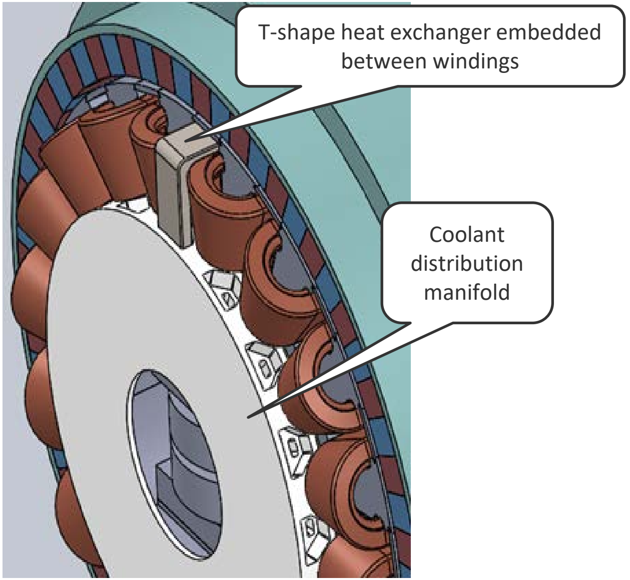
Axial integration

Integrated Traction Drive Thermal Management

- ORNL and NREL collaboration
  - Completed several design revisions of T-shaped heat exchanger embedded between winding phases.
  - Completed several design revisions for coolant distribution manifold-disk.
  - Completed several revisions for cylindrical inverter housing.

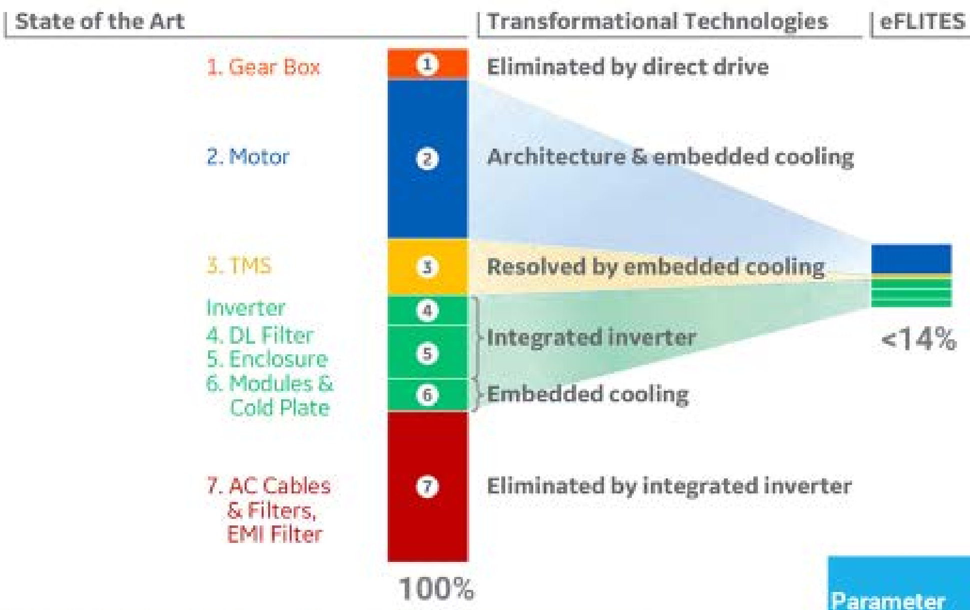


Key components of thermal management system for ORNL's outer-rotor integrated drive.



General view of thermal management system assembly for ORNL's outer-rotor integrated drive.

Integrated Electric Drive and Thermal Management for Aviation



State of the Art | Transformational Technologies | eFLITES

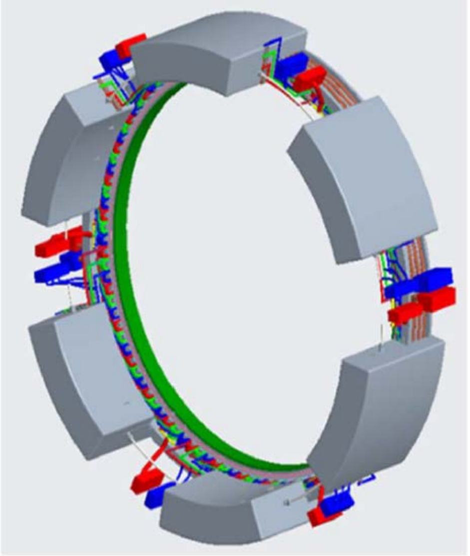
1. Gear Box — ① — Eliminated by direct drive
2. Motor — ② — Architecture & embedded cooling
3. TMS — ③ — Resolved by embedded cooling

Inverter
4. DL Filter — ④
5. Enclosure — ⑤ — Integrated inverter
6. Modules & Cold Plate — ⑥ — Embedded cooling

7. AC Cables & Filters, EMI Filter — ⑦ — Eliminated by integrated inverter

100%

<14%



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

Acknowledgments

U.S. Department of Energy

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Thank You

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