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Electric Motor Thermal Management

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National Renewable Energy Laboratory
2017 Annual Merit Review
Washington, D. C. June 6, 2017

EDT075

NREL/PR-5400-68076

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Overview

Timeline

- Project start date: FY2017
- Project end date: FY2019
- Percent complete: 17%

Budget

- Total project funding
  - DOE share: $600K
- Funding for FY 2017: $600K

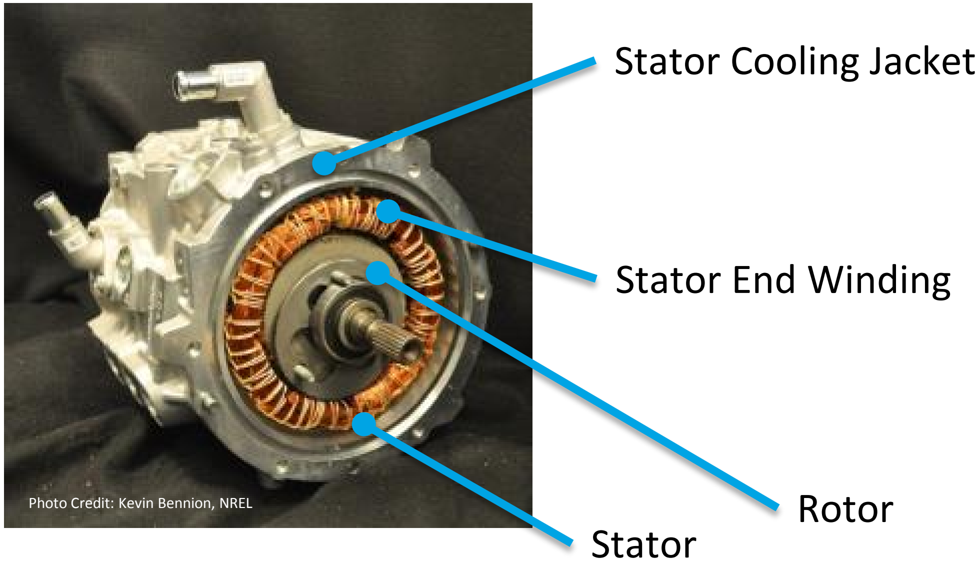
Barriers

- Cost
- Performance (Size, Weight)
- 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
  - Tim Burress
- Ames Laboratory – Magnet Materials
  - Iver Anderson
- National Renewable Energy Laboratory (NREL) – Thermal Project Lead

Thermal management enables more efficient and cost-effective motors



- **Impacts**
  - Size
  - Weight
  - Cost
  - Reliability
  - Efficiency
- **Examples**
  - Current density
  - Materials (magnets, laminations, windings, insulation, varnish, resin, epoxy)
  - System integration (cooling jacket, automatic transmission fluid)

Milestones

Date	Description
December 2016 (Complete)	Milestone • Down select motor thermal management technologies and improved heat transfer designs with input from ORNL for non-rare-earth motors.
March 2017 (Complete)	Milestone • Develop models to enable heat transfer analysis. • Evaluate and confirm thermal management approaches to overcome identified heat removal challenges through modeling and analysis.
June 2017 (In Progress)	Go/No-Go • Down select most promising motor thermal management technologies in partnership with project collaborators through modeling and analysis.
September 2017 (In Progress)	Milestone • Confirm selected stator and rotor thermal management technologies to overcome identified heat removal challenges.

Motor Thermal Management

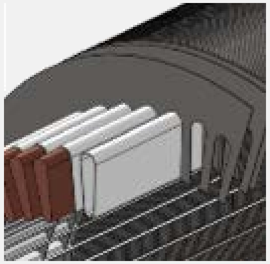
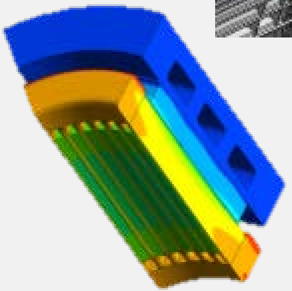
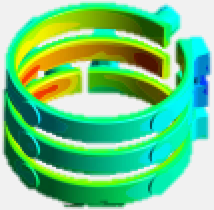
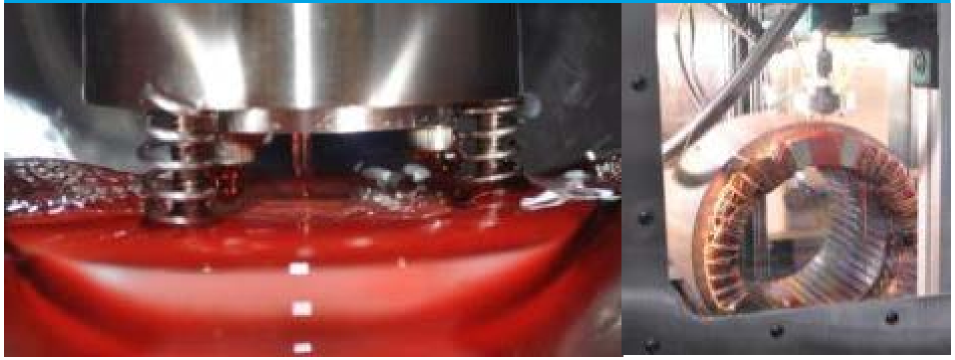
Material Characterization	Passive Thermal Design	Active Convective Cooling
	 	  

Photo Credits: Doug DeVoto, Jana Jeffers, Kevin Bennion NREL

Technical Accomplishments and Progress

Active Convective Cooling

Direct Impingement Cooling for Motor Windings



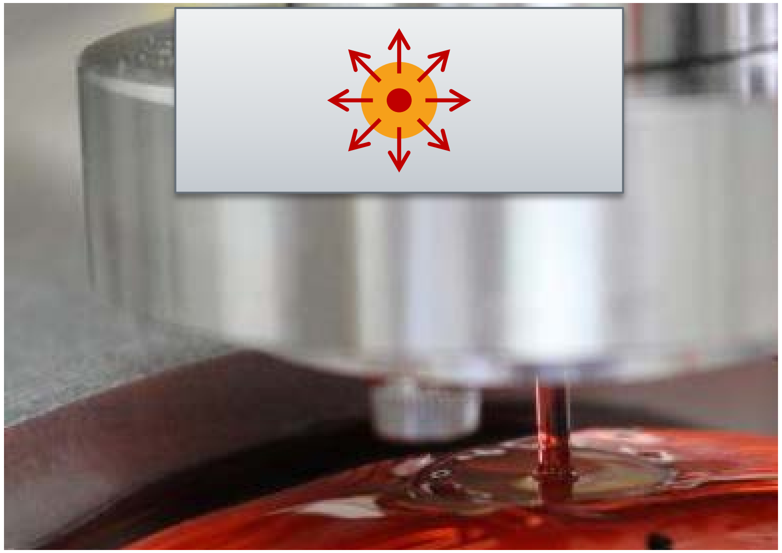
- Quantifies impact of new or alternative cooling approaches for ATF cooling of motors
- Enables work to characterize impact of cooling fluids

ATF: automatic transmission fluid

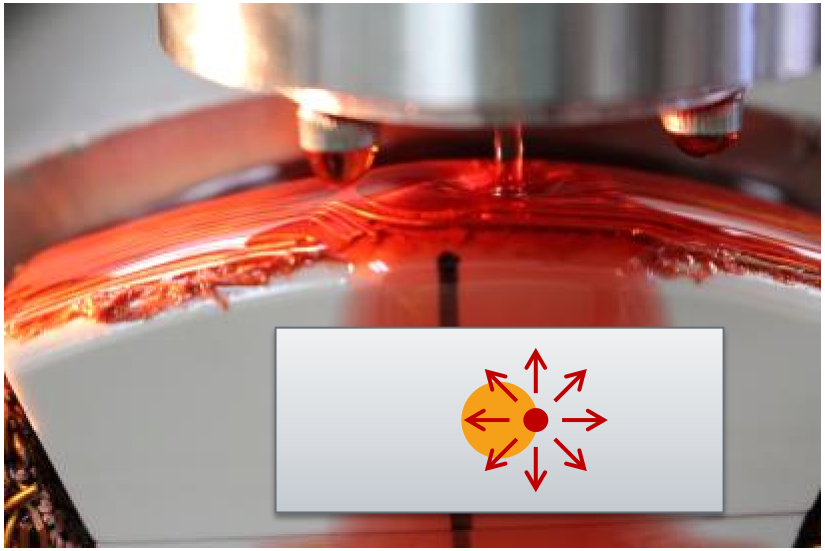
Photo Credits: Jana Jeffers and Kevin Bennion, NREL

Technical Accomplishments and Progress

- Experiments using new test setup capable of measuring heat transfer variation along winding, quantifying impact of new or alternative cooling approaches for ATF cooling of motors



Orifice Jet Center Impingement

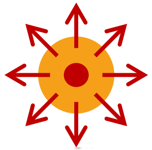


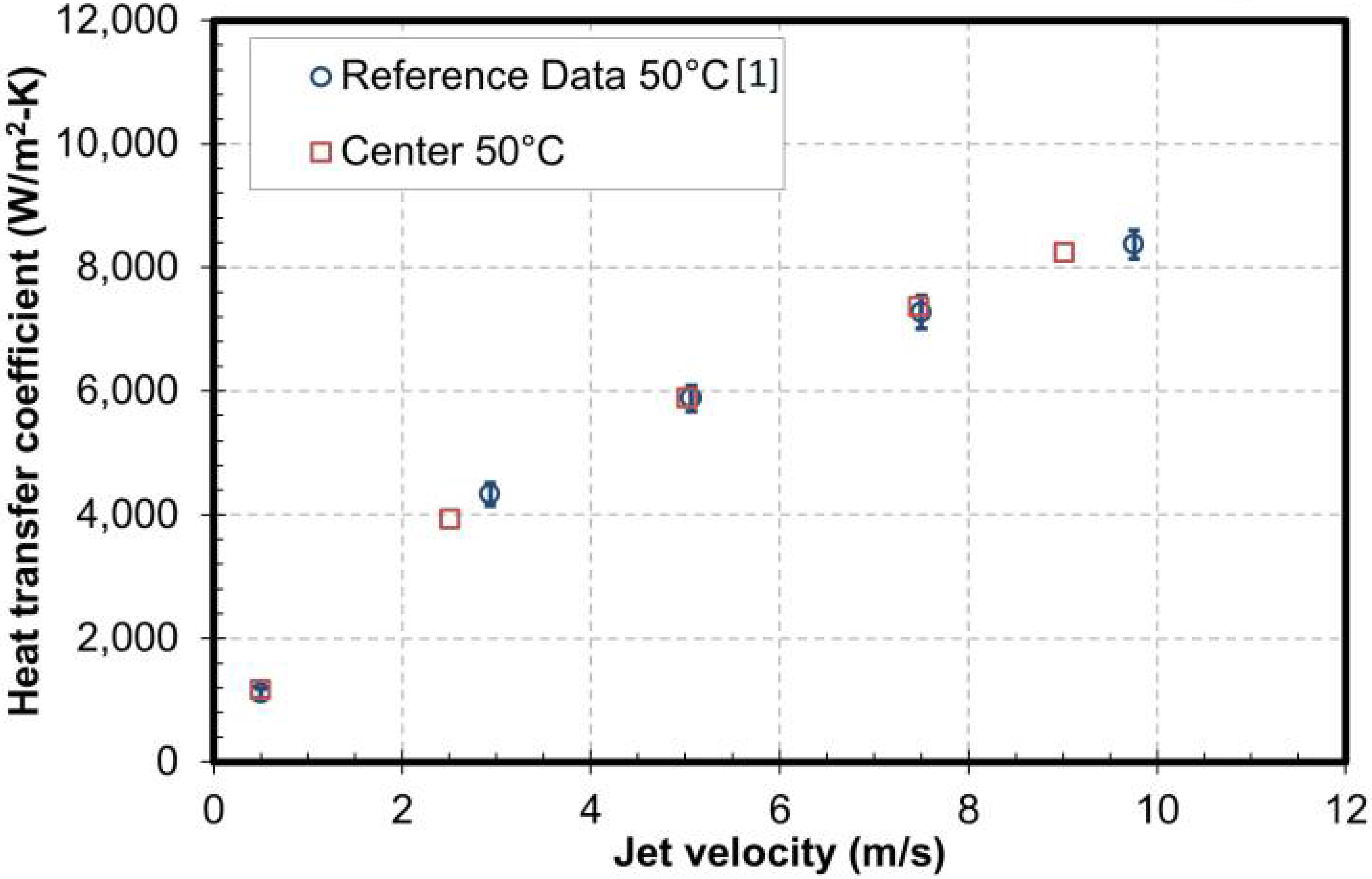
Orifice Jet Edge Impingement

Photo Credits: Bidzina Kekelia and Kevin Bennion, NREL

Technical Accomplishments and Progress

- Verified new experimental setup using past work [1] as reference for center impingement results.

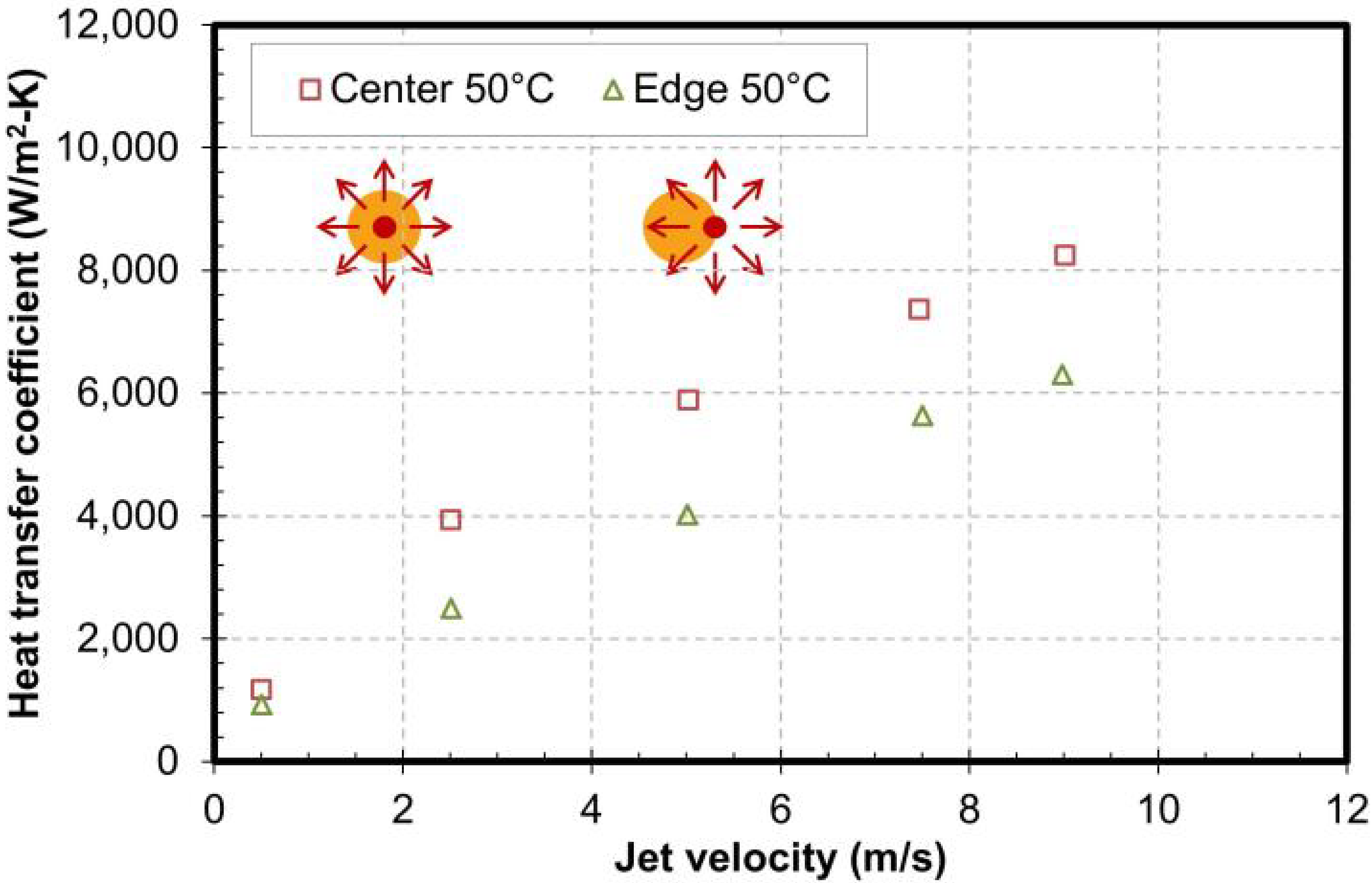




[1] K. Bennion and G. Moreno, "Convective Heat Transfer Coefficients of Automatic Transmission Fluid Jets with Implications for Electric Machine Thermal Management," in ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems and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

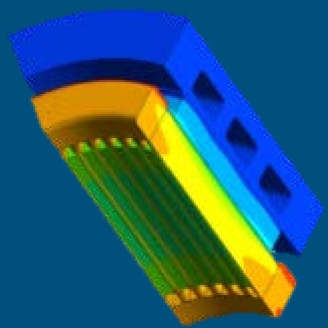
Technical Accomplishments and Progress

- The variation in heat transfer relative to nozzle placement is significant and important



Technical Accomplishments and Progress

Passive Thermal Design

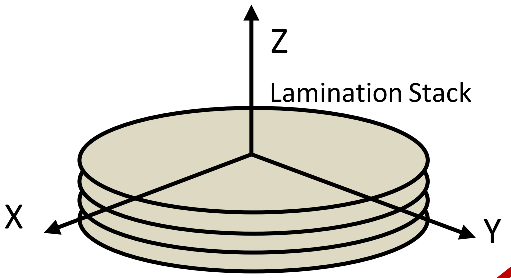


Passive Thermal Stack Measurements and Models

- Measured interface thermal resistances and direction-dependent thermal conductivity of motor components
- Supports work to evaluate impacts of new materials

Photo Credits: Emily Cousineau and Kevin Bennion, NREL

- Motor lamination thermal conductivity



$$k_z = \left(\frac{R_C}{t} + \frac{1}{k_L}\right)^{-1}$$

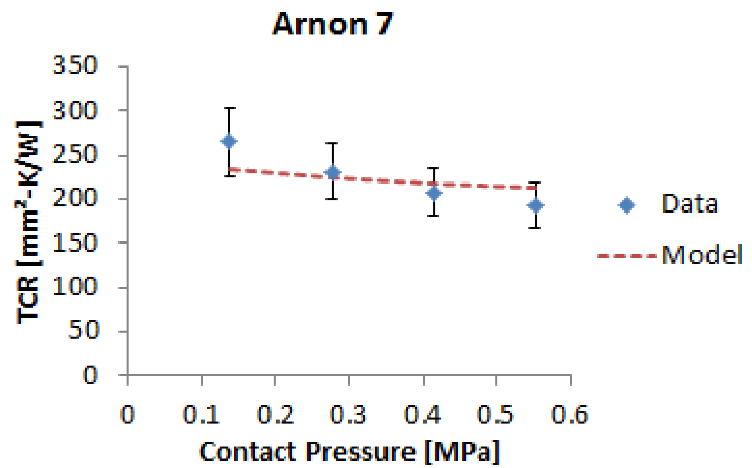
k_z	Through-stack thermal conductivity
R_c	Interlamination thermal contact resistance
k_l	Lamination thermal conductivity
t	Thickness

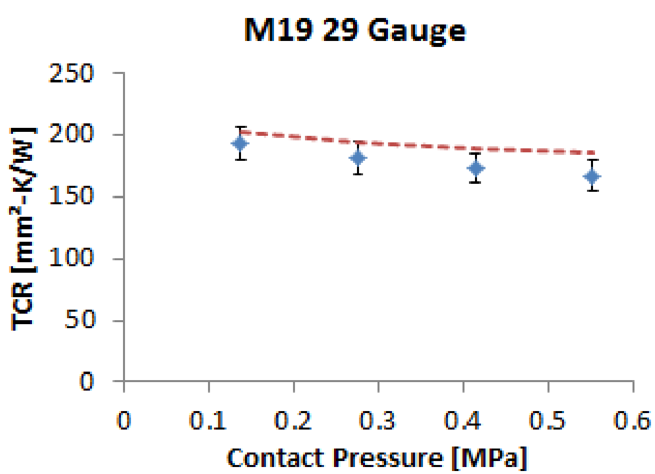
- Motor lamination thermal contact resistance (R_C)
    - Developed model for lamination thermal contact resistance to enable estimates of through-stack thermal conductivity for new materials

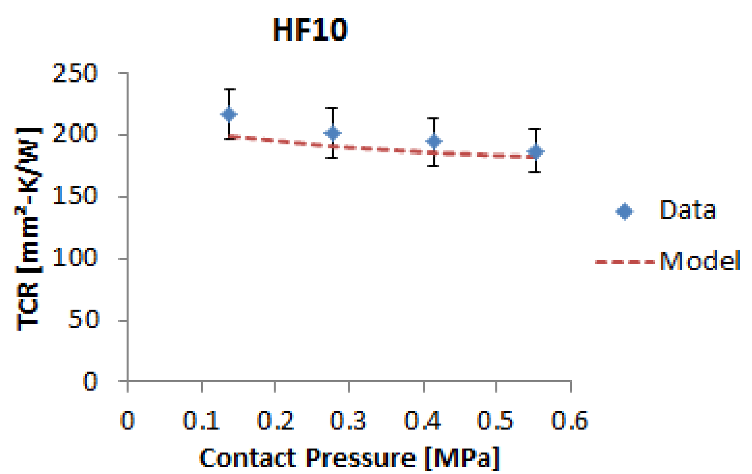
$$R_C = \left(1.53\sigma_{RMS}(P/H)^{-0.097} + t_{C5}\right)/k_{air}$$

R_c	Interlamination thermal contact resistance
σ_{RMS}	Surface roughness of contacting surfaces
P	Contact pressure
H	Surface micro hardness
t_{C5}	Lamination coating thickness
k_{air}	Air thermal conductivity

- Motor lamination thermal contact resistance
  - Validated model with experimental data using multiple materials
  - Publication in process of submission:
    - "Experimental Characterization and Modeling of Thermal Resistance of Electric Machine Lamination Stacks," submitting to *Applied Energy*



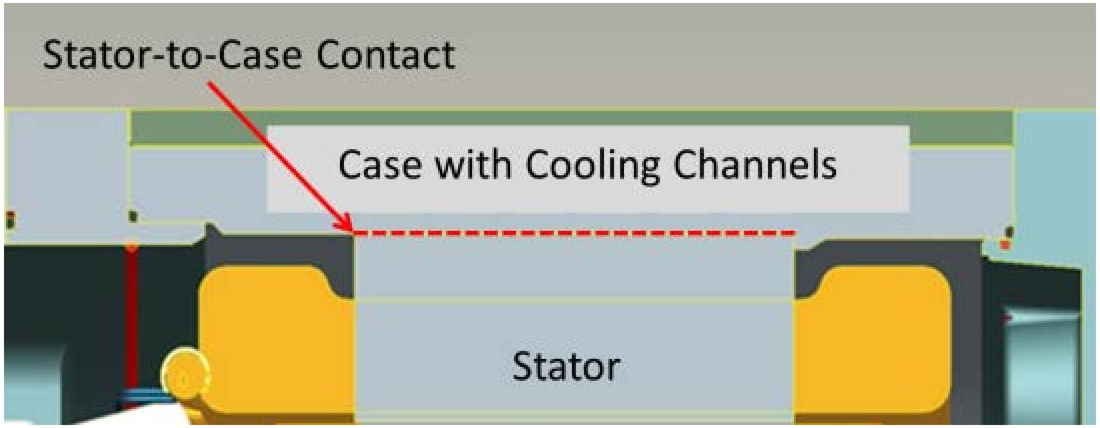




TCR: Thermal contact resistance

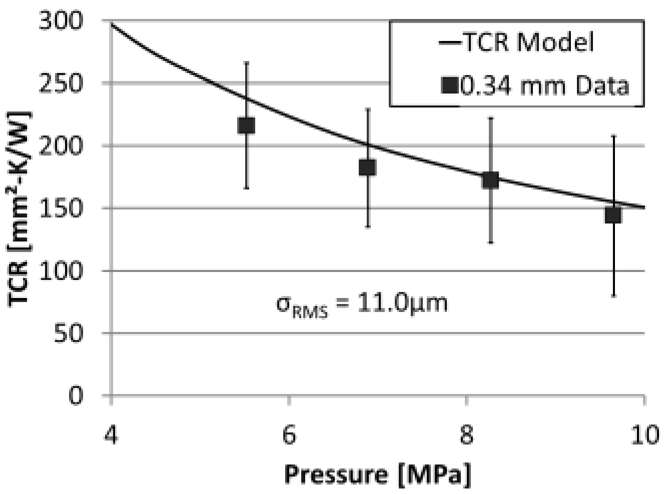
Technical Accomplishments and Progress

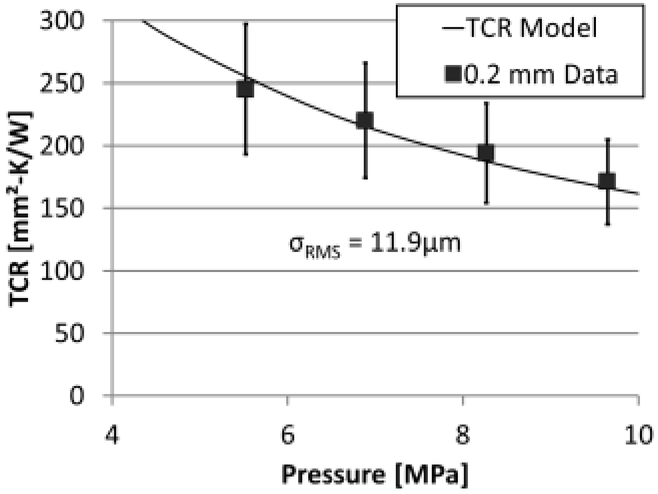
- Stator-to-case thermal contact resistance
  - Developed model for lamination thermal contact resistance to enable estimates of through stack thermal conductivity for new materials
  - The model includes both solid and fluid components to calculate the inverse of TCR, or thermal contact conductance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



Technical Accomplishments and Progress

- 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





  - Publication in process of submission:
    - "Experimental Characterization and Modeling of Thermal Contact Resistance of Electric Machine Stator-to-Cooling Jacket Interface under Interference Fit Loading," submitting to *Applied Thermal Engineering*.

- Motor Windings
  - Tests with ORNL demonstrated that the anisotropic thermal conductivity of packed copper wire can be satisfactorily estimated with appropriate specimen preparation using the laser flash and transmittance test methods.
  - The test results provide a baseline for comparing new materials, and highlight methods for appropriately testing the thermal impact of new materials or winding structures relevant to motor windings.
  - "Anisotropic Thermal Response of Packed Copper Wire," Andrew A. Wereszczak, J. Emily Cousineau, Kevin Bennion, Hsin Wang, Randy H. Wiles, Timothy B. Burress, and Tong Wu, *Journal of Thermal Science and Engineering Applications*, paper accepted for publication.

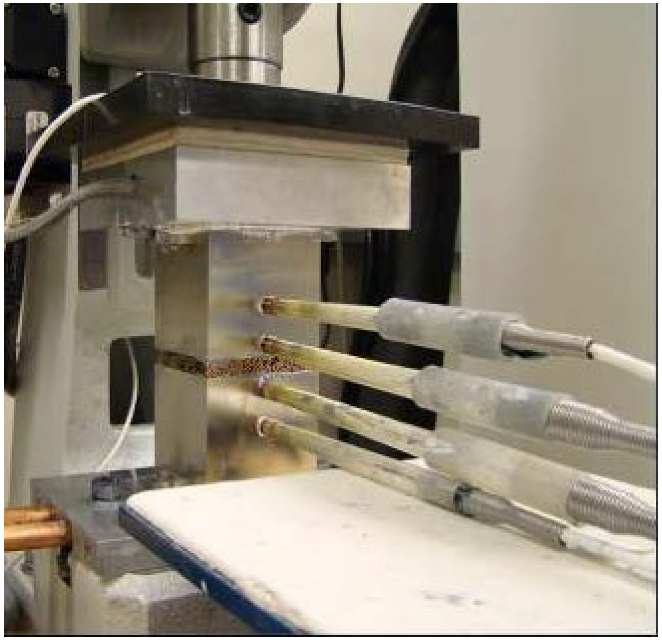


Photo Credit: Emily Cousineau, NREL

Technical Accomplishments and Progress

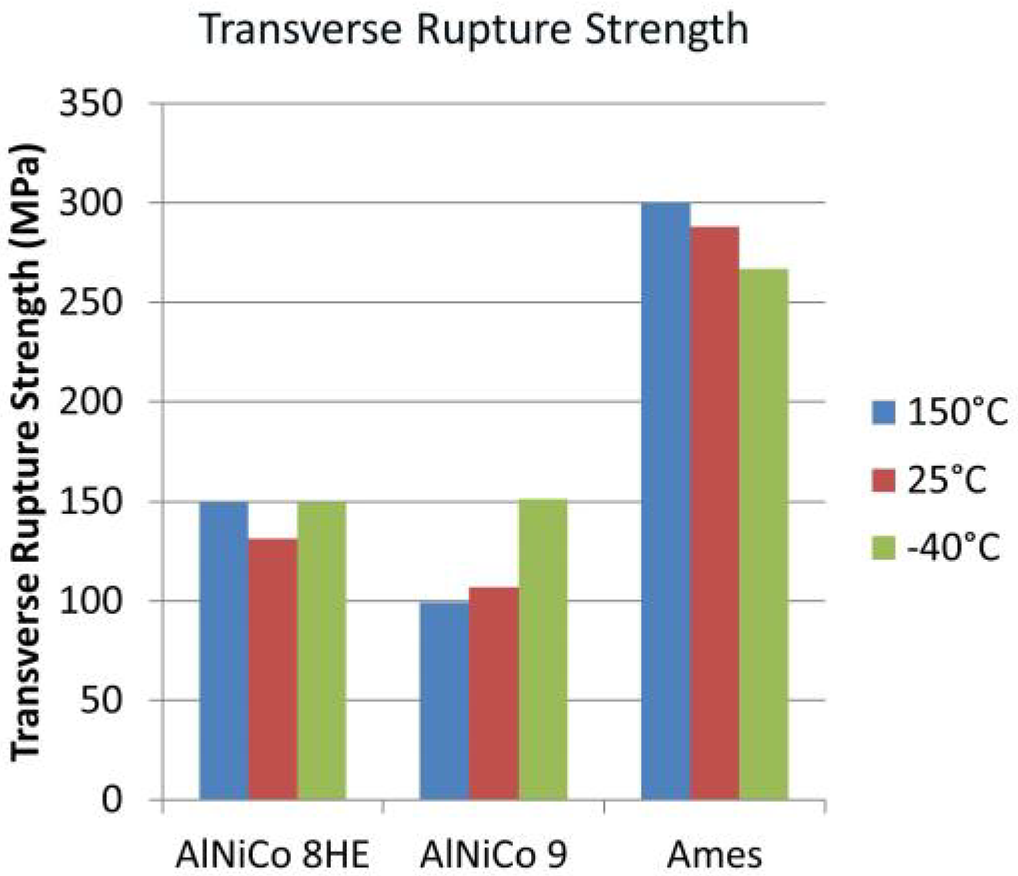
Material Characterization

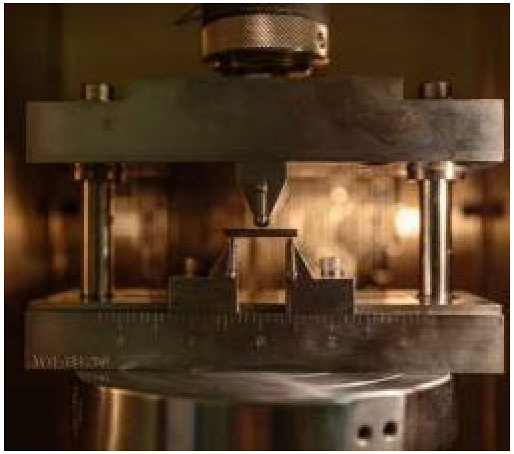
Bulk Material Measurements

- Collaboration with Ames Laboratory and ORNL for magnet material measurements

Photo Credit: Emily Cousineau and Doug DeVoto, NREL

Technical Accomplishments and Progress

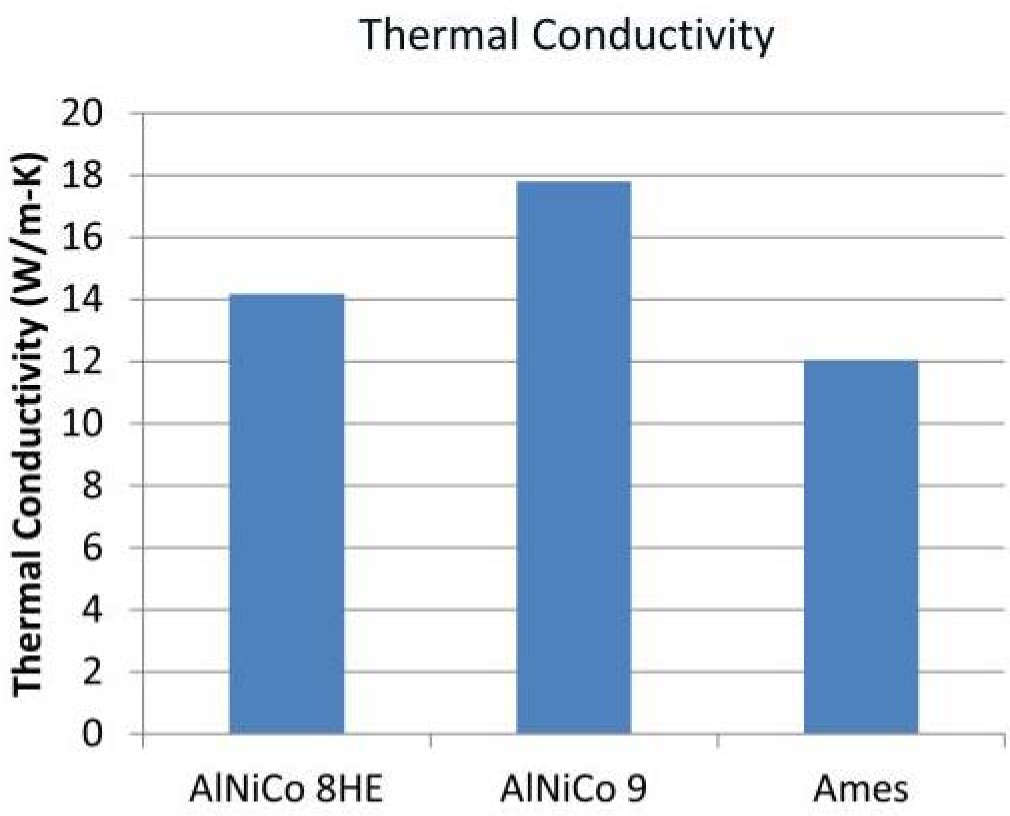




Measurements performed with Instron test system with samples inside environmental chamber

Photo Credits: Doug DeVoto, NREL

Technical Accomplishments and Progress



Thermal conductivity at 25°C

Measurements performed with xenon flash instrument

Photo Credit: Doug DeVoto, NREL

Response to Previous Year Reviewers' Comments

This project is new for FY2017 as a partner with the motor research activities at Oak Ridge National Laboratory, but relevant reviewer comments are provided below for the prior project.

- Reviewer asked if standardized models can be generated and shared broadly.
  - *We have published or are in the process of publishing models representing elements within the motor passive stack impacting heat transfer through the motor.*

- Reviewers commented on the usefulness of the data, such as, "there is no literature on the cooling effect of direct spraying of transmission fluids on surfaces representative of electrical machines, and certainly no publicly available empirical data that motor designers can use to optimize their machines."
  - *The feedback and confirmation of the usefulness of the data are appreciated.*

- Reviewer said collaboration with Ames Laboratory relating to this project was unclear.
  - *We tried to provide additional details in this presentation on the collaborations with Ames, and NREL's role in the collaborations.*

Collaboration and Coordination with Other Institutions

- **Industry**
  - Motor industry suppliers, end users, and researchers
    - Sharing experimental data, modeling results, and analysis methods
- **Other Government Laboratories**
  - ORNL
    - Support from benchmarking activities
    - Collaboration on motor designs to reduce or eliminate rare-earth materials
    - Collaboration on materials with improved thermal properties
  - Ames
    - NREL supporting magnet material physical property measurements

Remaining Challenges and Future Work

Challenges

- Heat transfer coefficients of ATF impingement on irregular surfaces of motor end windings
- Impact of alternative winding configurations that would change the end-winding form factor or geometry leading to different fluid flow and heat transfer (bar windings, concentrated windings)

Active Cooling

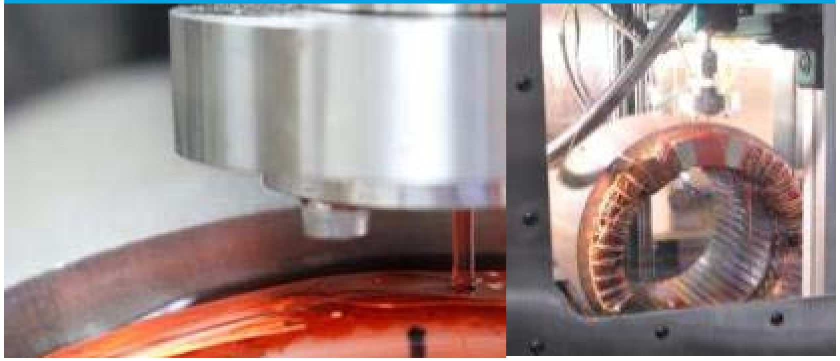


Photo Credits: Bidzina Kekelia and Kevin Bennion, NREL

Current Assumptions

- Flat surface with texture of wires

Future Work

- ATF heat transfer performance relative to ATF jet placement for alternative flow configurations
- ATF performance for alternative winding surfaces

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

Remaining Challenges and Future Work

Challenges

- Passive stack heat transfer impacted by motor insulation materials and interfaces
- Wide bandgap (WBG) enables higher voltages and higher frequency, which impacts motor insulation systems

Passive Thermal Stack Measurements and Models

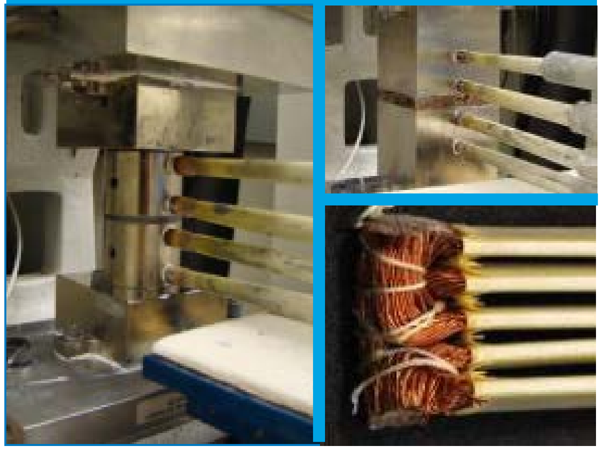


Photo Credits: Emily Cousineau and Kevin Bennion, NREL

Future Work

- In partnership with ORNL, identify thermal management technologies to overcome heat removal challenges through modeling and analysis for non-rare-earth motor designs
- Insulation materials and interface thermal resistances

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

Remaining Challenges and Future Work

Challenges

- Material development for motor applications enabling reduced cost and higher power density (Ames, ORNL)
- Identifying required thermal and mechanical material properties in collaboration with ORNL and Ames

Bulk Material Measurements

Photo Credits: Emily Cousineau and Doug DeVoto, NREL

Future Work

- Perform mechanical and thermal property measurements supporting magnet material developments at Ames
- Continue collaboration with ORNL on thermal impacts of motor material developments

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

Summary

Relevance

- Supports transition to more electric-drive vehicles with higher continuous power requirements
- Enables improved performance of motors without and with non-rare-earth materials.

Approach/Strategy

- Engage in collaborations with motor design experts 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
- Perform in-house thermal characterization of materials, interface thermal properties, and cooling techniques.

Technical Accomplishments

- Preparing publication for fan jet nozzle ATF heat transfer in motor application
- Built experimental apparatus to measure large-scale variation in convective heat transfer coefficients
- Published data – obtained from collaborations with ORNL – on measurement techniques to quantify thermal properties of passive stack materials within motor stators
- Collaborating with Ames on mechanical and thermal measurements on magnet materials.

Collaborations

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

Acknowledgments

Susan Rogers, U.S. Department of Energy

Team Members

Emily Cousineau (NREL)
Doug DeVoto (NREL)
Xuhui Feng (NREL)
Bidzina Kekelia (NREL)
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Technical Back-Up Slides

Technical Backup Slides

- Stator-to-case thermal contact resistance test apparatus

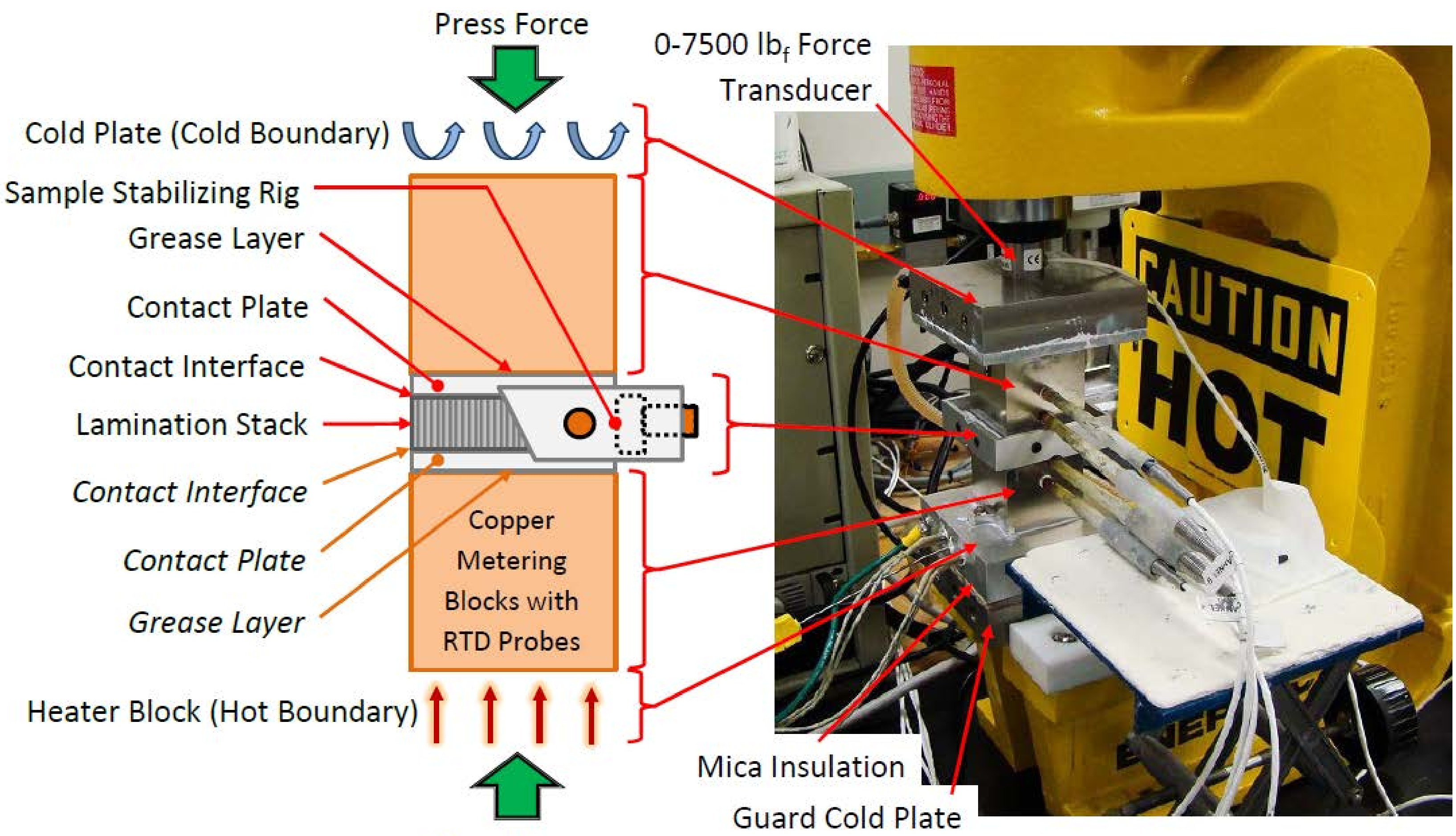


Photo Credit: Emily Cousineau, NREL

Technical Backup Slides

- **Magnet Compression Testing**
  - o 10-mm-long, 3-mm-diameter cylinder samples
- **Magnet Transverse Rupture Testing**
  - o 3-mm x 3-mm x 32-mm beam samples
  - o Follow ASTM B528-12 test standard
  - o Samples each tested at -40°C, 25°C, and 150°C
  - o Calculate transverse rupture strength (TRS):

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

where:

TRS = transverse rupture strength (MPa)

P = force required to rupture specimen (N)

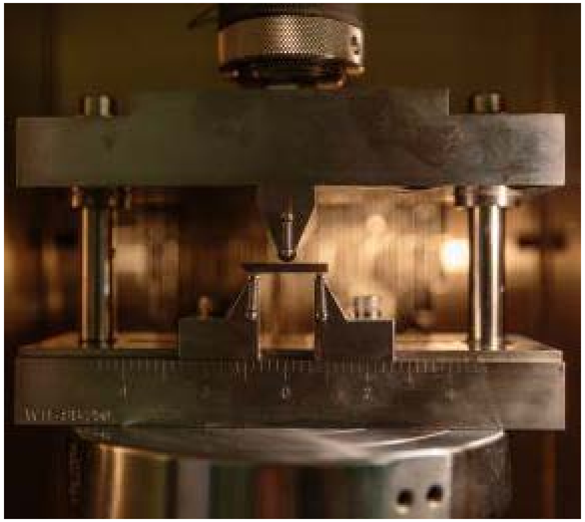
L = distance between supporting rods (25.4 mm)

w = specimen width (mm)

t = specimen thickness (mm)

- **Magnet Thermal Conductivity Testing**

Compression Test Fixture



Transverse Rupture Test Fixture

Photo Credits: Doug DeVoto, NREL