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Thermal Management of Power Electronics and Electric Motors for Electric-Drive Vehicles

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Session SS1

September 15, 2014

NREL/PR-5400-62878

Importance of Thermal Management

- Excessive temperature degrades the performance, life, and reliability of power electronics and electric motors.
- Advanced thermal management technologies enable
  - keeping temperature within limits
  - improved reliability
  - higher power densities
  - lower cost materials, configurations and system.

DOE APEEM Program Mission

- Department of Energy Vehicle Technologies Office (VTO)
  - Develop more energy-efficient and environmentally-friendly highway transportation technologies that enable America to use less petroleum.
- Advanced Power Electronics and Electric Motors (APEEM)
  - Develop APEEM technologies to enable large market penetration of electric-drive vehicles.

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

Research Laboratories

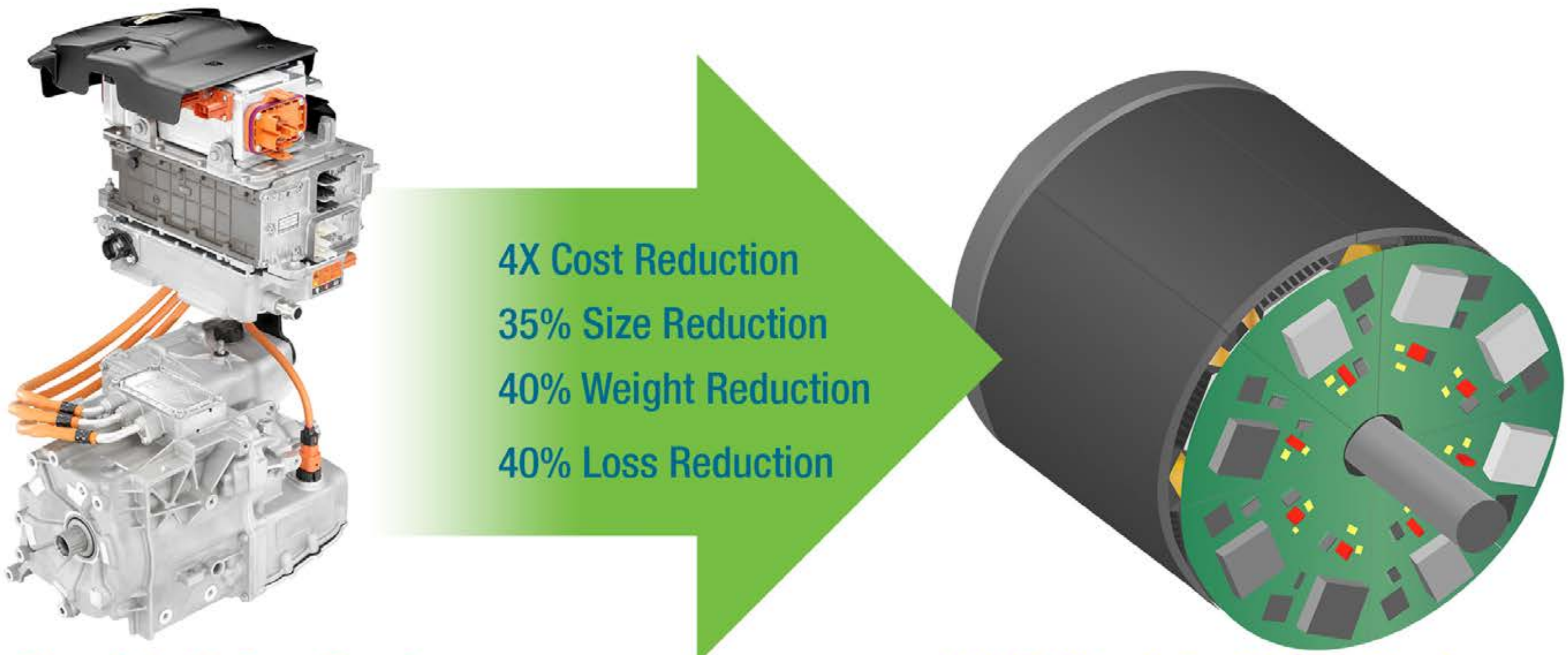
Oak Ridge National Laboratory
Lead: Power Electronics and Electric Motors

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Lead: APEEM Thermal Management

Others: Argonne National Laboratory, Ames Laboratory

Industry, Automotive Suppliers and University Interactions

VTO APEEM Electric Drive System 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

NREL APEEM Research Focus Areas

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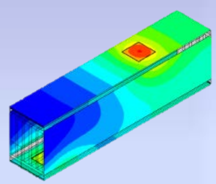
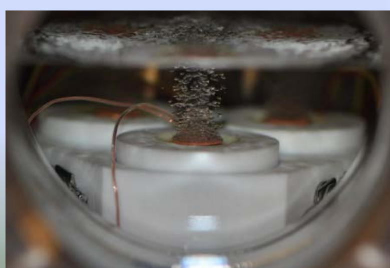
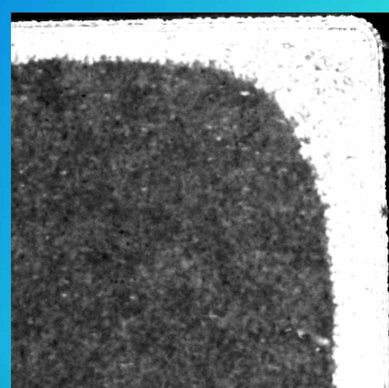
Power Electronics Thermal Management

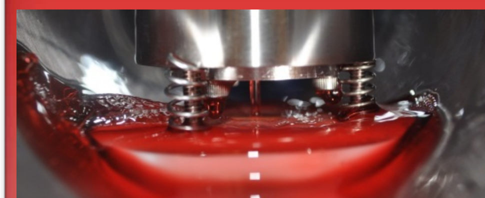


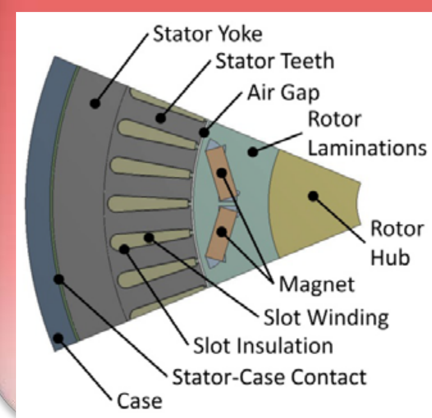


Advanced Packaging Reliability



Electric Motor Thermal Management





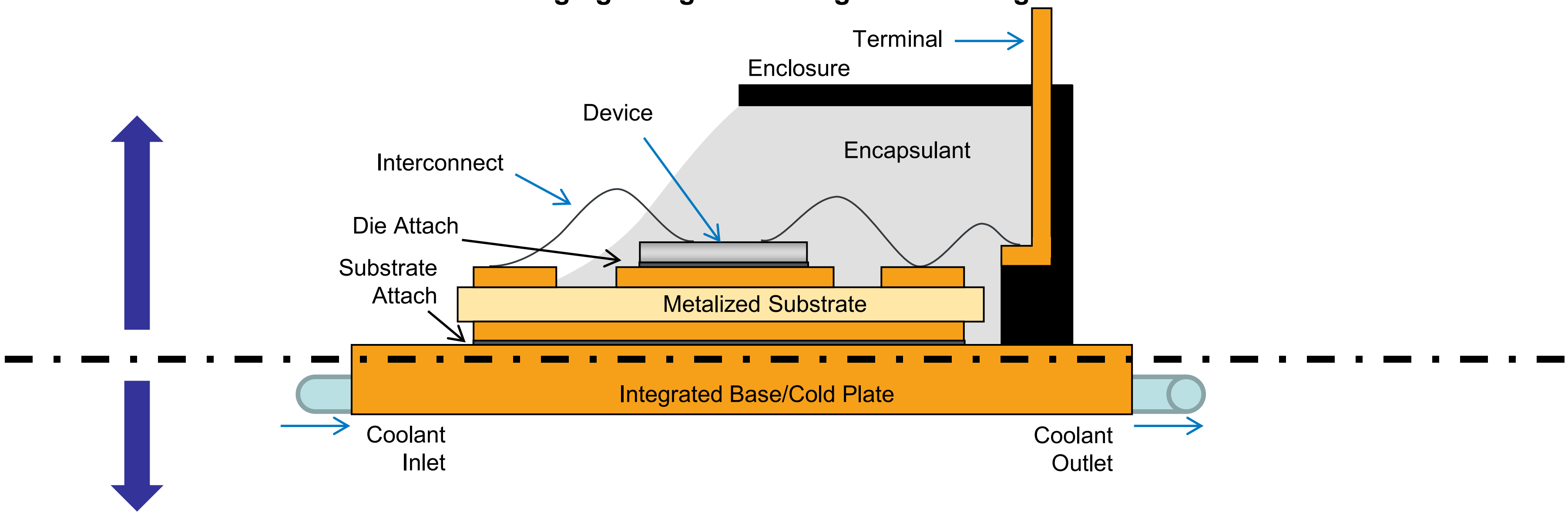
Enabling Materials

Research Focus Areas Will Reduce Cost, Improve Performance and Reliability

Power Electronics Thermal Management Strategy

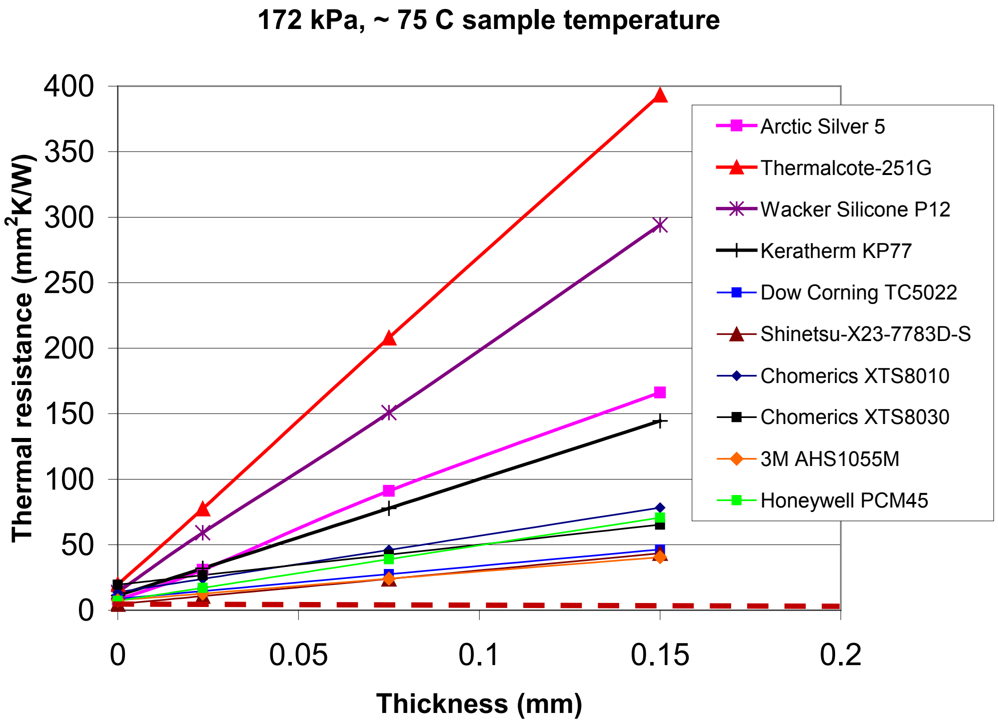
- **Packages based on WBG devices require advanced materials, interfaces, and interconnects**
  - Higher temperature capability
  - Higher effective thermal conductivity

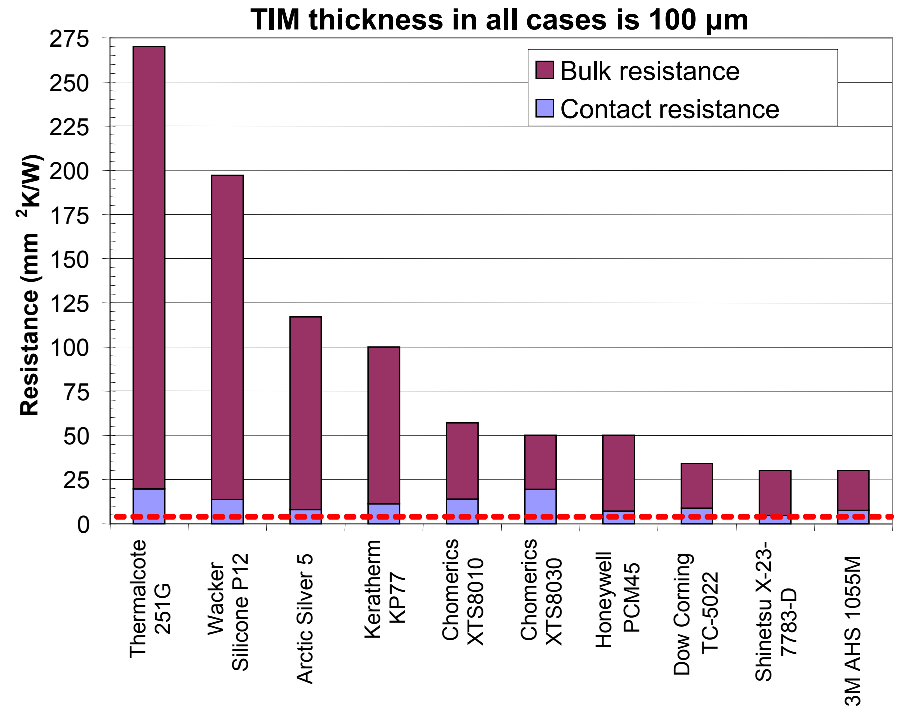
Module Packaging Design with Integrated Cooling



- **Low-cost techniques to increase heat transfer rates are required**
  - Coolants – water-ethylene glycol (WEG), air, transmission coolant, refrigerants
  - Enhanced surfaces
  - Flow configurations

Thermal Resistance of Various Non-Bonded TIMs





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

Thermal Resistance of Sintered Silver and Solder

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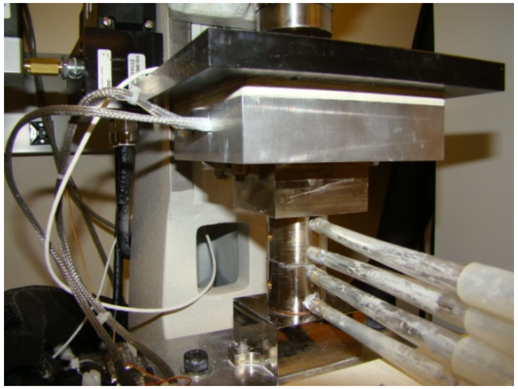


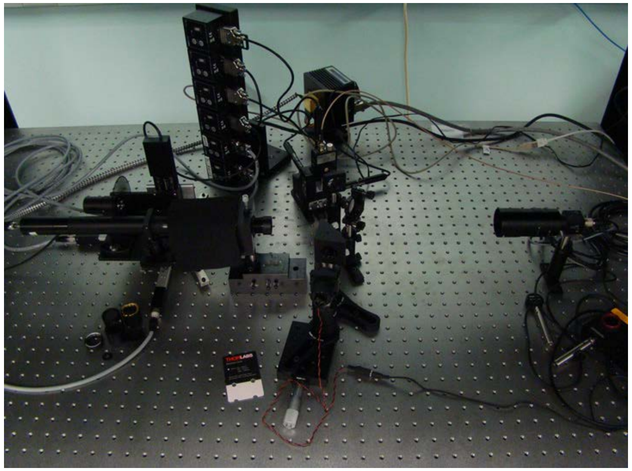
ASTM test fixture

Samples	Thickness (μm)	Resistance (mm^2K/W)
Silvered Cu-Cu sintered interface	**20**	**5.8**
	27	**8.0**
	64	**5.4**
Cu-Cu soldered interface (SN100C)	**80**	**1.0**
	150	**4.8**
	200	**3.7**

- The thermal resistance tests were performed using the NREL ASTM TIM apparatus
  - Average sample temperature ~ 65°C, pressure is 276 kPa (40 psi).
- The silvered silver and lead-free solder both showed promising results.
- Bonded interface resistance in the range of 1 to 5 mm^2K/W is possible.
  - Materials developed in the DARPA nTIM Program are in this range.

Thermal Resistance of Thermoplastics

	Thermoplastic film HM-2
Bondline thickness (μm)	60
Bulk thermal conductivity (W/m·K)	**44.5 ± 8.0**
Contact resistance (mm^2·K/W)	**3.1 ± 1.1**
Total thermal resistance (mm^2·K/W)	**7.5 ± 1.9**



Transient Thermoreflectance Technique Setup

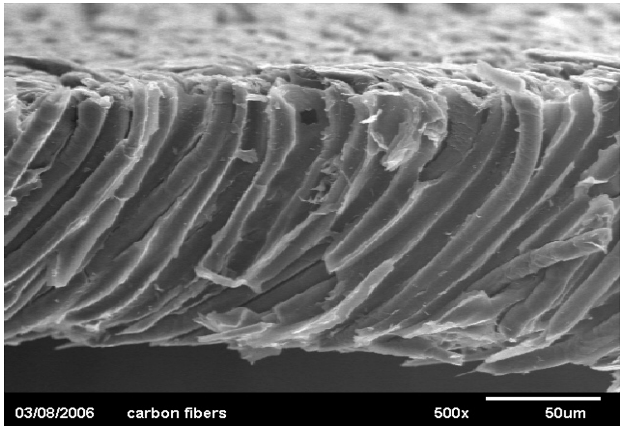
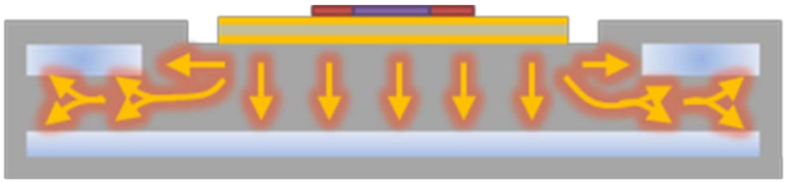


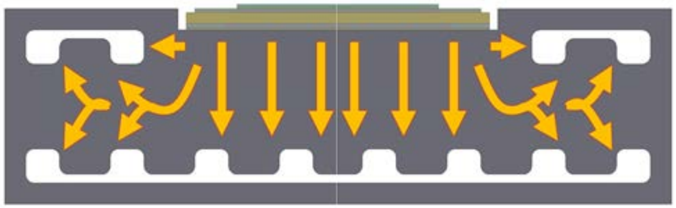
Photo: Courtesy of BtechCorp

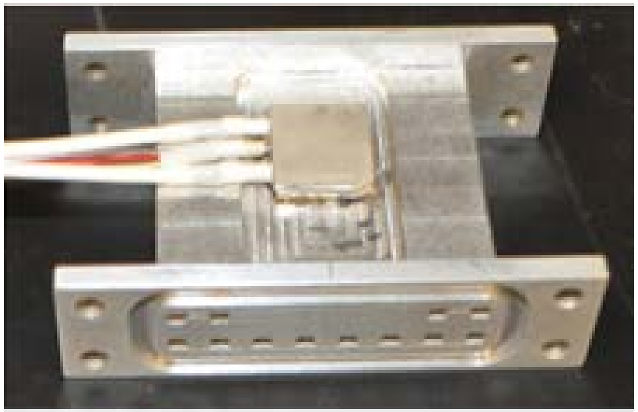
- Thermoplastics with embedded carbon fibers show very good thermal performance.
- Thermal performance characterized via the transient thermoreflectance technique.

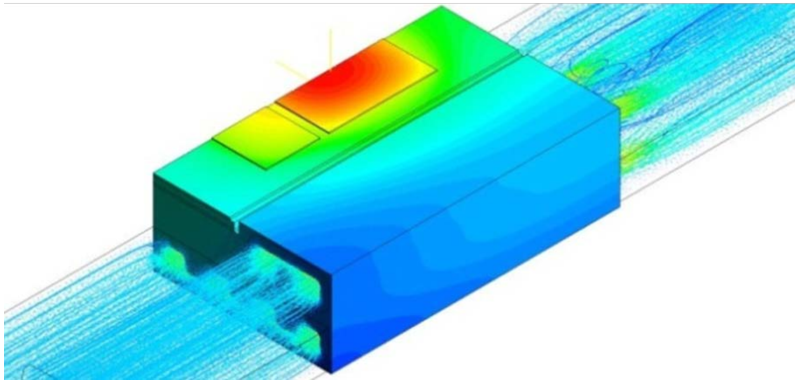
Integrated Module Heat Exchanger

NREL integrated module heat exchanger
Patent No.: US 8,541,875 B2 (Kevin Bennion and Jason Lustbader)



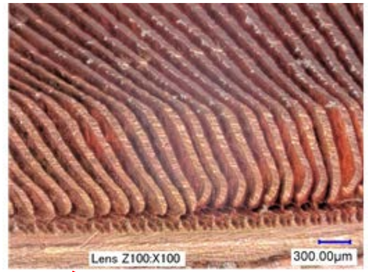


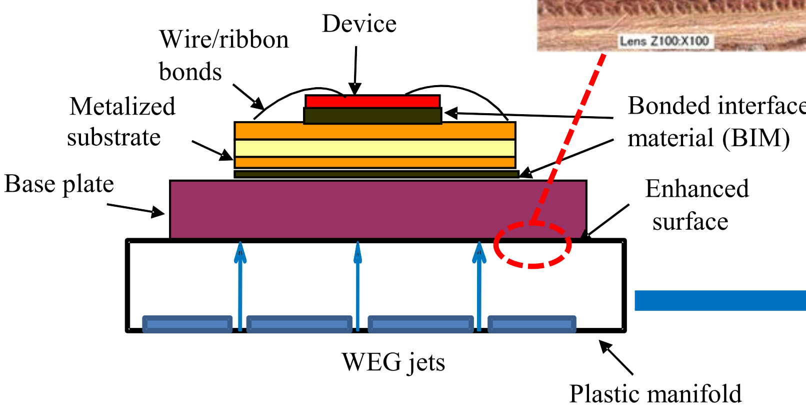


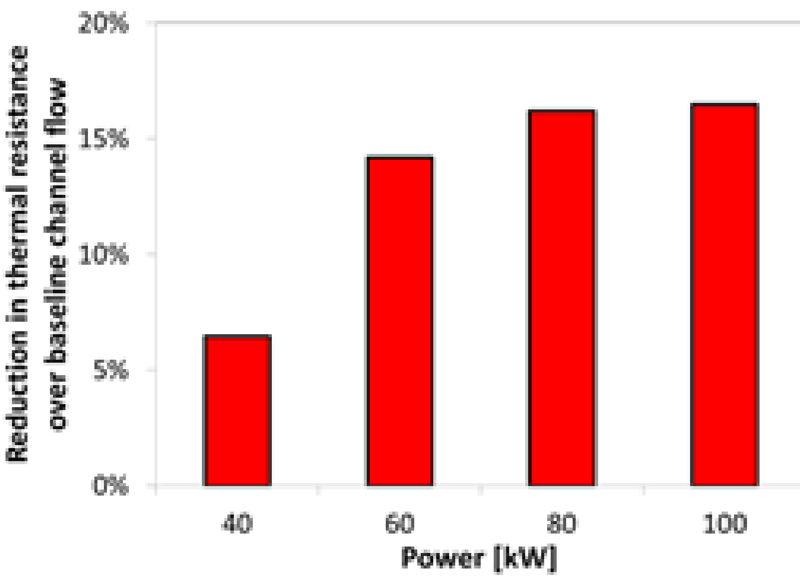


- Up to 100% increase in power per die area
- Up to factor of 8 increase in coefficient of performance

Liquid Jet-Based Plastic Heat Exchanger





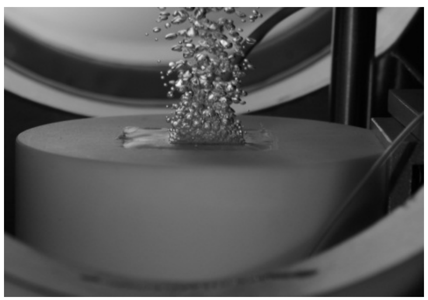


- Up to 12% increase in power density
- Up to 36% increase in specific power

Two-Phase Cooling for Power Electronics

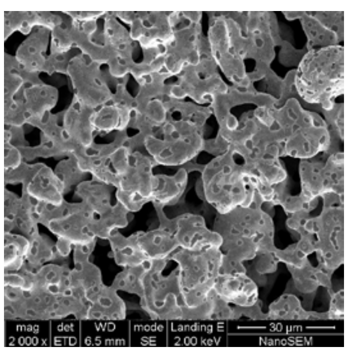
Fundamental Research	Module-Level Research	Inverter-Scale Demonstration

Fundamental Research



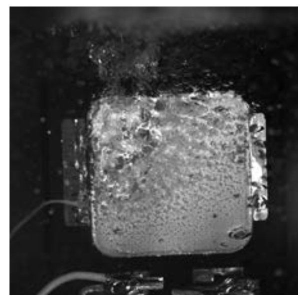
Characterized performance of HFO-1234yf and HFC-245fa.

Photo Credit: Bobby To, NREL

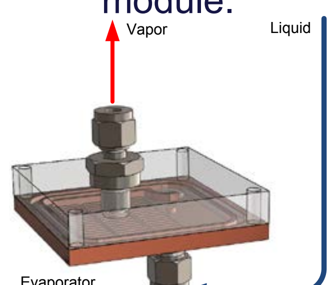


Achieved heat transfer rates of up to ~200,000 W/m^2-K.

Module-Level Research

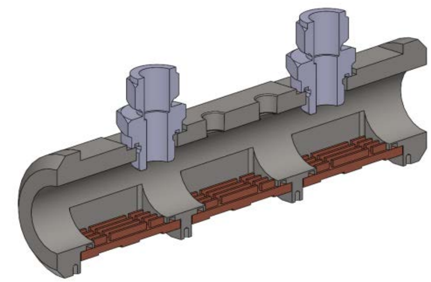


Reduced thermal resistance by over 60% using immersion two-phase cooling of a power module.

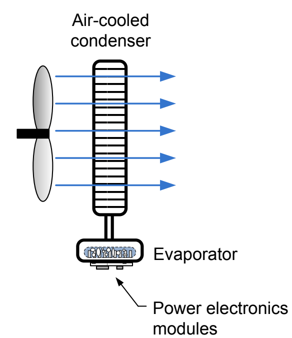


Quantified refrigerant volume requirements.

Inverter-Scale Demonstration

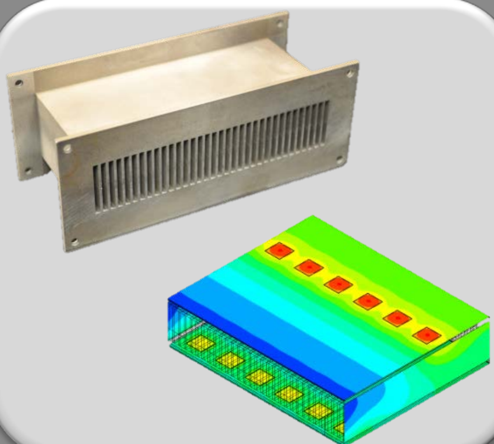


Dissipated 3.5 kW of heat with only 180 mL of refrigerant.

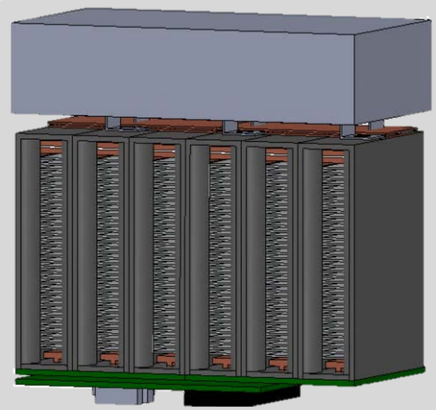


Predicted 58%-65% reduction in thermal resistance via indirect and passive two-phase cooling.

Air Cooling for High-Power Electronics



Cooling Technology



Packaging

Balance of System

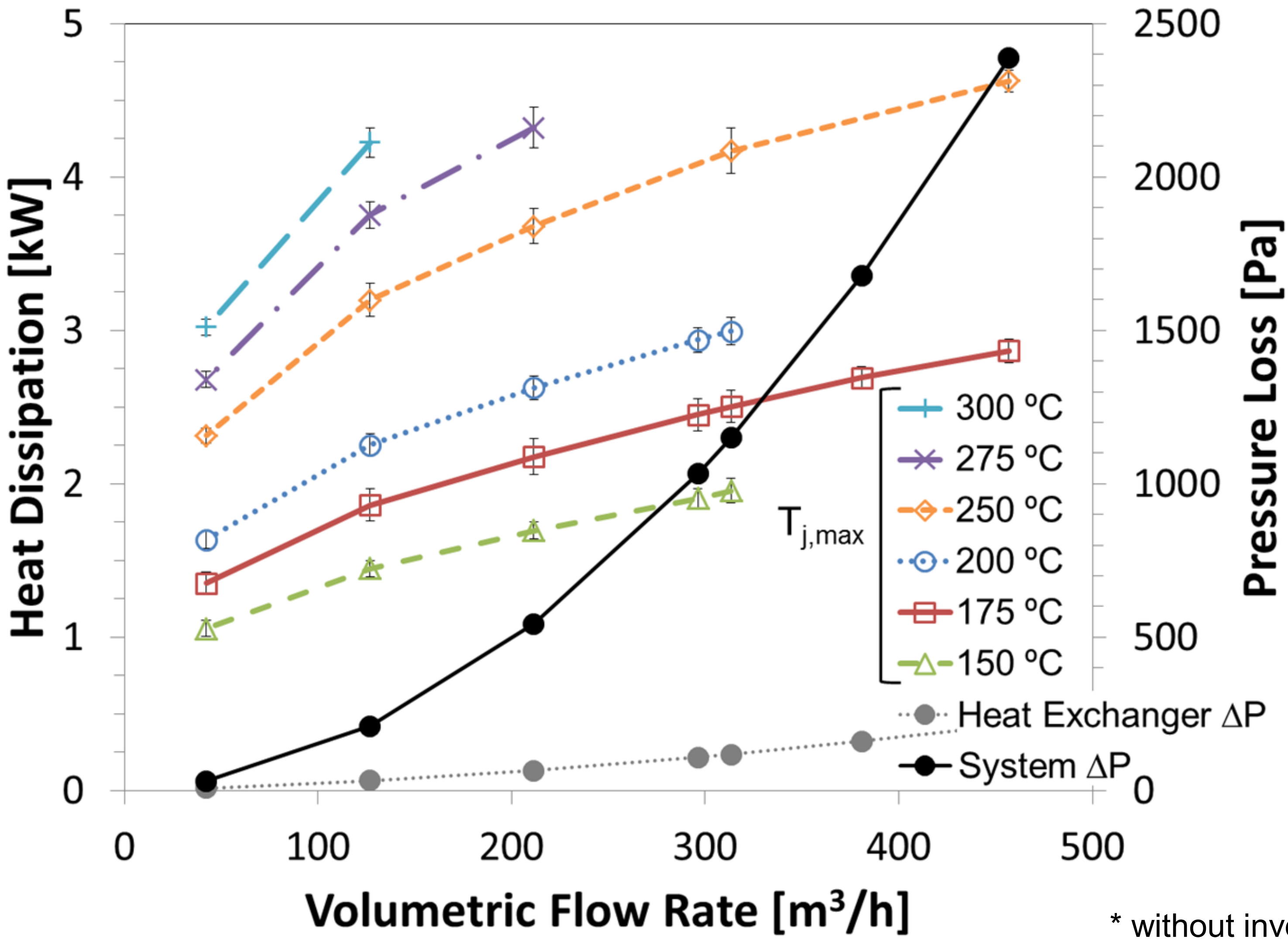
- Maximum Temperatures
- Device Efficiency

- Inverter Components
- Under-hood Location

- Parasitic Power (fan)
- Air Source (ducting)

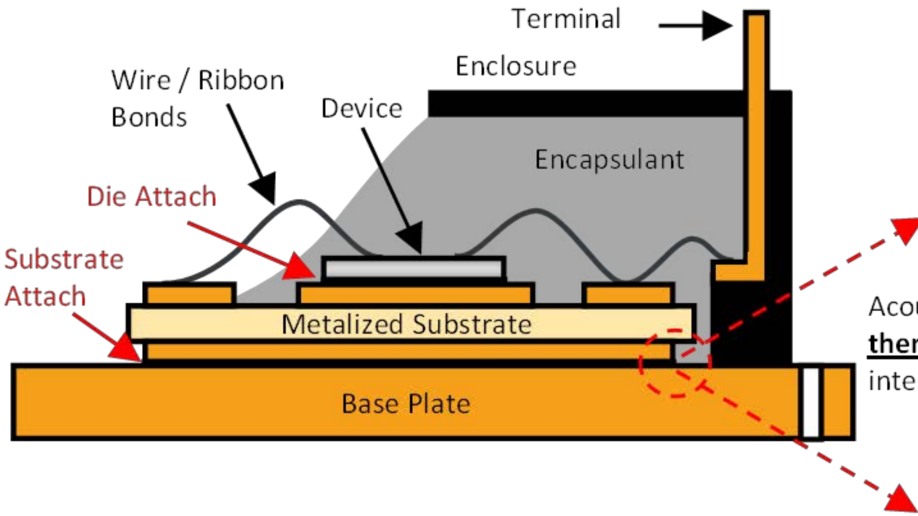
Heat Dissipation for Optimized Case
(6 modules)

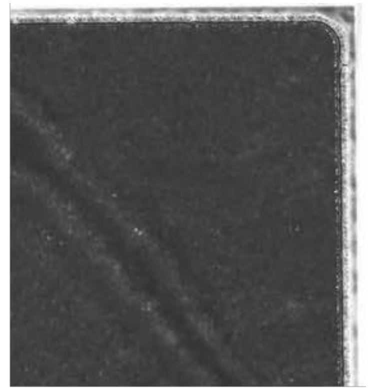
Shows the potential for air cooling



* without inverter housing

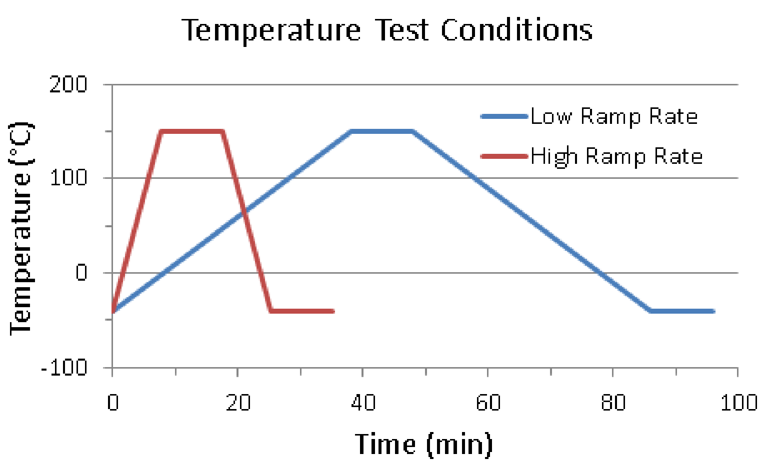
Bonded Interface Material Reliability





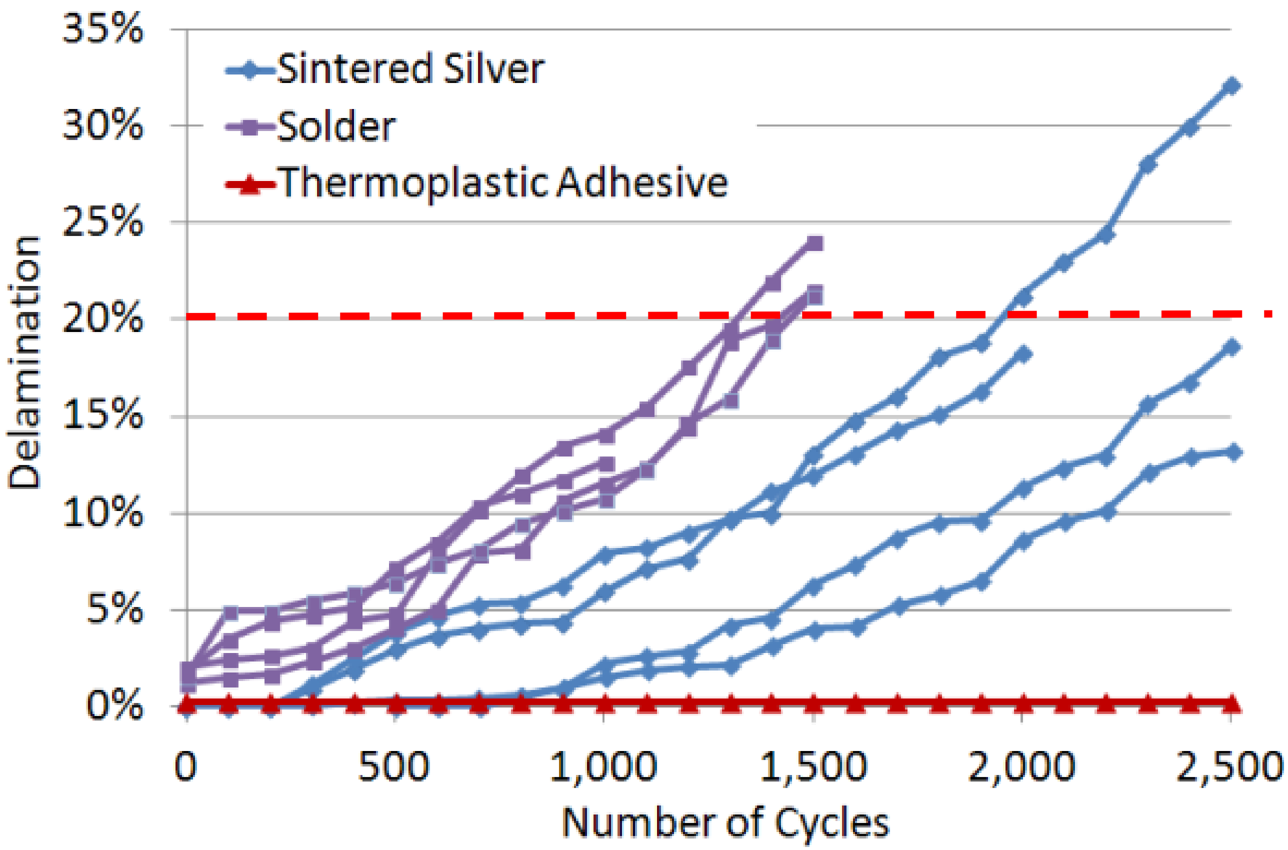
Acoustic microscope image of **thermoplastic** bonded interface with no defects

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



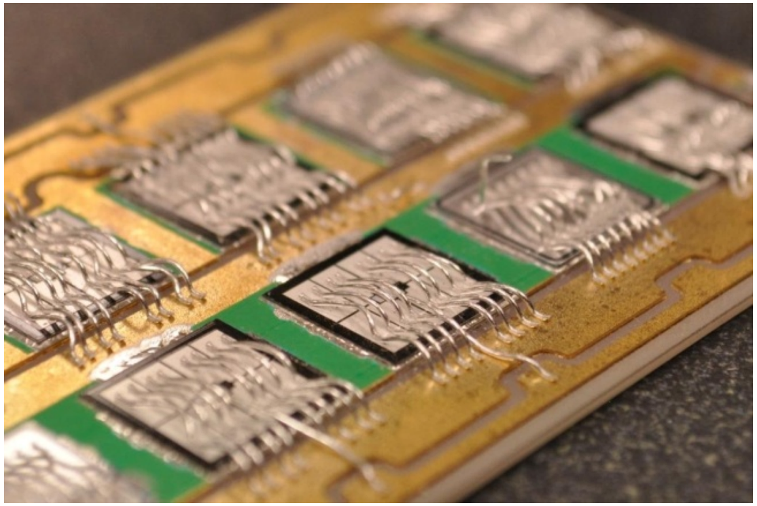
- Thermoplastics yield very good reliability.
- Reliability of sintered silver is better than solder.

Bonded Interface Material Reliability

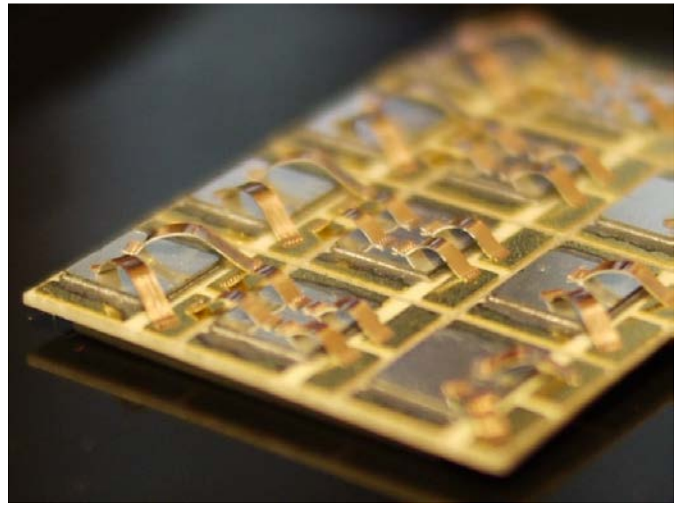


- Thermoplastics yield very good reliability.
- Reliability of sintered silver is better than solder.

Electrical Interconnects Reliability

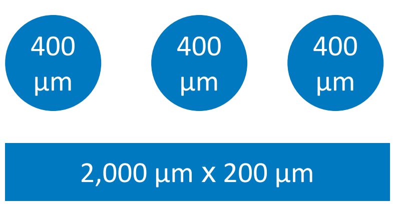


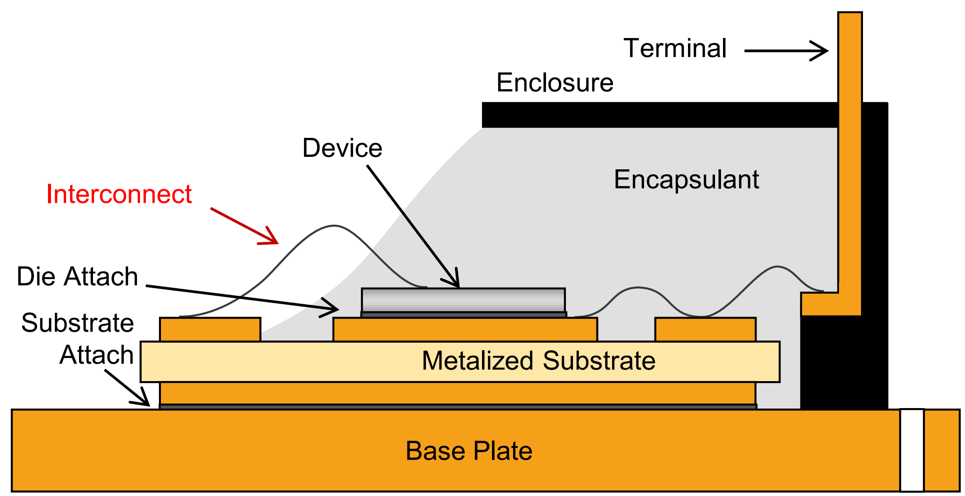
Wire Bonding



Ribbon Bonding

Three 400-µm wires can be replaced by a single 2,000-µm x 200-µm ribbon for equivalent current carrying capability

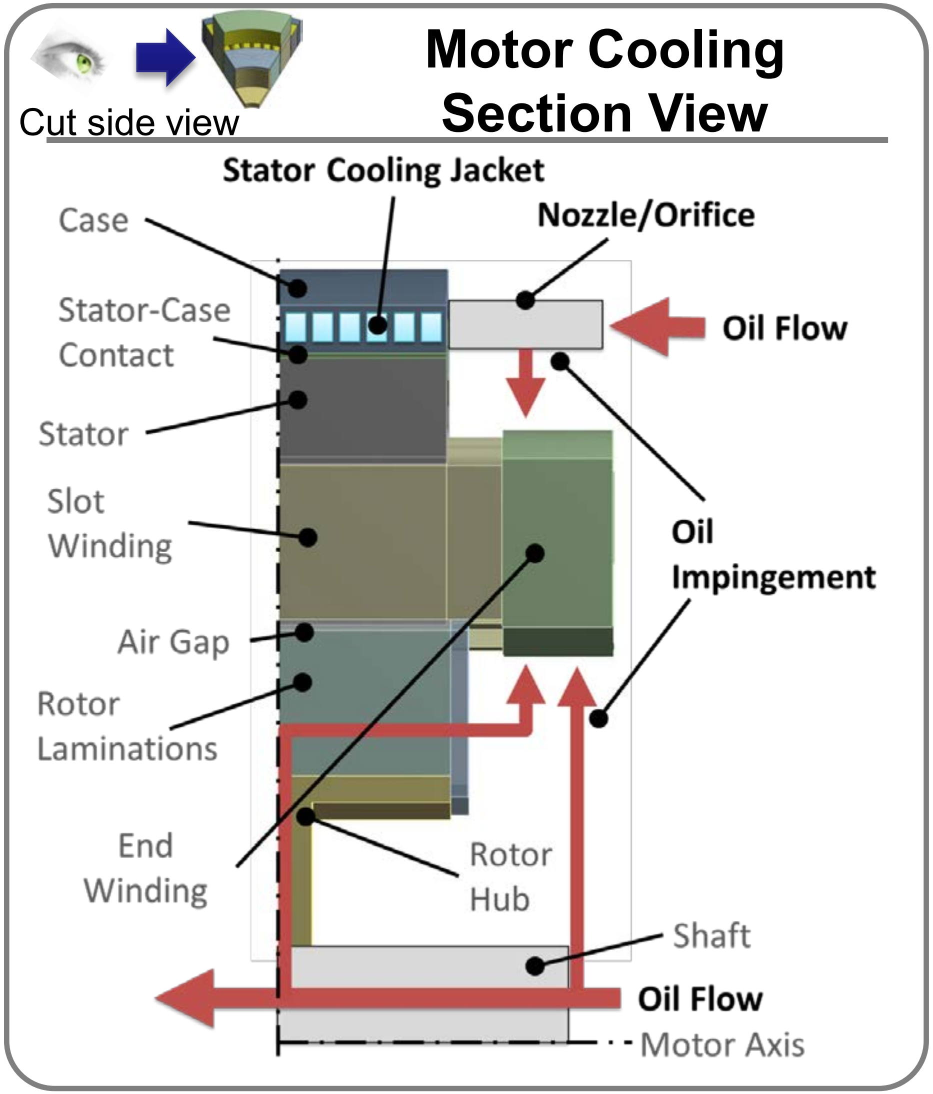




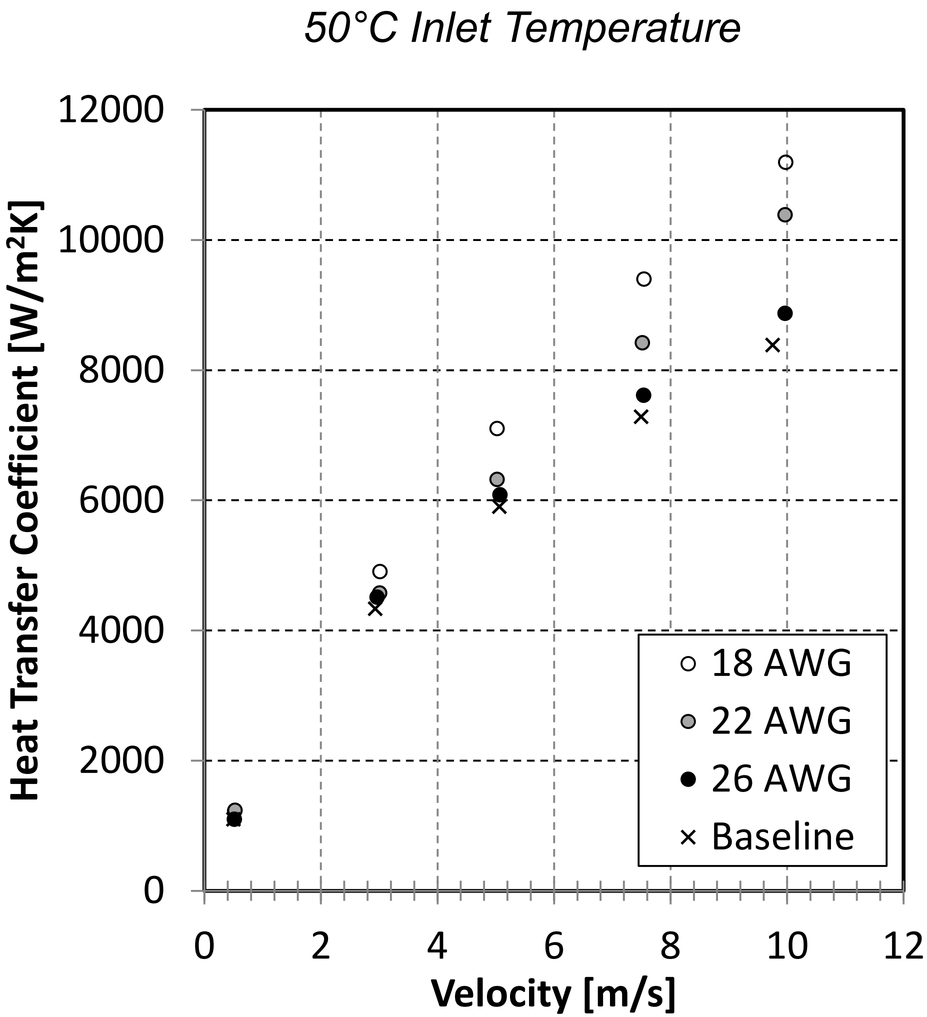
Traditional Power Electronics Package

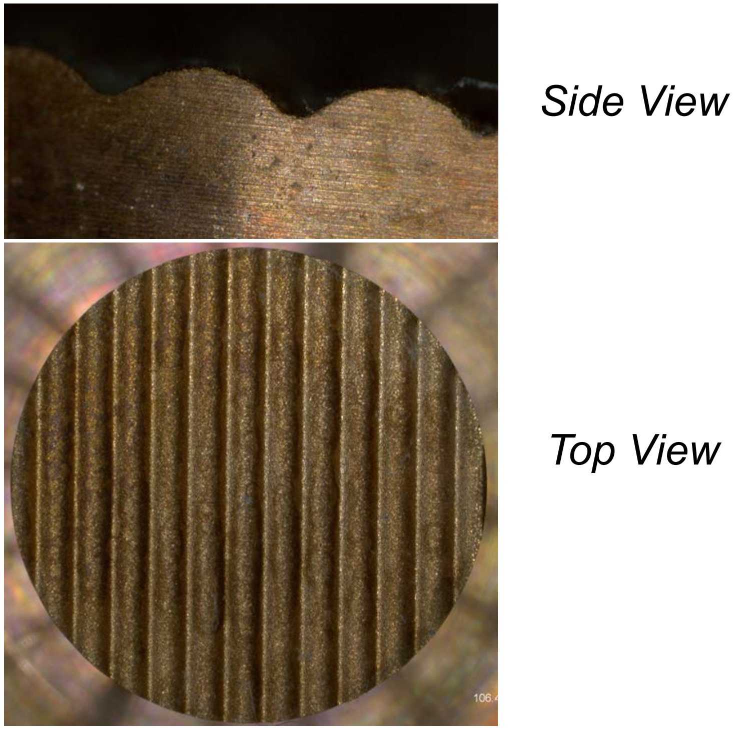
Electric Motor Thermal Management Strategy

- Advanced materials and interfaces are required
  - Lower cost (less rare earth) materials
  - Higher effective thermal conductivity
- Low-cost techniques to increase heat transfer rates are required
  - Coolants – water-ethylene glycol (WEG), air, transmission coolant, refrigerants
  - Enhanced surfaces
  - Flow configurations
  - Reduce temperature



Transmission Oil Jet Heat Transfer Characterization





18 AWG surface target

- Heat transfer coefficients on all target surfaces at 50°C inlet temperature.
- At lower impingement velocities, all samples achieve similar heat transfer.

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

Lamination Stack Effective Thermal Conductivity

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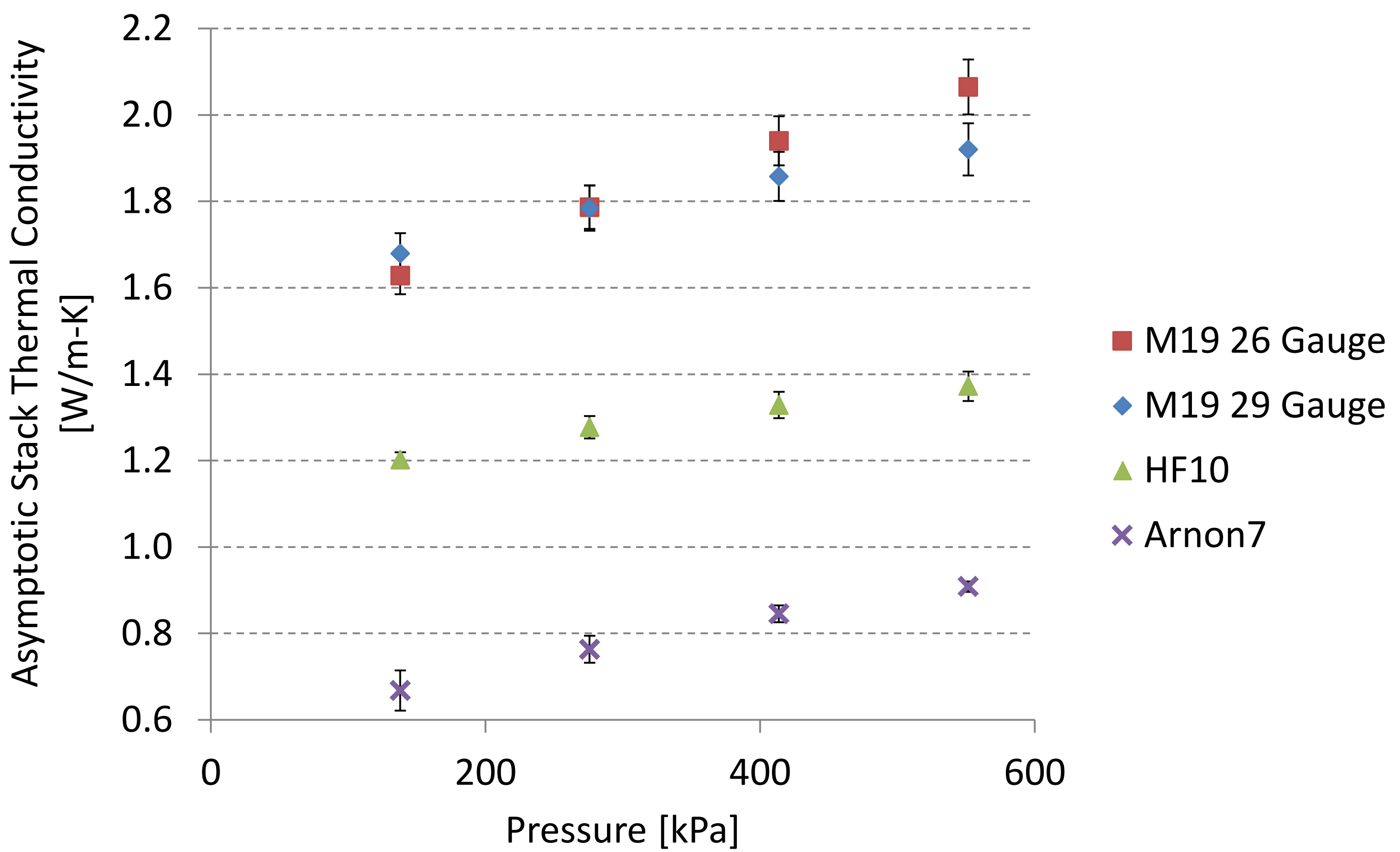
Measured Stack Thermal Resistance → Lamination-to-Lamination Thermal Contact Resistance → Effective Through-Stack Thermal Conductivity



Error bars represent 95% confidence level

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 motors.

- NREL is working closely with industry and research partners to help influence development of components which meet aggressive performance and cost targets
  - Through development and characterization of cooling technologies.
  - Passive stack materials and interfaces thermal characterization and improvements.

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

Acknowledgments:

Susan Rogers and Steven Boyd

Technology Managers

APEEM Program

Vehicle Technologies Office

U.S. Department of Energy

NREL APEEM Team

Kevin Bennion, Justin Cousineau, Doug DeVoto, Xuhui Feng, Charlie King, Gilbert Moreno, Paul Paret, Caitlin Stack, Suraj Thiagarajan, Scot Waye

Industry and Research Partners

Ford, GM, Chrysler, John Deere, Toyota, Oak Ridge National Laboratory, DARPA, Virginia Tech, University of Colorado Boulder, University of Wisconsin, 3M, NBETech, Curamik, DuPont, GE Global Research, Semikron, Kyocera, Sapa, Delphi, Btechcorp, Remy, Heraeus, Henkel, Wolverine Tube Inc., Arkansas Power Electronics International, Kulicke & Soffa, UQM Technologies Inc.

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Slide 4: EV-Everywhere Grand Challenge Document (http://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_blueprint.pdf).

Slide 5:
Left box
Top picture: Doug DeVoto, NREL
Lower picture: Gilbert Moreno, NREL

Middle box
Top picture: Doug DeVoto, NREL
Lower picture: Doug DeVoto, NREL

Right box
Top picture: Jana Jeffers, NREL

Slide 8: Sreekant Narumanchi, NREL

Slide 9: Charlie King, NREL (top photo)

Slide 10: Kevin Bennion, NREL (lower photo)

Slide 11: Doug DeVoto, NREL (photo on the right)
Gilbert Moreno, NREL (photo on the top)

Slide 12:
Left box: lower image: Bobby To, NREL
Gilbert Moreno, NREL (all other photos)

Slide 15: Doug DeVoto, NREL (acoustic microscope images)

Slide 17: Doug DeVoto, NREL (photos on the top)

Slide 19: Gilbert Moreno, NREL (both photos)