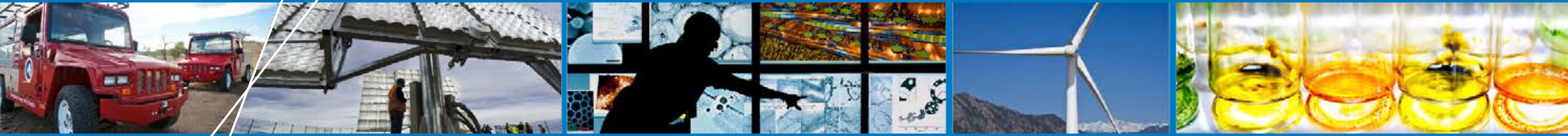
NATIONAL RENEWABLE ENERGY LABORATORY

Thermal Management and Reliability of Power Electronics and Electric Machines



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Advancements in Thermal Management Conference
Denver, Colorado
August 3, 2016

NREL/PR-5400-66754

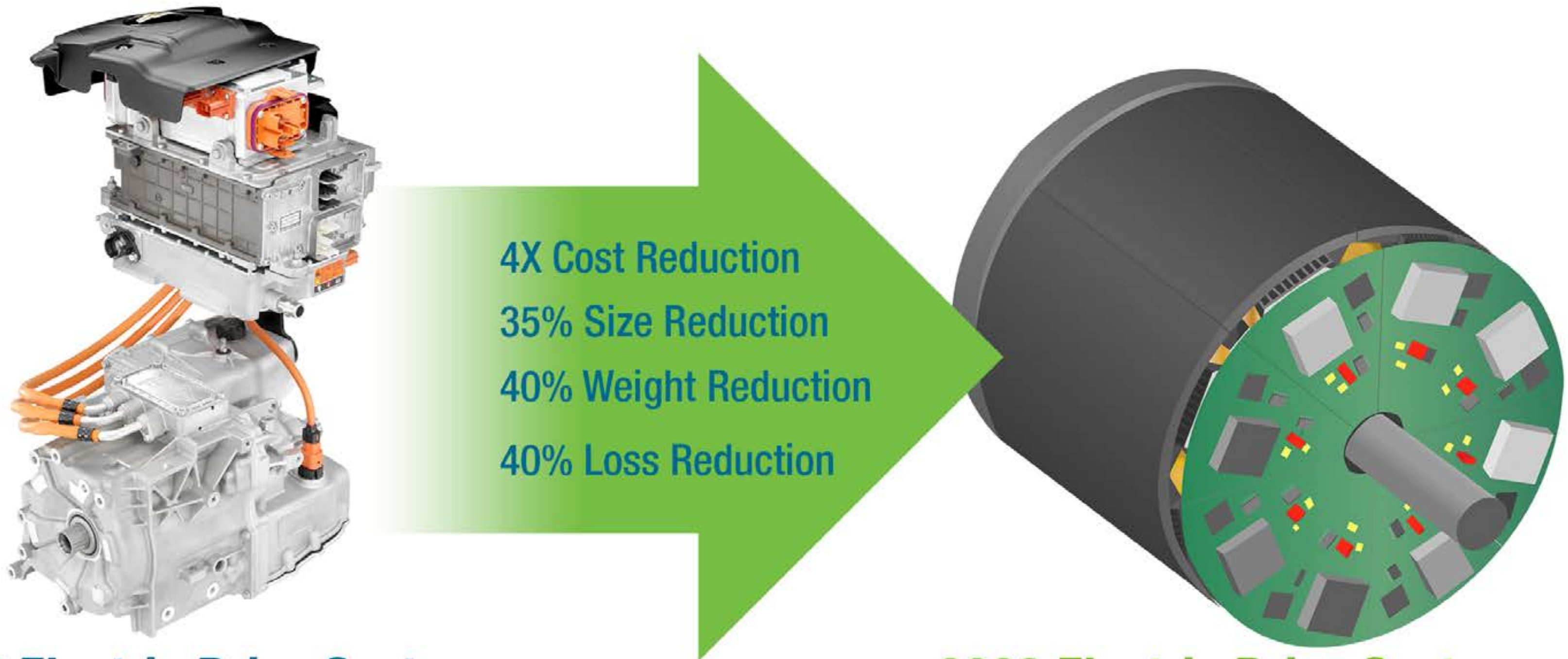
Importance of Thermal Management and Reliability

- Excessive temperature degrades the performance, life, and reliability of power electronics and electric machines.

- Advanced thermal management technologies enable
  - Keeping temperature within limits
  - Higher power densities
  - Lower-cost materials, configurations, and system
  - Improve lifetime/reliability

- Predictive lifetime models help in time-and cost-effective design.

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



2012 Electric Drive System
$30/kW, 1.1 kW/kg, 2.6 kW/L
90% system efficiency
(on-road status)

- Discrete components
- Silicon semiconductors
- Rare-earth motor magnets

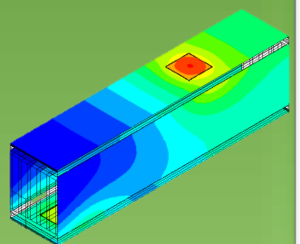
2022 Electric Drive System
$8/kW, 1.4 kW/kg, 4.0 kW/L
94% system efficiency

- Fully integrated components
- Wide-bandgap (WBG) semiconductors
- Non rare-earth motors

From *DOE EV Everywhere Grand Challenge Blueprint,*
http://energy.gov/sites/prod/files/2016/05/f31/eveverywhere_blueprint.pdf

NREL EDT Research Focus Areas

Power Electronics Thermal Management



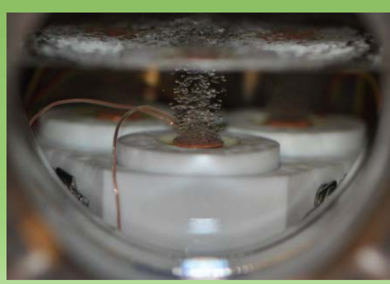
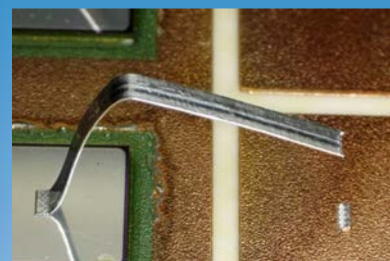


Photo Credits: Doug DeVoto and Gilbert Moreno, NREL

Advanced Packaging Reliability



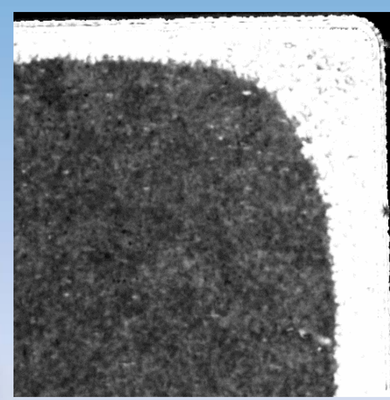


Photo Credits: Doug DeVoto, NREL

Electric Machines Thermal Management

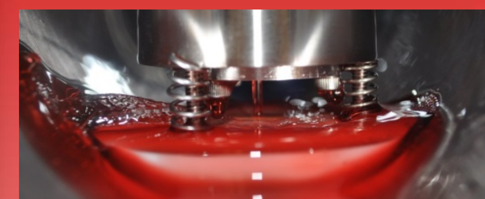
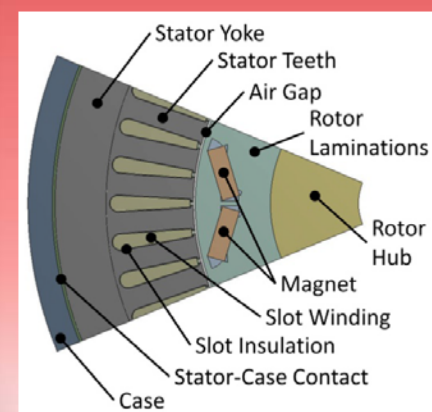


Photo Credit: Jana Jeffers, NREL



Enabling Materials

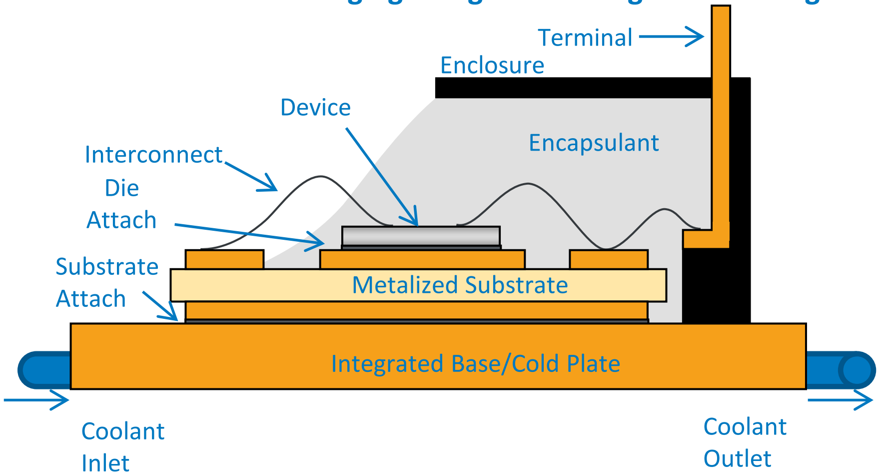
Research Focus Areas Will Reduce Cost and Improve Performance and Reliability

Power Electronics Thermal Management

Power Electronics Thermal Management Strategy

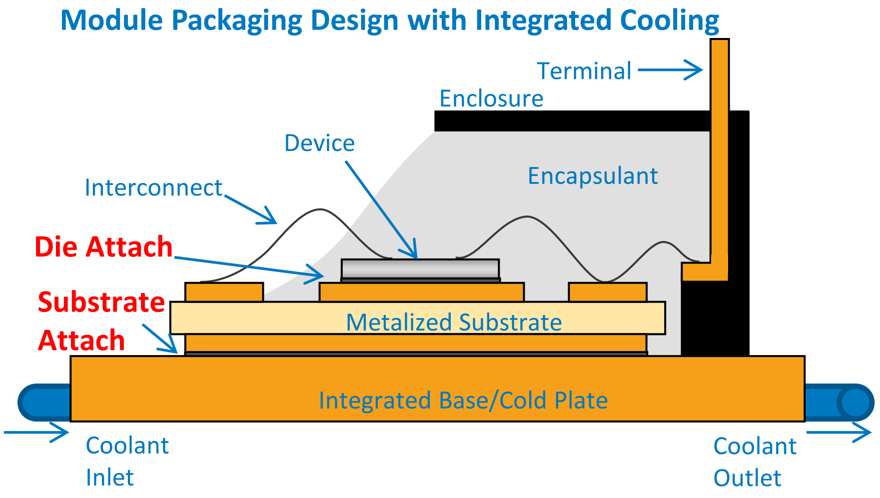
- **Packages based on WBG devices require advanced materials, interfaces, and interconnects**
  - Higher temperature capability
  - Higher effective thermal conductivity
- **Low-cost techniques to increase heat transfer rates**
  - Coolants – water-ethylene glycol (WEG), air, transmission coolant, refrigerants
  - Enhanced surfaces
  - Flow configurations
- **System-level thermal management (capacitor and other passives)**

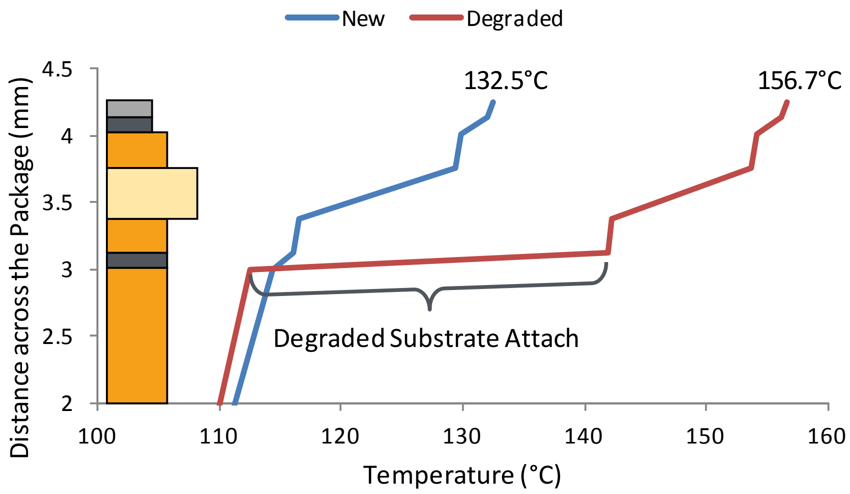
WBG Module Packaging Design with Integrated Cooling



The Challenge with Interfaces/Interface Materials

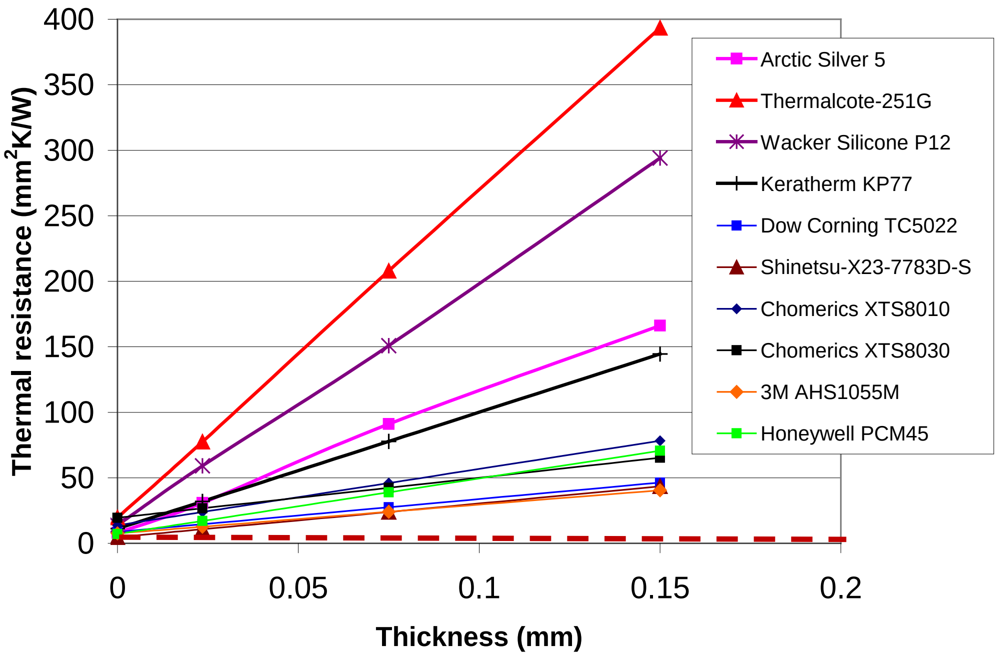
- Interfaces can pose a major bottleneck to heat removal.
- Bond materials, such as solder, degrade at higher temperatures and are prone to thermomechanical failure.
- Problem can become more challenging for configurations employing WBG devices.



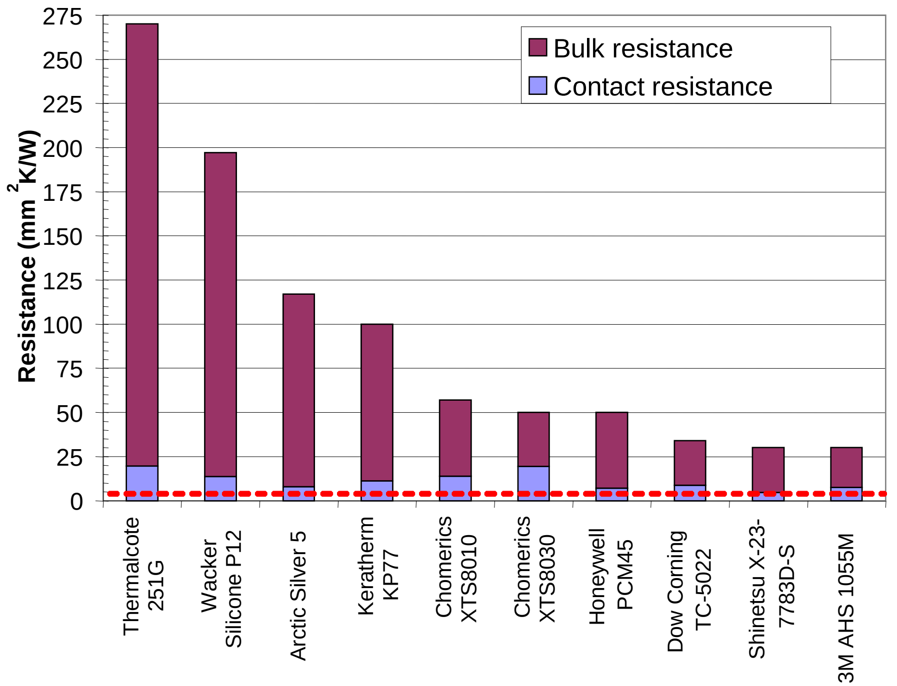


Thermal Resistance of Various Non-Bonded Thermal Interface Materials (TIMs)

172 kPa, ~ 75 C sample temperature



TIM thickness in all cases is 100 µm

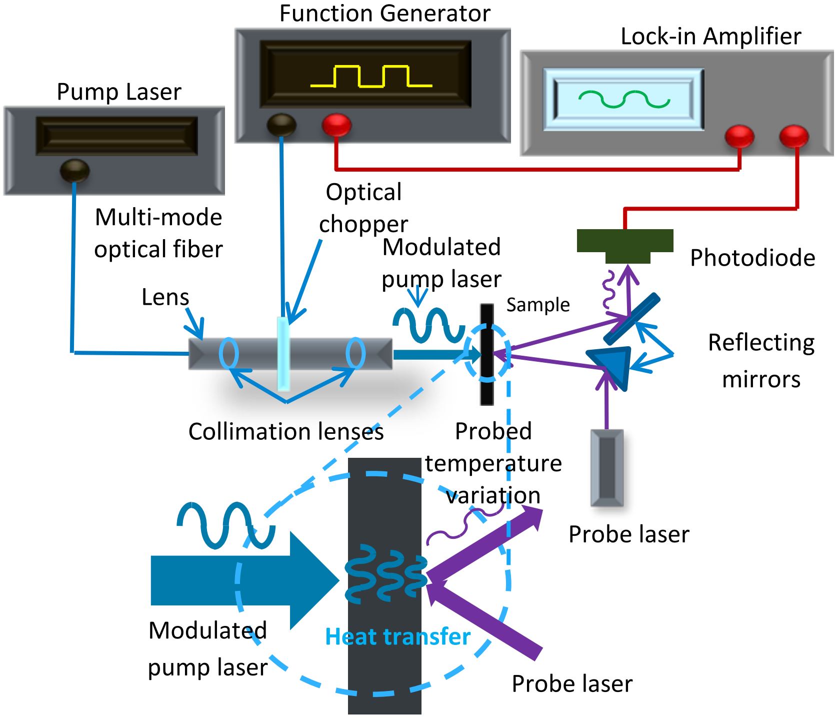


- Red dashed line in the two figures above is the target thermal resistance (**3 to 5 mm^{2}K/W**).
- Most non-bonded TIMs do not come close to meeting thermal specification of 3 to 5 mm^{2}K/W at approximately **100-µm** bond line thickness.

Thermal Resistance of Thermoplastics with Embedded Carbon Fibers

	Thermoplastic film HM-2
Bondline thickness (μm)	60
Bulk thermal conductivity (W/m·K)	**37.5 ± 6.8**
Contact resistance ($mm^2 \cdot K/W$)	**3.1 ± 1.1**
Total thermal resistance ($mm^2 \cdot K/W$)	**7.5 ± 1.9**

Frequency-domain transient thermoreflectance experiment configuration



- **Thermoplastics with embedded carbon fibers show very good thermal performance**

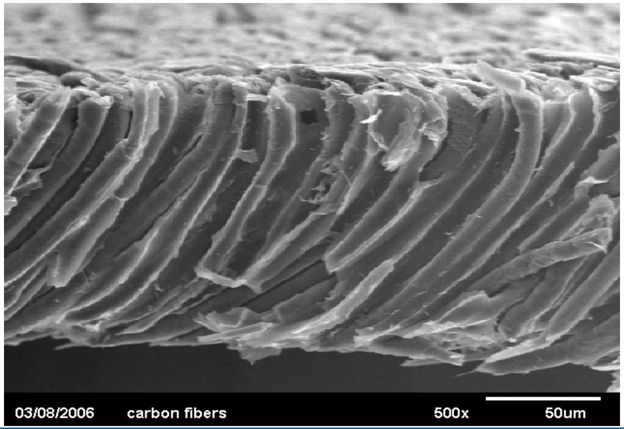


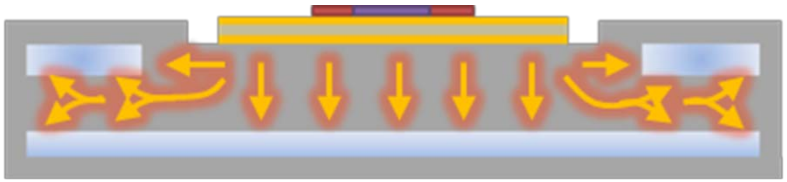
Photo: Courtesy of BtechCorp

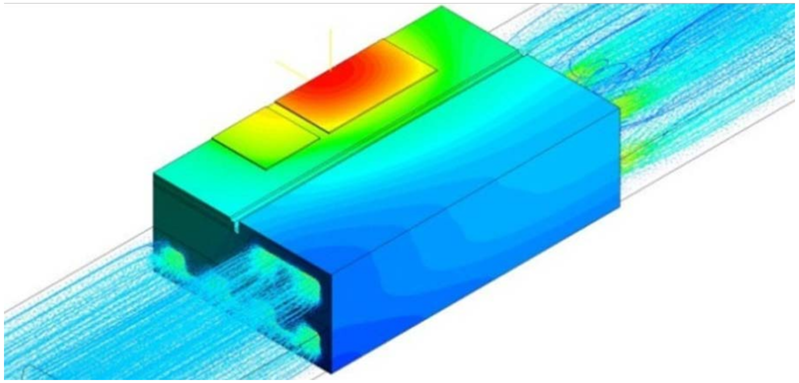
Other Bonded Interface Materials

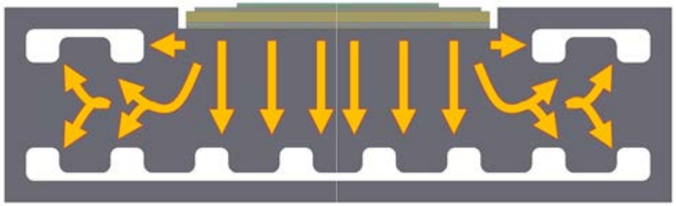
- Bonded interface resistance in the range of 0.4 to 2 mm^2K/W is possible.
  - Materials developed in the DARPA programs are in this range
    - Copper nanowires
    - Boron-nitride nanosheets (0.4 mm^2K/W for 30- to 50-µm bondline thickness)
    - Copper nanosprings (1 mm^2K/W for 50-µm bondline thickness with very good reliability)
    - Graphite solder
    - Nanotube-based

Integrated Module Heat Exchanger

NREL integrated module heat exchanger
Patent No.: US 8,541,875 B2







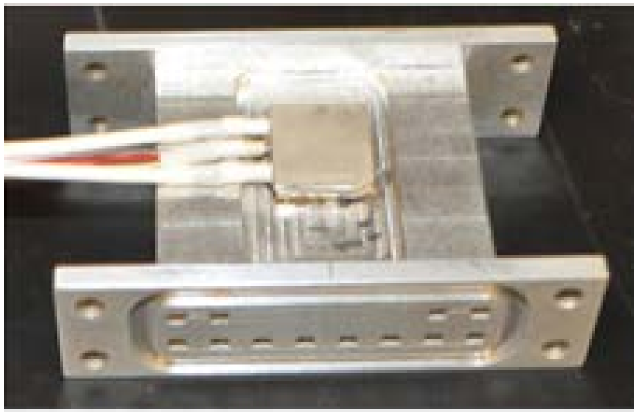
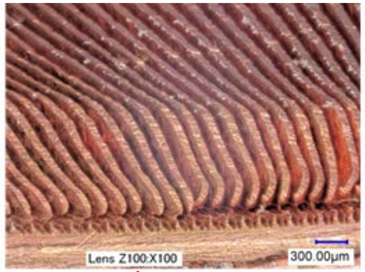


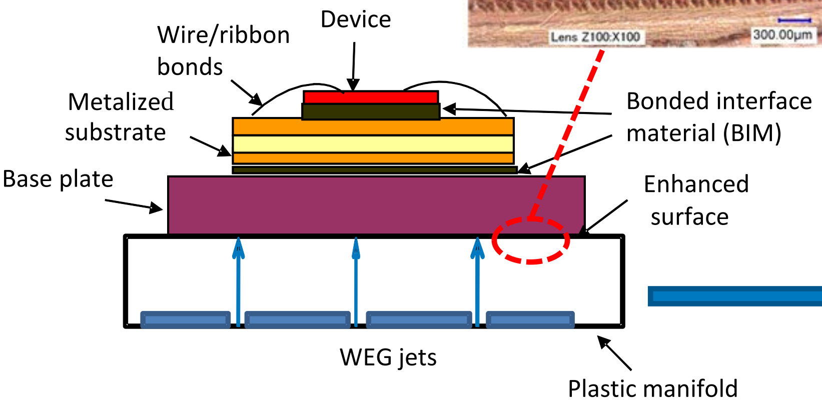
Photo Credit: Kevin Bennion, NREL

- **Up to 100% increase in power per die area**
- **Up to 34% increase in coefficient of performance (efficiency)**

Liquid Jet-Based Plastic Heat Exchanger

Photo Credit: Gilbert Moreno, NREL





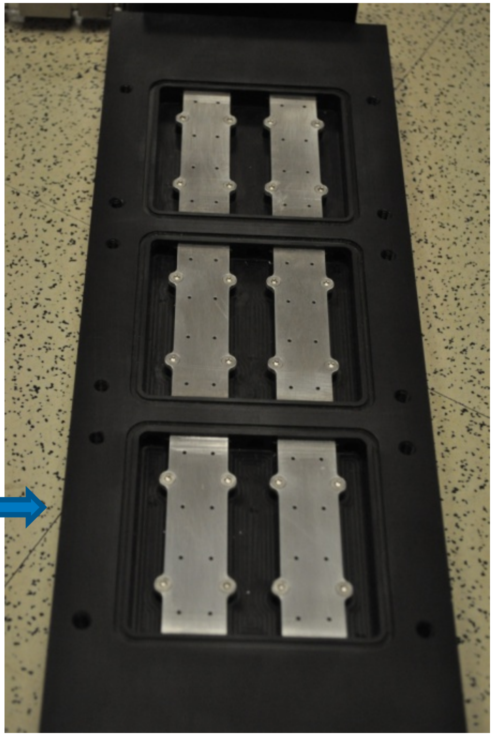
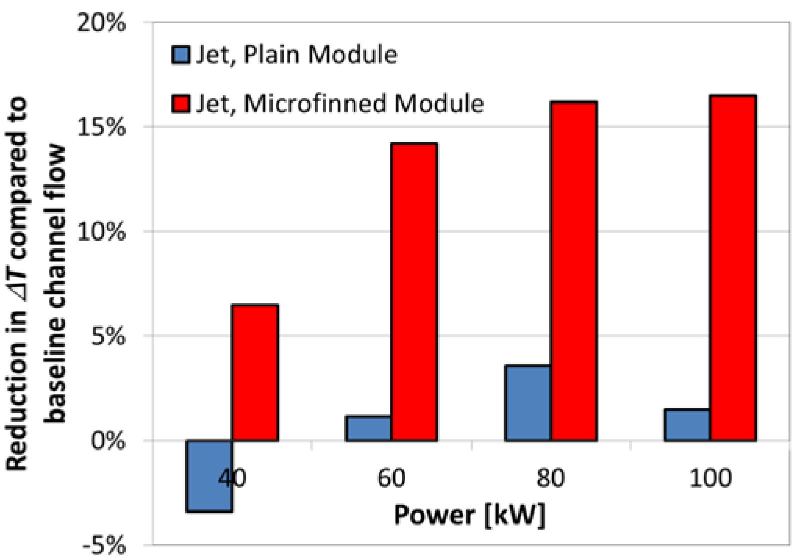


Photo Credit: Doug DeVoto, NREL



- **Up to 12% increase in power density**
- **Up to 36% increase in specific power**

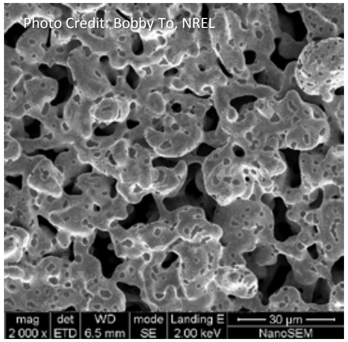
Two-Phase Cooling for Power Electronics

Fundamental Research → **Module-Level Research** → **Inverter-Scale Demonstration**

Fundamental Research

Photo Credit: Gilbert Moreno, NREL

Characterized performance of HFO-1234yf and HFC-245fa



Achieved heat transfer rates of up to ~200,000 W/m^2-K

Module-Level Research

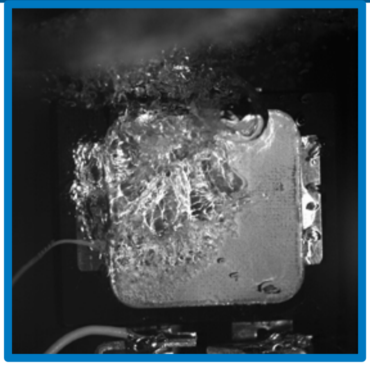
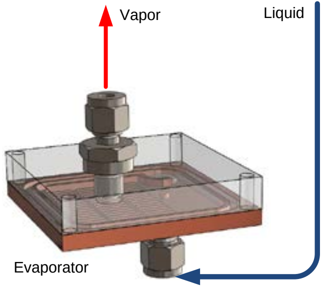


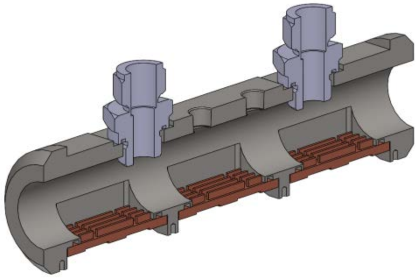
Photo Credit: Gilbert Moreno, NREL

Reduced thermal resistance by over 60% using immersion two-phase cooling of a power module

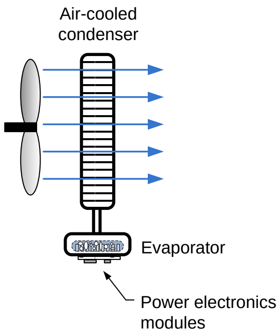


Quantified refrigerant volume requirements

Inverter-Scale Demonstration



Dissipated 3.5 kW of heat with only 250 mL of refrigerant



Predicted 58%–65% reduction in thermal resistance via indirect and passive two-phase cooling

WBG Power Electronics Thermal Management

Create thermal models of an automotive inverter

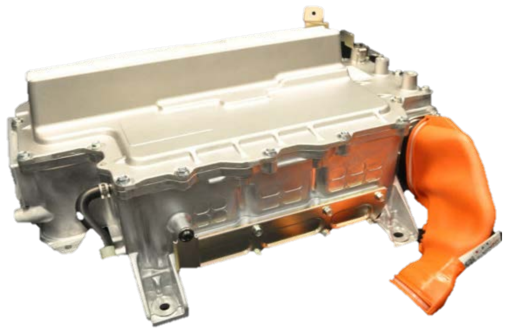
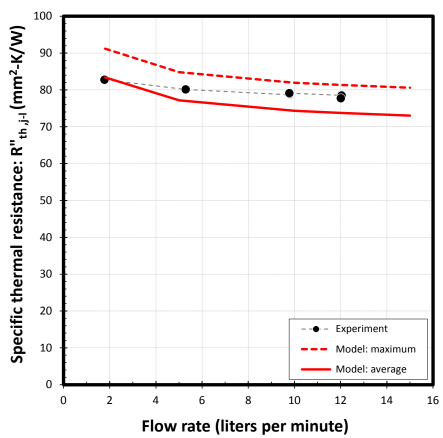
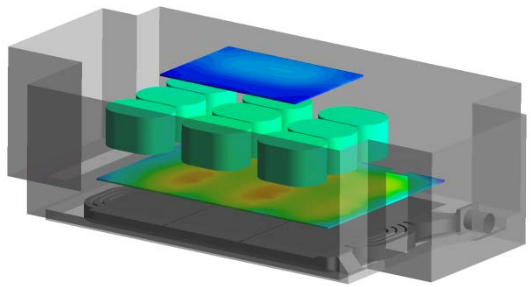


Photo Credit: Scot Waye, NREL

Validate the thermal models



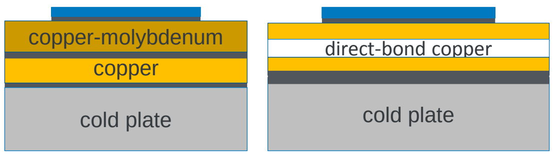
Simulate WBG operation using the inverter model



Quantify the inverter component temperatures under elevated device temperatures

Identify the primary thermal paths through which heat is conducted from the devices to the other components

Explore advanced cooling strategies



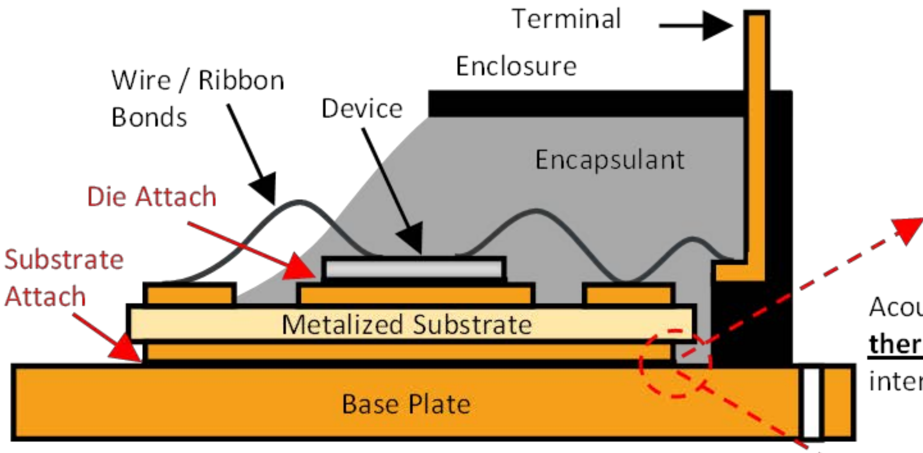
Evaluate different module topologies

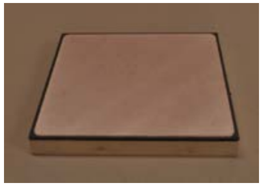
Develop thermal management concepts to enable WBG power electronics

Experimentally validate some key thermal management concepts

Advanced Packaging Reliability

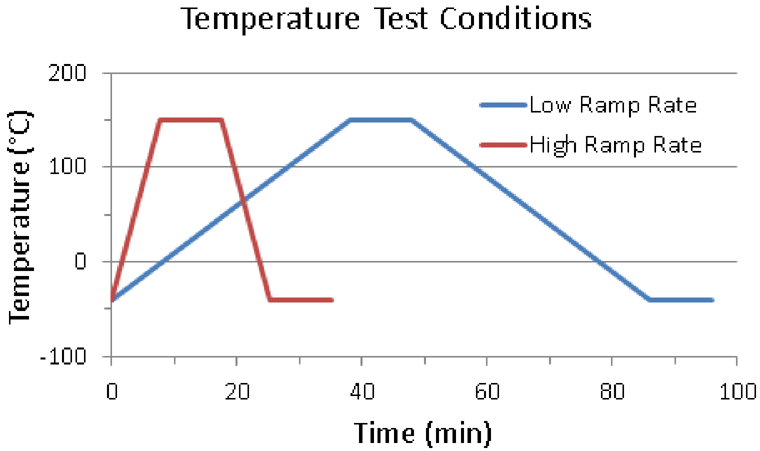
Bonded Interface Material Reliability





Acoustic microscope image of **thermoplastic** bonded interface with no defects

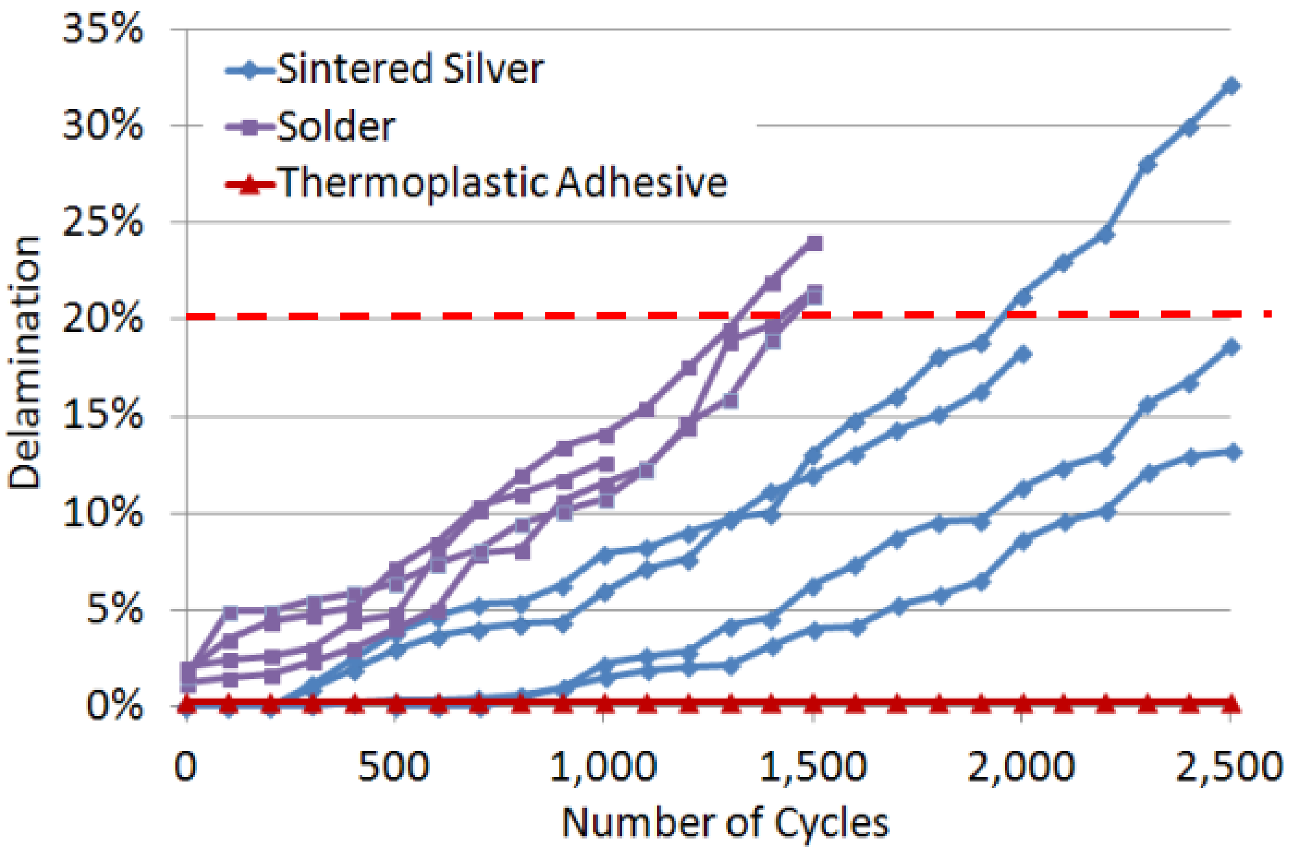
Image of **sintered silver** bonded interface with edge fracture defect



- **Thermoplastics yield very good reliability**
- **Reliability of sintered silver is better than solder**

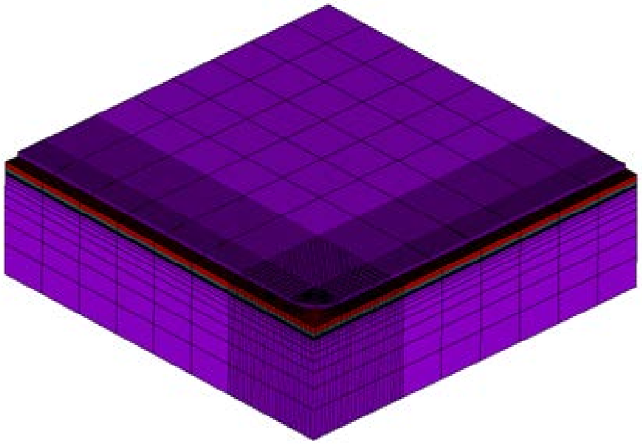
Photo Credit: Doug DeVoto, NREL

Bonded Interface Material Reliability

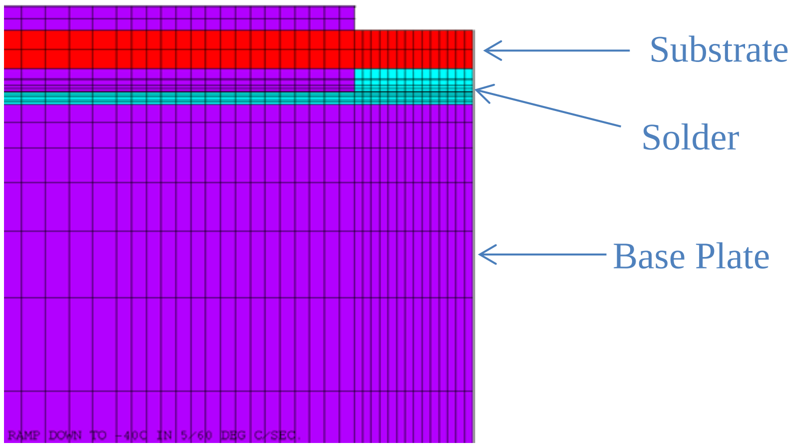


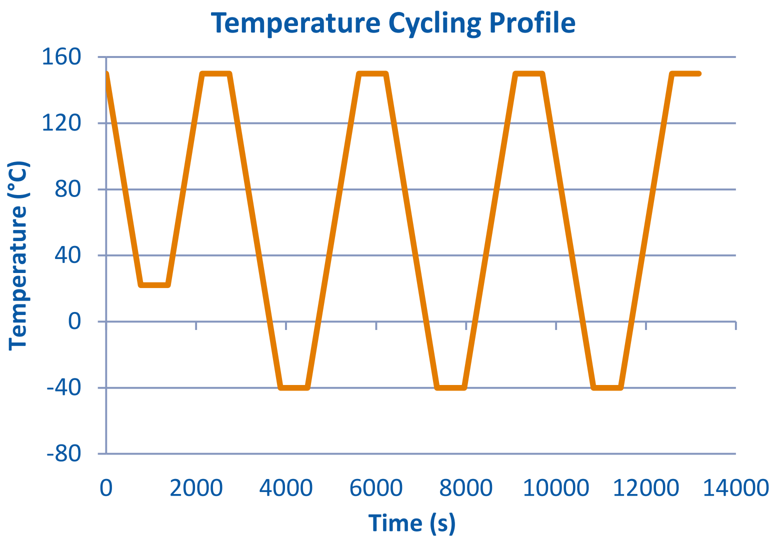
- **Thermoplastics yield very good reliability**
- **Reliability of sintered silver is better than solder**

Bonded Interface Material Finite Element Modeling



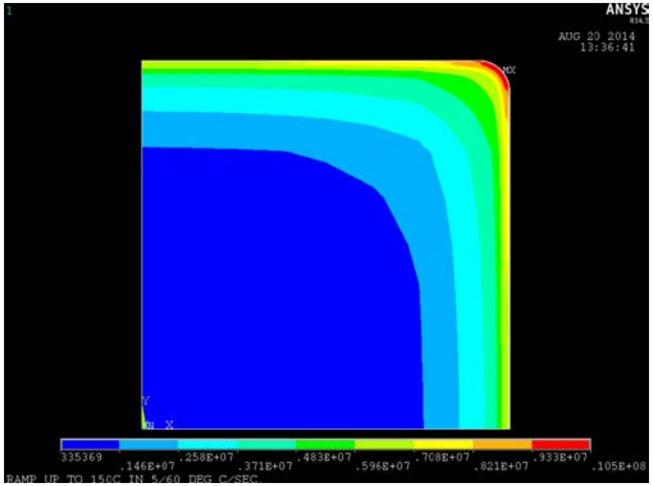
Quarter Symmetry Model



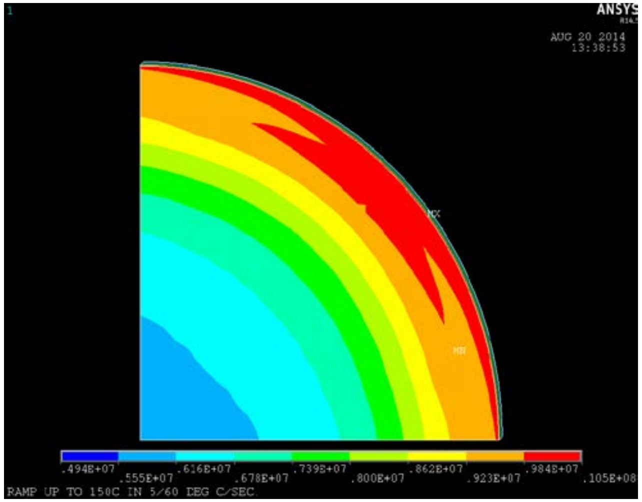


- Temperature cycling parameters:
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Anand viscoplastic material model applied to solder layer
- Temperature-dependent elastic material properties incorporated for base plate and substrate

Strain Energy Density



Top view of strain energy density contour plot in the solder layer



Corner fillet region

- ***Volume-averaged strain energy density/cycle (ΔW) in the corner fillet region is the final output***

Impact of Geometric Variations on Reliability

- ***Joint Thickness***

Predictive Lifetime Model, $N_f = 2312.5 (\Delta W)^{-1.645}$

Profile	Joint Thickness (µm)	ΔW (MPa)	Predicted experimental cycles to failure – N_f
Thermal cycle	50	2.65	465
	100	1.36	1,400
	150	0.93	2,600

- ***Substrate Variation***

Profile	Substrate	CTE (x 10^{-6}/°C)	ΔW (MPa)	Predicted experimental cycles to failure – N_f
Thermal cycle	Si_3N_4	2.8	1.36	1,400
	AlN	4.5	1.08	2,000
	Al_2O_3	8.1	0.44	9,000

CTE: coefficient of thermal expansion
Si_3N_4 : silicon nitride
AlN: aluminum nitride
Al_2O_3: aluminum oxide

Electric Machines Thermal Management

Electric Machines Thermal Management Strategy

Problem

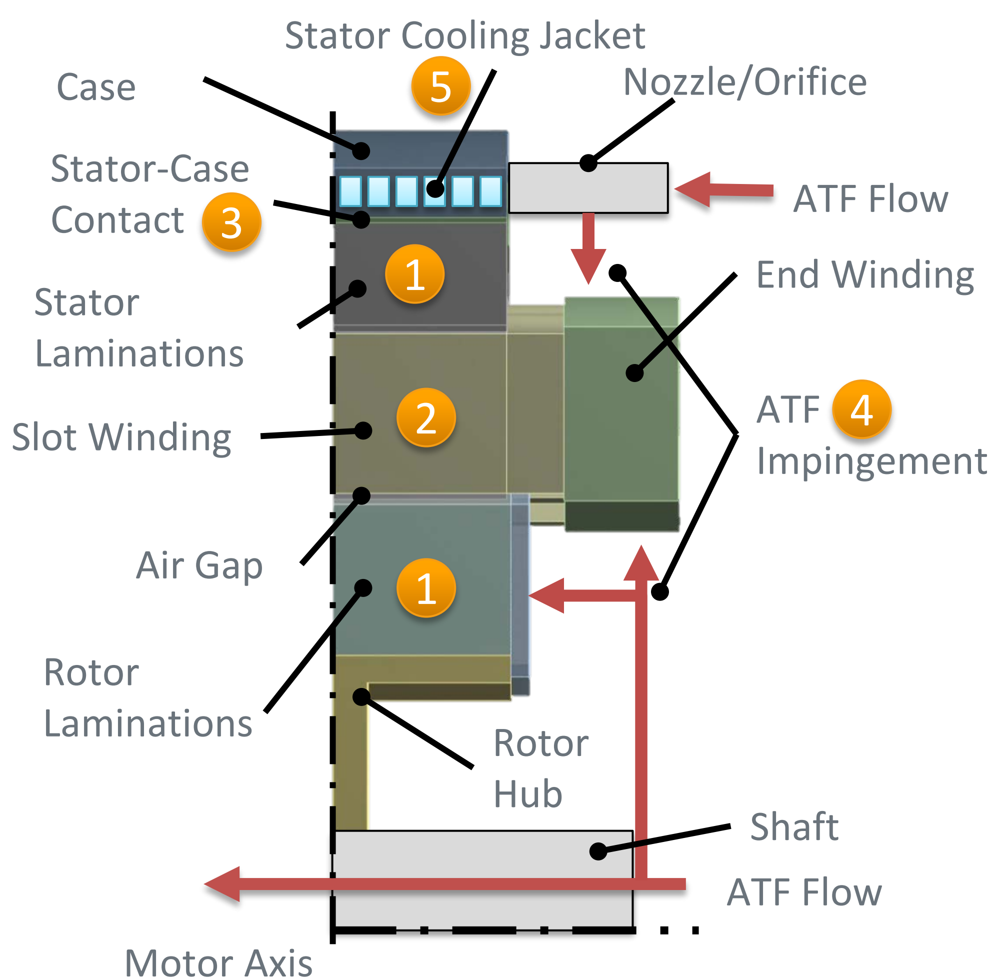
- Multiple factors impacting heat transfer are not well quantified or understood.

Contributing Factors

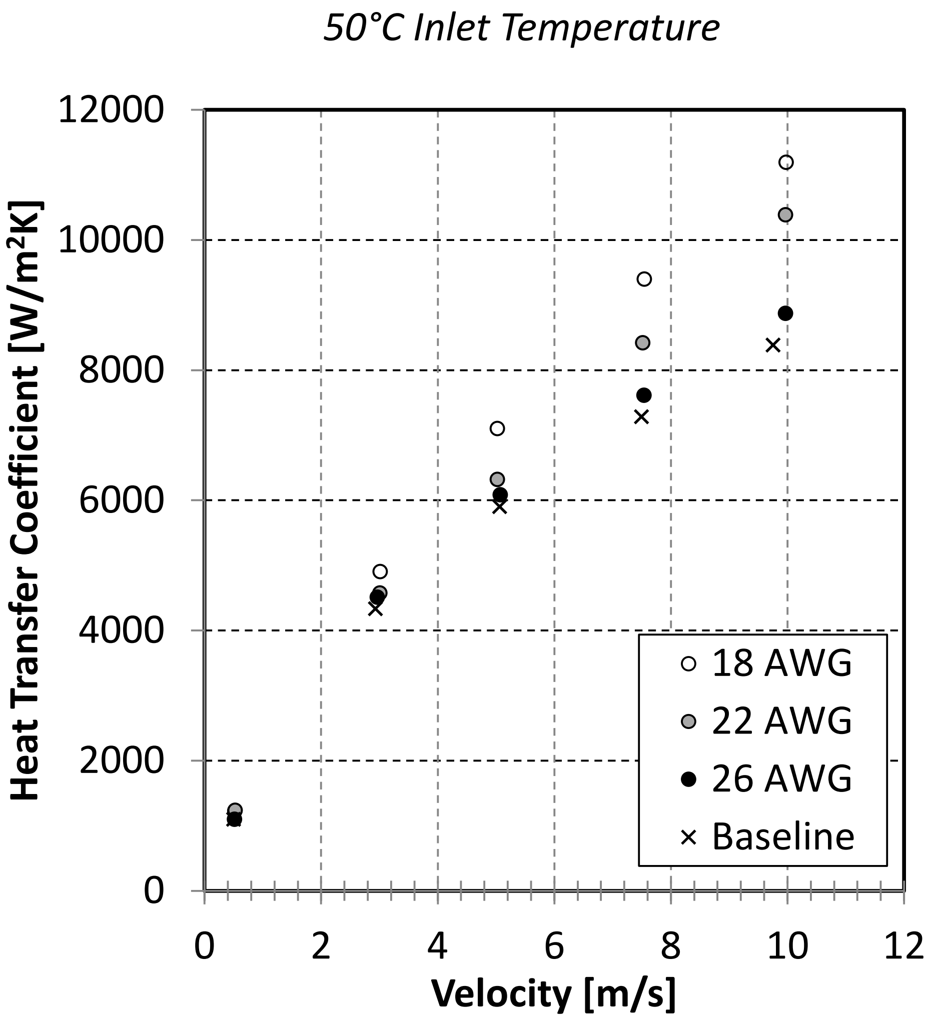
1. Direction-dependent thermal conductivity of lamination stacks
2. Direction-dependent thermal conductivity of slot windings and end windings
3. Thermal contact resistances (stator-case contact, slot-winding interfaces)
4. Convective heat transfer coefficients for ATF cooling
5. Cooling jacket performance

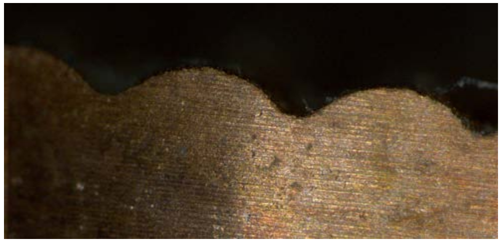
ATF: Automatic Transmission Fluid

Motor Cooling Section View

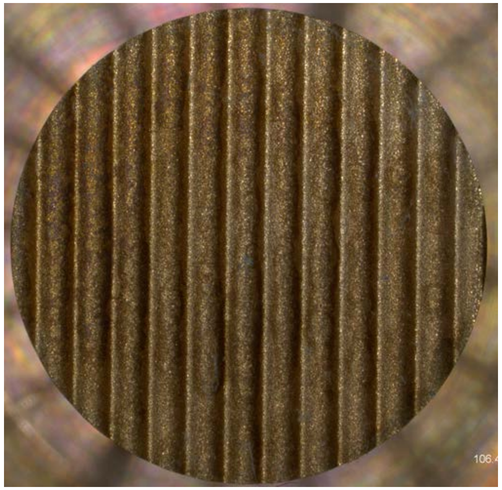


Transmission Oil Jet Heat Transfer Characterization





Side View



Top View

18 AWG surface target

Heat transfer coefficients of all target surfaces at 50°C inlet temperature

- Surface features increase heat transfer

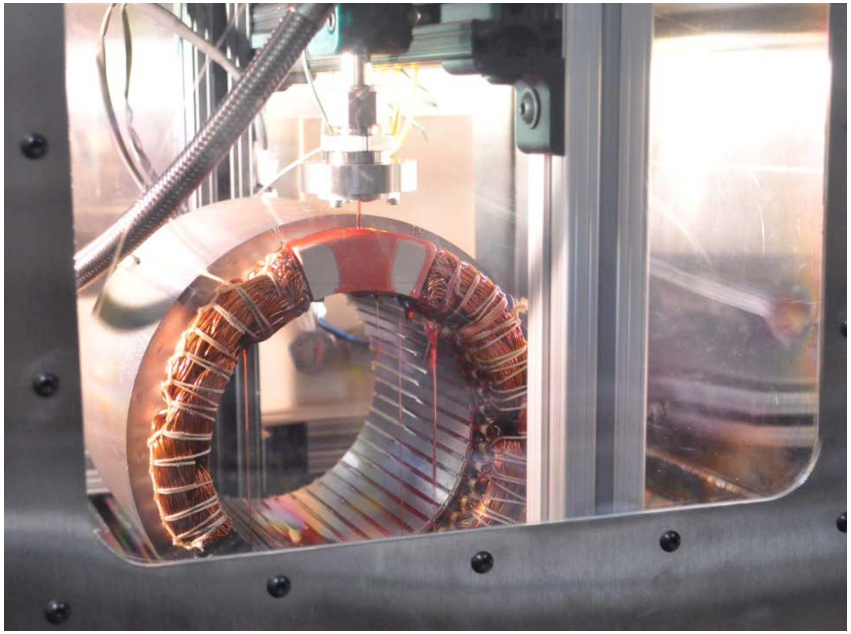
Note: Heat transfer coefficient calculated from the base projected area (not wetted area)

Photo Credits: Gilbert Moreno, NREL

Stator Thermal Management with Transmission Oil

- **Enclosure allows direct impingement on motor for heat transfer measurements and flow visualization**

Enclosure with stator and ATF cooling



Jet impingement on target surface

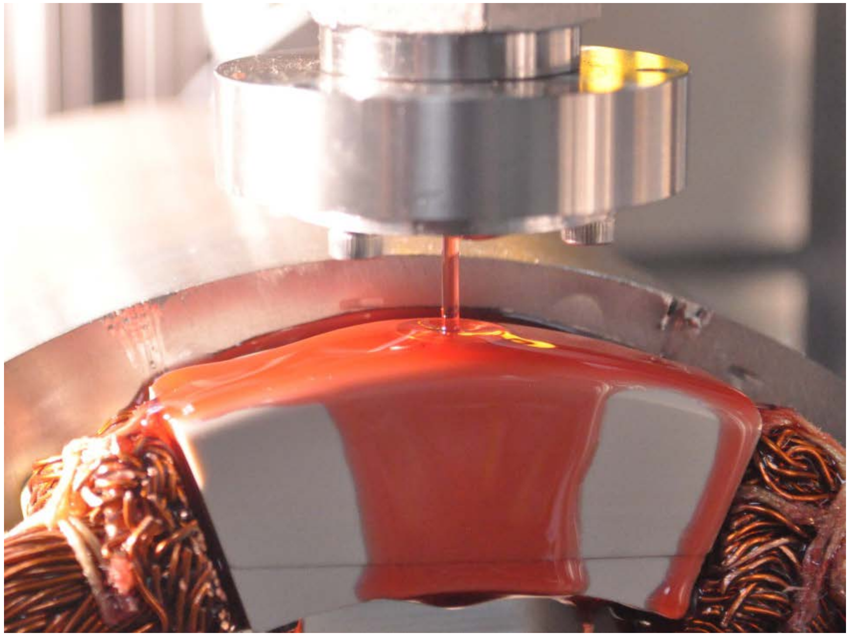
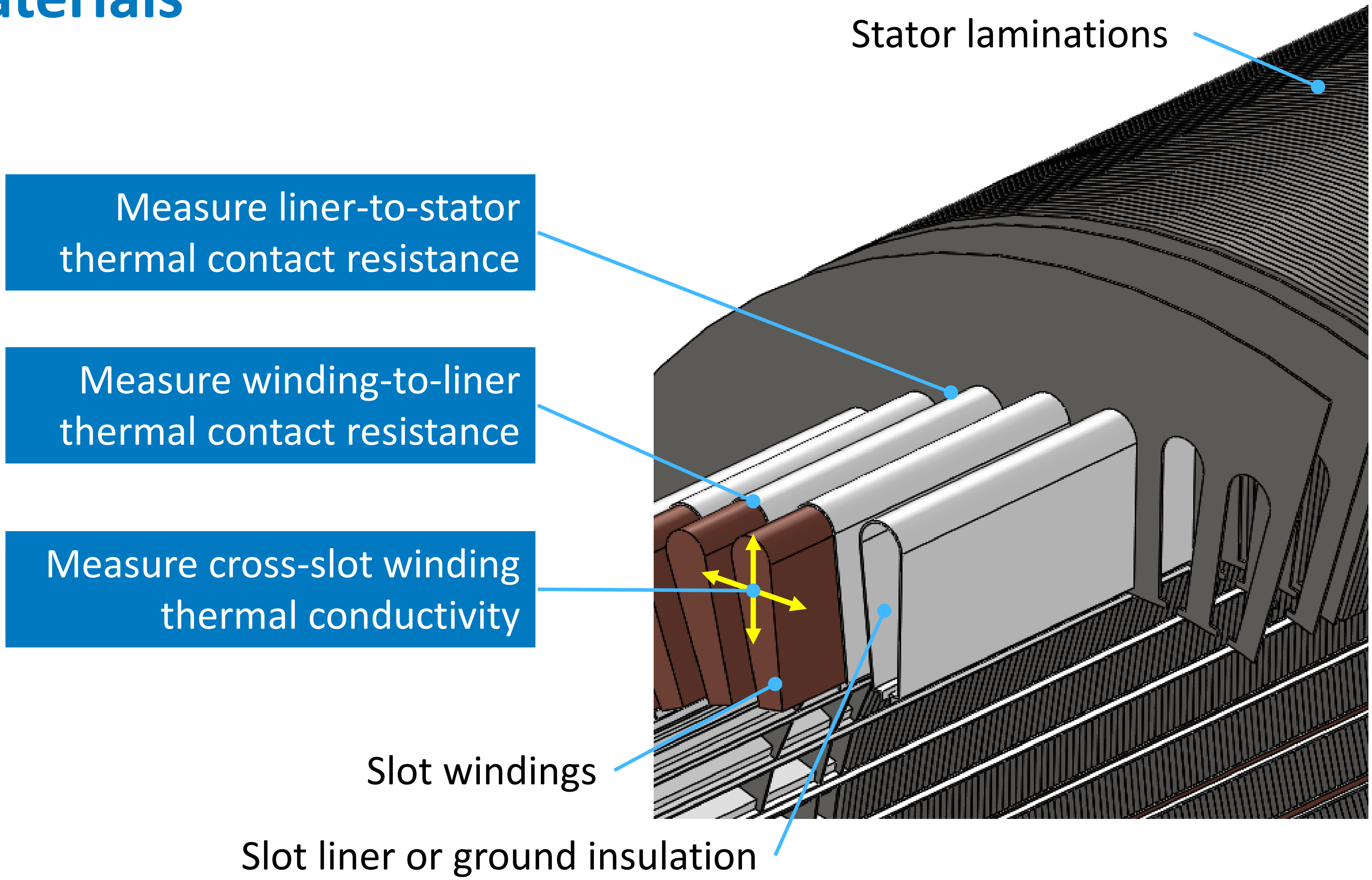


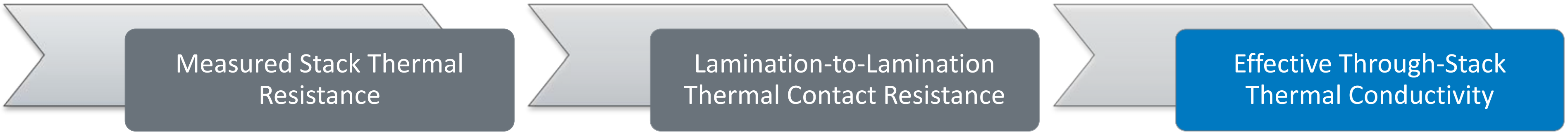
Photo Credits: Kevin Bennion, NREL

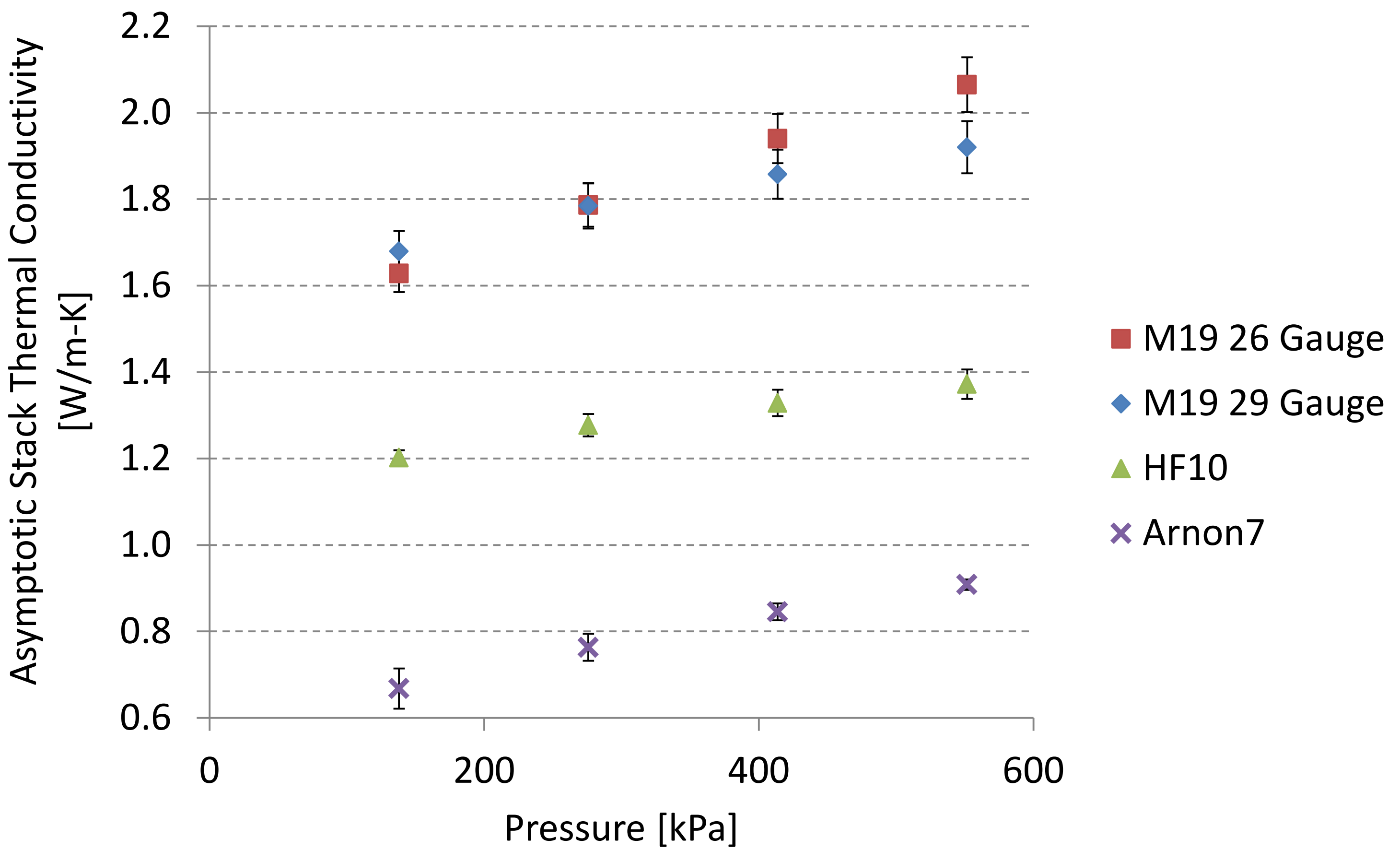
Motor Passive Thermal Materials Characterization

- **Performing thermal analysis on passive thermal materials**



Lamination Stack Effective Thermal Conductivity

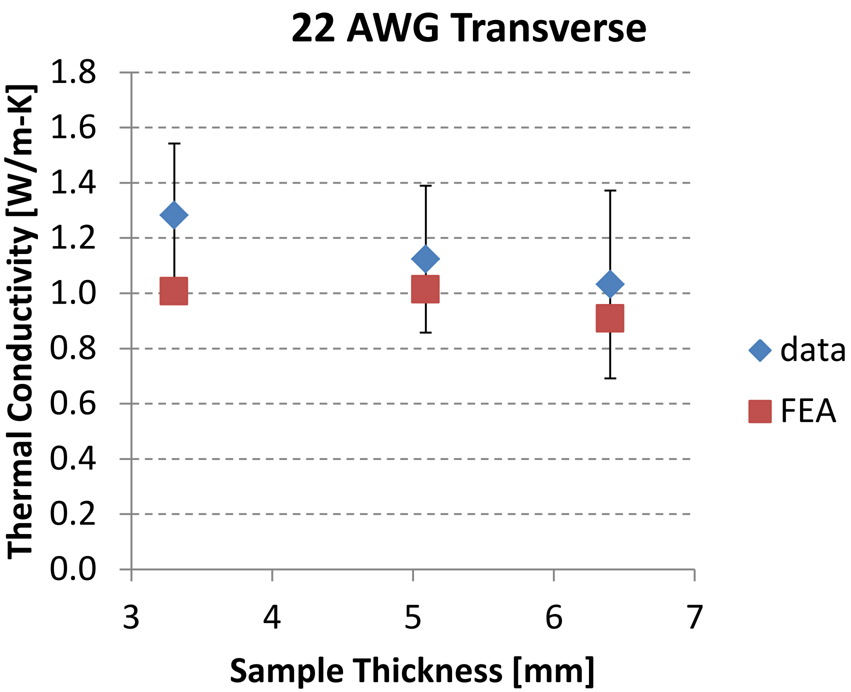


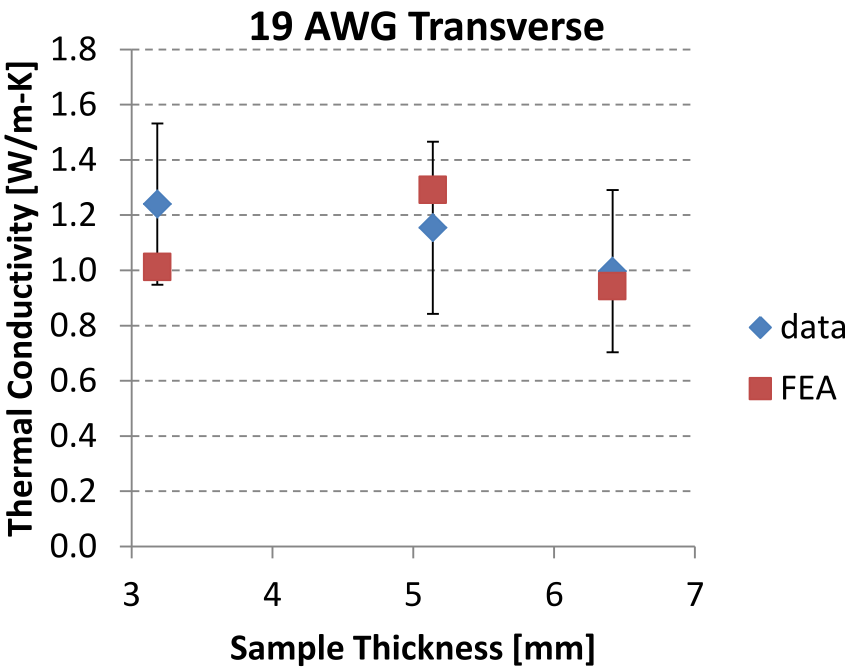


Error bars represent 95% confidence level

Transverse Winding Thermal Conductivity

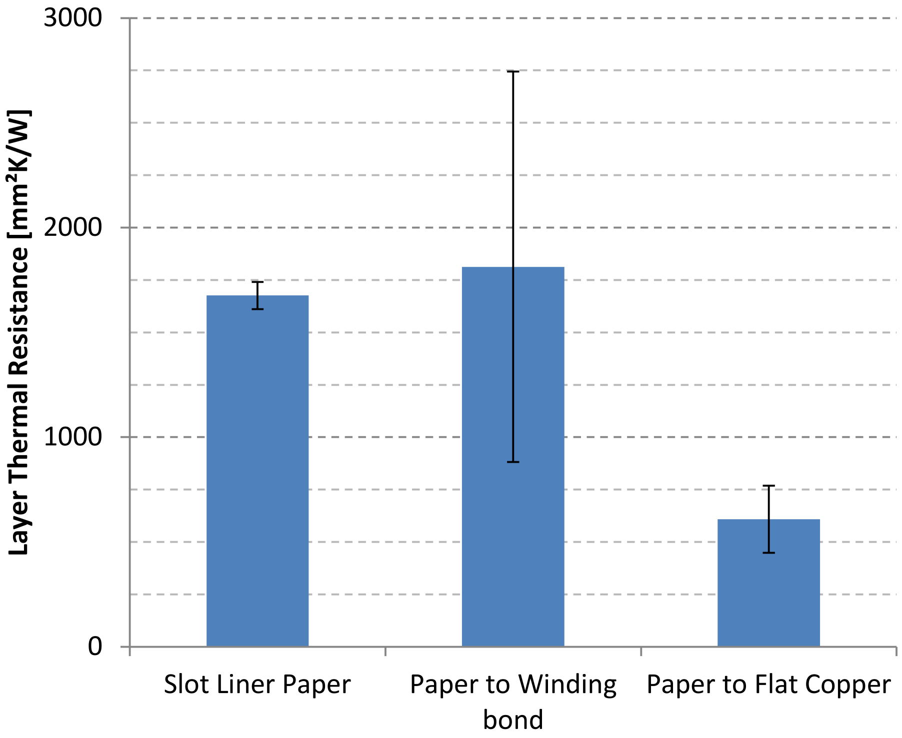
Photo Credit: Emily Cousineau, NREL





- Error bars represent 95% measurement uncertainty (U95)
- Finite element analysis (FEA) model results based on measured sample copper fill factor
- FEA assumes hexagonal or closed-pack wire pattern

Slot Liner Paper and Thermal Interface Resistances



- Limited sample size for measurements
- Slot liner paper thermal conductivity of 0.18 W/m-K (thickness 0.29 mm)
- Winding thermal conductivity measured to be 0.88 ± 0.11 W/m-K (U_{95})
- FEA estimate of thermal conductivity is 0.99 W/m-K for measured copper fill factor

Participation in Industry-Led Projects

- **Industry-led inverter development with VTO and AMO funding**
  - Delphi inverter (VTO)
  - GM inverter (VTO)
  - Wolfspeed WBG inverter (VTO)
  - John Deere WBG inverter (AMO)

- **UQM Technologies motor development (VTO funding)**

AMO: Advanced Manufacturing Office
VTO: Vehicle Technologies Office

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.

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Industry and Research Partners

Industry OEMs	Ford, GM, FCA, John Deere, Tesla, Toyota
Suppliers/Others	3M, NBETech, Curamik, DuPont, 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
Universities	Virginia Tech, University of Colorado Boulder, University of Wisconsin, Carnegie Mellon University, Texas A&M University, North Carolina State University, Ohio State University, U.S. Naval Academy