Thermal Management and Reliability of Automotive Power Electronics and Electric Machines

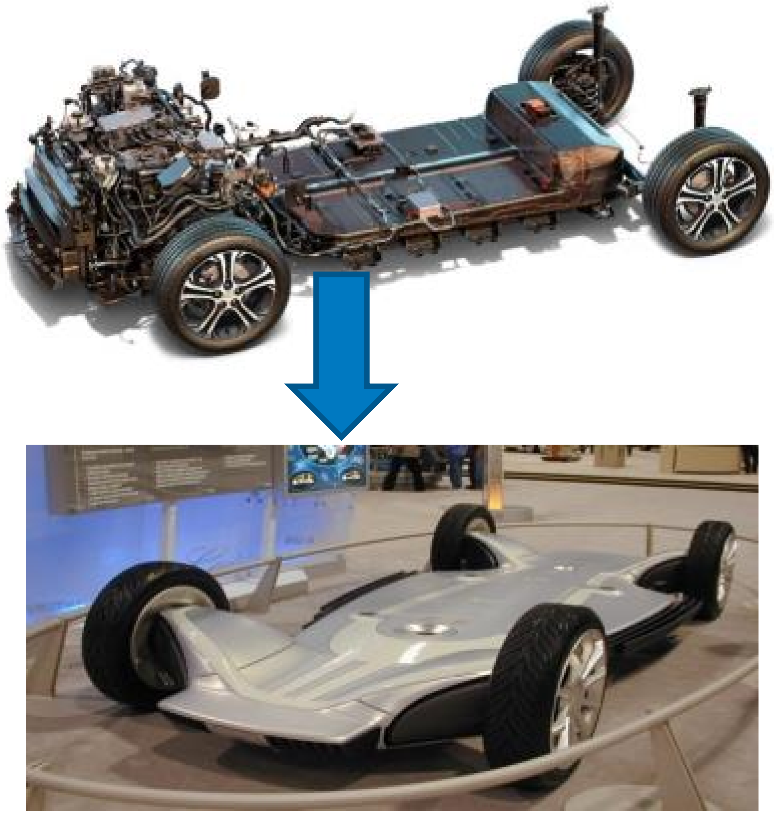
Sreekant Narumanchi
National Renewable Energy Laboratory
sreekant.narumanchi@nrel.gov; 303-275-4062
Team: Kevin Bennion, Emily Cousineau, Doug DeVoto, Xuhui Feng, Bidzina Kekelia, Joe Kozak, Joshua Major, Gilbert Moreno, Paul Paret, Jeff Tomerlin

2017 Electronics Packaging Symposium and Workshop
GE Global Research Center
September 20, 2017

NREL/PR-5400-70156

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



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)

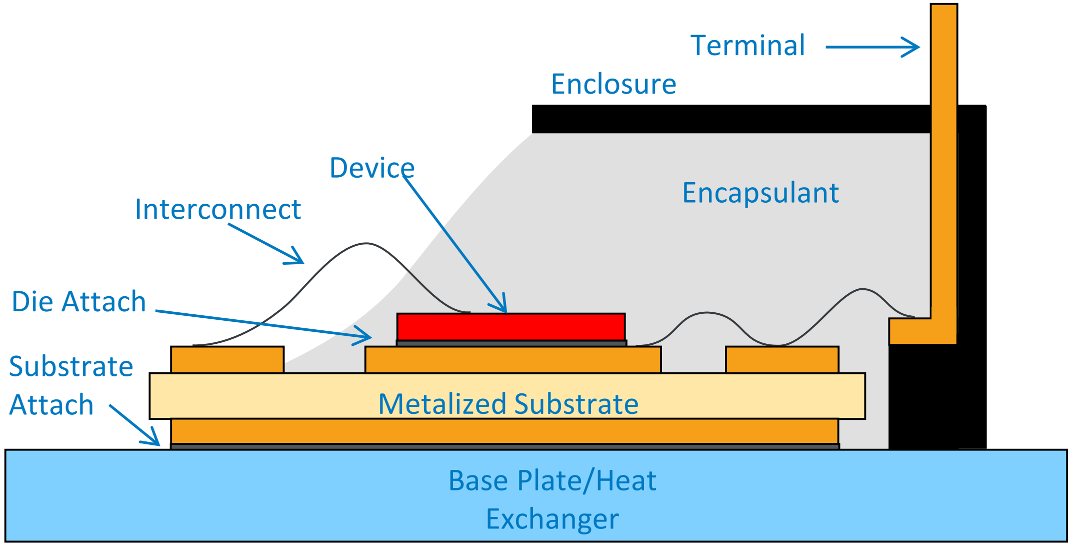
BEV: Battery Electric Vehicle

DC: Direct Current

Power Electronics Thermal Management Strategy

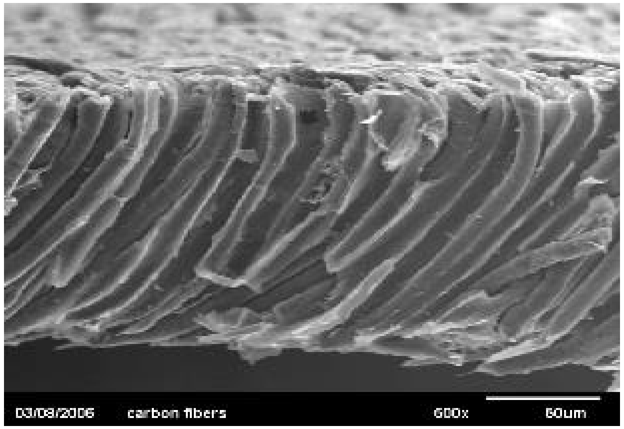
- Wide-bandgap (WBG) device-based packaging requires advanced materials, interfaces, and interconnects
- Low-cost techniques to increase heat transfer rates
- System-level thermal management (capacitor and other passives)

WBG Module Packaging Design with Integrated Cooling



High-Performance Bonded Interface Materials

- Bonded interface resistance as low as 0.4 mm^2K/W achieved
    - Copper nanowires (1 mm^2K/W for 50-µm bondline thickness)
    - Boron-nitride nanosheets (0.4 mm^2K/W for 30- to 50-µm bondline thickness)
    - Copper nanosprings (1 mm^2K/W for 50-µm bondline thickness with good reliability)
    - Graphite solder
    - Nanotube-based
    - Thermoplastics with embedded carbon fibers
    - Sintered Silver



Courtesy: BtechCorp

WBG Power Electronics Thermal Management

Create thermal models of an automotive inverter

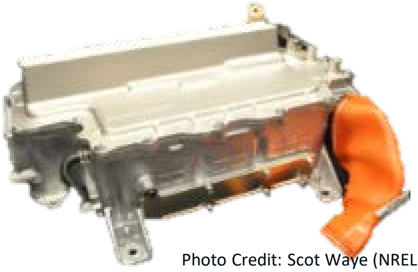
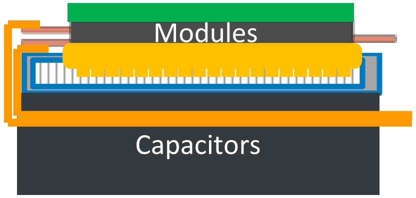


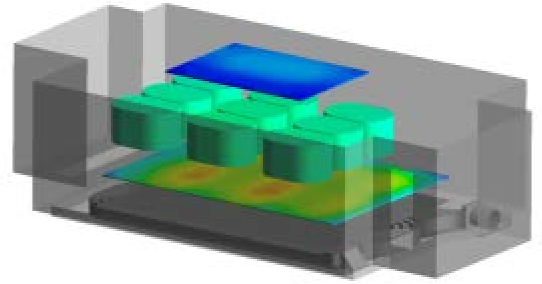
Photo Credit: Scot Waye (NREL)

Validate the thermal models



Advanced compact inverter designs

Simulate WBG operation using the inverter model



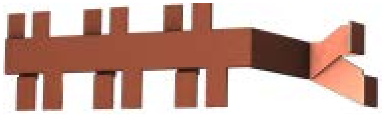
Simulate elevated junction temperature conditions (up to 250°C)

Evaluate effect of different under-hood temperature environments (hybrid and all-electric)

Identify the components (e.g., capacitor) that are not expected to survive WBG conditions

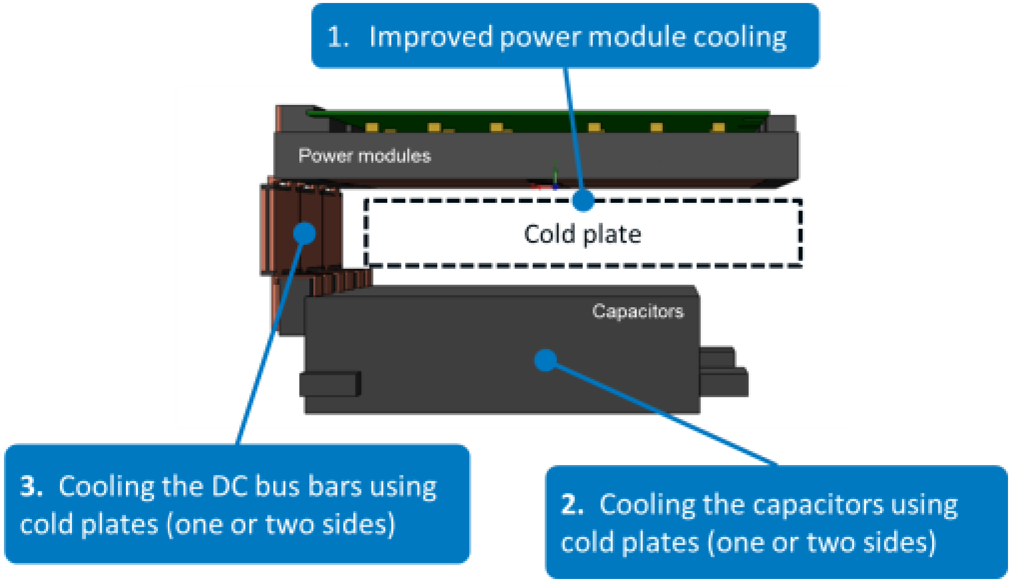
Develop thermal management strategies for WBG-based inverters

Cooling strategies
- Capacitor cooling
- Bus bar cooling
- Aggressive thermal management solutions



Experimentally validate some key thermal management concepts

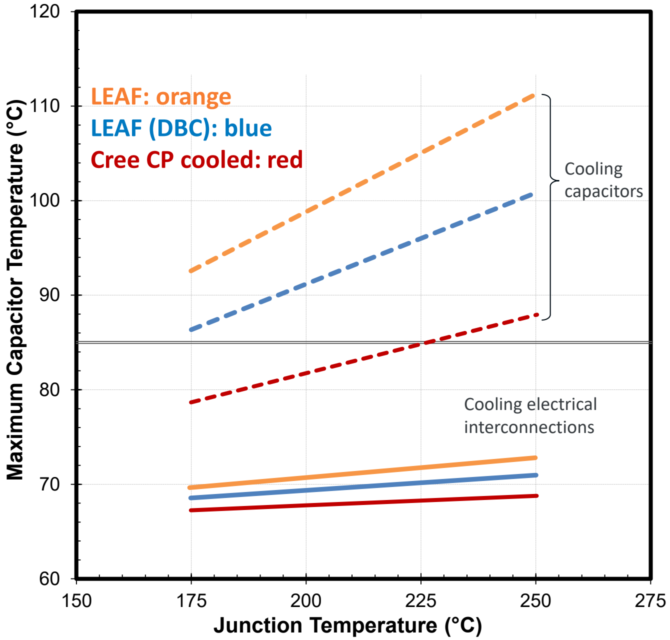
WBG Power Electronics Thermal Management



1. Improved power module cooling

2. Cooling the capacitors using cold plates (one or two sides)

3. Cooling the DC bus bars using cold plates (one or two sides)

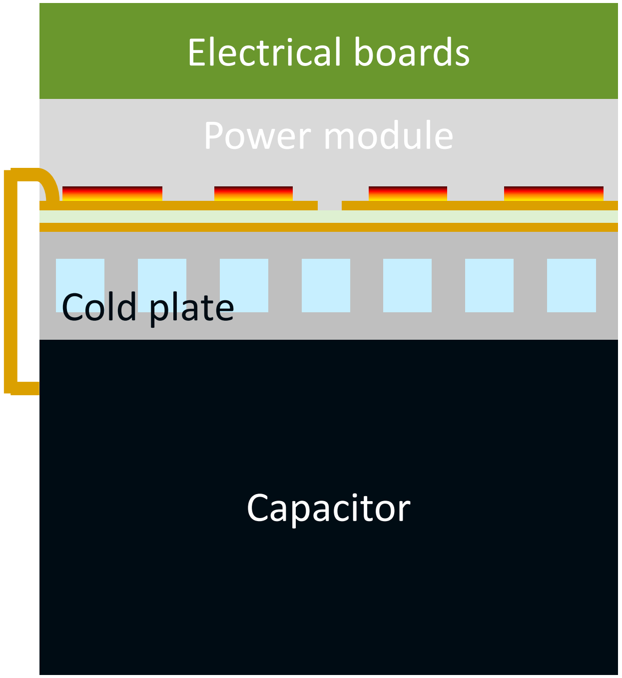


- Cooling electrical interconnects very effective

Future Work: Cooling Strategies

May consider other configurations

Configuration 1: Channel flow cold plate



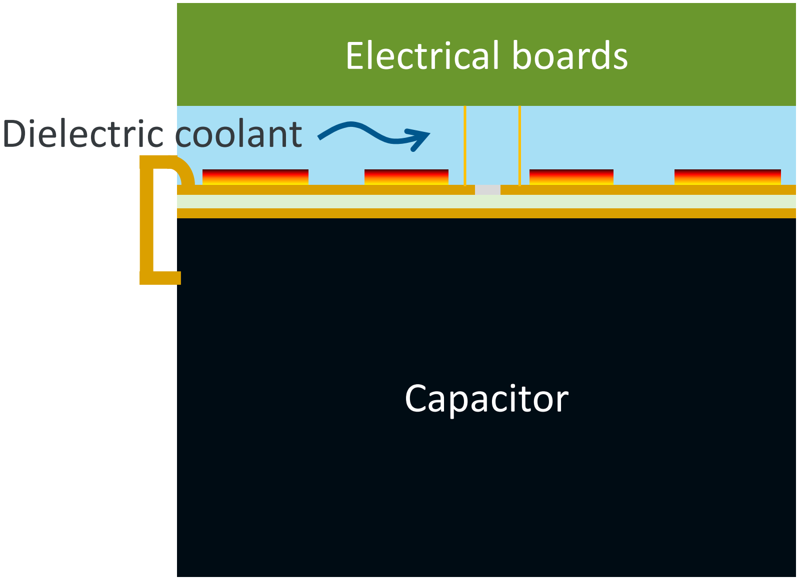
Advantages:

- Confined fluid, conventional cold plate

Disadvantages:

- Lack of gate driver cooling

Configuration 2: Direct-cooling of the devices



Advantages:

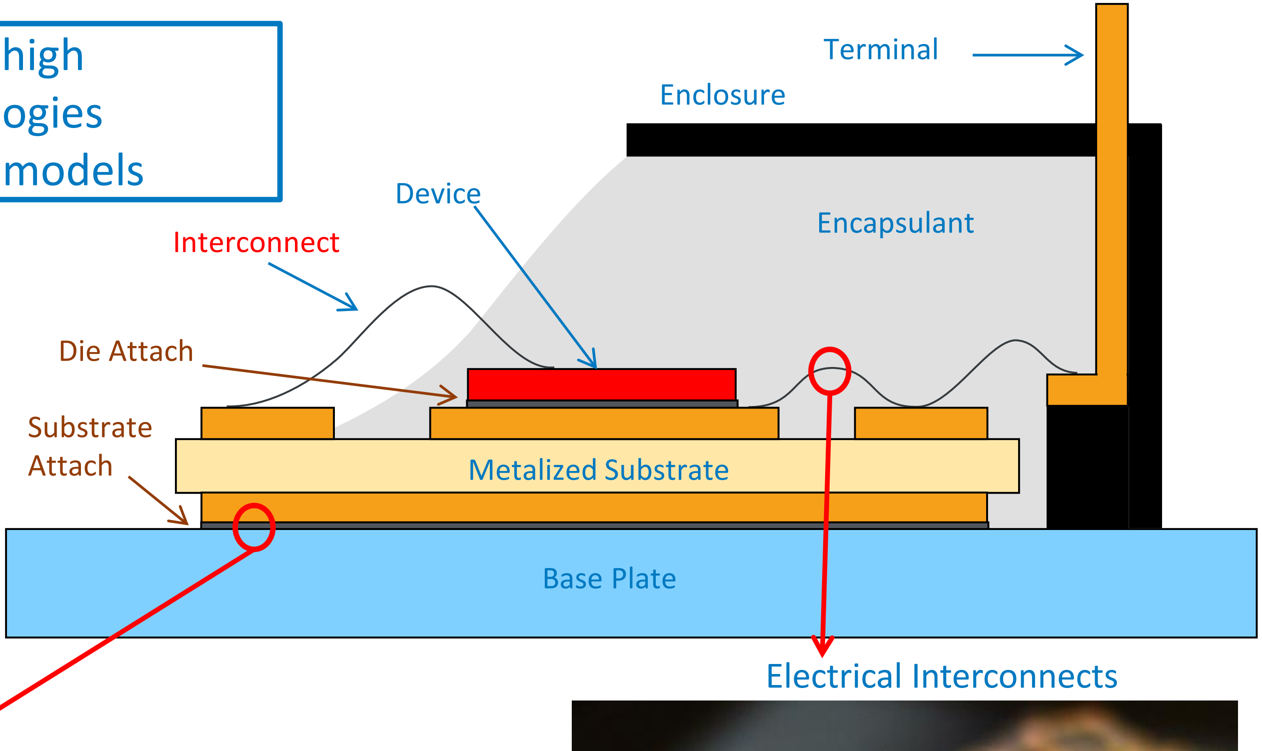
- Cools electrical interconnects

Disadvantages:

- Fluid compatibility and confinement
- Reduced cooling area (small die sizes)

Advanced Power Electronics Packaging Performance and Reliability

- Improve reliability of new (high temperature/WBG) technologies
- Develop predictive lifetime models



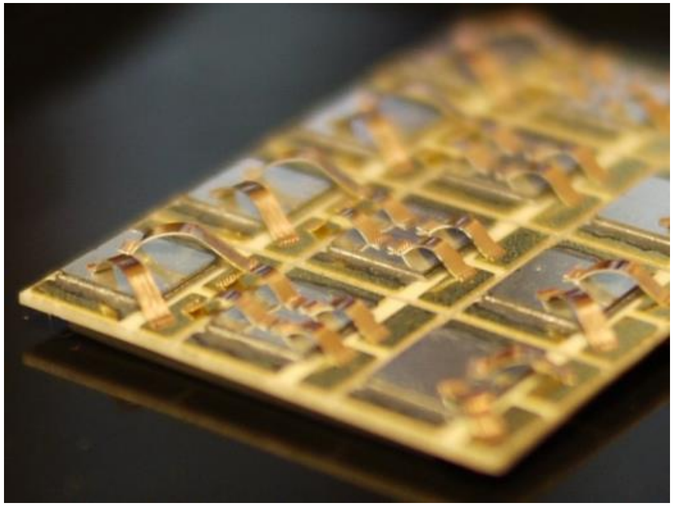
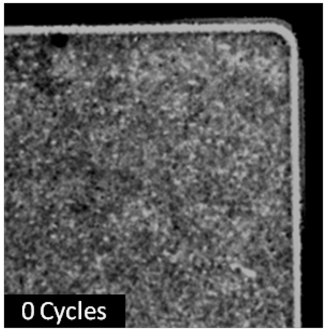


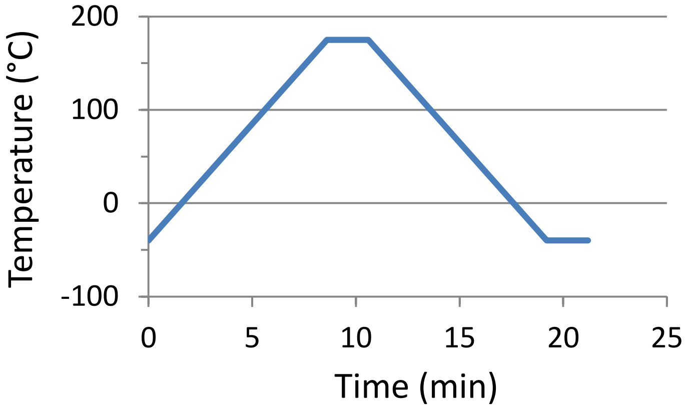
Photo Credits: Doug DeVoto

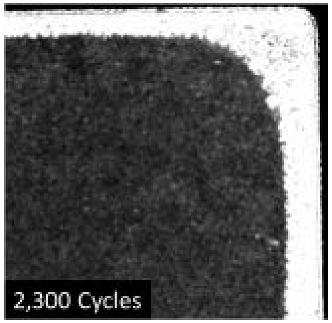
Reliability Research Approach – Experimental

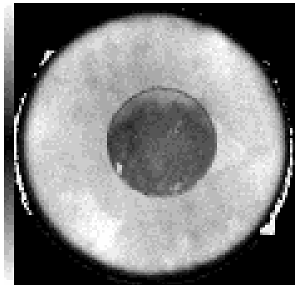
Sample Synthesis



Accelerated Testing

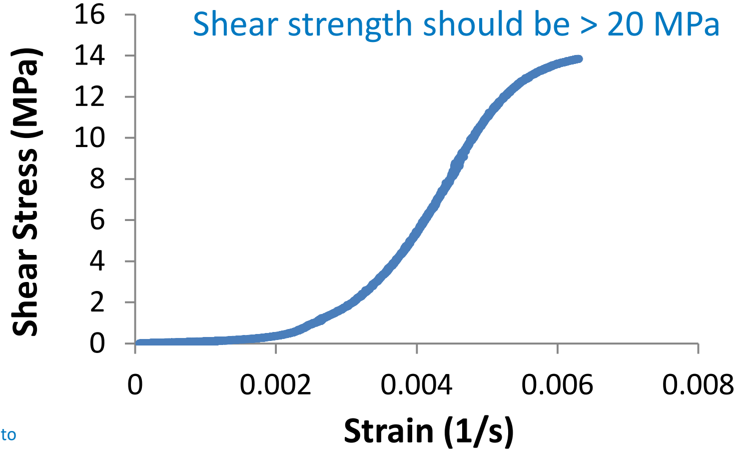






Shear Testing

Stress-Strain Curves

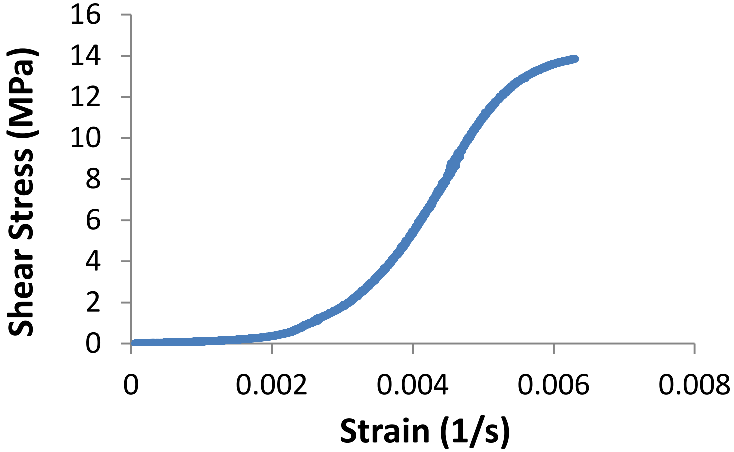


Shear strength should be > 20 MPa

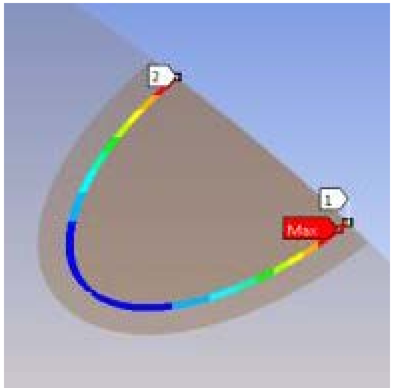
Photo Credits: Doug DeVoto

Reliability Research Approach – Modeling

Shear-Strain Curves



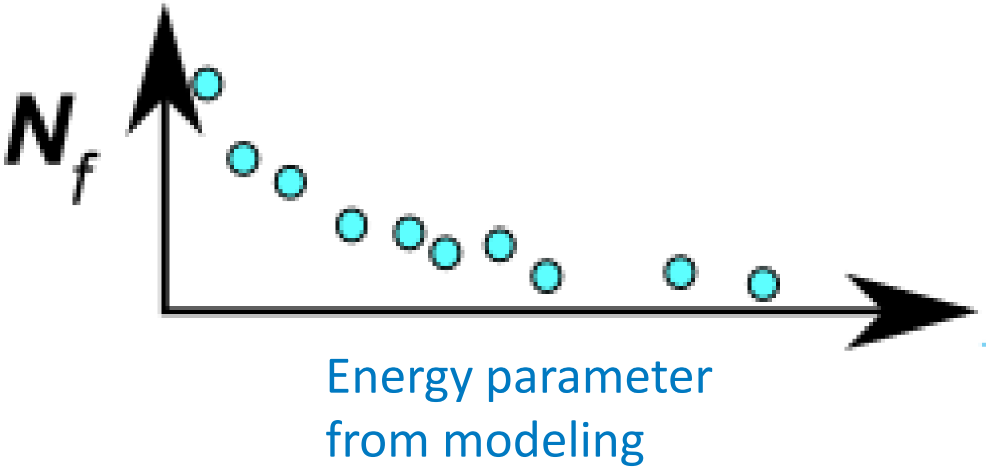
Interface Modeling



Modeling Outputs

Energy-related metrics

Reliability Research Approach – Predictive Lifetime Model

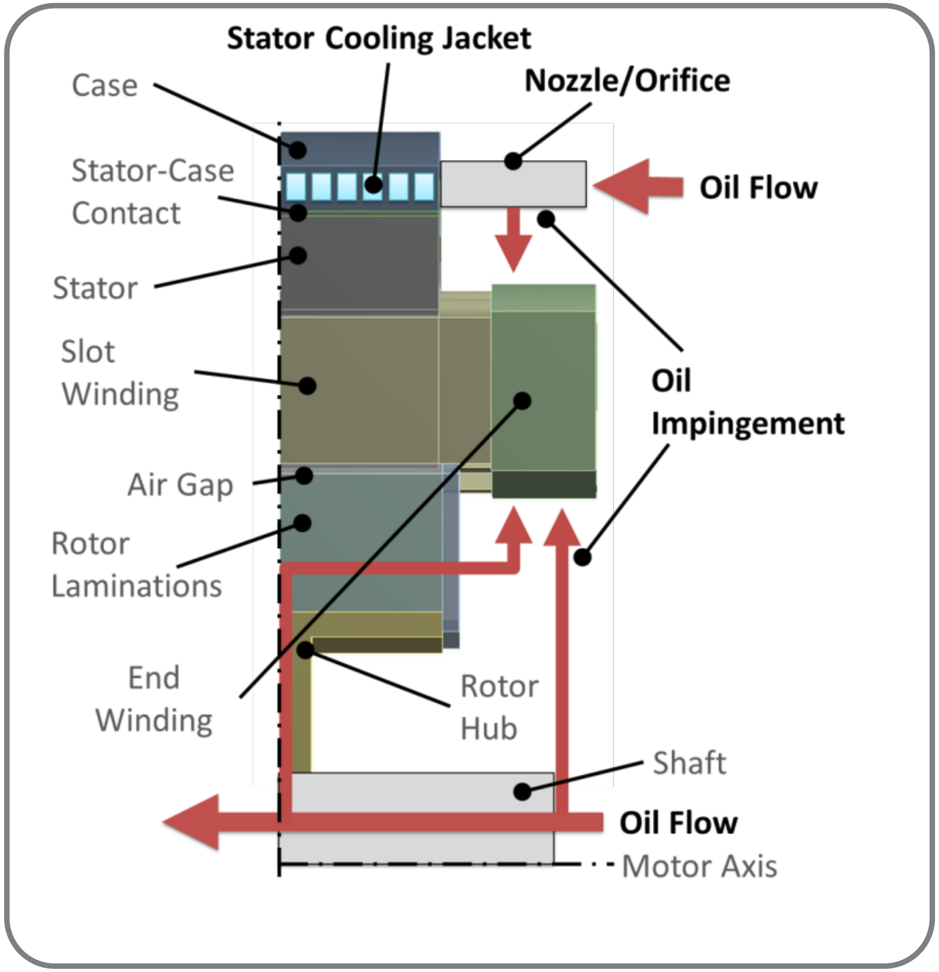


N_f - Experimental Cycles to Failure

Predictive lifetime model is for a specific failure mode observed under thermal cycling – e.g., cohesive fracture in sintered-silver bonded interface.

Electric Motor Thermal Management

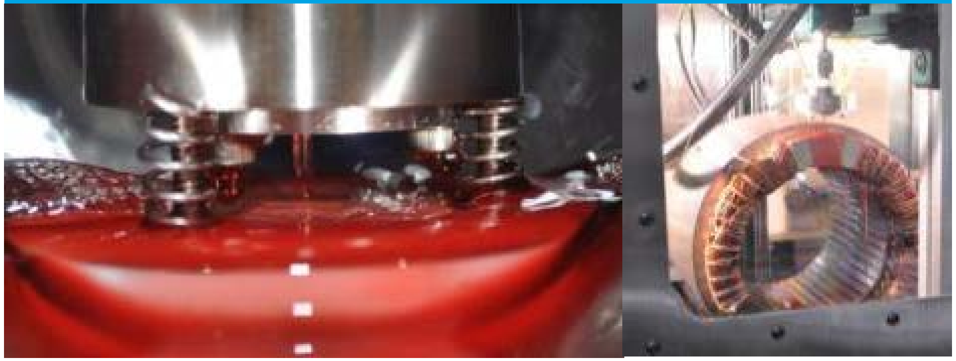
- Advanced materials and interfaces
  - Thermal Characterization
  - Reliability Characterization
- Fluid-based thermal management techniques to increase heat transfer rates
  - Transmission Oil
  - Water-Ethylene Glycol



Transmission Fluid Impingement Cooling

Active Convective Cooling

Direct Impingement Cooling for Motor Windings



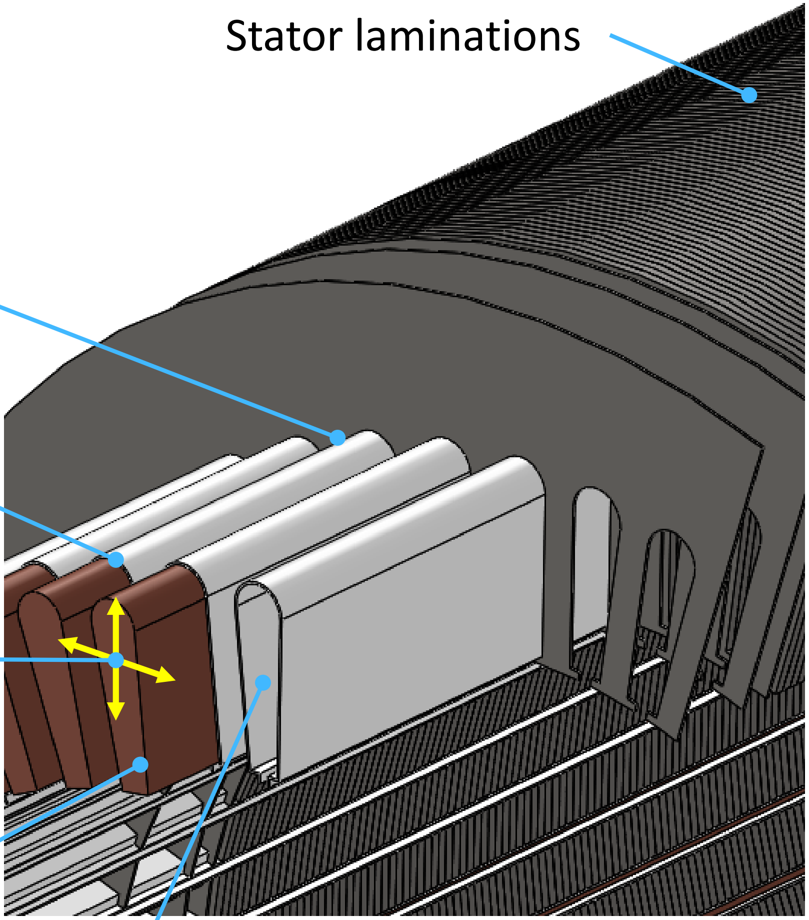
- Quantifies impact of new or alternative cooling approaches for ATF cooling of motors.
- Enables work to characterize impact of cooling fluids.

Photo Credits: Kevin Bennion

ATF: automatic transmission fluid

Motor Packaging Materials Thermal Characterization

- Performing thermal measurements on motor packaging materials.



Stator laminations

Measure liner-to-stator thermal contact resistance

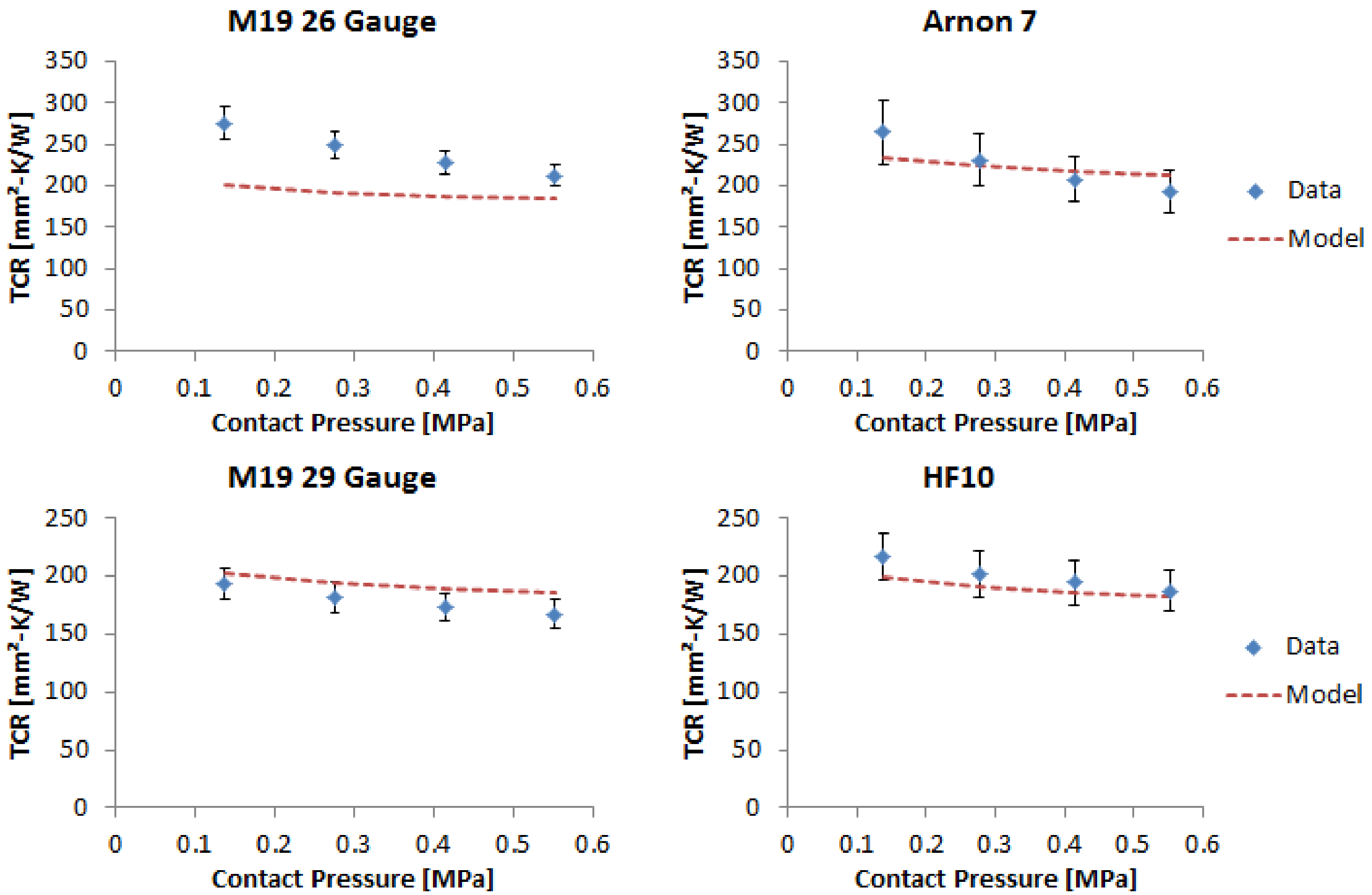
Measure winding-to-liner thermal contact resistance

Measure cross-slot winding thermal conductivity

Slot windings

Slot liner or ground insulation

Motor Lamination Thermal Contact Resistance

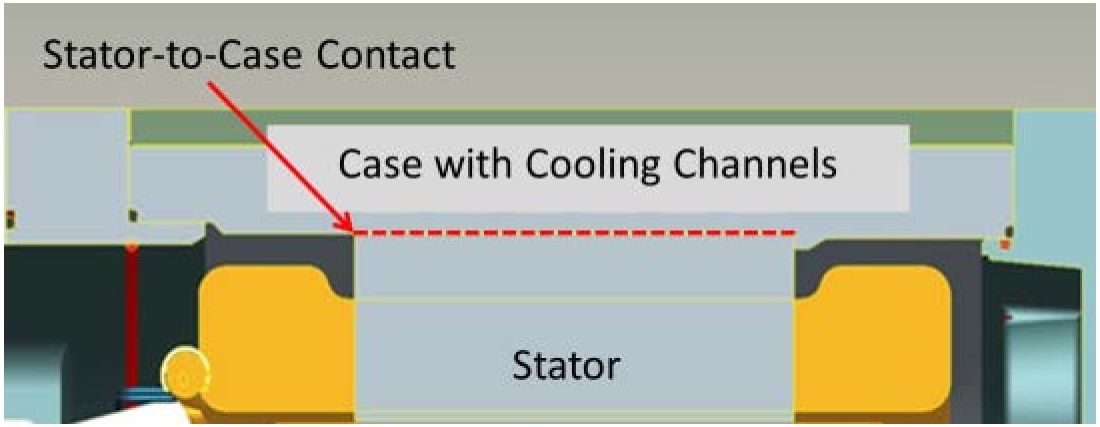


- Validated model with experimental data using multiple materials.
- Manuscript in process of submission:
  - "Experimental Characterization and Modeling of Thermal Resistance of Electric Machine Lamination Stacks"

TCR: Thermal contact resistance

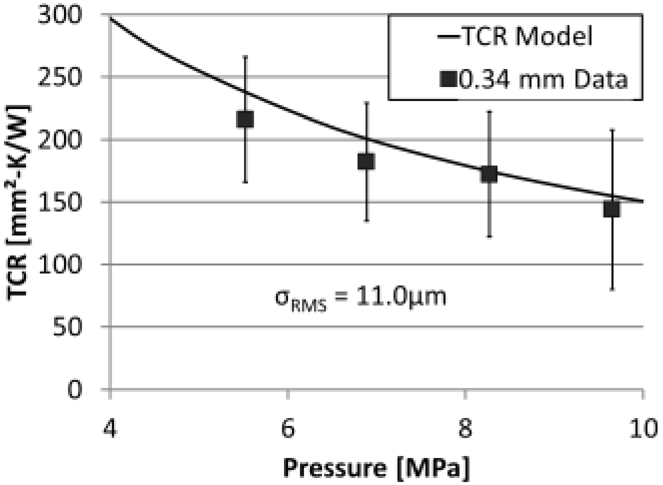
Stator-to-Case Thermal Contact Resistance

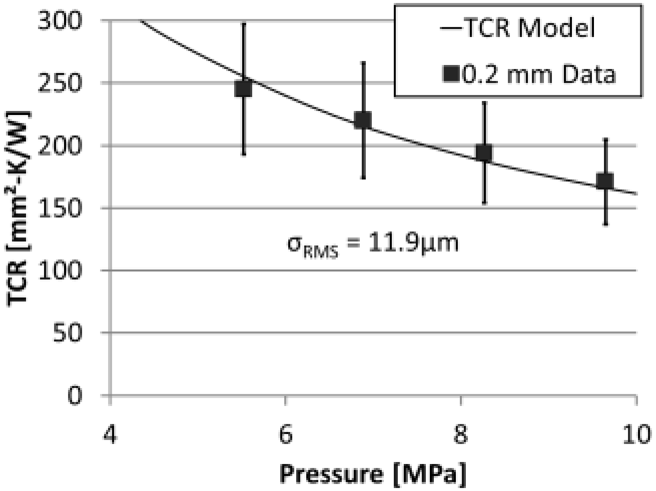
- Developed model for lamination thermal contact resistance to enable estimates of through-stack thermal conductivity for new materials.
- The model includes both solid and fluid components to calculate the inverse of TCR, or thermal contact conductance (TCC).



Stator-to-Case Contact Resistance

- Validated model with experimental data using two different lamination materials with two lamination thicknesses.
- Error bars show 95% uncertainty levels.





- Manuscript in process of submission:
  - “Experimental Characterization and Modeling of Thermal Contact Resistance of Electric Machine Stator-to-Cooling Jacket Interface under Interference Fit Loading," submitted to *ASME Thermal Science and Engineering Applications*.

Supporting Multiple EERE Research Activities and Direct-Industry Projects

PowerAmerica	Manufacturing wide-bandgap power electronics
Next Generation Electric Machines	Energy efficient, high power density, high-speed integrated medium-voltage drive systems for critical energy applications
Wide-Bandgap Power Electronics Traineeship	Traineeship and curriculum development on wide-bandgap power electronics
SunShot	Drive down the cost of solar electricity and support solar adoption
Technology Commercialization	Working on technology-development -phase project to transfer technology to industry

Several direct industry-funded projects in sub-topics related to thermal management and reliability

EERE: Office of Energy Efficiency and Renewable Energy within Department of Energy

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.

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

Acknowledgments:

Susan Rogers
EDT Program
Vehicle Technologies Office
Advanced Manufacturing Office
U.S. Department of Energy

For more information, contact:

NREL APEEM Team Leader

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

Industry and Research Partners

Industry OEMs	Ford, GM, FCA, John Deere, Tesla, Toyota
Suppliers/Others	3M, NBETech, Curamik, DuPont, Energetics, GE Global Research, Semikron, Kyocera, Sapa, Delphi, Btechcorp, ADA Technologies, Remy/BorgWarner, Heraeus, Henkel, Wolverine Tube Inc., Wolfspeed, Kulicke & Soffa, UQM Technologies, nGimat LLC
Agencies	DARPA
National Laboratories	Oak Ridge National Laboratory, Ames Laboratory, Argonne National Laboratory
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