Thermal Management and Reliability of Automotive Power Electronics and Electric Machines

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Research Pathway to Electrification

- Vehicle architecture change
  - Driven by long-range BEVs and need for commonality for production scale
- Greater fleet applications of BEVs
  - Mobility as a Service
  - Driving increase in reliability (15 years/300K miles)
- Long-range BEVs
  - Driving need for high-rate power transfer – high-power charging
- Innovations to overcome gaps
  - Understanding the physics of new materials
  - Quantifying the impact of new designs

BEV: Battery Electric Vehicle

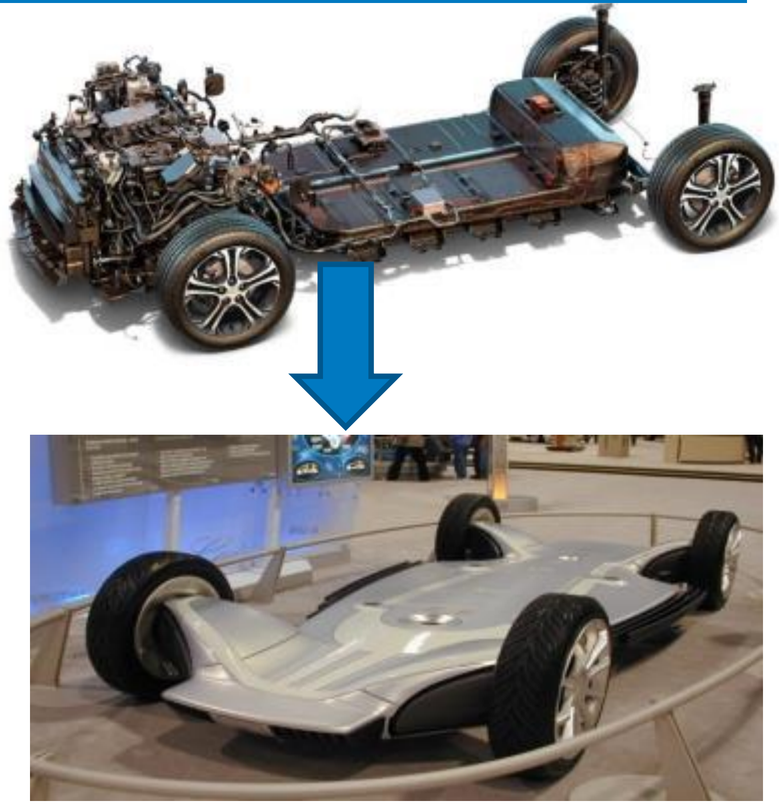
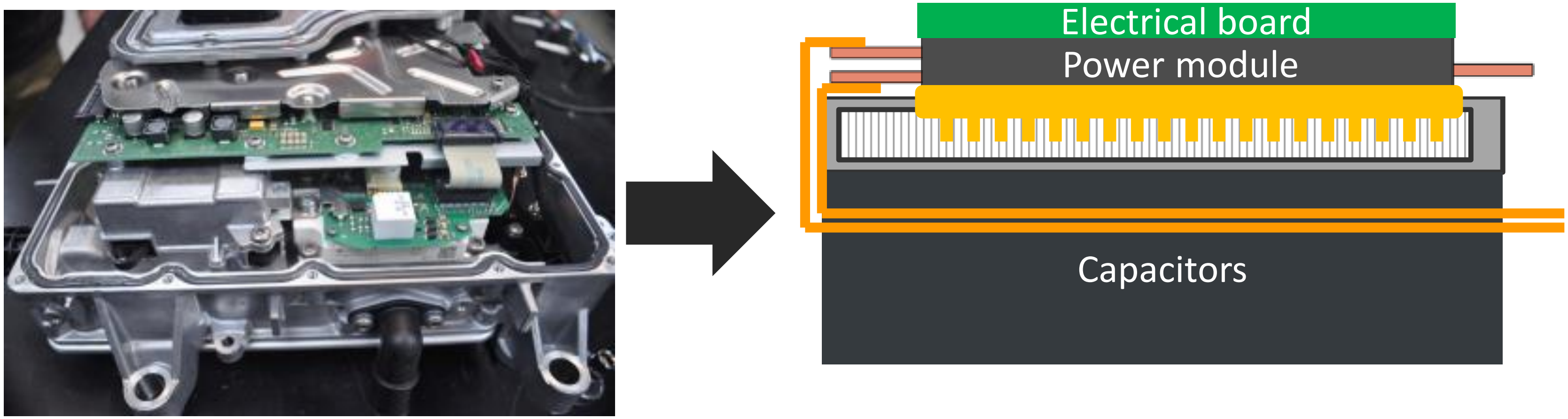


Photo from the 2017 Electrical and Electronics Technical Team Roadmap, https://energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap% 2010-27-17.pdf

Significant volume reduction (factor of 10)
Improved reliability (factor of 2)
Lower cost (50% lower)

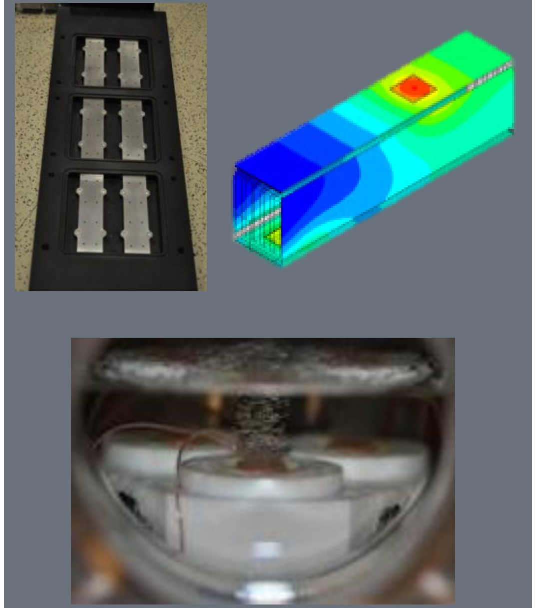
Future Power Electronics Designs – Gaps and Challenges



- Planar power electronics construction
- Reduction in volume/size by a factor of 10 – thermal and reliability challenges
- Materials innovations needed (electrical, thermal, mechanical, and magnetic properties)

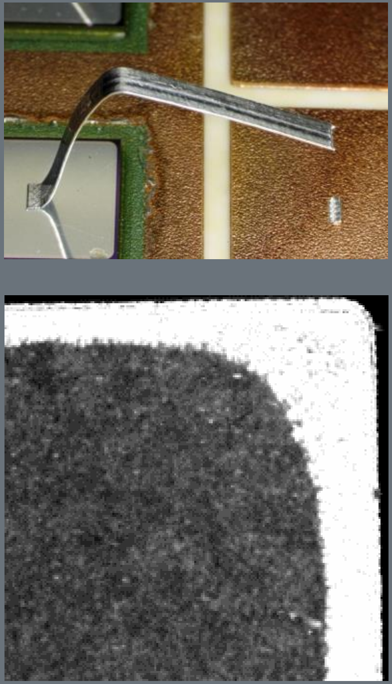
NREL APEEM Research Focus Areas

Power Electronics Thermal Management



Photos by Gilbert Moreno, NREL

Advanced Packaging Designs and Reliability



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Electric Motor Thermal Management

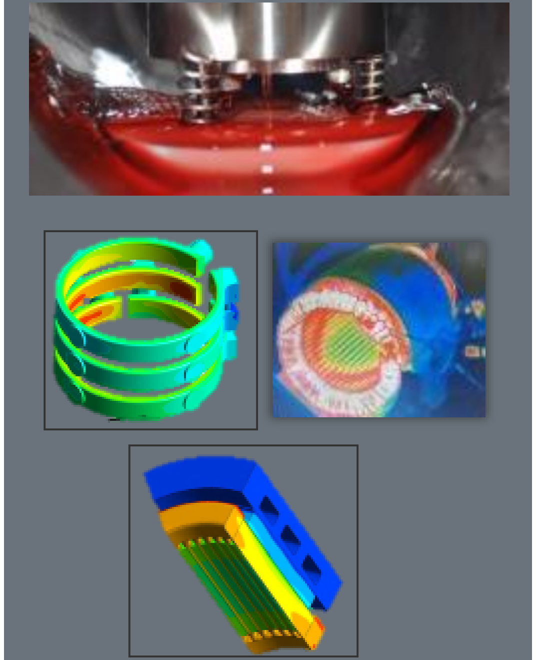
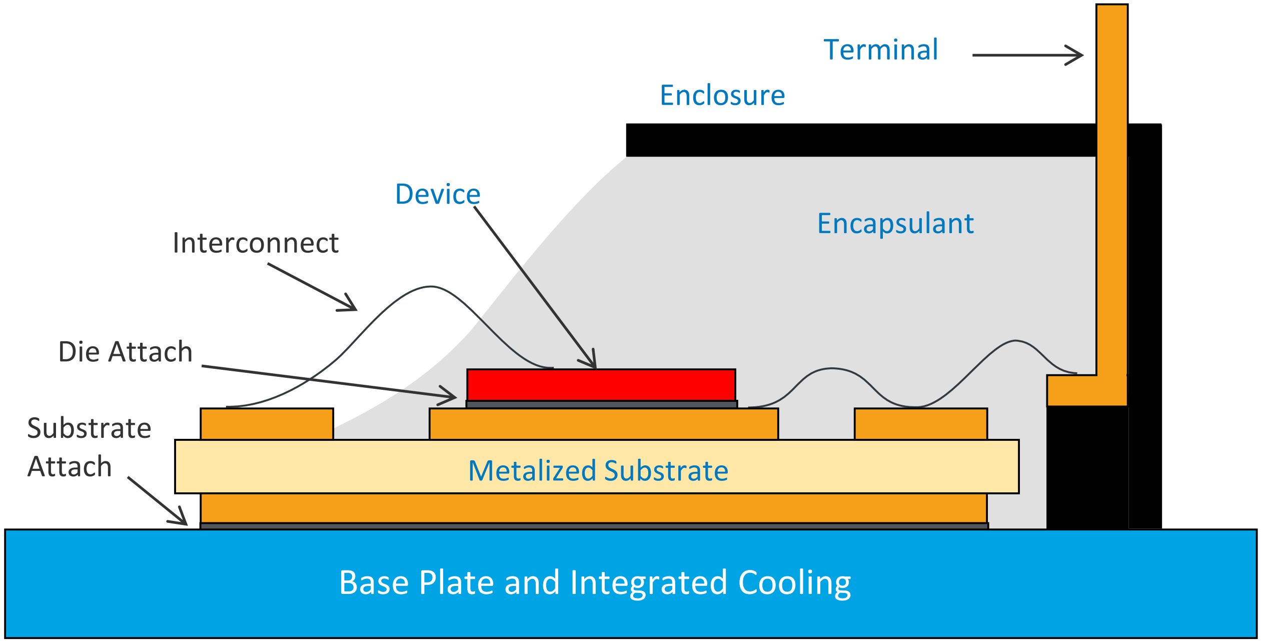


Photo by Kevin Bennion, NREL

APEEM: Advanced Power Electronics and Electric Motors

Power Electronics Thermal Management

- Compact, power-dense wide-bandgap (WBG)-device-based power electronics require
  - Higher-temperature-rated components and materials
  - Advanced heat transfer technologies
  - System-level thermal management

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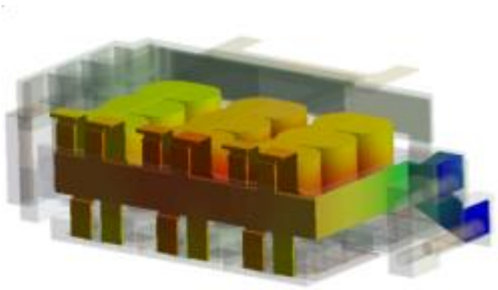
Advanced cooling

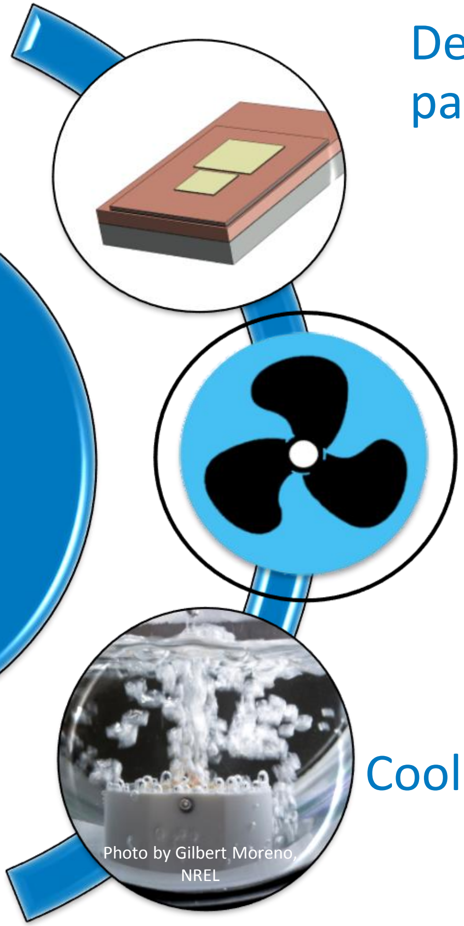


Component-level and system-level heat transfer

Thermal Strategy to Reach a Power Density of 100 kW/L

Define the thermal target to achieve 100 kW/L

Design the cooling strategies



Device packaging

Convective cooling

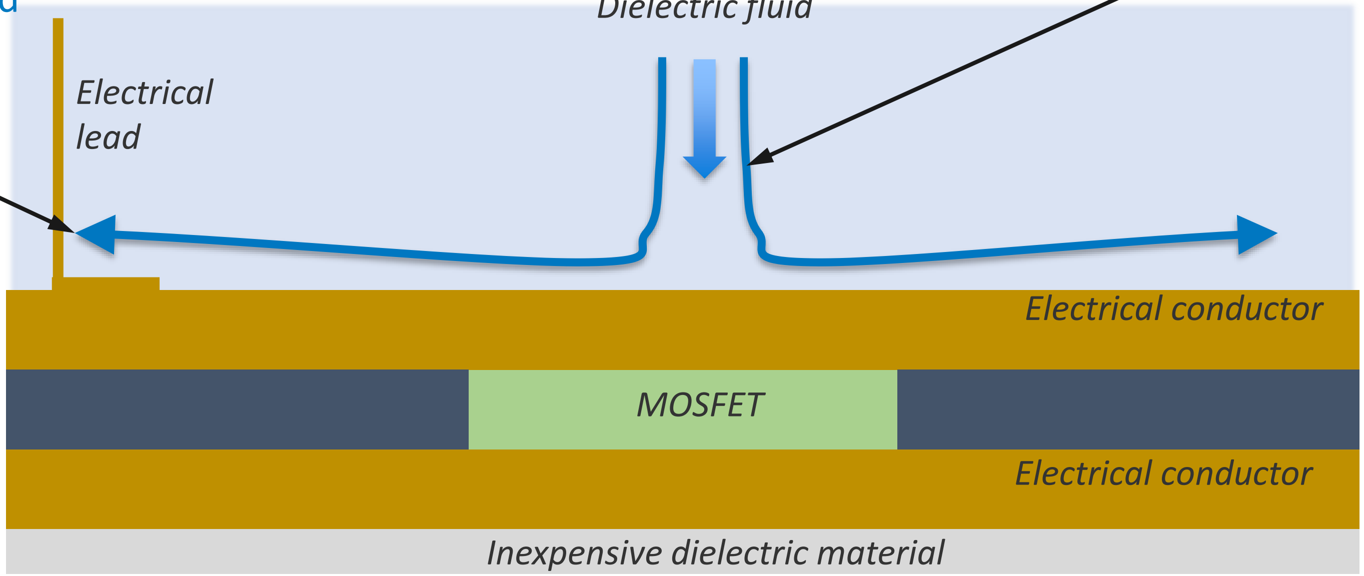
Cooling fluid

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

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

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

Dielectric Cooling Concept



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

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

Eliminates expensive ceramic materials

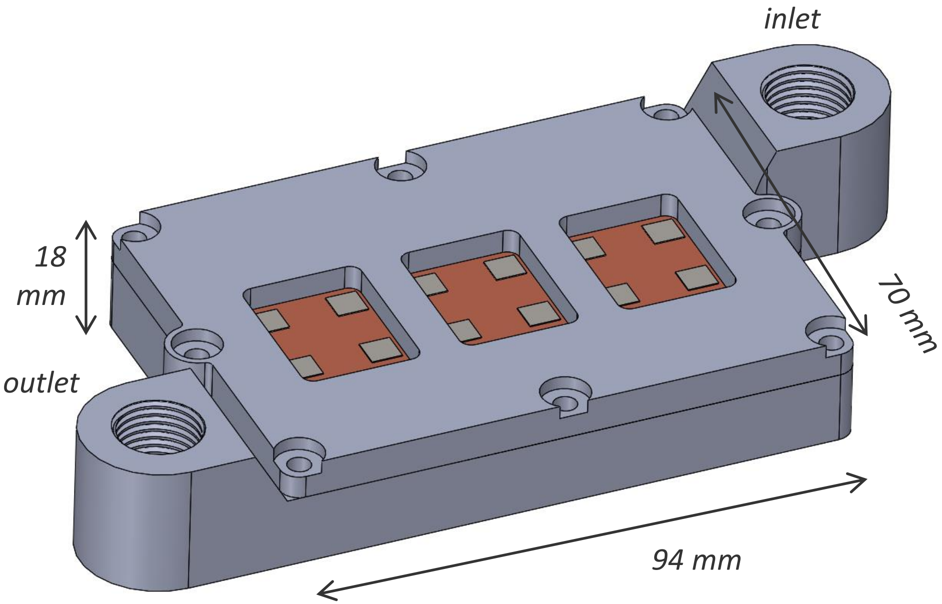
Improved performance over conventional direct-bond-copper (DBC)-based designs

MOSFET: metal–oxide–semiconductor field-effect transistor

Cooling System Design: Modeling Results

Designed fluid manifold to distribute flow to 12 devices

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



Computer-aided design model of the cold plate with finned heat spreaders

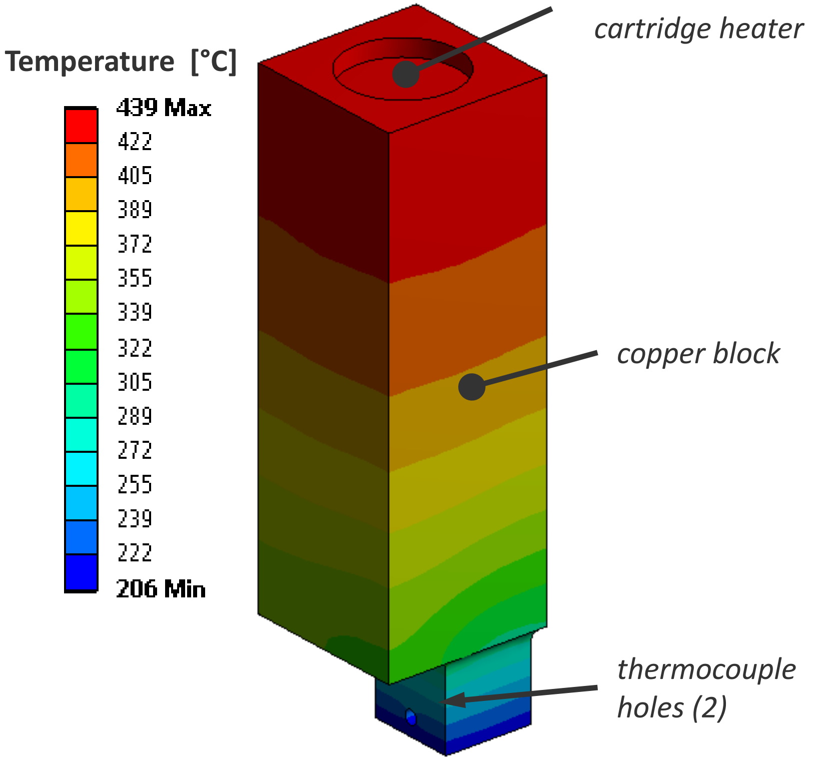
Image by Gilbert Moreno, NREL

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

Experimental Validation

Designed the heaters

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



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

Completed cold plate fabrication

- ✓ 3D printed using inexpensive, lightweight plastic to test prototype
- ✓ Cold plate can be fabricated using conventional manufacturing methods

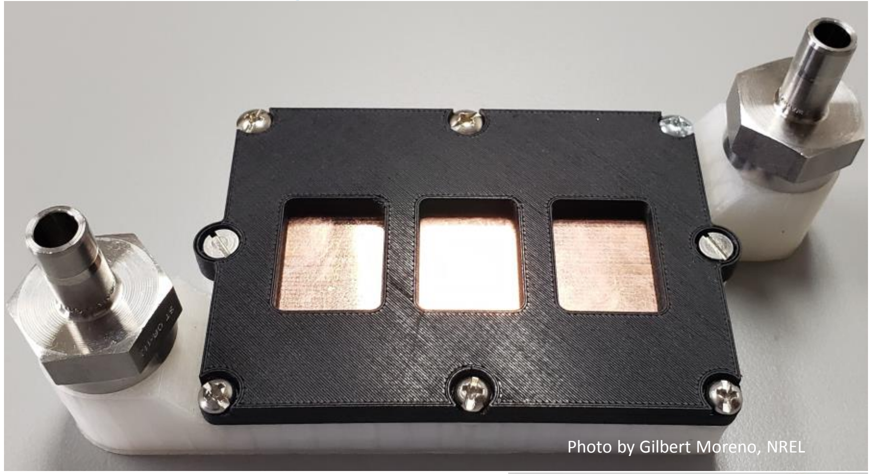


Photo by Gilbert Moreno, NREL

Nylon cold plate manifold prototype


Photo by Paul Paret, NREL

Cold plate size compared to cell phone

Advanced Power Electronics Packaging Performance and Reliability

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

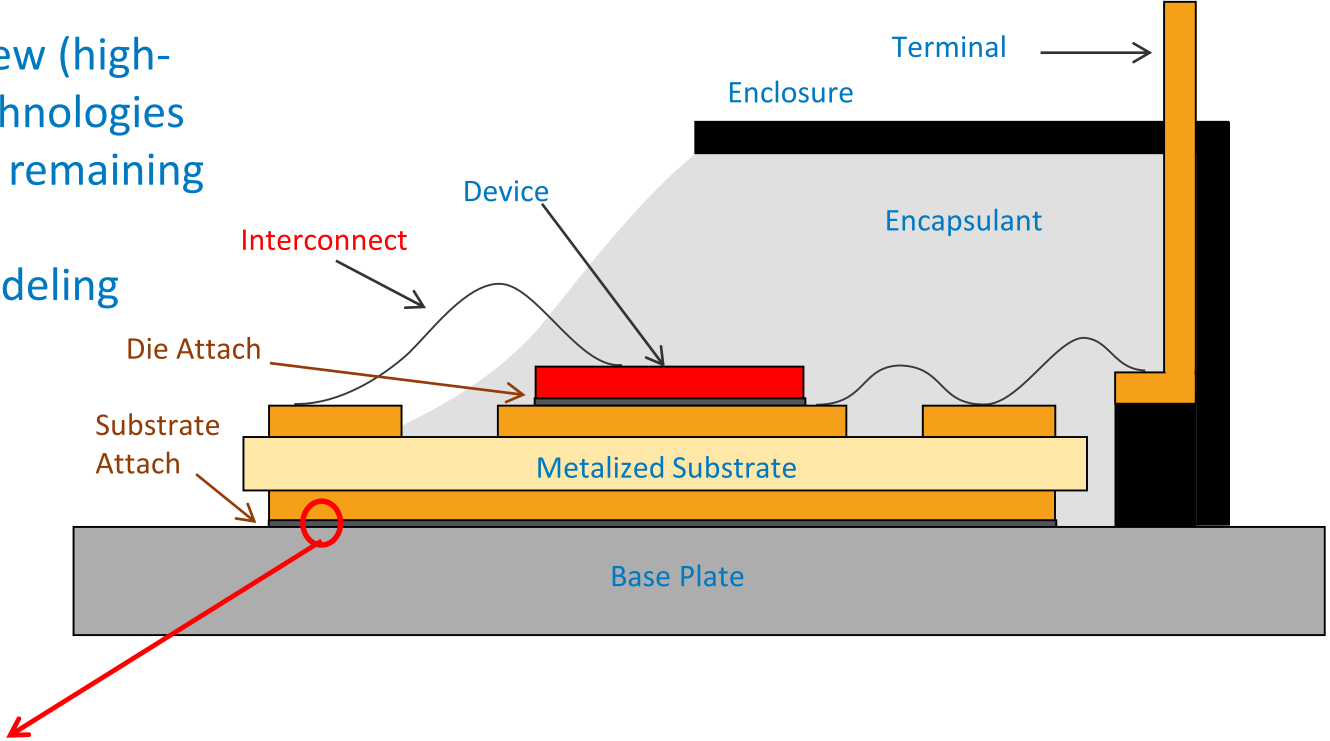
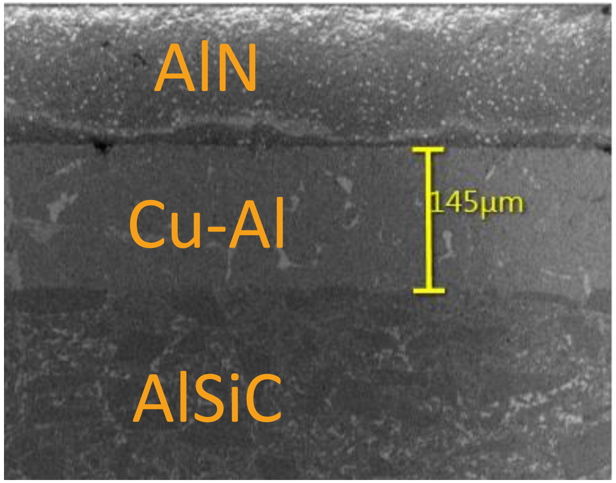


Photo by Paul Paret, NREL

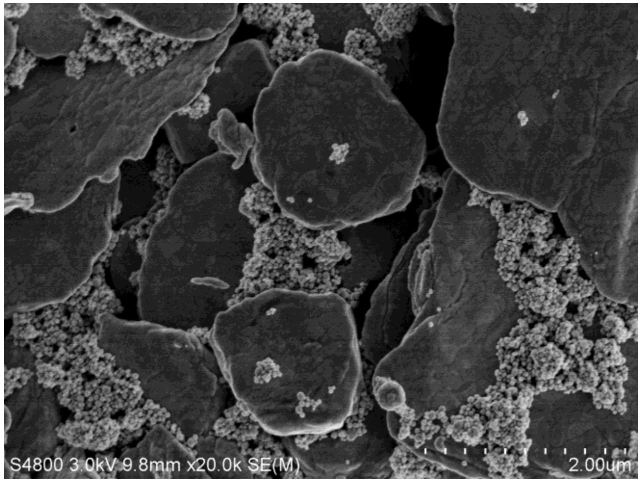
Crack Propagation in Pressure-Assisted (30 – 40 MPa) Sintered Silver

Approach – Materials

- High-Temperature Bonded Material
  - Georgia Tech
    - Cu/Al, Cu/Sn
  - Virginia Tech
    - Hybrid-silver
      - Pressureless
      - Low pressure-assisted
  - NREL
    - Nano-silver
      - Pressureless



Cu-Al bond – SEM image[1]



Hybrid-silver – SEM image[2]

SEM: scanning electron microscope

[1] Photo by Darshan Pahinkar, Georgia Tech

[2] Photo by G.-Q. Lu, Virginia Tech

Cu: copper, Al: aluminum, Sn: tin

AlN: aluminum nitride

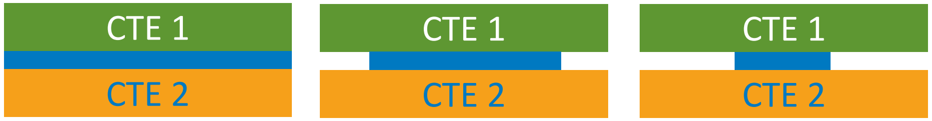
AlSiC: aluminum silicon-carbide

Sintered Silver Reliability Evaluation

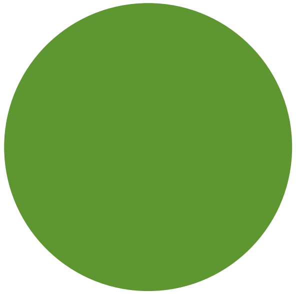
Copper – Invar Coupons

Photo by Douglas DeVoto, NREL

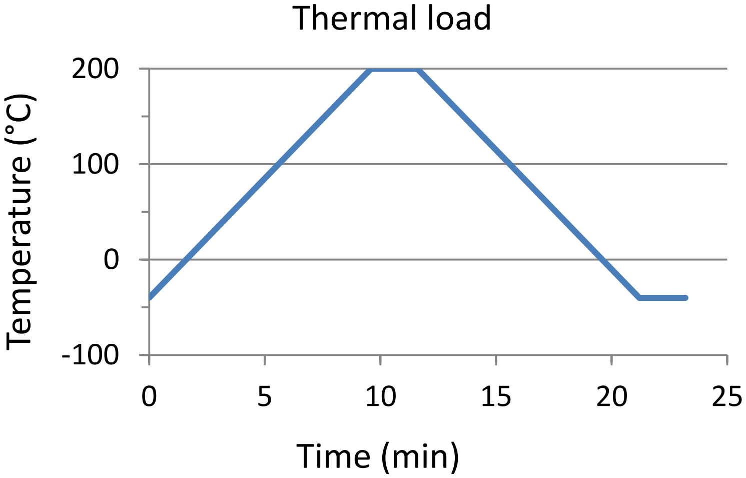
Side Views



Top View



Φ 25.4 mm



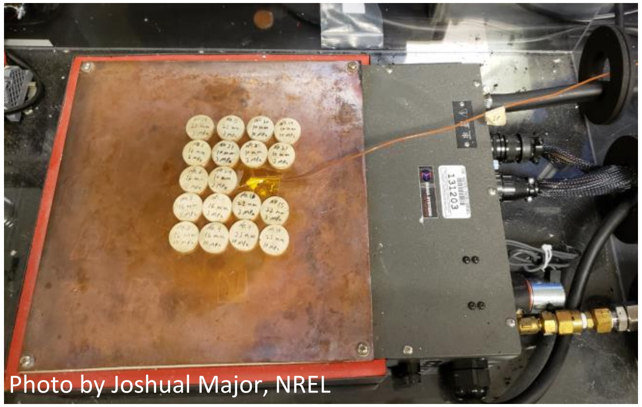


Photo by Joshual Major, NREL

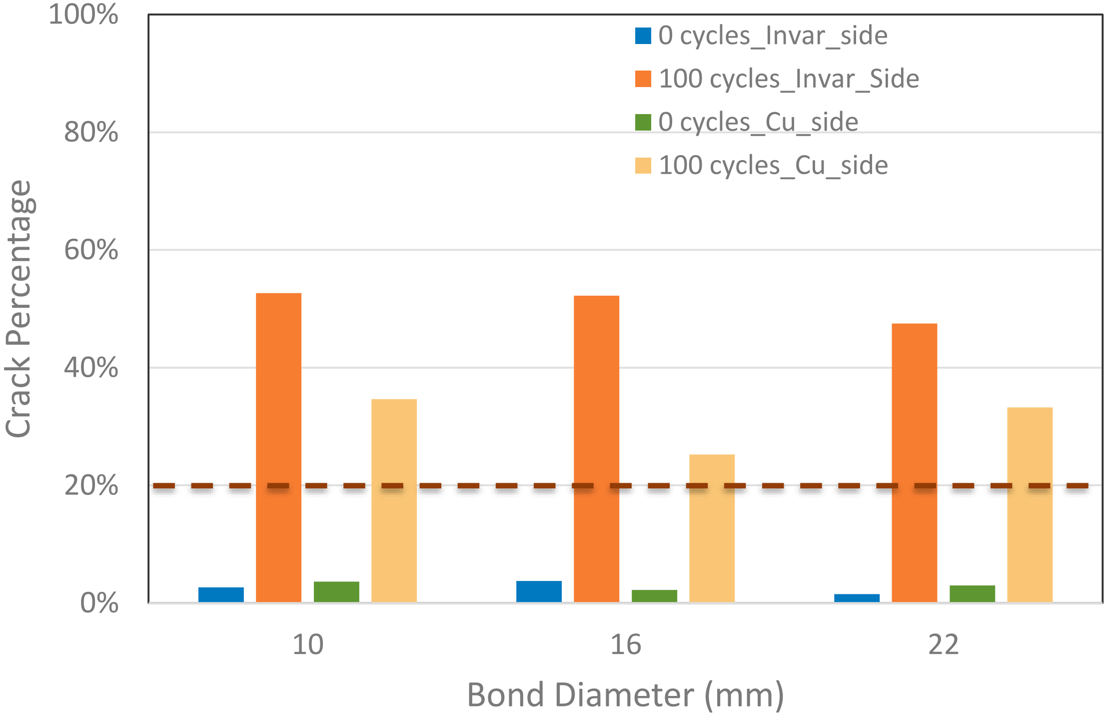
Thermal platform for thermal cycling

- Subject CTE-mismatched samples bonded with the material of interest to thermal cycling from -40°C to 200°C
- Obtain C-SAM images of the bond material at periodic cycling intervals
- Estimate crack growth rate from C-SAM images through image analysis

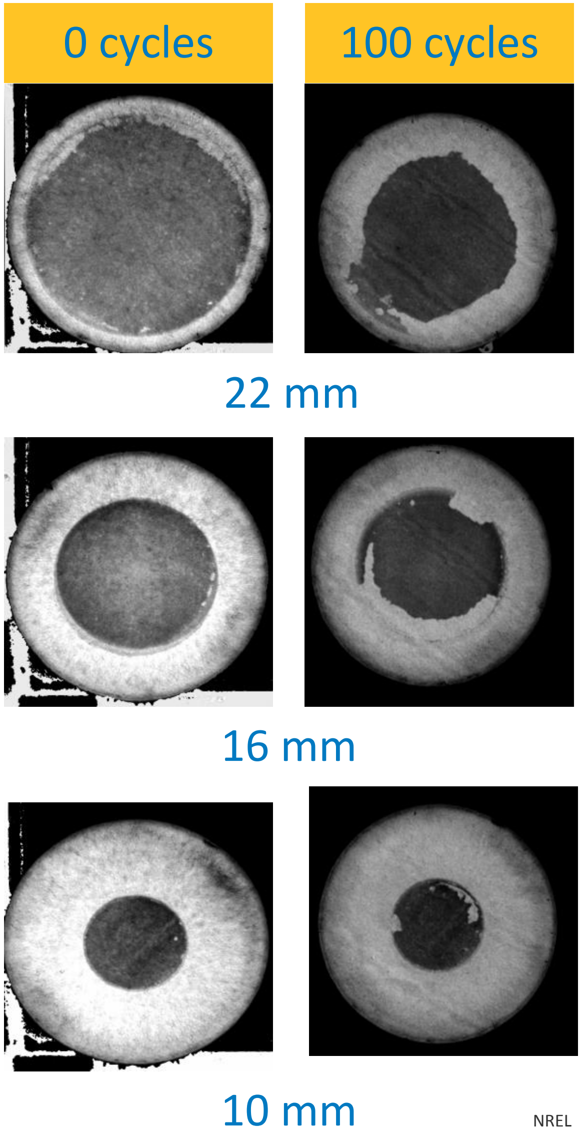
C-SAM: C-mode scanning acoustic microscope

CTE: co-efficient of thermal expansion

Thermal Cycling of Pressure-Assisted Sintered Samples (3 MPa)

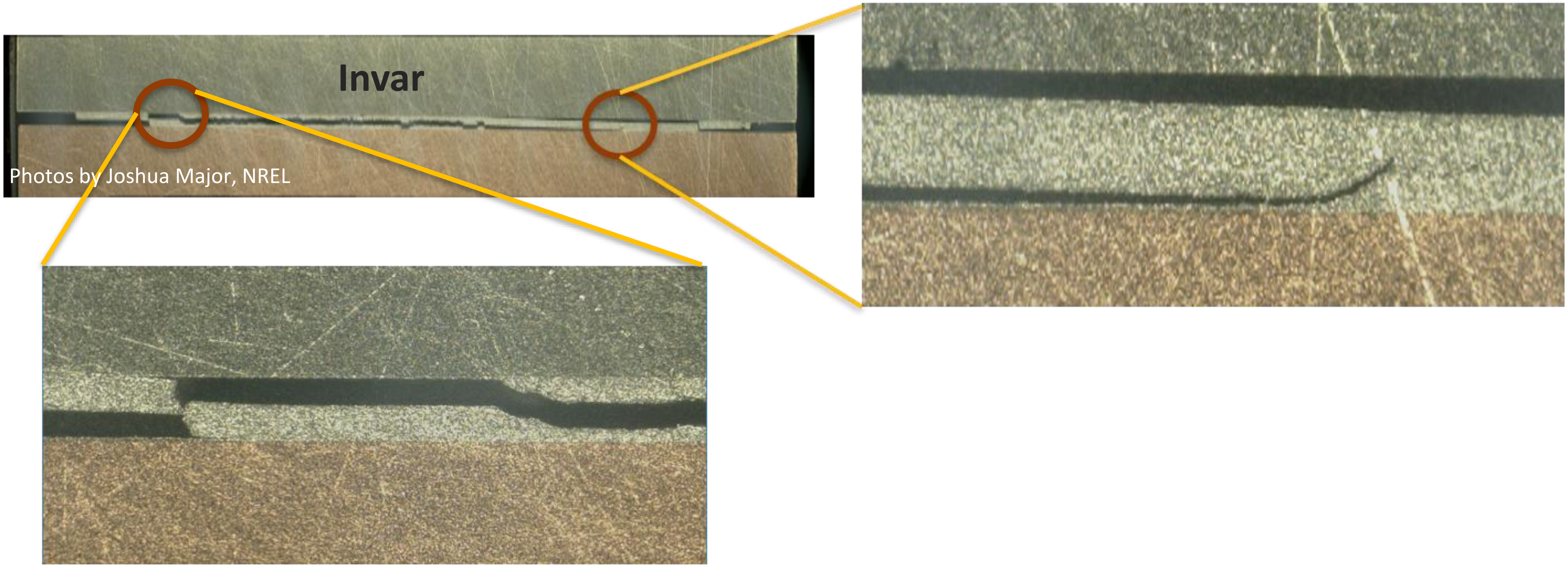


C-SAM images of sintered silver from Cu side



- Four samples were cycled for each diameter case.
- Failure (> 20% crack growth) may have occurred within 50 cycles.
- Crack growth rate was higher on the Invar side.

Images of Defect Propagation



Photos by Joshua Major, NREL

Cross-Sectional Microscopic Images of Crack Propagation in Sintered Silver

- Mode of crack propagation was found to be a combination of cohesive and adhesive failure mechanisms.
- Presence of different crack modes possibly indicates the strong impact of both global (Cu and Invar) and local (silver and Invar) CTE mismatch.
- Multiple cracks observed explain the difference in C-SAM images/crack percentage calculations from Cu and Invar side.

Organic Direct-Bond-Copper Substrate Thermal Performance

- Substrates were placed between diode and cold plate.
- A transient power pulse was applied to the package, and the decay of the temperature in the diode was monitored over time to establish the resistance-capacitance network for the package.
- ODBC thermal performance is similar to AlN.

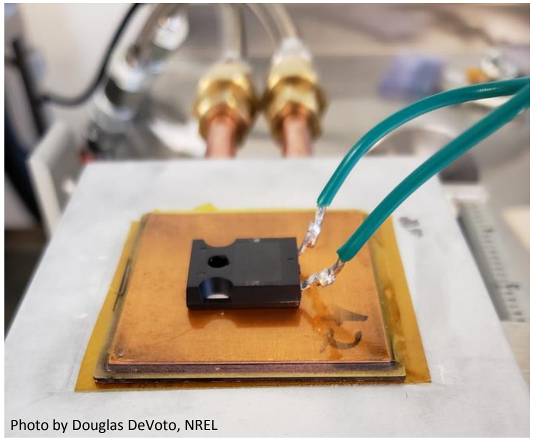
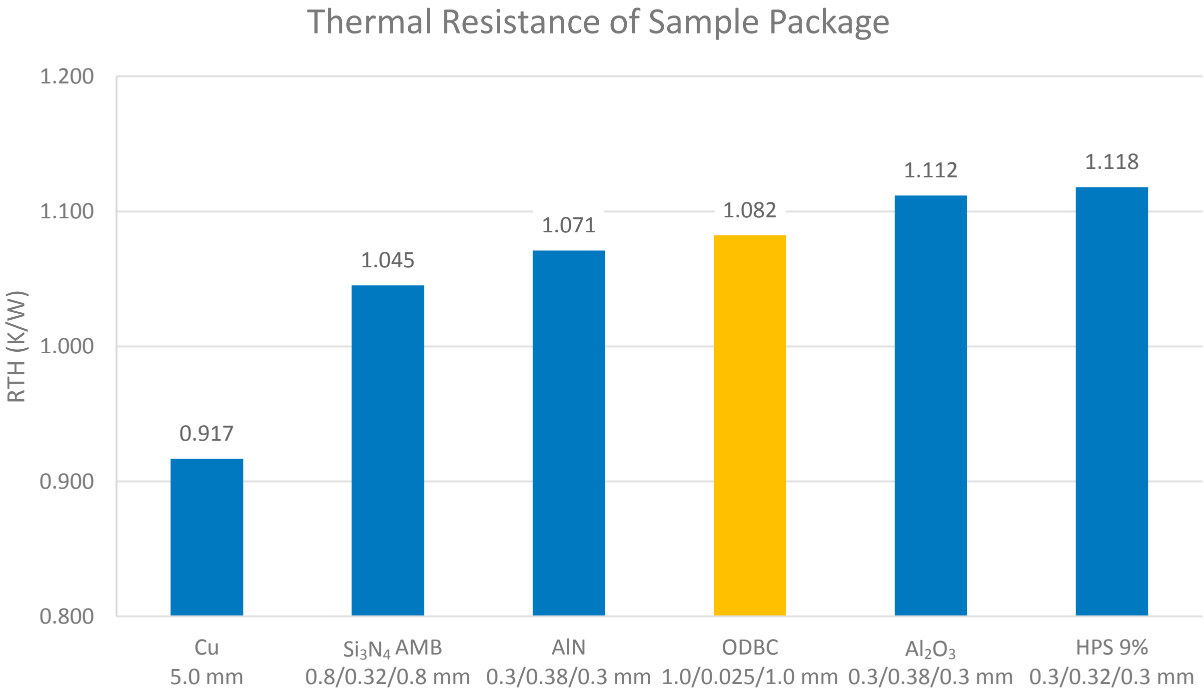
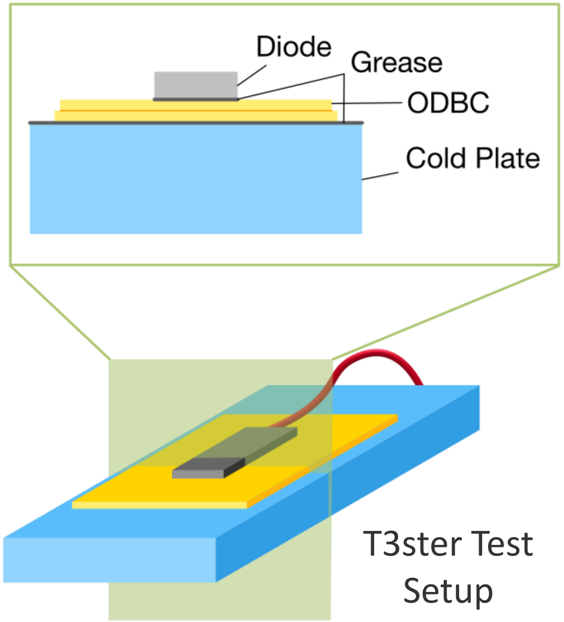


Photo by Douglas DeVoto, NREL





T3ster Test Setup

ODBC: Organic Direct-Bond-Copper

Si_3N_4 AMB: Silicon nitride atomic metal brazing

AlN: Aluminum nitride

Al_2O_3: Aluminum oxide

HPS: High-performance substrate

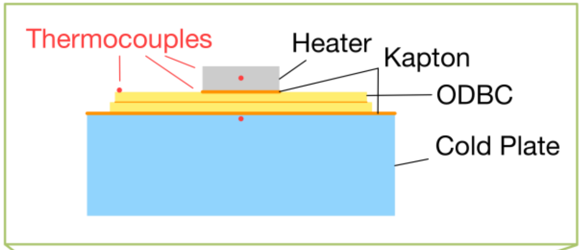
ODBC Reliability

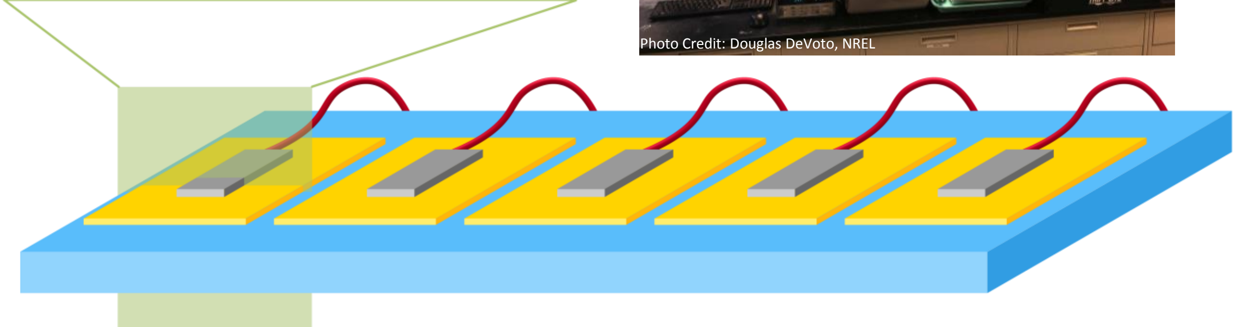
- Thermal Shock: -40°C to 200°C, 5-minute dwells
- Thermal Aging: 175°C
- Power Cycling: 40°C to 200°C
- ODBC substrates have reached 5,000 thermal shock cycles, 1,900 thermal aging hours, and 2,200 power cycles
- No significant decrease in electrical or thermal performance has been observed.

Photo by Douglas DeVoto, NREL

Substrates Undergoing Aging

Photo Credit: Douglas DeVoto, NREL

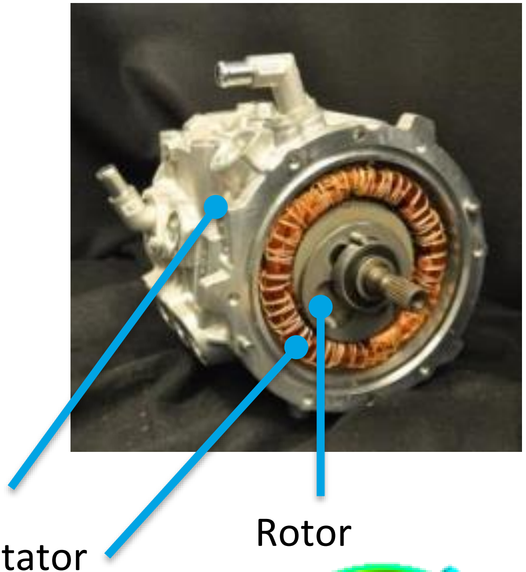


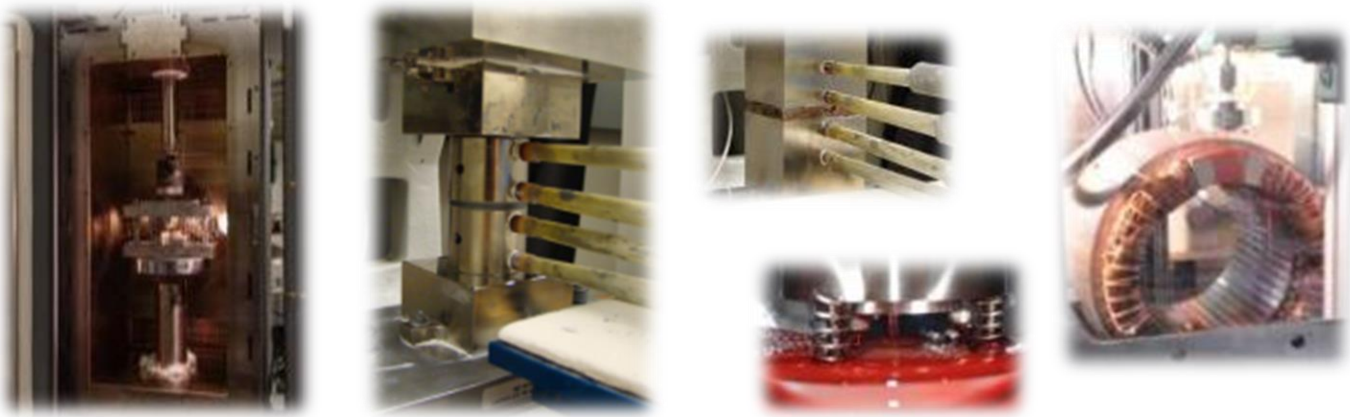


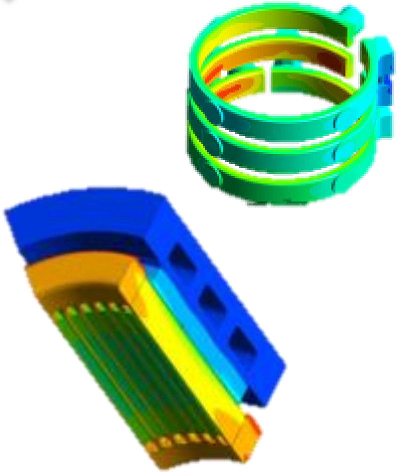
Power Cycling Test Setup

Electric Motor Thermal Management

- Increase current density, power density
- Increase reliability
- Higher voltages and switching frequencies
- Understand material properties as a function of temperature and material lifetime
- Advanced cooling strategies







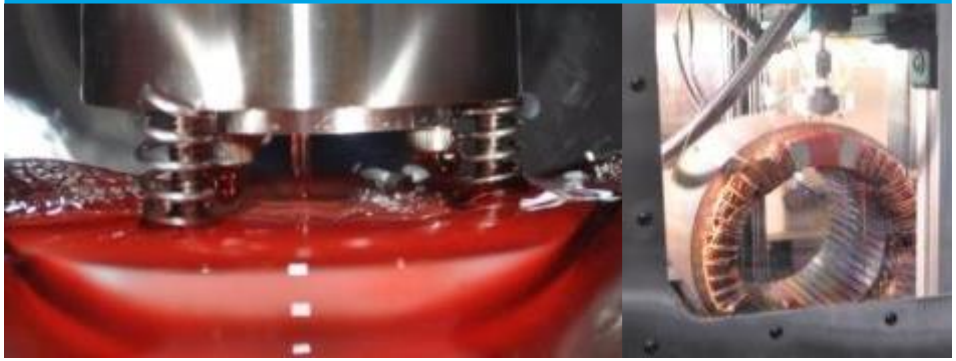
Photos by Doug DeVoto, Emily Cousineau, Kevin Bennion and Bidzina Keklia, NREL

Transmission Fluid Jet Impingement Cooling

Active Convective Cooling

→

Direct Impingement Cooling for Motor Windings



- Quantify impact of new or alternative cooling approaches for ATF cooling of motors.
- Characterize impact of new cooling fluids.

ATF: automatic transmission fluid

Photos by Kevin Bennion and Bidzina Kekelia, NREL

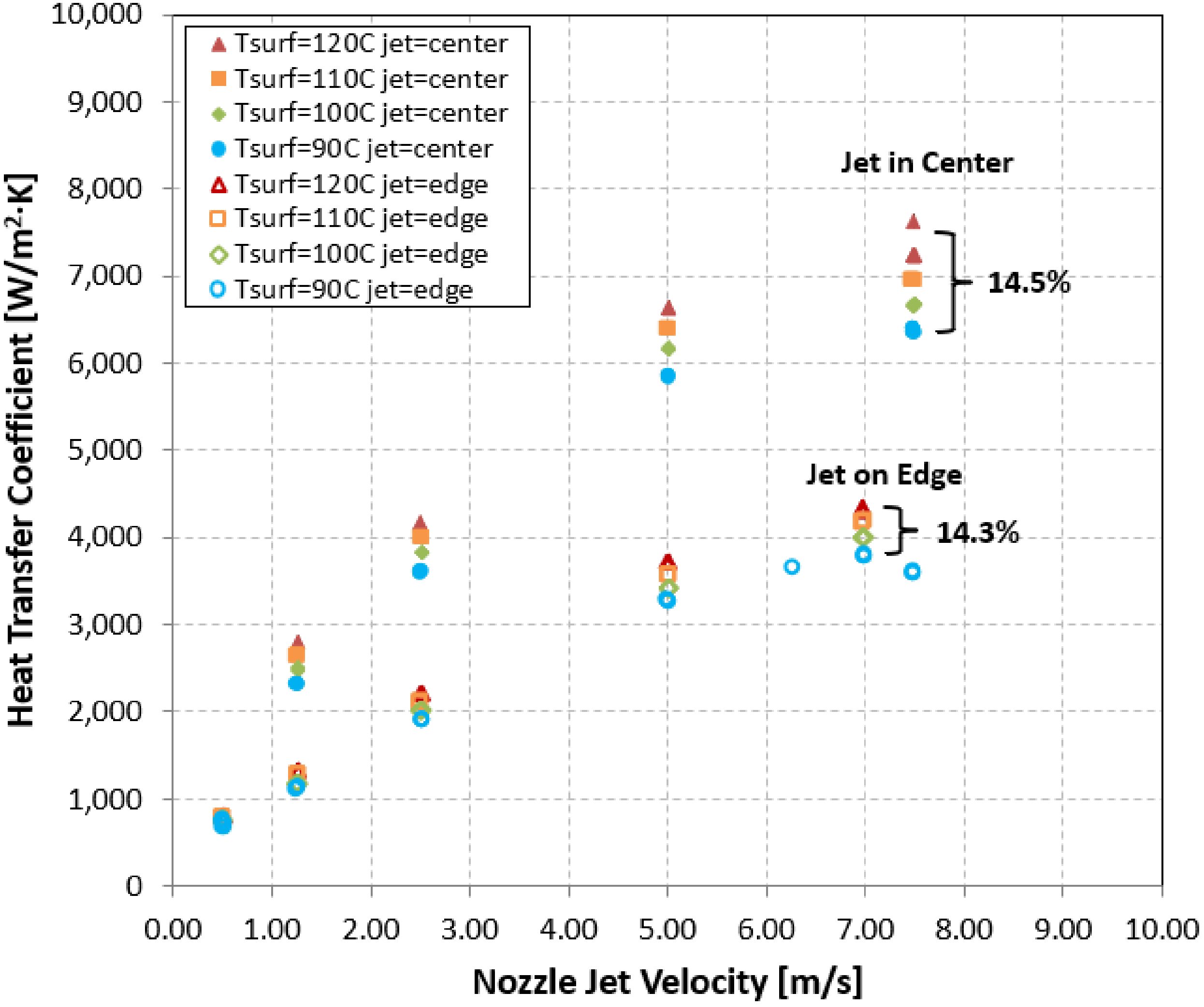
ATF Orifice Jet Impingement

- Temperature of the cooled surface affects HTC values:

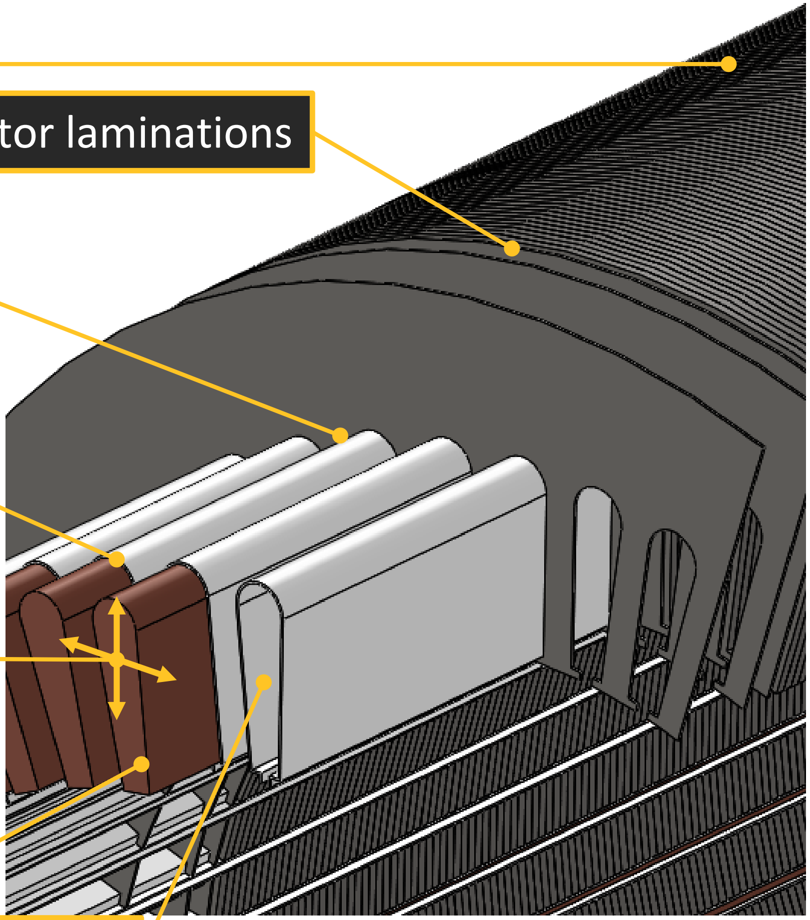
  $T_{surface}$ ↑ => *h* ↑

- Experiments ongoing to evaluate impact of varying other parameters on HTC:
  - incidence angle
  - nozzle distance from target surface

Heat transfer coefficients (HTC) for ATF at **T_{fluid} = 70°C**



Material/Interface Thermal Characterization



Stator-to-case thermal contact resistance

Stator laminations

Liner-to-stator thermal contact resistance

Winding-to-liner thermal contact resistance

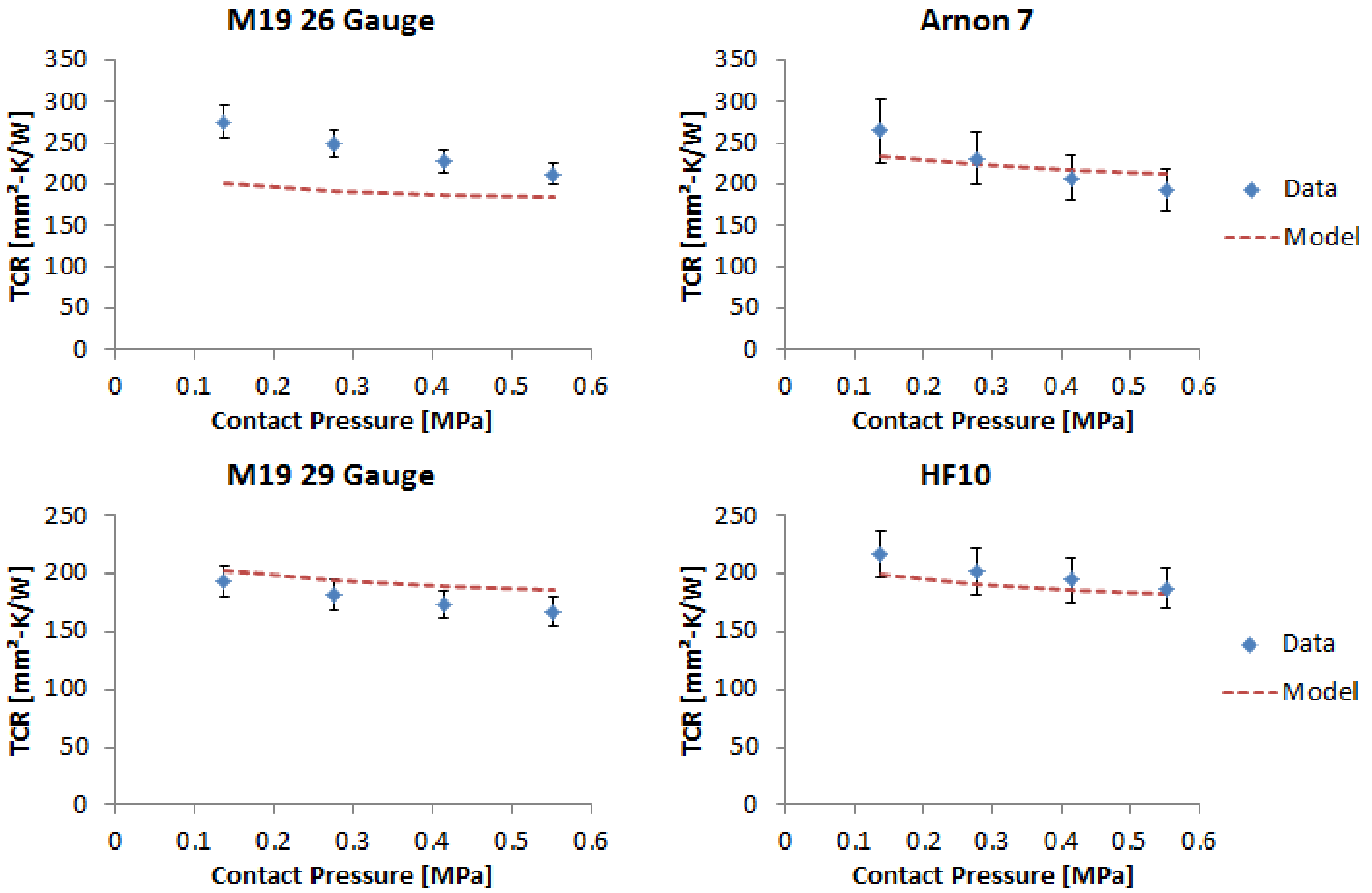
Cross-slot winding thermal conductivity

Slot windings

Slot liner or ground insulation

Illustration by Kevin Bennion, NREL

Motor Lamination Thermal Contact Resistance



TCR: thermal contact resistance

- Validated model with experimental data using multiple materials.
- Results published in J. E. Cousineau, K. Bennion, D. DeVoto, and S. Narumanchi, “Experimental Characterization and Modeling of Thermal Resistance of Electric Machine Lamination Stacks,” *International Journal of Heat and Mass Transfer*, vol. 129, pp. 152–159, Feb. 2019.

Multiple Research Activities and Projects

DOE VTO Electrification R&D	Thermal management and reliability of electric-drive vehicle power electronics and electric machines; high-power fast charging
ARPA-E	Advanced WBG power electronics and thermal management techniques
DOE AMO PowerAmerica	Manufacturing WBG power electronics
AMO Next- Generation Electric Machines	Energy-efficient, high-power-density, high-speed integrated medium-voltage-drive systems for critical energy applications
AMO Medium-Voltage Power Electronics	Grid-tied power electronics
AMO Traineeship in Power Engineering	Traineeship and curriculum development leveraging WBG power electronics
Technology Commercialization	Bringing lab-developed technology closer to commercialization/production
DOD and Industry-Funded	DOD agency and industry-funded projects in the broad areas of thermal management and reliability
NREL Laboratory Directed Research and Development	Projects in the areas of power electronics prognostics and ultra-WBG power electronics packaging

R&D: Research and Development
VTO: Vehicle Technologies Office
ARPA-E: Advanced Research Projects Agency- Energy
AMO: Advanced Manufacturing Office
DOD: Department of Defense

Summary

- Low-cost, high-performance thermal management technologies are helping meet aggressive power density, specific power, cost, and reliability targets for power electronics and electric machines.

- NREL is working closely with numerous industry and research partners to help influence development of components that meet aggressive performance and cost targets through:
  - Development and characterization of cooling technologies
  - Thermal characterization and improvements of passive stack materials and interfaces
  - Reliability evaluation, lifetime, and physics-of-failure models.

- Thermomechanical reliability and lifetime estimation models are important enablers for industry in cost- and time-effective design.

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Industry and Research Partners

Industry Original Equipment Manufacturers	Ford, General Motors, Fiat-Chrysler Automobiles, John Deere, Tesla, Toyota, Caterpillar
Suppliers/Others	3M, NBETech, Curamik, DuPont, Energetics, GE Global Research, GE Aviation, Indian Integrated Circuits, Semikron, Kyocera, Sapa, Delphi, Btechcorp, ADA Technologies, Remy/BorgWarner, Heraeus, Henkel, Wolverine Tube Inc., Wolfspeed, Kulicke & Soffa, UQM Technologies, nGimat LLC
Agencies	DARPA, U.S. Army Research Laboratory
National Laboratories	Oak Ridge National Laboratory, Ames Laboratory, Argonne National Laboratory, Sandia National Laboratories
Universities	Virginia Tech, University of Colorado Boulder, University of Wisconsin, Carnegie Mellon University, Texas A&M University, North Carolina State University, Ohio State University, Georgia Tech, University of Missouri Kansas City, North Dakota State University, University of Maryland