NREL Transforming ENERGY

Jet Impingement Cooling of Electric Machines with Driveline Fluids

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Advanced Power Electronics and Electric Machines Group, Center for Integrated Mobility Sciences

LES4ECE 2021 Virtual Conference

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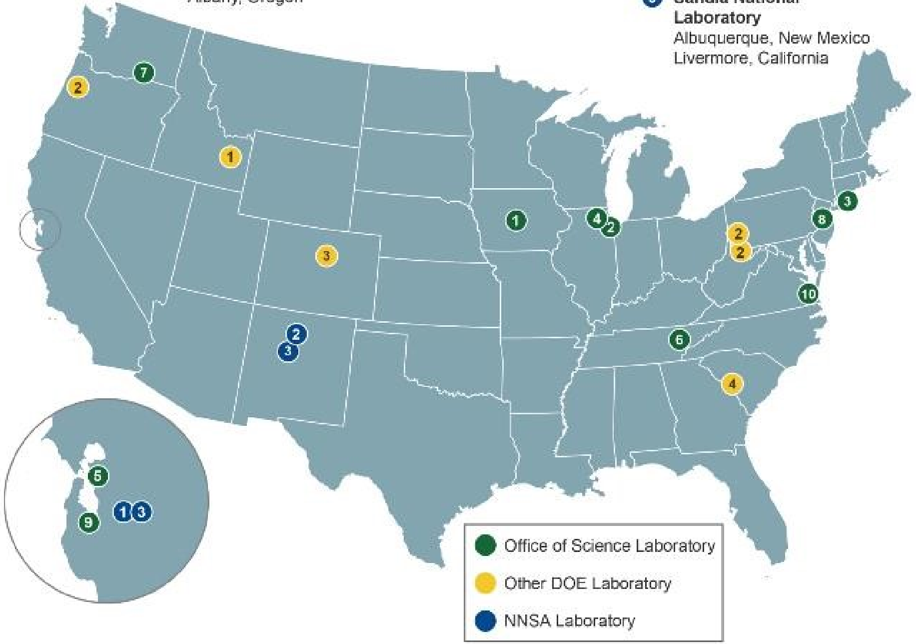


National Renewable Energy Laboratory

Leading clean energy innovation for 43 years

2,400+ employees with world-class facilities

Campus is a living model of sustainable energy

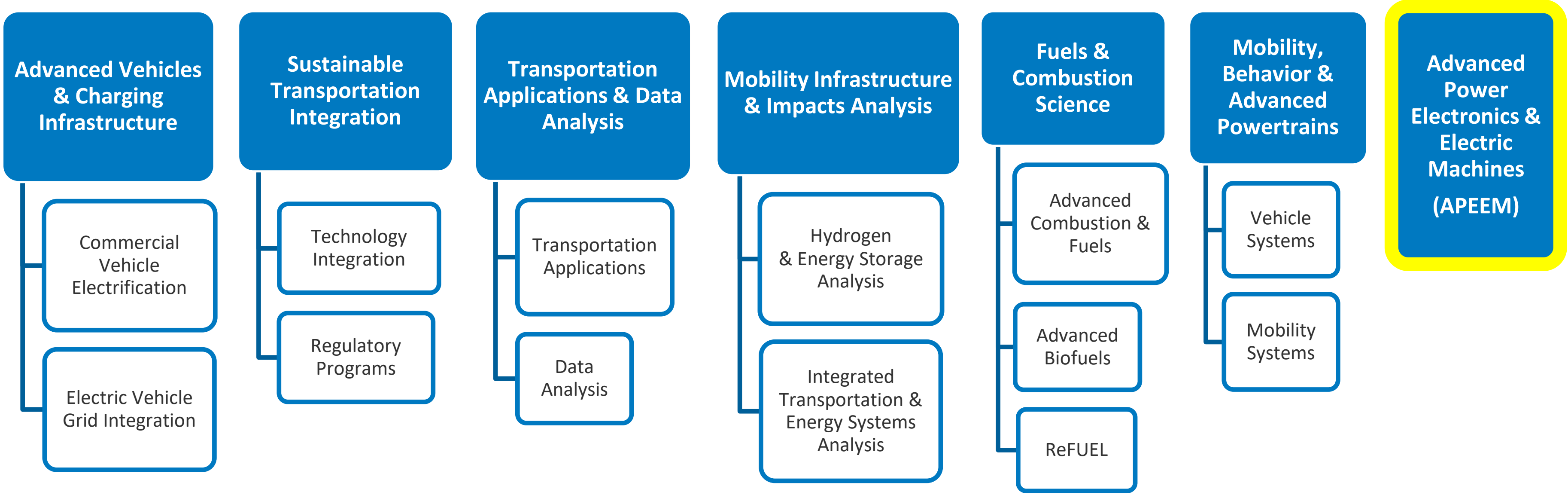
Owned by the U.S. Department of Energy (DOE)

Operated by the Alliance for Sustainable Energy[1]

[1] https://www.allianceforsustainableenergy.org/about.html

Scope of NREL Mission

Sustainable Transportation	Energy Productivity	Renewable Electricity	Systems Integration	Partnerships
Vehicle Technologies	Residential Buildings	Solar	Grid Integration of Clean Energy	Private Industry
Hydrogen	Commercial Buildings	Wind	Distributed Energy Systems	Federal Agencies
Biofuels	Manufacturing	Water: Marine Hydrokinetics	Batteries and Thermal Storage	State/Local Government
		Geothermal	Energy Analysis	International



Center for Integrated Mobility Sciences (CIMS)

APEEM Group: Eleven (11) staff members involved in thermal, electrothermal, thermomechanical, and reliability research activities.

DOE Electric Drive Technologies (EDT) Program

USDRIVE[1]
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

***U.S. DRIVE* Partners:**

- **US Automotive Industry (FCA, Ford, GM, OEMs)**
- **Electric Utility Industry**
- **Fuels Industry (BP, Chevron, Phillips 66, ExxonMobil, Shell)**

Research Laboratories

Oak Ridge National Laboratory
Lead: Power Electronics and Electric Motors

NREL Transforming ENERGY
Lead: APEEM Thermal Management/Reliability

Others: Sandia National Labs, Ames Laboratory

Industry, Automotive Suppliers, and University Interactions

1 https://www.energy.gov/eere/vehicles/us-drive

Research Pathway for Electric-Drive Vehicle Electrification

U.S. DRIVE Electrical and Electronics Technical Team (EETT) Roadmap defines the pathway to 2025 targets

Current EV Platform
(GM's 2017 Chevrolet Bolt BEV Chassis with Electric Powertrain)

Future Skateboard Platform Design Concept
(GM's Flat Skateboard Chassis Containing Electric Powertrain)

2025 Targets	
Cost	\$6/kW (50% reduction)
Power Density	33 kW/L (850% increase)
Power Level	100 kW
Reliability/Lifetime	300,000 miles (100% increase)

Volumetric power density!

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

(ARPA-E) Aviation Electric Drive Efforts

Single-aisle (narrow-body) airplanes with 100–200 passengers

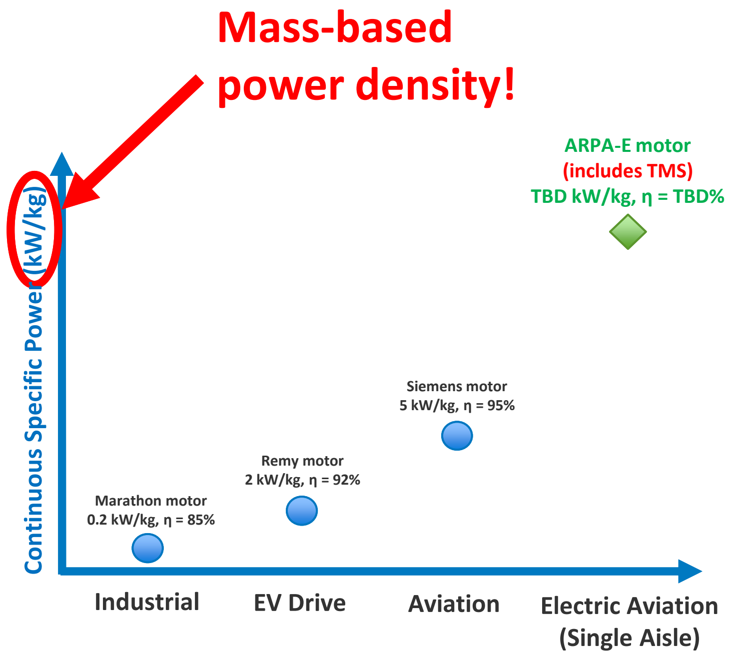
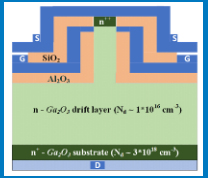


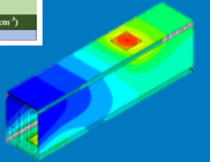
Photo credit: Dennis Schroeder, NREL

Source: Based on overview presentation by Dr. Michael Ohadi at the ARPA-E Workshop on Electrified Aviation, August 2019, Arlington, VA.

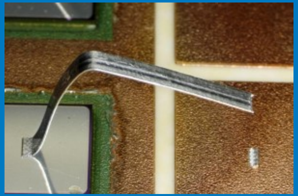
NREL APEEM Group Research Focus Areas

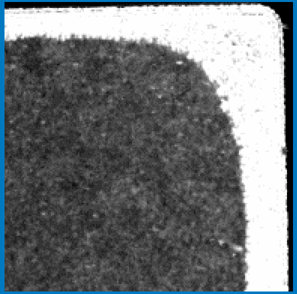
Power Electronics Thermal and Electrothermal



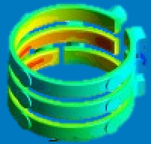


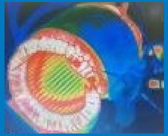
Advanced Packaging Designs and Reliability

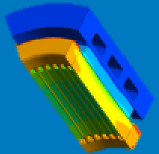




Electric Motor Thermal Management



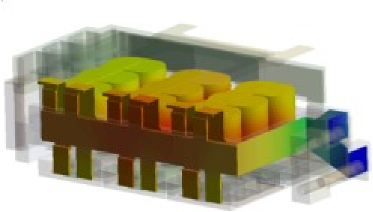




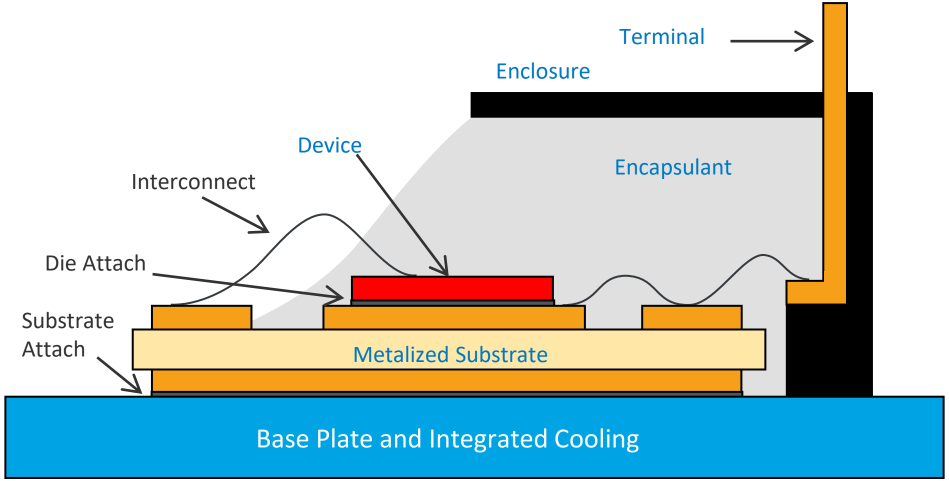
Power Electronics Thermal and Electrothermal Research

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

Advanced cooling

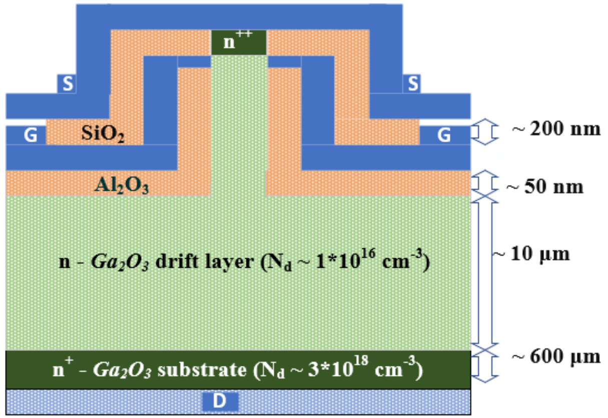


Component- and system-level heat transfer

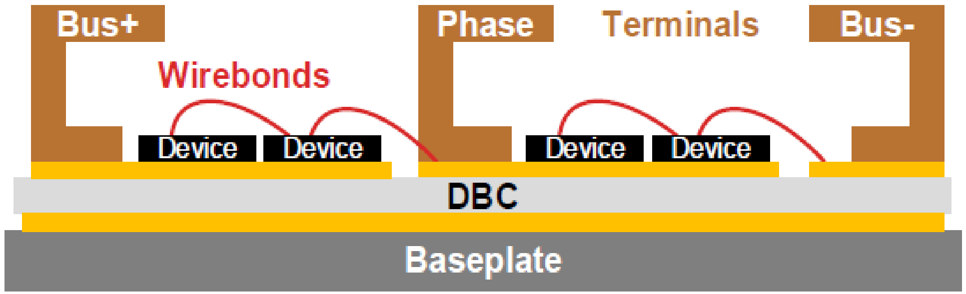


Power Electronics: Semiconductor Device and Package Research

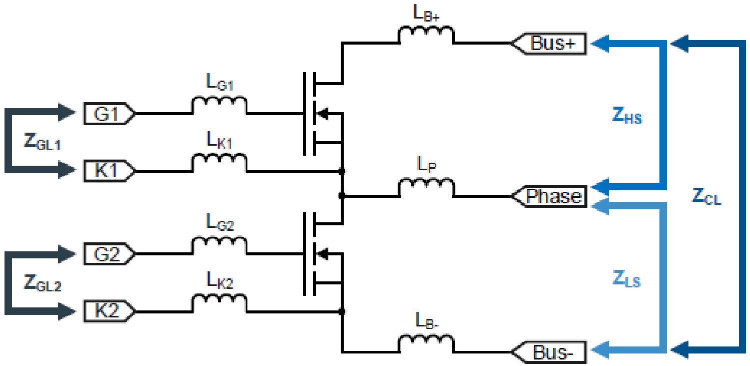
- Semiconductor modeling research for WBG and ultrawide-bandgap (UWBG) devices
- Electrical and electromagnetic



Micro- to nanoscale device modeling



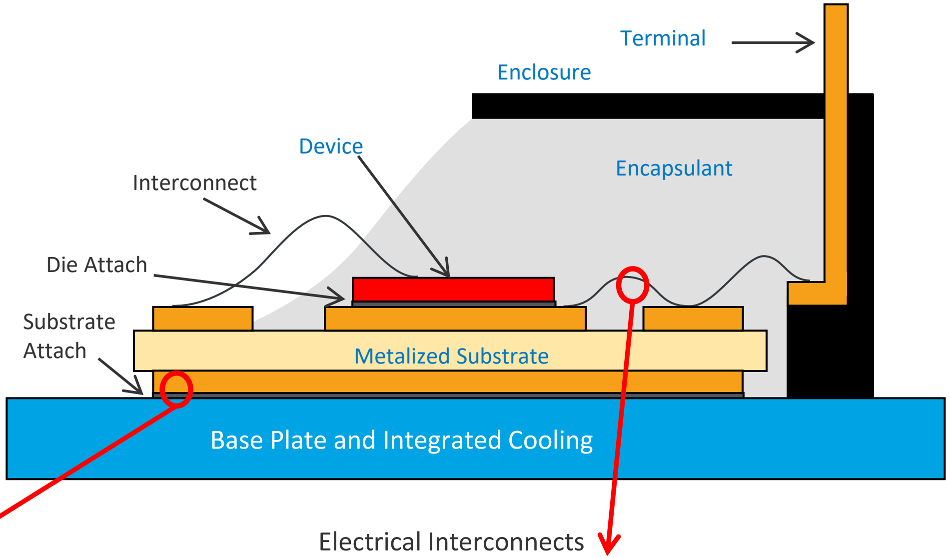
Multi-chip power module



Equivalent circuit of extracted package

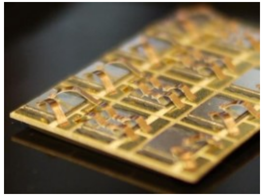
Advanced Power Electronics Packaging Performance and Reliability

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



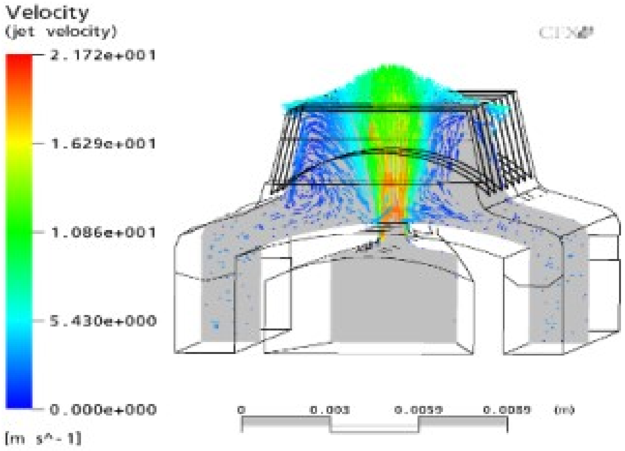
Bonded Interface

Electrical Interconnects

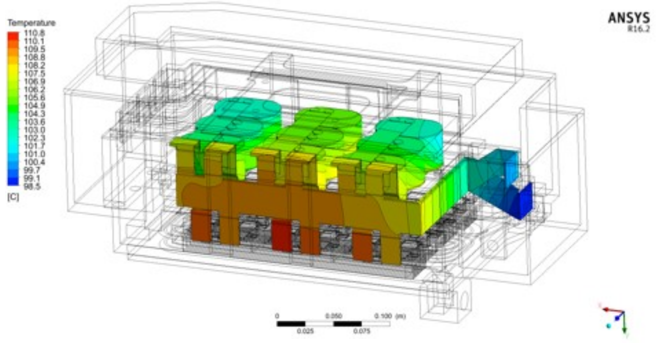


Thermal and Electrothermal Capabilities

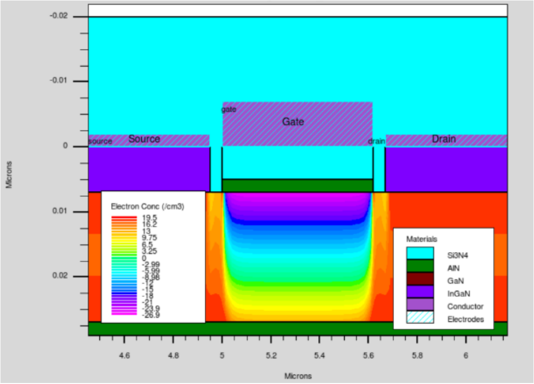
Modeling Capabilities



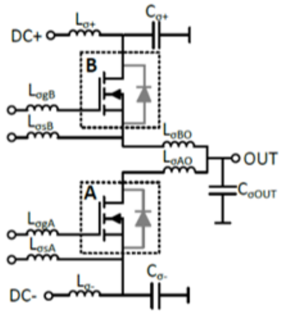
Single-Phase CFD



Thermal FEA



Power Device Electrothermal FEA



Module Parasitics Extraction and Modeling

FEA: Finite element analysis
CFD: Computational fluid dynamics

Electric Motor Thermal Management

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

Photo credit: Kevin Bennion, NREL

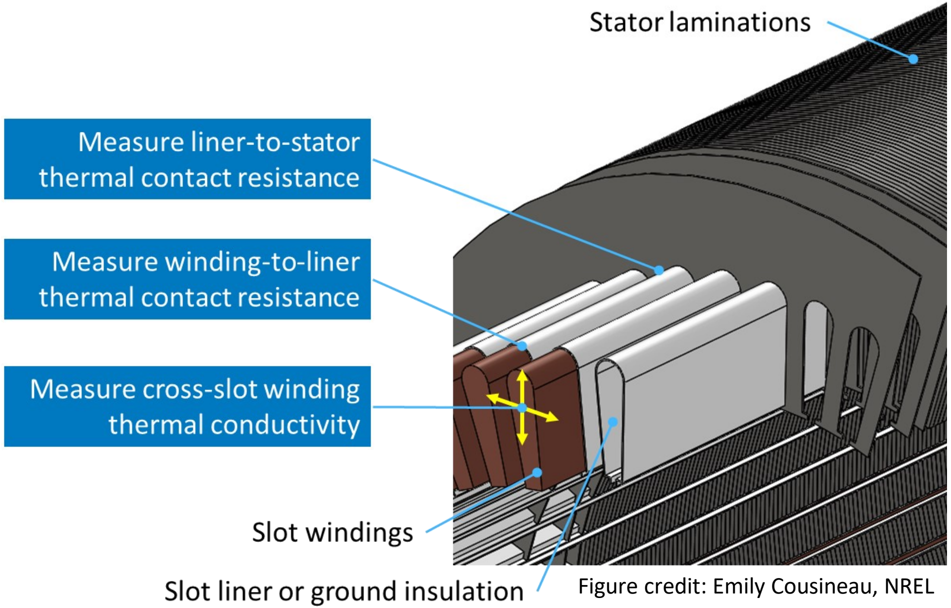
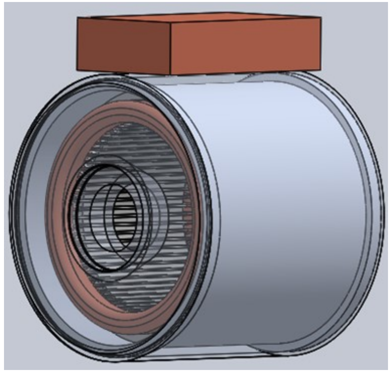


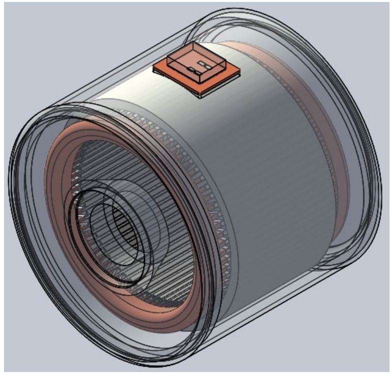
Figure credit: Emily Cousineau, NREL

Integrated Traction Drive System

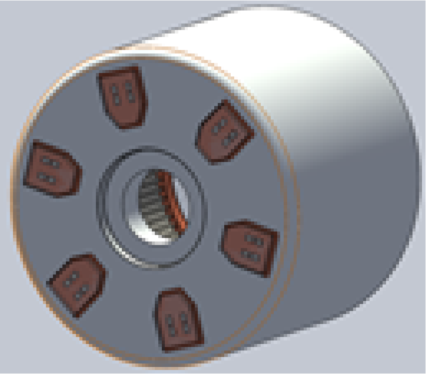
- Current industry trend: highly integrated, compact, single unit traction drive design
- Different motor integration techniques of power electronics
- Various cooling strategies for most efficient heat removal from integrated traction drive components
    - Preferably a single fluid loop approach for integrated cooling system for motor + inverter cooling



Separate Enclosures



Radial Integration



Axial Integration

Figure credits: Bidzina Kekelia, NREL

Active Cooling with Driveline Fluids

- Direct cooling with driveline fluids
  - Develop experimental methods to measure heat transfer
  - Quantify impact of new or alternative cooling approaches for automatic transmission fluid (ATF) cooling of electric machines
  - Measure convective heat transfer coefficients for ATF and other driveline fluid jet impingement cooling of end windings

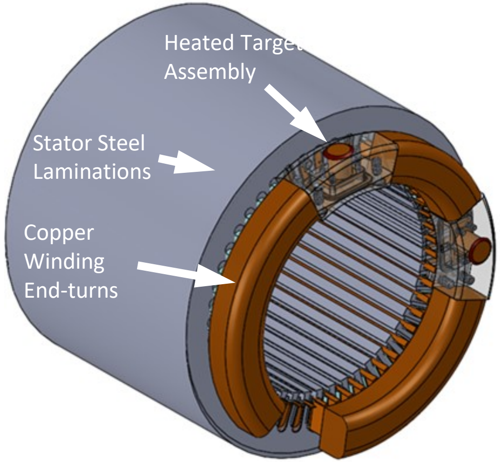
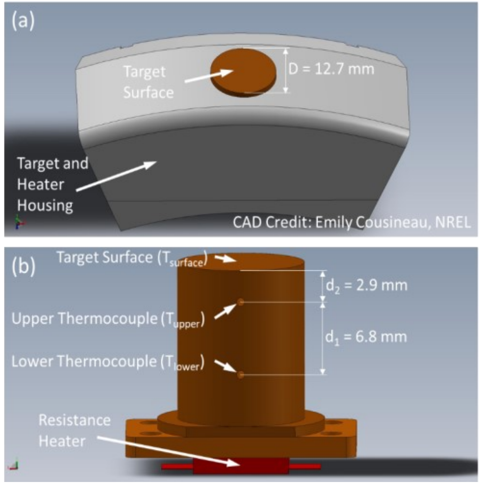


Figure credits: Emily Cousineau, NREL



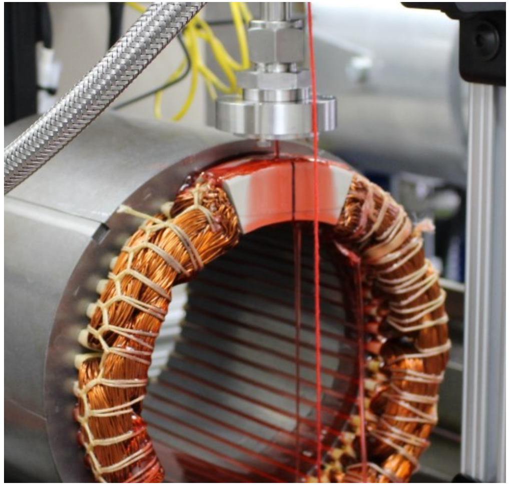


Photo credit: Bidzina Kekelia, NREL

Experimental Heat Transfer Coefficient Measurements

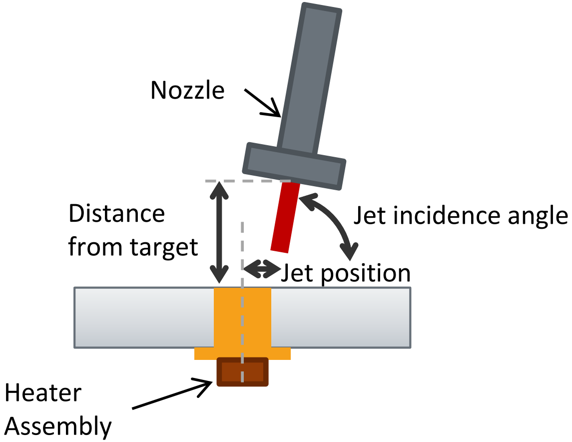


Figure credit: Kevin Bennion, NREL

$$h = \frac{Q_s}{A_s(T_s - T_f)}$$

$h = average\ heat\ transfer\ coefficient$

$Q_s = heat\ removed\ from\ target\ surface$

$A_s = area\ of\ target\ surface$

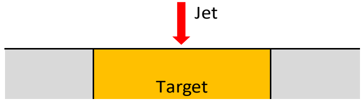
$T_s = target\ surface\ temperature$

$T_f = fluid\ or\ liquid\ temperature$

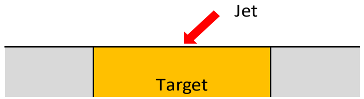
Parameter	Values
Fluid temperature (T_f)	50°C, 70°C, 90°C
Surface temperature (T_s)	90°C, 100°C, 110°C, 120°C
Jet incidence location	center, edge
Jet incidence angle	90°, (planned: 60°, 45°)
Nozzle distance from target	10 mm, (planned: 5 mm, 15 mm)

Orifice Jet Impingement Positions

Center



a) Impinging at 90° on target center



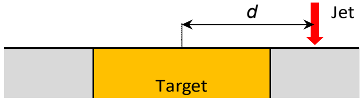
d) Impinging at 45° on target center

Edge

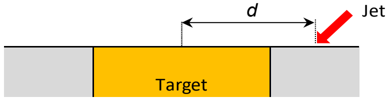
b) Impinging at 90° on target edge

e) Impinging at 45° on target edge

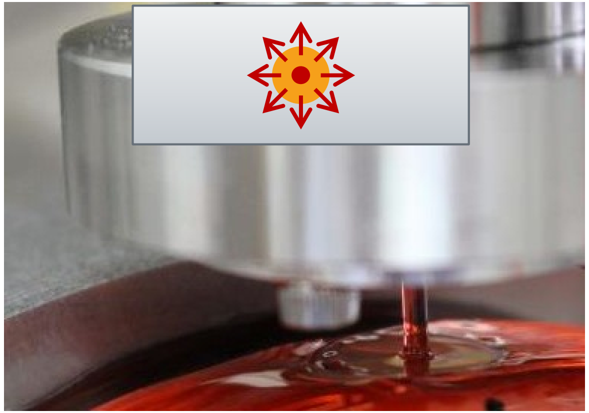
Away from edge



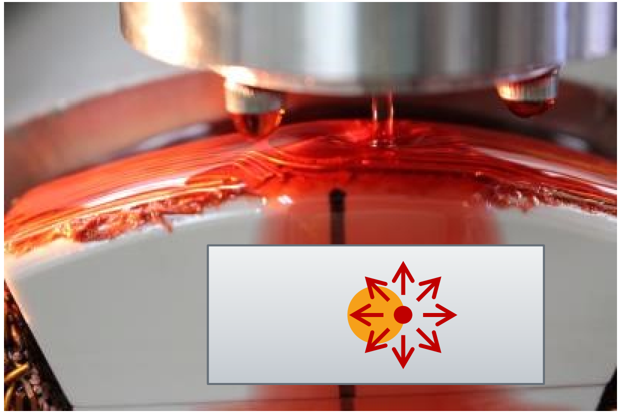
c) Impinging at 90° off target edge



f) Impinging at 45° off target edge



Orifice jet center impingement

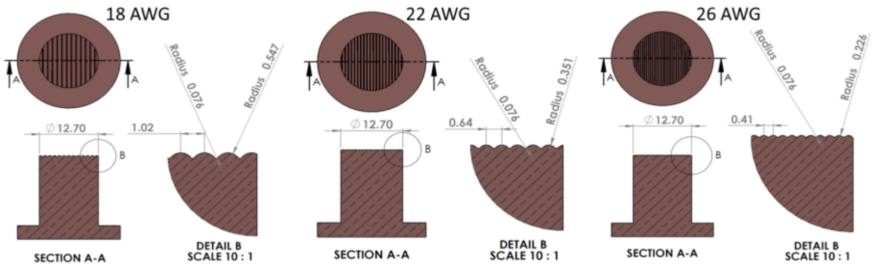


Orifice jet edge impingement

Figure and photo credits: Bidzina Kekelia, NREL

Orifice Jet Impingement Cooling with ATF

- Experimental measurements with Ford MERCON® LV ATF
- Target surface **topography enhancement** impact on heat transfer [1]
- Target surface **temperature** impact on heat transfer [2]:



  - Increasing target surface temperature increases heat transfer coefficient (HTC): $\boldsymbol{T_s}\uparrow \Rightarrow \boldsymbol{h}\uparrow$
  - Increasing surface temperature from 90°C to 120°C enhanced HTC values by **15%**
  - Likely due to increased fluid film temperature near heated surface
    - Reduced viscosity (strongly temperature-dependent for ATF)
    - Thinner viscous boundary layer (increased fluid flow above target surface)
    - Thinner thermal boundary layer with higher temperature gradients $\left(\frac{\partial T}{\partial y}\right)$ enhancing heat transfer (higher HTC)

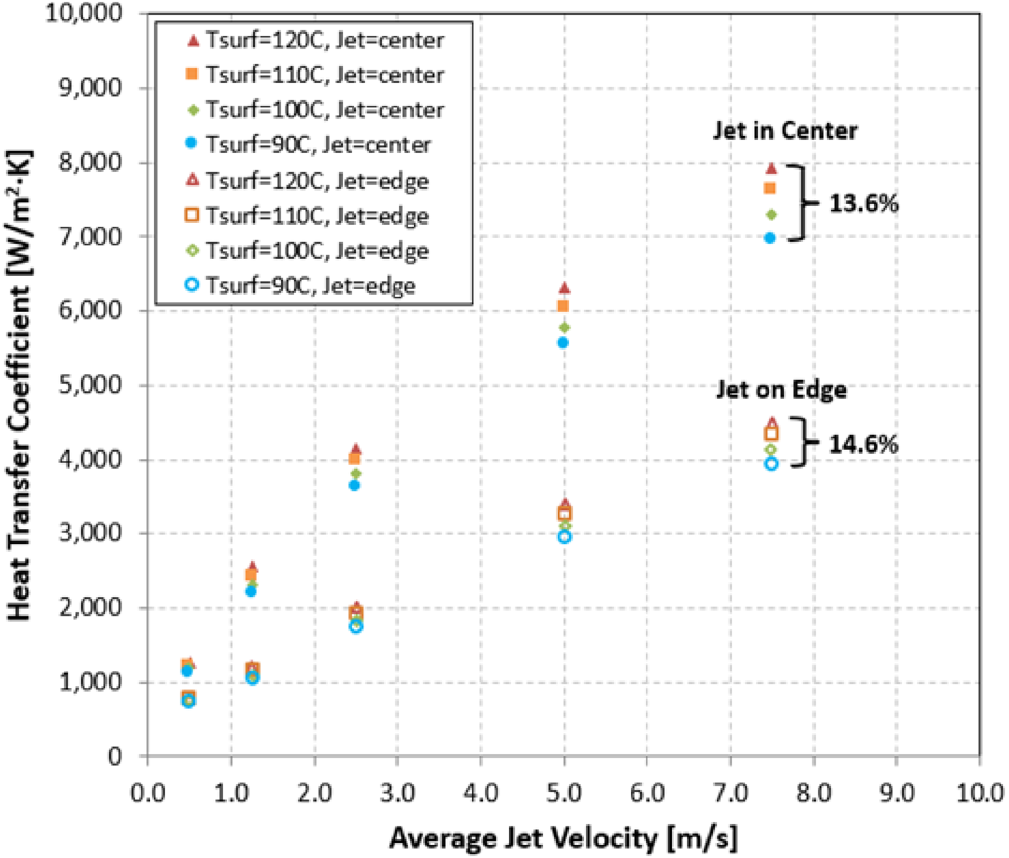
[1] Bennion, K., and Moreno, G., 2015. "Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management," ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, San Francisco, CA, United States.
[2] Kekelia, B., Bennion, K., Feng, X., Moreno, G., Cousineau, J.E., Narumanchi, S., and Tomerlin, J., 2019. "Surface Temperature Effect on Convective Heat Transfer Coefficients for Jet Impingement Cooling of Electric Machines With Automatic Transmission Fluid." Proceedings of the ASME 2019 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. Anaheim, California, USA. October 7–9, 2019. https://doi.org/10.1115/IPACK2019-6457.

Heat Transfer Coefficients for ATF at $T_f = 50°C$

- Temperature (T) of the cooled surface affects HTC values:

$$T_s\uparrow \Rightarrow h\uparrow$$

- Target surface temperature increase from 90°C to 120°C yielded 13%–15% increase in HTC values

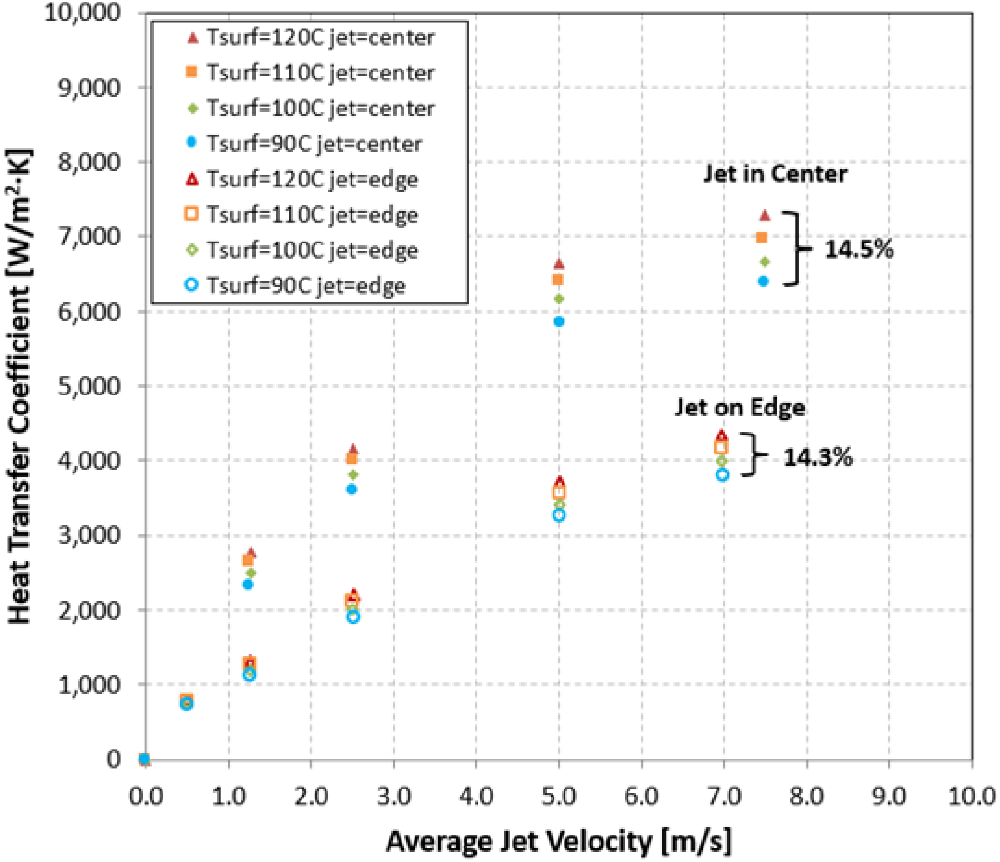


Heat Transfer Coefficients for ATF at $T_f = 70°C$

- Temperature (T) of the cooled surface affects HTC values:

$$T_s\uparrow \Rightarrow h\uparrow$$

- Target surface temperature increase from 90°C to 120°C yielded 14%–15% increase in HTC values



Summary

- Active cooling is critical for today's (and especially future) power-dense electric vehicle traction drives
- Direct driveline fluid jet impingement cooling is one of the most effective (single fluid) thermal management solutions
- Experimental HTC measurements – data useful for design and modeling of electric machines for electric traction drive vehicles
  - Target surface **topography enhancement** impact on heat transfer
  - Target surface **temperature** impact on heat transfer (ATF)

$$T_s\uparrow \Rightarrow h\uparrow$$

- Current experimental measurements with Ford MERCON® LV ATF, but characterization of other driveline fluids is planned.

Acknowledgments

Susan Rogers, U.S. Department of Energy

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Thank You

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NREL/PR-5400-80261

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NREL Transforming ENERGY

Additional Slides

More Information

How To Work with NREL

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

- Shared Resources Collaboration (DOE EDT Projects)

- Cooperative Research and Development Agreements (CRADAs)
  - Shared Resources
  - Funds-In

- Strategic Partnership Projects
  - Interagency Agreement
  - Funds-In Agreement
  - Technical Services Agreement

- Teaming on Proposals in Response to Solicitations

Experimental Heat Transfer Coefficient Measurements - Equations

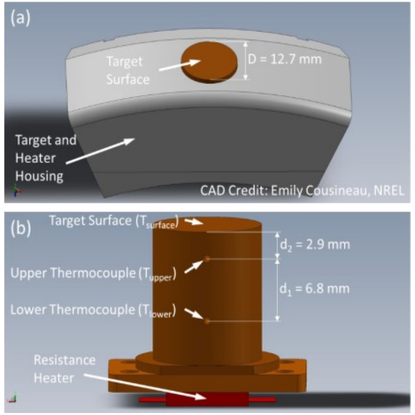

Figure credits: Emily Cousineau, Bidzina Kekelia, NREL

$$\bar{h} = \frac{Q_{surf}}{A_{surf}(T_{surf} - T_{fluid})}$$

$\bar{h}$ = *average heat transfer coefficient*

Q_{surf} = *heat removed from target surface*

A_{surf} = *area of target surface*

T_{surf} = *target surface temperature*

T_{fluid} = *fluid or liquid temperature*

k = *thermal conductivity*

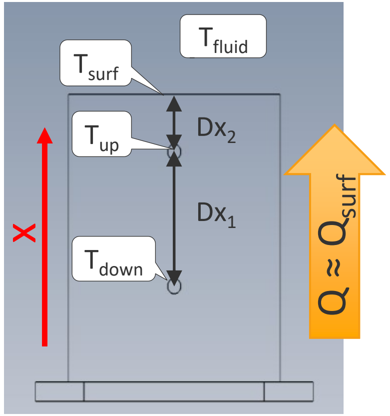

Figure credit: Bidzina Kekelia, NREL

- Sides of the target are insulated and negligible losses to the sides (but not to the bottom) are assumed

➢ Heat flow Q in x-direction (from bottom to top), <u>neglecting heat losses to the sides</u>: $-kA_{surf}\frac{T_{up} - T_{down}}{D_{x1}} = -kA_{surf}\frac{T_{surf} - T_{up}}{D_{x2}} = \bar{h}A_{surf}(T_{surf} - T_{fluid})$

➢ Expressing $\bar{h}$ from above equations: $\bar{h} = k\frac{T_{down} - T_{up}}{D_{x1}(T_{surf} - T_{fluid})}$

➢ Expressing T_{surf} from above equations: $T_{surf} = T_{up} + \frac{D_{x2}(T_{up} - T_{down})}{D_{x1}}$

➢ **Final equation for heat transfer coefficient calculation (after substituting T_{surf}):**

$$\boldsymbol{\bar{h} = k\frac{T_{down} - T_{up}}{D_{x1}(T_{up} - T_{fluid}) - D_{x2}(T_{down} - T_{up})}}$$