Electric Motor Thermal Management

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DOE Vehicle Technologies Office
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID: ELT075

NREL/PR-5400-71208

Overview

Timeline

- Project start date: FY2017
- Project end date: FY2019
- Percent complete: 50%

Budget

- Total project funding
  - DOE share: $1,100K
- Funding for FY 2017: $600K
- Funding for FY 2018: $500K

Barriers

- Cost, Power Density, Life

Partners

- Motor Industry – R&D Input and Application of Research Results
  - Suppliers, end users, and researchers
- Oak Ridge National Laboratory (ORNL)
  - Motor Research Lead
- Ames Laboratory
  - Magnet Materials Lead
- National Renewable Energy Laboratory (NREL)
  - Thermal and Reliability Lead

Relevance

- Research enabling compact, reliable, and efficient electric machines
  - Motor 10x power density increase (2025 versus 2015 targets) [1]
  - Motor 2x increase in lifetime [1]
  - Motor 53% cost reduction (2025 versus 2015 targets) [1]

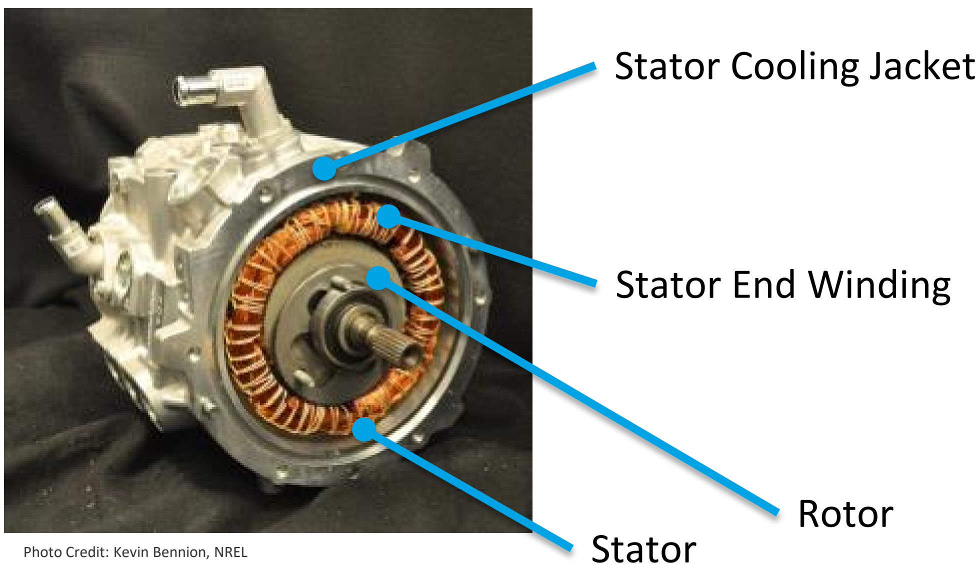
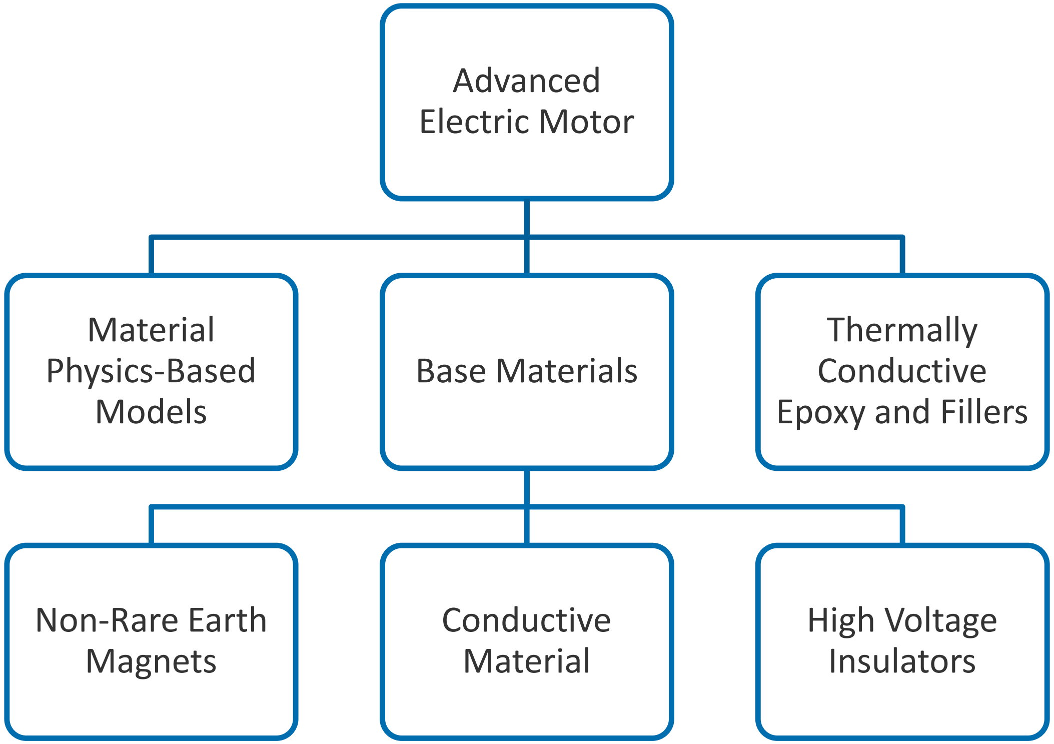


Photo Credit: Kevin Bennion, NREL

[1] U.S. DRIVE Electrical and Electronics Technical Team Roadmap, 2017.

Relevance



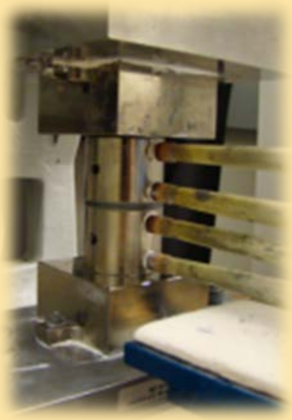
Electric Drive Motor R&D Areas [1]

- Material conductivity thermally drives the amount of material necessary to create the required magnetic field to create mechanical power [1]
- Material performance characterization techniques are not well known or identified in the literature [1]
- It is important to reduce the thermal resistance of the motor packaging stack-up to help increase the power density [1]

[1] U.S. DRIVE Electrical and Electronics Technical Team Roadmap, 2017.

Relevance

- Increased accuracy of key parameters with less data can enable fewer design iterations and reduce time and cost

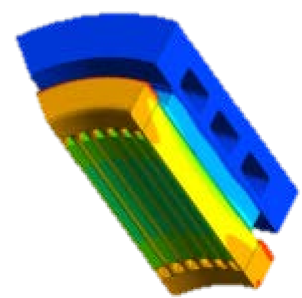


a

b

c

Key Parameter Characterization Data and Models



Component Design

d

Hardware Build

Design Iterations

Photo Credits:
a,b: Emily Cousineau, NREL
c: Jana Jeffers, NREL
d: Kevin Bennion, NREL

Milestones

Date	Description
December 2017 (Complete)	Milestone • Measure in-situ convective cooling resistance to quantify impacts of reducing thermal stack-up resistance through material, interface, and cooling improvements.
March 2018 (Complete)	Milestone • Research motor thermal management technologies and improved heat transfer designs with input from industry and ORNL for non rare-earth and reduced rare-earth motors.
June 2018 (In Progress)	Go/No-Go • Select heat transfer technologies for improved active convective and passive cooling research.
September 2018 (In Progress)	Milestone • Prepare report on research results.

Overall Approach

- Research emphasis on heat transfer of new materials and active cooling interactions

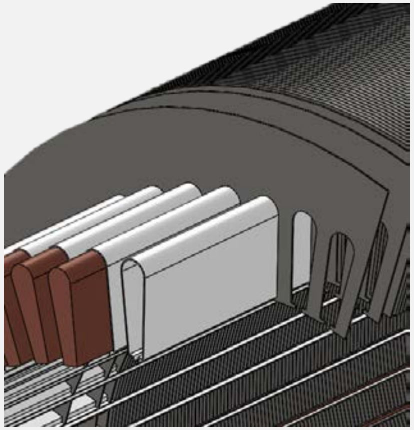
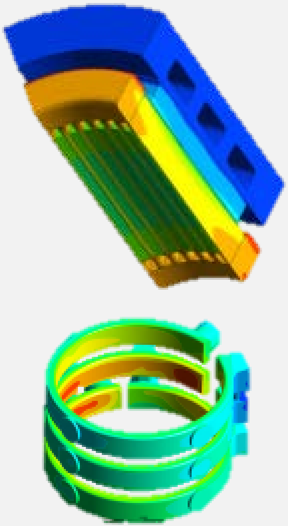
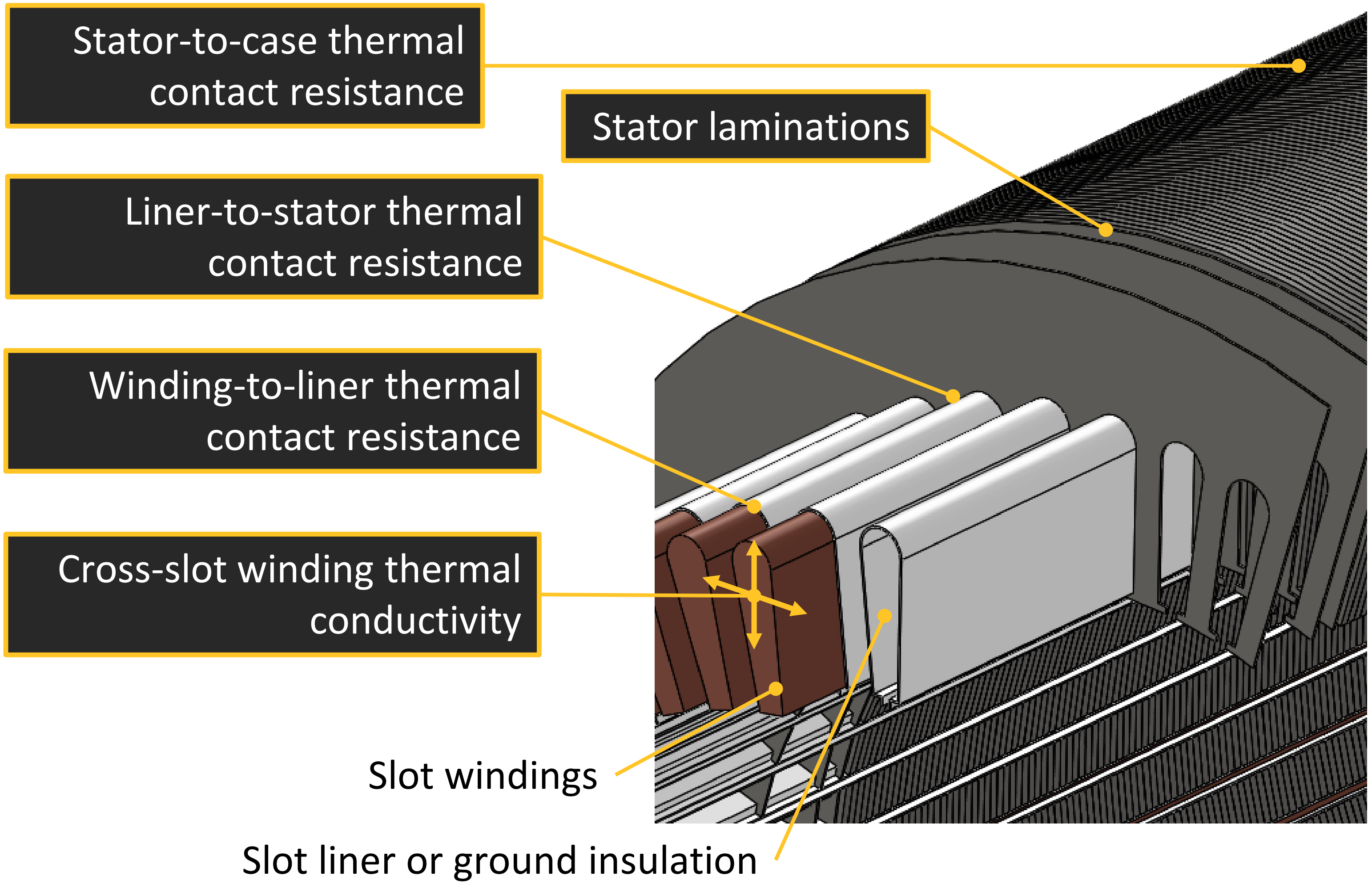
Material and Interface Thermal Characterization	Motor System Impacts of Active Cooling
  a	  b

Photo Credits:
a: Doug DeVoto, NREL
b: Kevin Bennion, NREL

Approach: Material Thermal Characterization

- Material and interface thermal resistance impact heat transfer



Technical Accomplishments and Progress

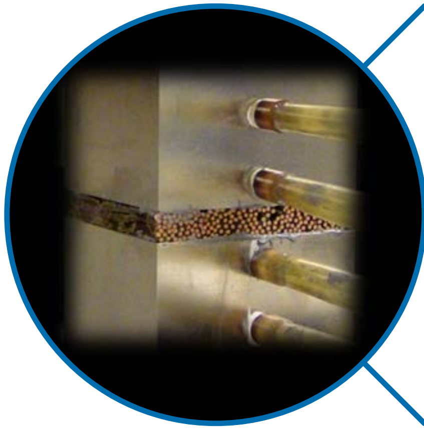


Photo Credit: Emily Cousineau, NREL

Windings

- Cross-slot winding thermal conductivity measurement methods
- Collaboration with ORNL
- Journal publication [1]

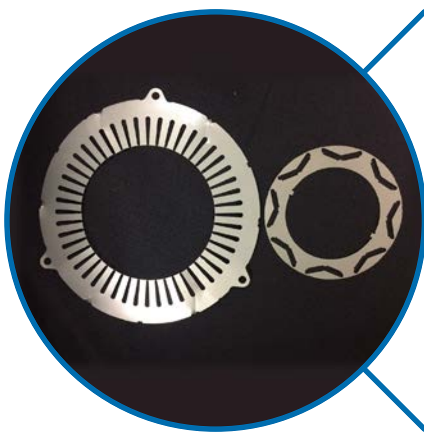


Photo Credit: Kevin Bennion, NREL

Laminations

- Lamination thermal contact resistance measurements and through-stack lamination thermal conductivity measurements
- NREL technical report [2]
- Journal publication describing thermal modeling results in progress

[1] A. A. Wereszczak *et al.*, "Anisotropic Thermal Response of Packed Copper Wire," *J. Thermal Sci. Eng. Appl*, vol. 9, no. 4, pp. 041006, Apr. 2017 (9 pages).

[2] E. Cousineau et al., *Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines.* NREL Technical Report NREL/TP-5400-63887, June 2015.

Technical Accomplishments and Progress

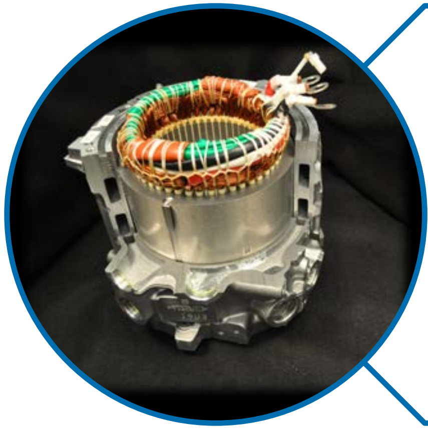


Photo Credit: Kevin Bennion, NREL

Stator-to-Case Thermal Contact Resistance

- Demonstrated measurement methods
- Developed and validated model with experimental data
- Publication in press [1]

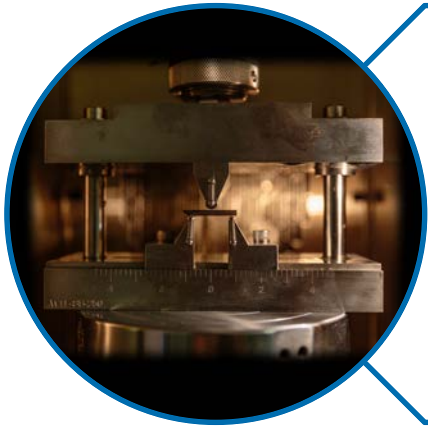


Photo Credit: Doug DeVoto, NREL

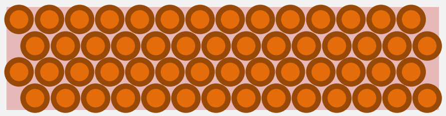
Magnet Materials

- Measured thermal properties and mechanical properties of magnets
- Collaboration with Ames

[1] J. E. Cousineau, et al., "Experimental Characterization and Modeling of Thermal Contact Resistance of Electric Machine Stator-to-Cooling Jacket Interface Under Interference Fit Loading," *J. Thermal Sci. Eng. Appl.*, Accepted for publication.

Technical Accomplishments

Winding

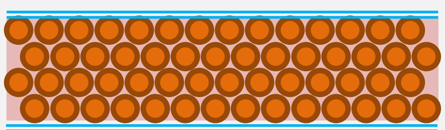


Wire size, type, insulation, Impregnation material

Slot Liner/Ground Insulation

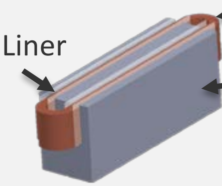
Materials for Wide-Bandgap (WBG) inverters

Slot Winding Bonded to Slot Liner



Slot liner to winding interface

Motorette



Slot liner to stator interface, System validation

Photo Credit: Doug DeVoto, NREL

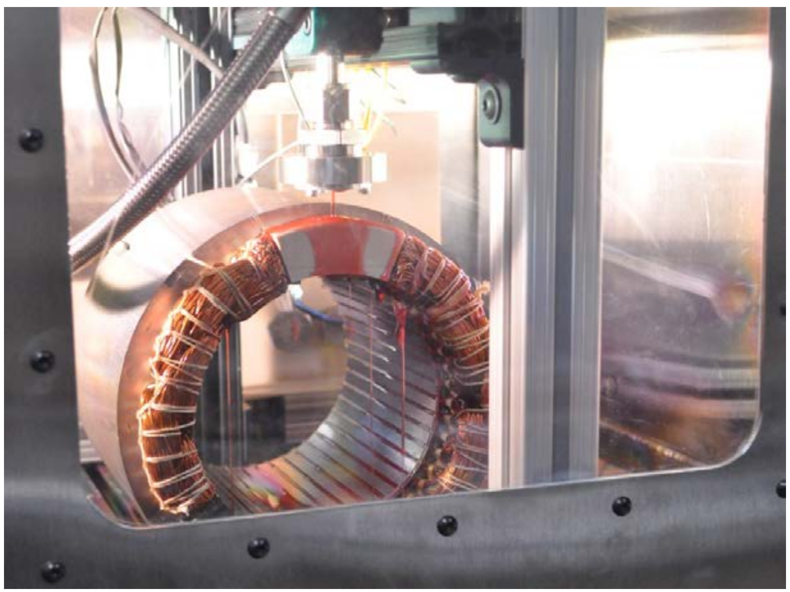
Thermal Measurements and Reliability

Temperature Cycles

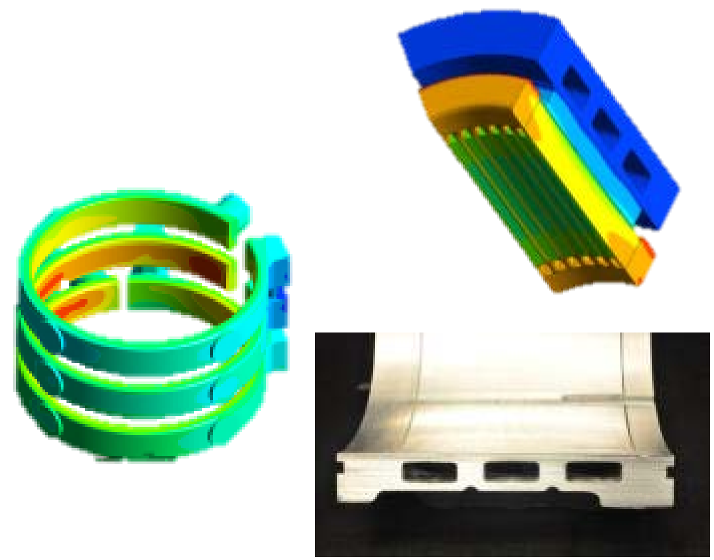
Vibration Cycles

Approach: Active Cooling Impacts

- Active cooling technologies influence the impact of new motor materials



Direct Cooling of Motor Windings



Indirect Cooling of Motor through Case

Photo Credits:
Kevin Bennion, NREL

Technical Accomplishments and Progress

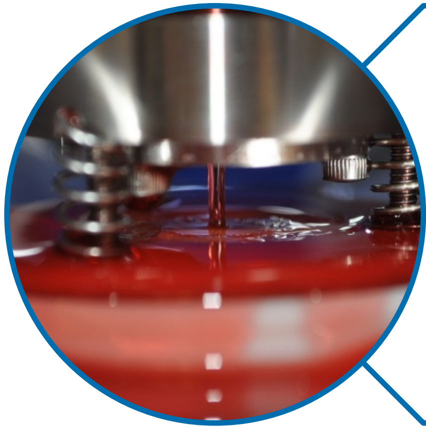


Photo Credit: Jana Jeffers, NREL

Orifice jet impingement

- Impingement on fixed target surfaces
- Quantify impact of wire gauge, velocity, and fluid temperature [1]

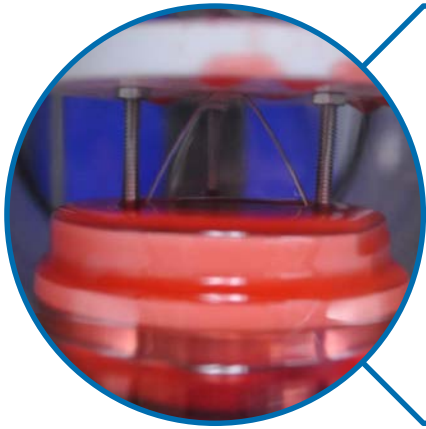


Photo Credit: Xuhui Feng, NREL

Fan jet impingement

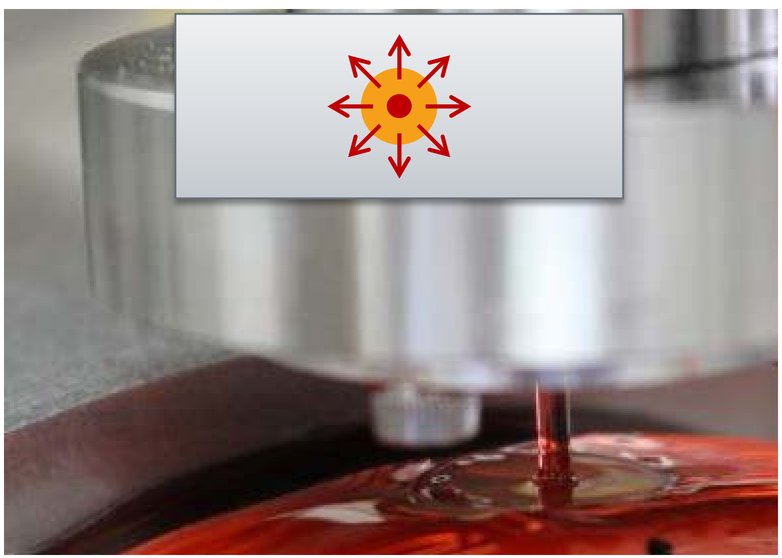
- Quantified heat transfer over equivalent target surface area
- Not all of the fluid impinges on measured target surface

[1] K. Bennion and G. Moreno, "Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management," in ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems and ASME 2015 12th International Conference on Nanochannels, Microchannels, and Minichannels, San Francisco, CA, United States, 2015.

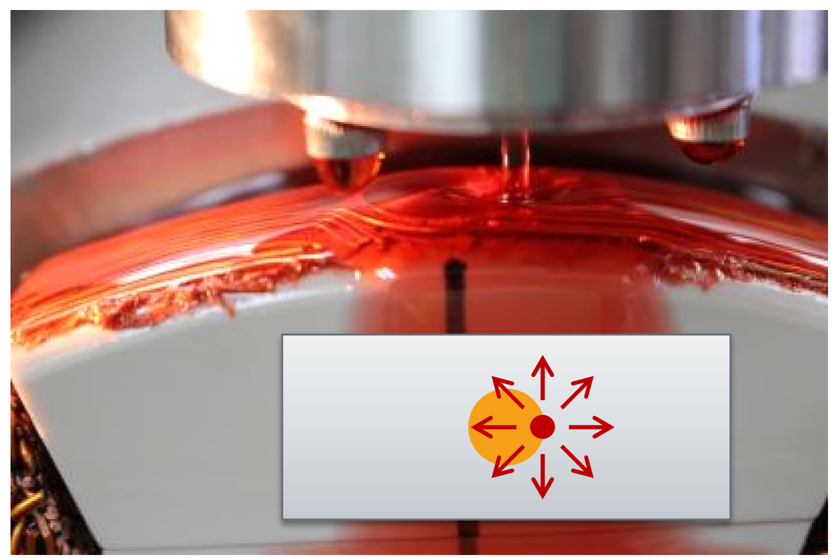
Technical Accomplishments and Progress

- Direct Automatic Transmission Fluid (ATF) Cooling
  - Developing experimental methods to measure heat transfer
  - Quantifying impact of new or alternative cooling approaches for ATF cooling of motors to take advantage of new motor materials

Photo Credit: Kevin Bennion, NREL



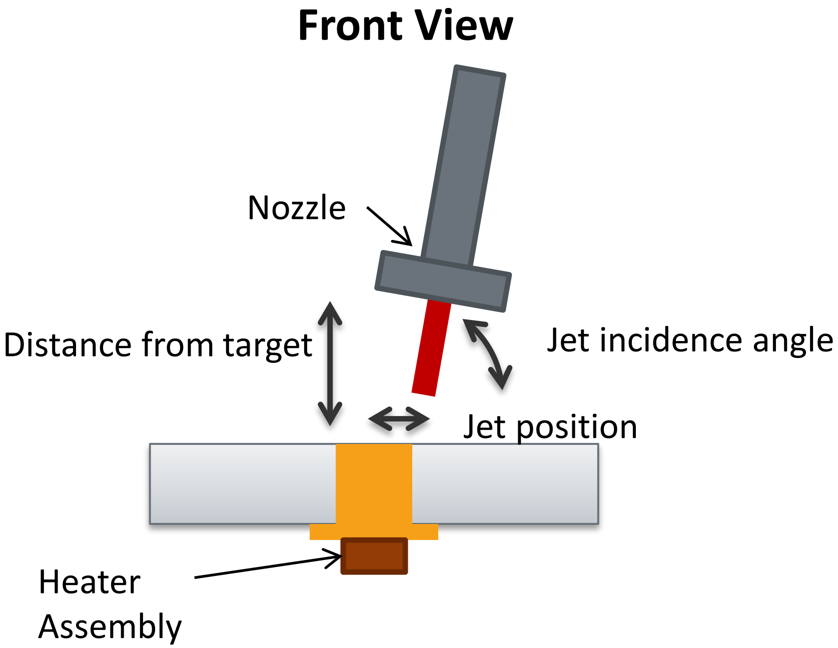
Orifice Jet Center Impingement



Orifice Jet Edge Impingement

Photo Credits: Bidzina Kekelia, NREL

Technical Accomplishments and Progress



$$h = \frac{q_s}{A_s(T_s - T_l)}$$

$h = heat\ transfer\ coefficient$

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

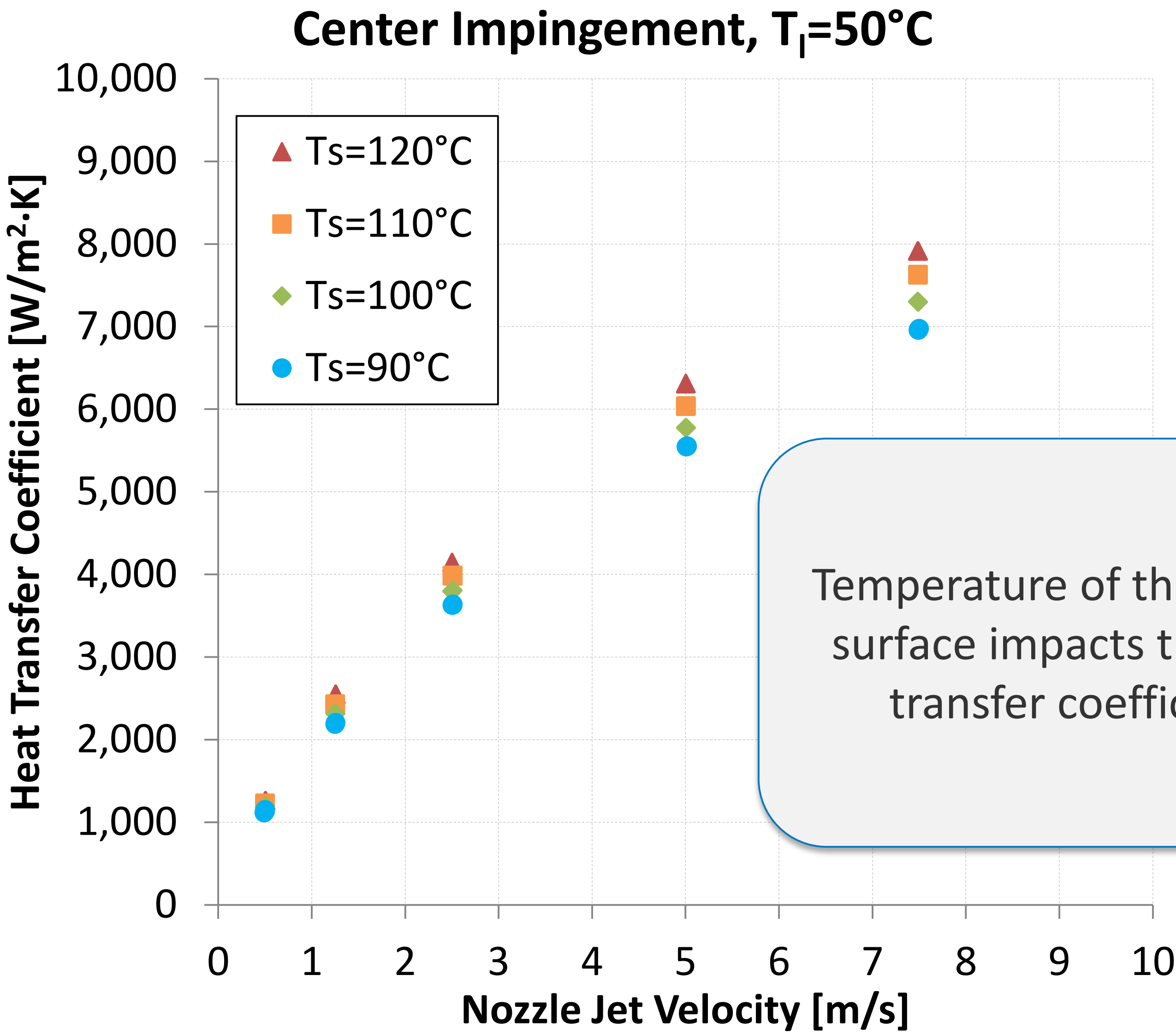
$A_s = Area\ of\ target\ surface$

$T_s = Target\ surface\ temperature$

$T_l = Fluid\ or\ liquid\ temperature$

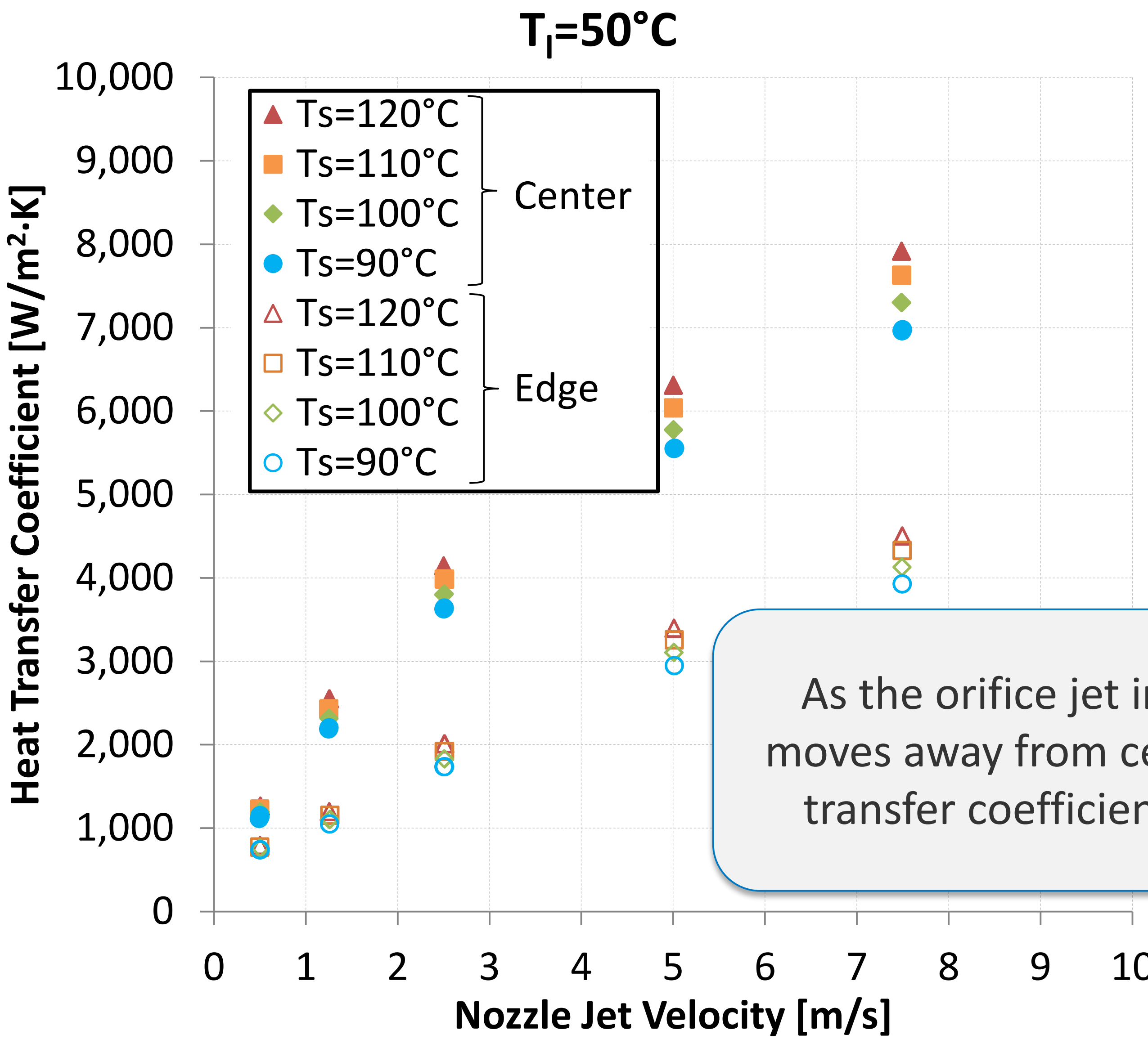
Experimental Factor	Values
Jet incidence angle [degrees]	90, 60, 45
Jet distance from target [mm]	5, 10, 15
Jet position on target [mm]	0 (center), 6.3, 11.4
Fluid inlet temperature [°C]	50, 70, 90
Surface temperature [°C]	90, 100, 110, 120

Technical Accomplishments and Progress



Temperature of the cooled surface impacts the heat transfer coefficient

Technical Accomplishments and Progress



As the orifice jet impingement moves away from center, the heat transfer coefficient decreases.

Responses to Previous Year Reviewers' Comments

- Multiple comments highlighted that the experimental results were very useful; once the results feed into an electric motor design process, the work will become more valuable.
  - *We are working on plans to perform tests on sample stator assemblies (motorettes) to validate models and quantify performance of material improvements combined with cooling strategies.*

- Reviewer comments mentioned that the project needs to focus more on quantifying the impact of different insulation materials on the motor's thermal performance, and the long-term/life impact of jet cooling on the insulation system needs to be quantified.
  - *The comment matches the updated focus in the revised U.S. DRIVE Electrical and Electronics Technical Team Roadmap. For this reason we are working to build material samples that could be thermally cycled, vibration tested, and exposed to driveline fluids.*

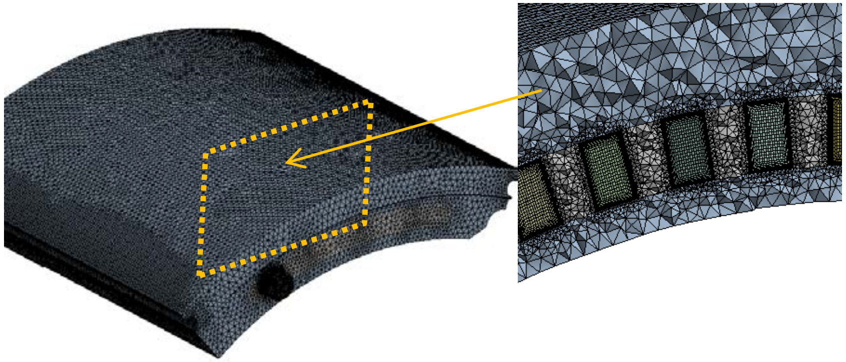
- Reviewers mentioned that active cooling of the electric machine will allow size reduction and will improve peak load capability. However, cost and complexity due to active cooling system in terms of pumping power or performance should be justifiable for a given application.
  - *For this reason potential future work will include integrated system tests including sample stator assemblies (motorettes) with active cooling.*

Collaboration and Coordination with Other Institutions

- **<u>Industry</u>**
  - Motor industry suppliers, driveline fluid suppliers, end users, and researchers
    - NREL providing
      - Experimental data
      - Modeling results
      - Analysis methods
    - Industry providing
      - Driveline fluid information and properties
      - Information on insulation materials
      - Boundary conditions for experimental and analytical work
      - Application information

Collaboration and Coordination with Other Institutions

- **<u>Other Government Laboratories</u>**
  - ORNL
    - Collaboration on motor designs to reduce or eliminate rare-earth materials
    - NREL supported computational fluid dynamics for fluid flow and heat transfer analysis



  - Ames
    - NREL supporting magnet material physical property measurements

Remaining Challenges and Barriers

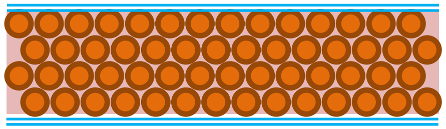
- Research enabling compact, reliable, and efficient electric machines
  - Motor 10x power density increase (2025 versus 2015 targets) [1]
  - Motor 2x increase in lifetime [1]
  - Motor 53% cost reduction (2025 versus 2015 targets) [1]

Material and Interface Thermal Characterization	Motor System Impacts with Active Cooling
• Material conductivity improvements • Methods to quantify thermal interfaces • Reliability to support increased lifetime targets	• Methods to improve heat transfer through convective cooling (flow geometry and placement) • Opportunities for improved driveline fluids targeted for motor cooling • Impacts of aged fluids • Alternative winding configurations (bar windings)

[1] U.S. DRIVE Electrical and Electronics Technical Team Roadmap, 2017.

Proposed Future Research

Material and Interface Thermal Characterization



Wire size, type, insulation, impregnation material slot liner, interface resistances

Active Cooling

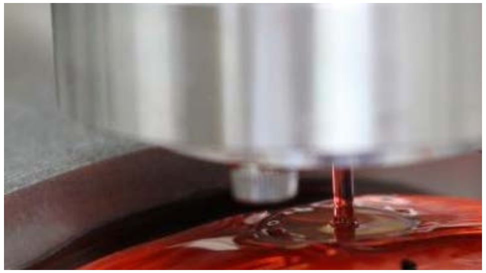
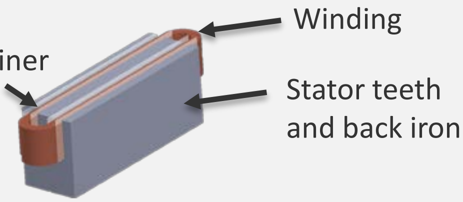


Photo Credits: Bidzina Kekelia, NREL

Fluid characterization

System Impacts (Materials and Active Cooling)



Motorette with alternative winding geometries, materials, and convective cooling approaches

"Any proposed future work is subject to change based on funding levels."

Summary

Relevance

- Supports research enabling compact, reliable, and efficient electric machines aligned with Roadmap research areas

Approach/Strategy

- Engage in collaborations with motor design experts and component suppliers within industry
- Collaborate with ORNL to provide motor thermal analysis support on related motor research at ORNL
- Collaborate with Ames to provide material properties to support Ames-led magnet development
- Develop and document characterization methods of materials, interface thermal properties, fluids, and cooling techniques

Technical Accomplishments

- Published data and analysis methods related to material and interface characterization methods
- Developed thermal interface models to predict thermal resistances of new motor designs
- Quantifying factors impacting the cooling performance of driveline fluids such automatic transmission fluid for cooling electric motors

Collaborations

- Motor industry representatives: manufacturers, suppliers, researchers, and end users (light-duty and medium/heavy-duty applications)
- Oak Ridge National Laboratory
- Ames Laboratory

Acknowledgments

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Thank You

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Technical Back-Up Slides

Technical Back-Up Slides

- Stator-to-case thermal contact resistance test apparatus

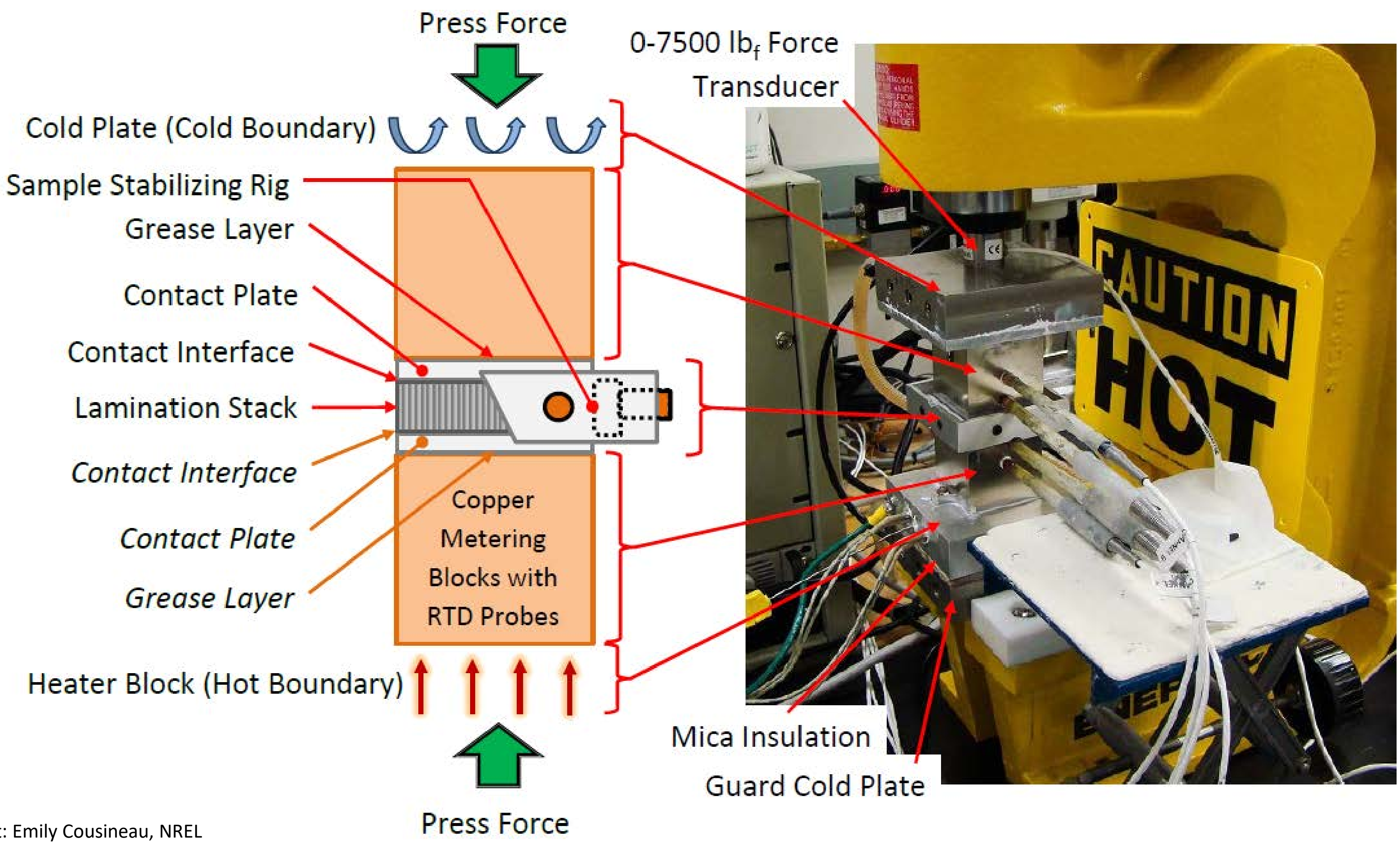


Photo Credit: Emily Cousineau, NREL

Technical Back-Up Slides

- **Magnet Transverse Rupture Testing**
  - 3-mm x 3-mm x 32-mm beam samples
  - Follow ASTM B528-12 test standard
  - Samples each tested at 25°C
  - Calculate transverse rupture strength:

$$TRS = (3 \times P \times L)/(2 \times t^2 \times w)$$

where:

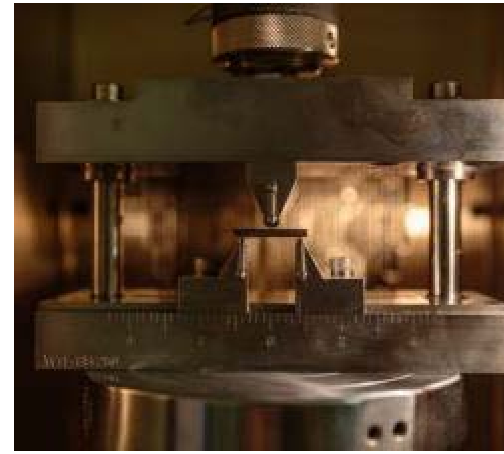
TRS = transverse rupture strength (MPa)

P = force required to rupture specimen (N)

L = distance between supporting rods (25.4 mm)

t = specimen thickness (mm)

w = specimen width (mm)



Measurements performed with Instron test system with samples inside environmental chamber

Photo Credits: Doug DeVoto, NREL

Technical Back-Up Slides

- Data show improved transverse rupture strength as compared to previously tested materials
- Baseline material shows consistent results between tests