

Electric Motor Thermal Management

Keystone Project 2

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DOE Vehicle Technologies Program
2019 Annual Merit Review and Peer Evaluation Meeting

Project ID: ELT214

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2021
- Percent complete: 15%

Budget

- Total project funding
 - DOE share: \$250K (FY 2019 Planned)
- Funding for FY 2019: \$250K

Barriers

- Cost, Power Density, Life

Partners

- Motor Industry
 - Suppliers, end users, and researchers
- Oak Ridge National Laboratory (ORNL)
 - Motor development, modeling, and material research
- Ames Laboratory
 - Motor material research
- Sandia National Laboratory
 - Motor and materials Research
- National Renewable Energy Laboratory (NREL)
 - Lead for thermal and reliability research

Relevance

- This is a new project that is part of the new Electric Drive Technologies Consortium and focuses on NREL's role under Keystone 2

Keystone 1

- Power Electronics

Keystone 2

- Electric Motors

Keystone 3

- Traction Drive System

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]

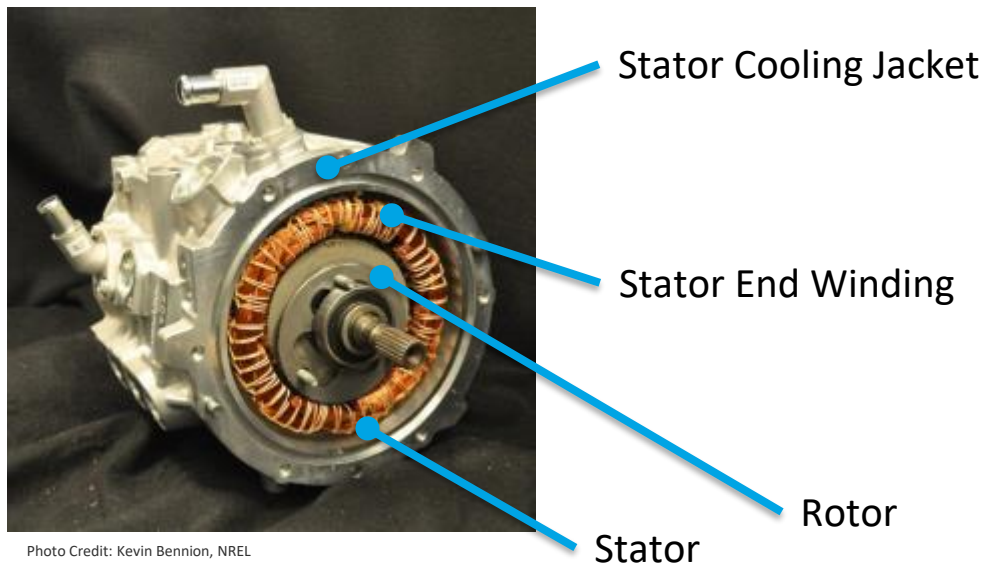
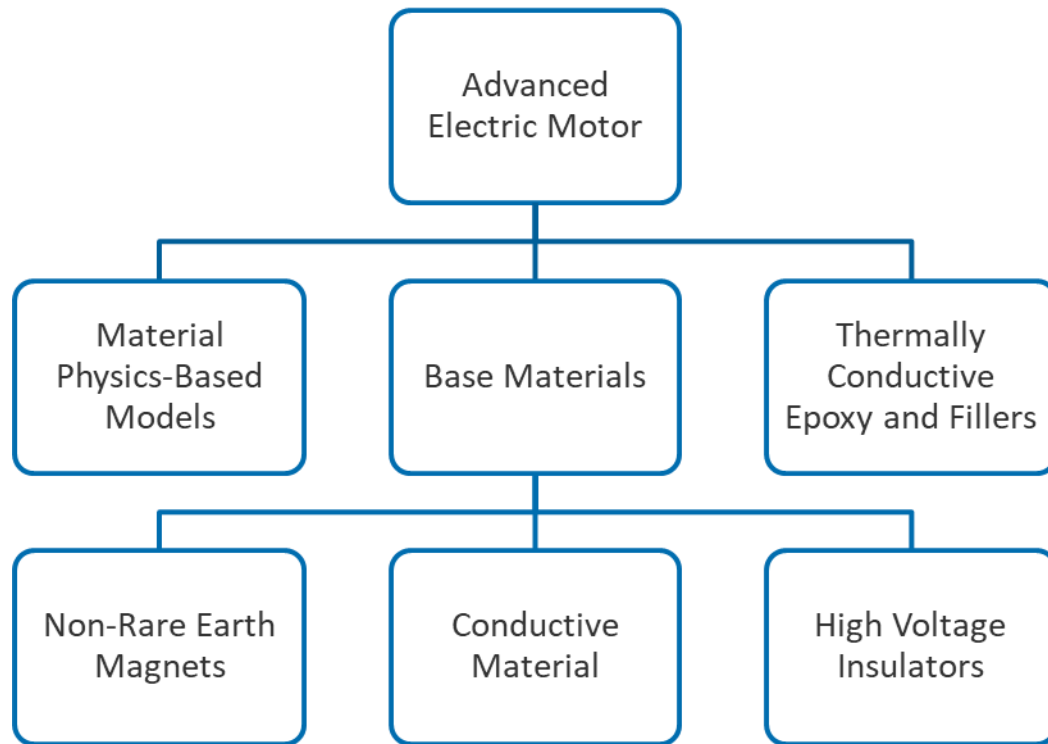


Photo Credit: Kevin Bennion, NREL

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

Relevance

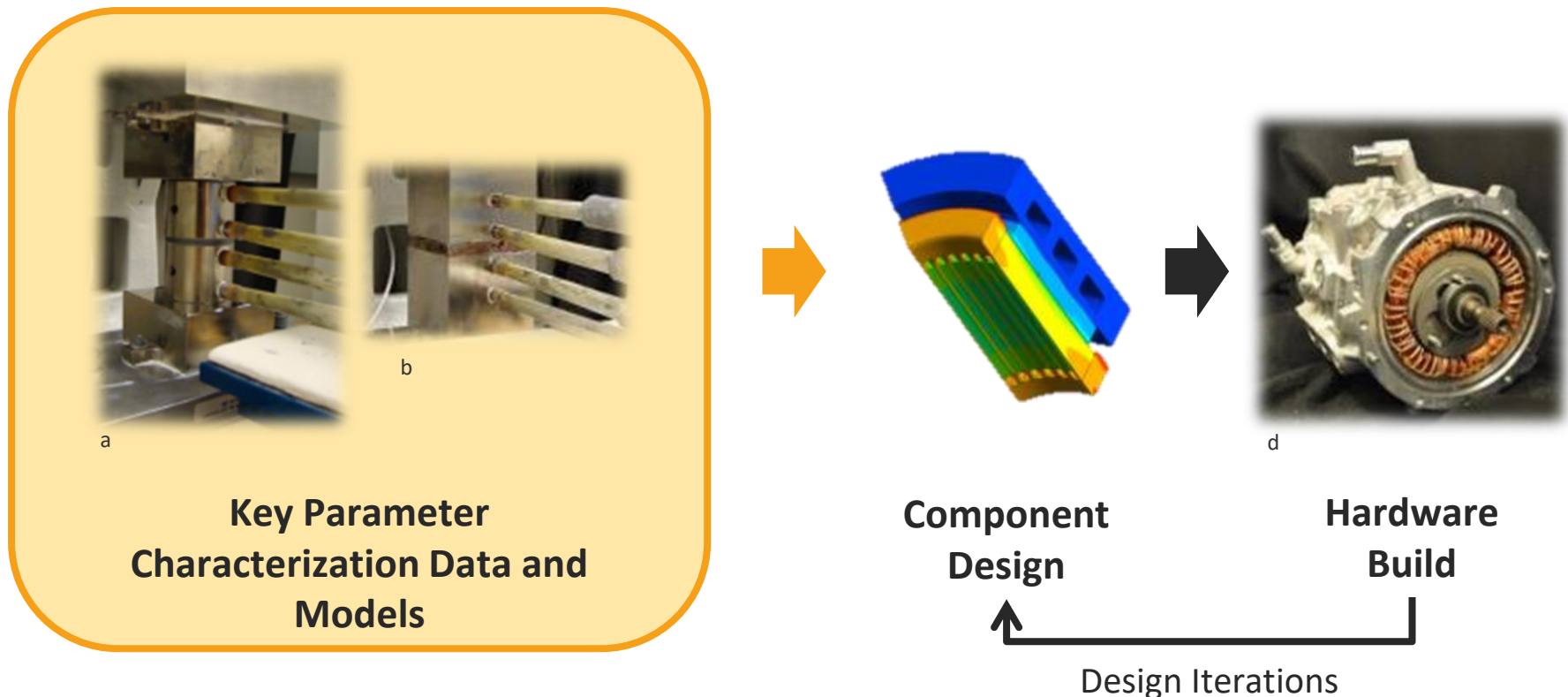


Electric Drive Motor R&D Areas ^[1]

- 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]

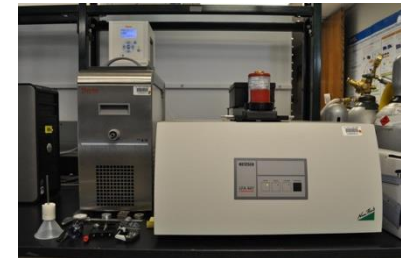
Relevance

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



Resources

- Sample of Existing Equipment and Resources
 - Thermal Interface Material Stand
 - Xenon Flash
 - Differential Scanning Calorimeter
 - Vertical Thermal Shock Chamber
 - Thermal Cycle Chambers
 - Vibration System
 - Hot Press
 - Dual Column Tabletop Universal System
 - Instron 5966 dual column testing system
 - An environmental chamber has a temperature range from -100°C to 350°C



Milestones

Date	Description
December 2018 (Complete)	Milestone <ul style="list-style-type: none">With project partners, define evaluation criteria for motor material research including sample configurations and operating temperatures
March 2019 (Complete)	Milestone <ul style="list-style-type: none">Complete instrument setup for evaluating low thermal conductivity materials at temperatures up to 200°C.
June 2019 (In Progress)	Go/No-Go <ul style="list-style-type: none">Experimentally quantify measurement uncertainties and thermal resistance ranges for each metering block material.
September 2019 (In Progress)	Milestone <ul style="list-style-type: none">Prepare report on research results.

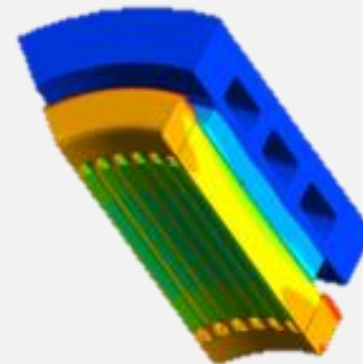
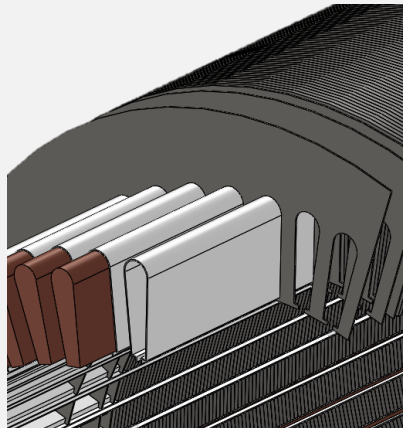
Overall Approach

- Research emphasis on motor materials and impacts of thermal interfaces

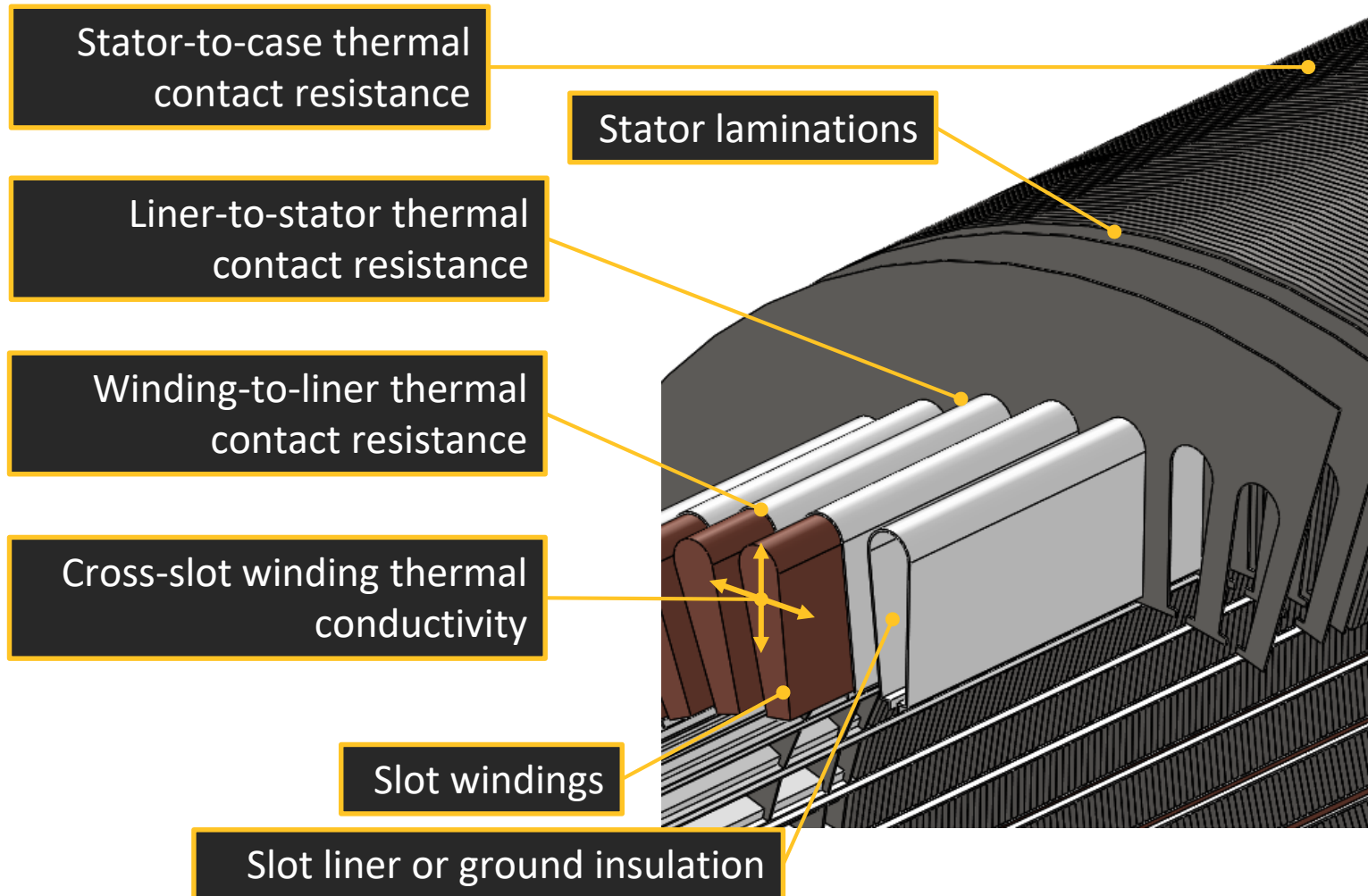
Material Mechanical and Thermal Properties Interface Thermal Characterization and Reliability



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Approach: Material Thermal Characterization



Technical Accomplishments and Progress

Designed and built experimental setup to:

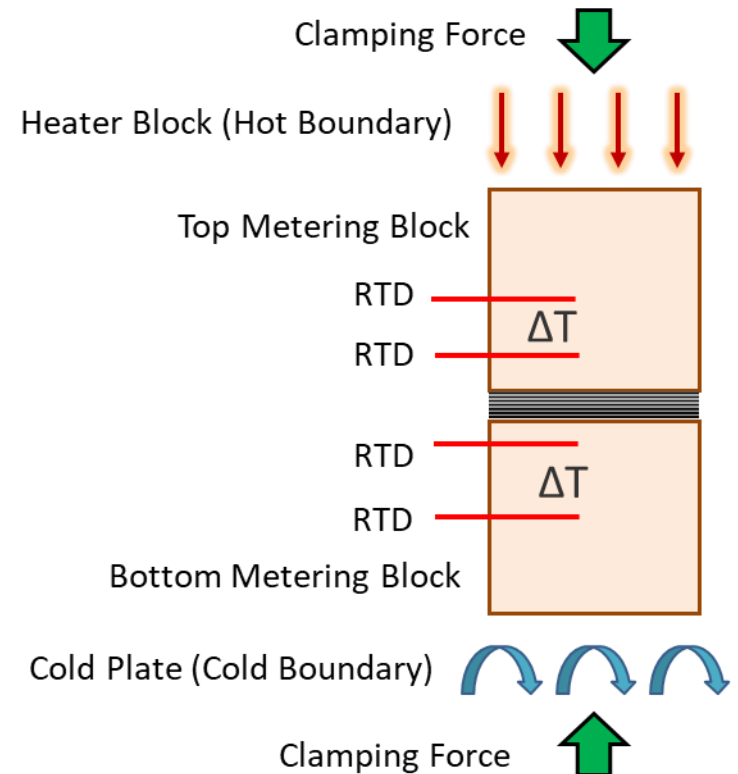
- Improve measurements of low-thermal-conductivity (high-resistance) materials
- Enable material and interface thermal resistance characterization up to 200°C



Photo Credit: Emily Cousineau, NREL

Technical Accomplishments and Progress

- Challenge
 - High systematic error on high thermal resistance (R_{th}) samples
 - Caused by RTD temperature measurement uncertainty ($\pm 0.030^{\circ}\text{C}$)
- Heat flux measurement relies on the temperature difference (ΔT) between RTDs.
 - High R_{th} leads to low heat flux which reduces the ΔT measured by the RTDs
- Modifying the metering block material increases ΔT measured by RTDs which reduces overall systematic error

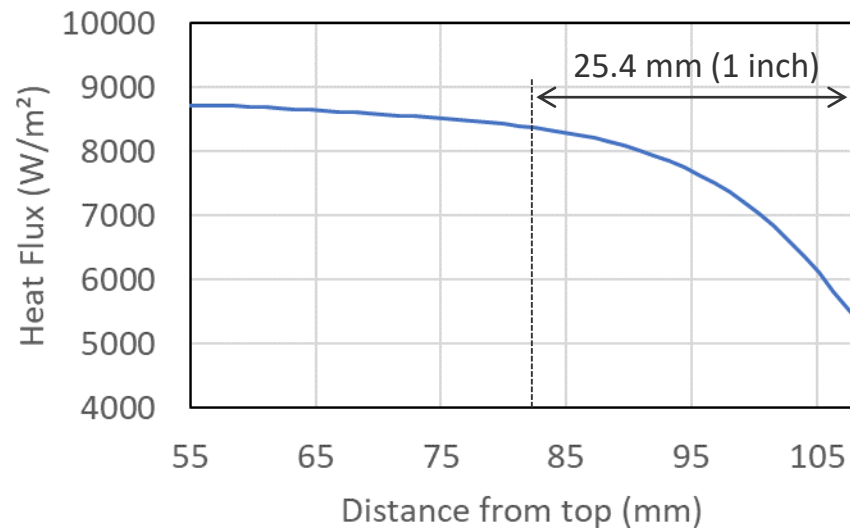


RTD: Resistance Temperature Detector

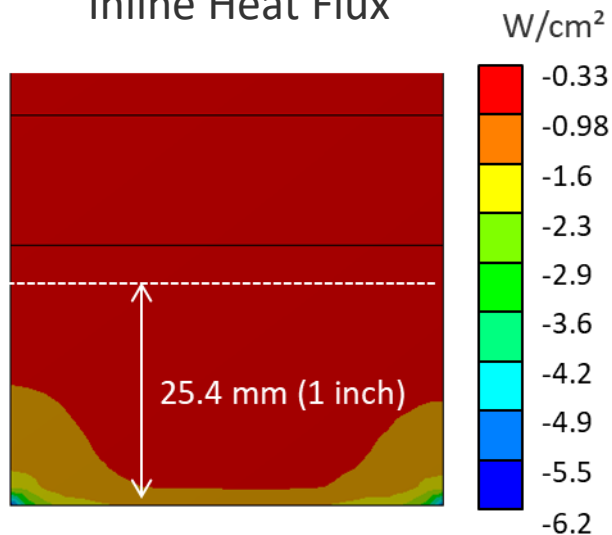
Technical Accomplishments and Progress

Impact of Temperature Measurement Location

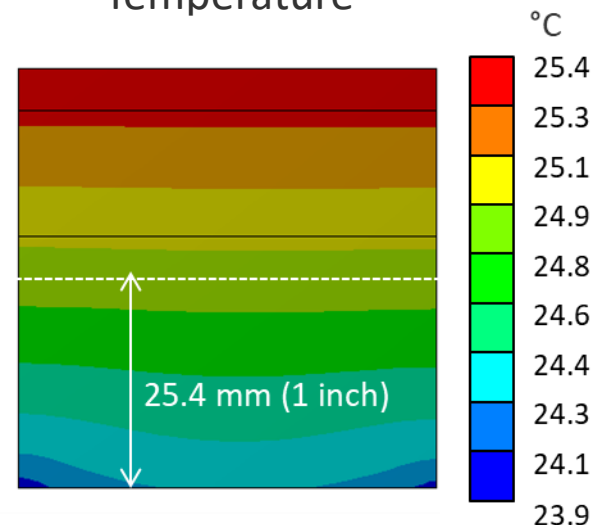
Bottom Block



Inline Heat Flux

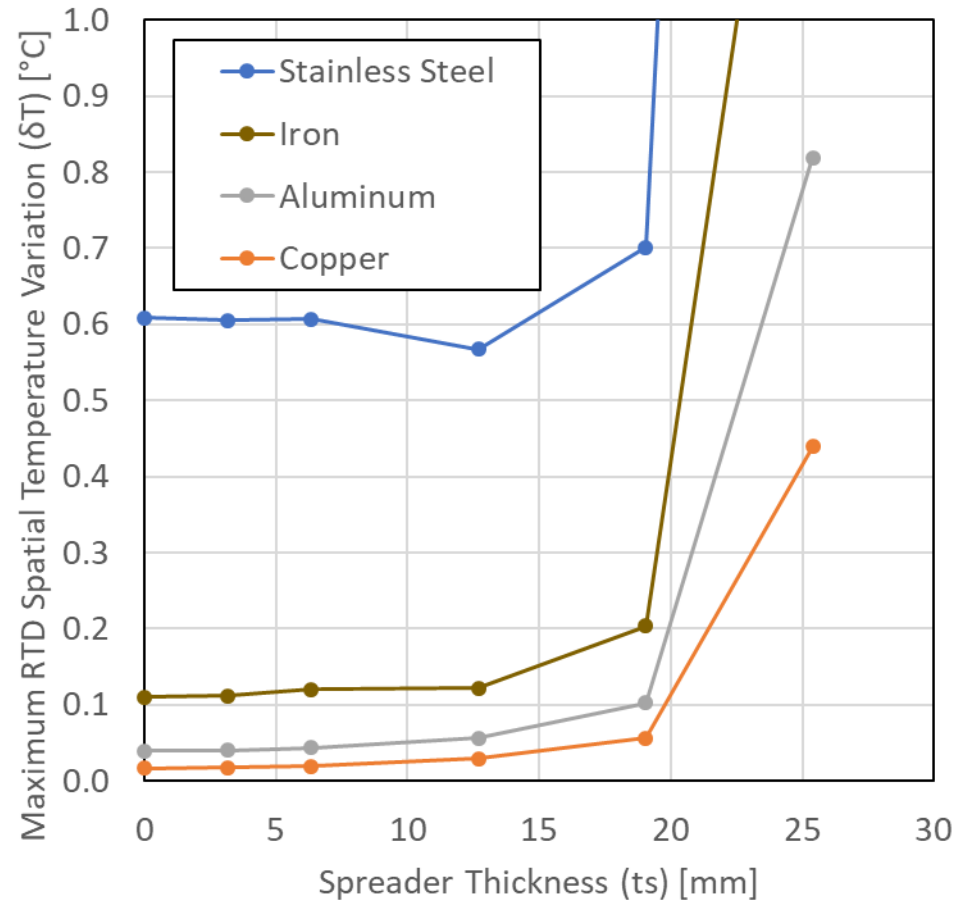
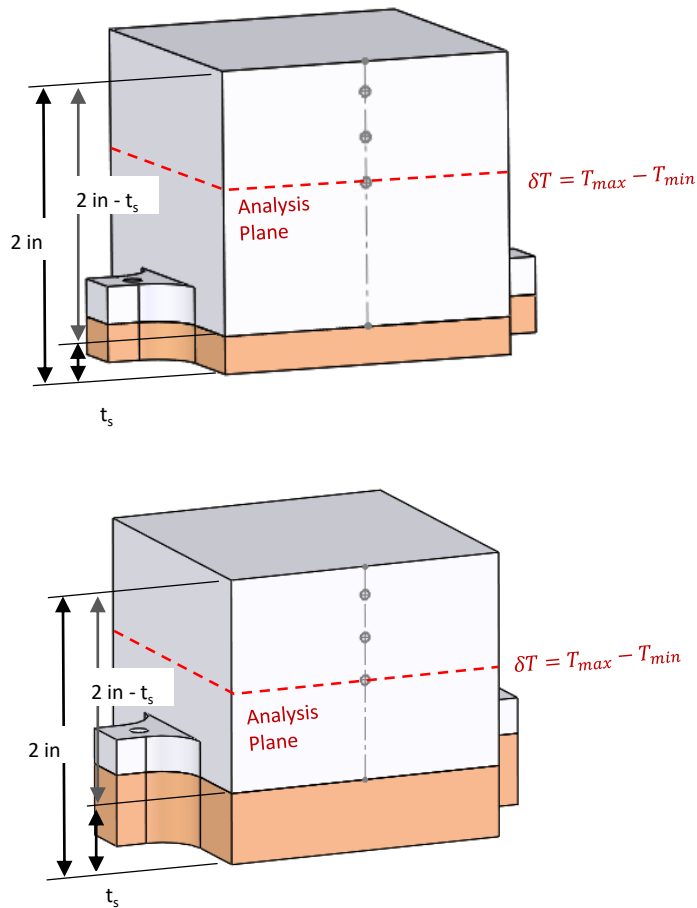


Temperature



Technical Accomplishments and Progress

Copper Spreader Thickness Impacts



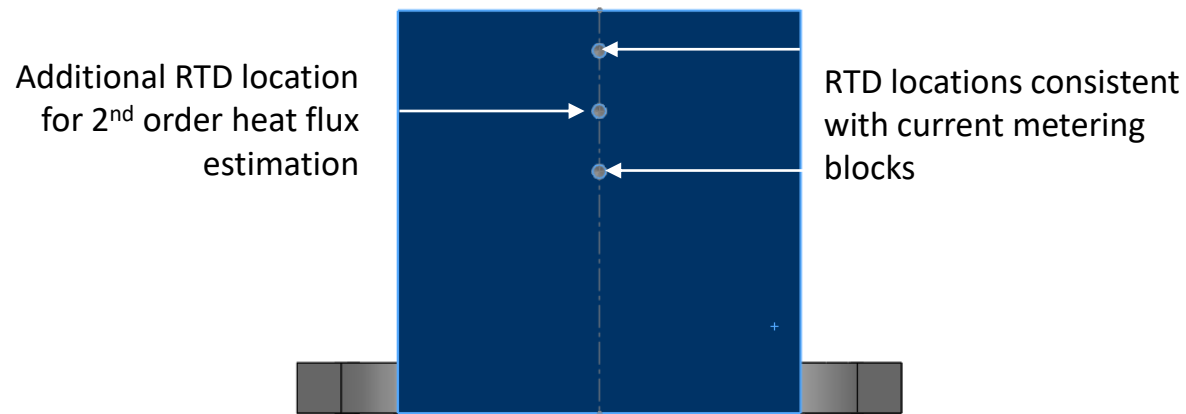
Technical Accomplishments and Progress

- Example analysis with very high thermal resistance sample
 - Lower thermal conductivity metering blocks increase ΔT , resulting in more accurate estimation of heat flux
 - Lower thermal conductivity metering blocks result in greater uncertainty in the in-place temperature with the RTD measurement
 - Even for stainless steel, with predicted in-plane variation 22 times greater than copper, there is significant overall improvement in systematic uncertainty

Metering block type	Metering block thermal conductivity	Sample R_{th} (actual)	Systematic Error including RTD uncertainty and in-plane temperature variation
	[W/m-K]	[mm ² -K/W]	[%]
Copper	391	17780	18.4%
Aluminum	154	17780	9.60%
Iron	58	17780	3.30%
Stainless Steel	14	17780	1.20%

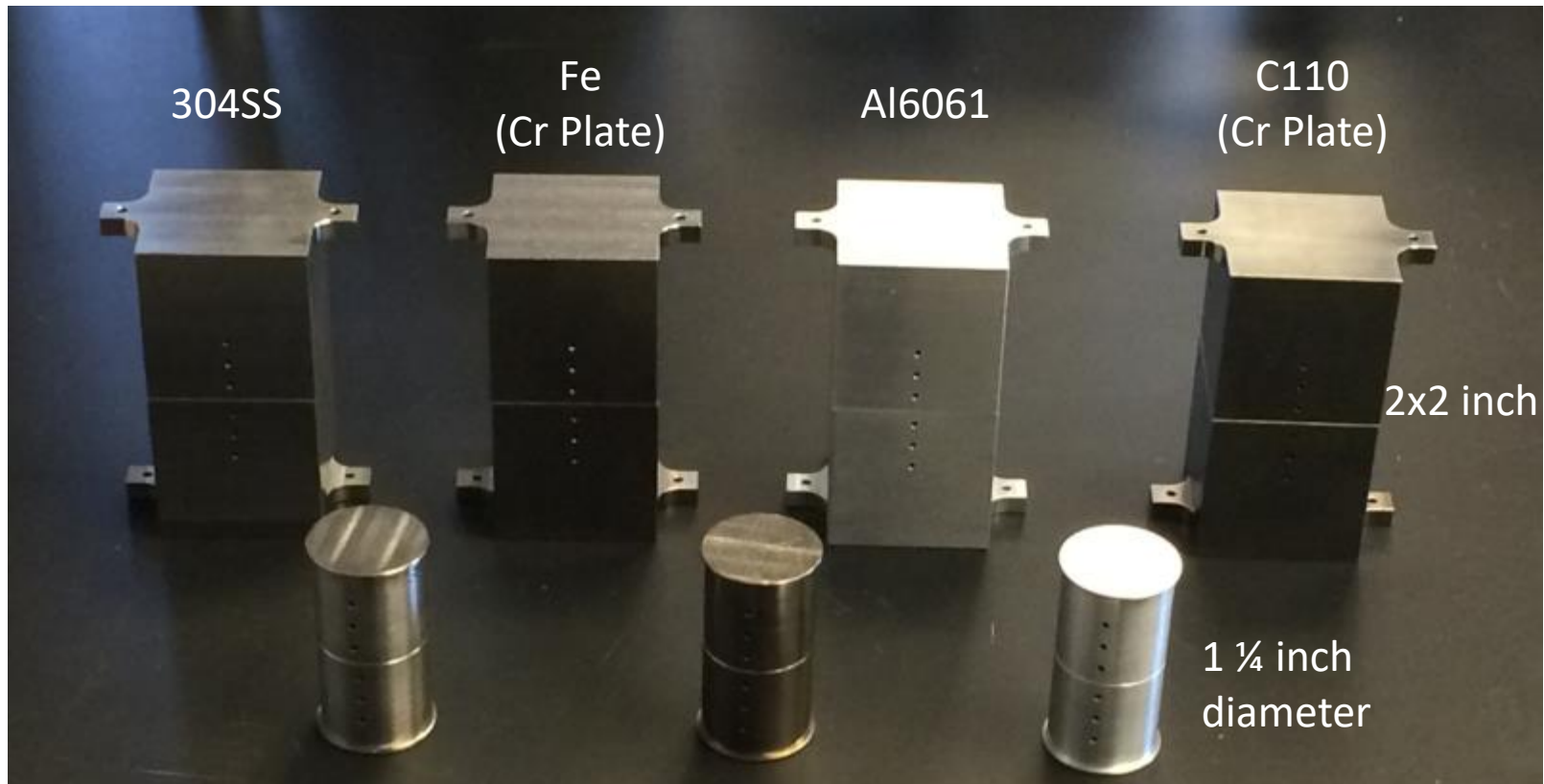
Technical Accomplishments and Progress

- Design analysis summary
 - Spreader block does not benefit design
 - Largest temperature field distortion caused by the mounting tabs
 - Lower thermal conductivity metering blocks improve measurement accuracy for low-conductivity materials



Technical Accomplishments and Progress

- Built measurement metering blocks for square and round cross sections



Technical Accomplishments and Progress

- Designed for evaluating materials up to 200°C
- Accurate control for pressure and displacement
- Improves accuracy over range of materials including high-resistance materials applicable to motor winding and insulation materials



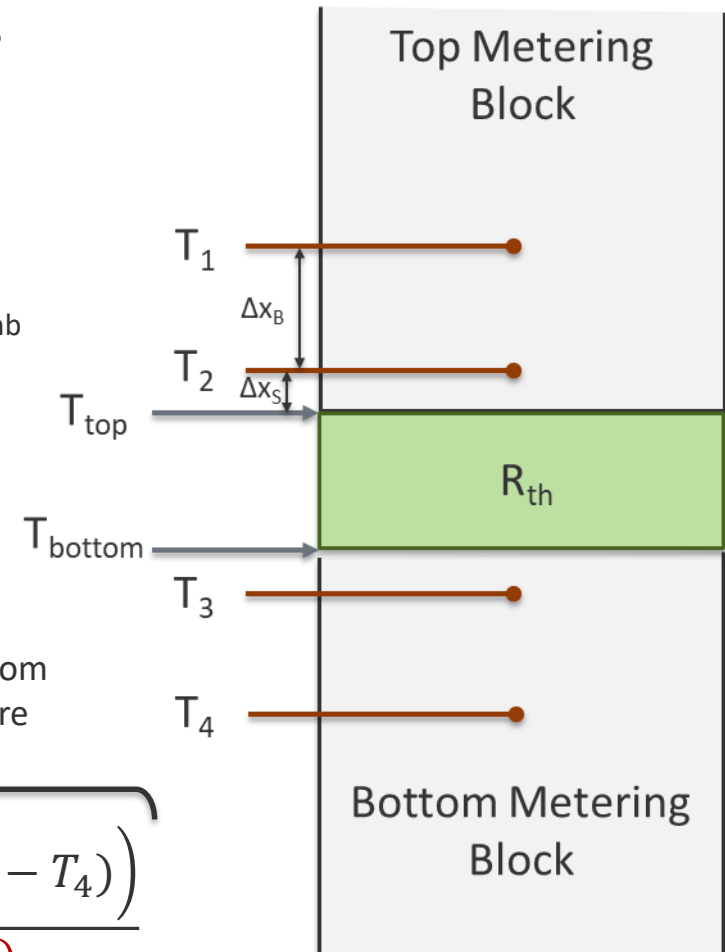
Photo Credit: Emily Cousineau, NREL

Technical Accomplishments and Progress

- Developing robust calibration procedure for calibrating different metering block materials

- R_{th} is the total thermal resistance between T_{top} and T_{bottom}
- Below is the model in terms of directly measured quantities, with one exception: k_{mb}
 - This parameter is critical to accurate measurement
 - Calibration procedure determines k_{mb} utilizing a reference R_{th}

$$R_{th} = 2 \cdot \Delta x_B \frac{\overbrace{\left(T_2 - \frac{\Delta x_S}{\Delta x_B} (T_1 - T_2) \right)}^{\text{Sample top Temperature}} - \overbrace{\left(T_3 + \frac{\Delta x_S}{\Delta x_B} (T_3 - T_4) \right)}^{\text{Sample bottom Temperature}}}{\underbrace{k_{mb} \cdot (T_1 - T_2) + k_{mb} \cdot (T_3 - T_4)}_{\text{Heat Flow}}}$$



Responses to Previous Year Reviewers' Comments

- This is a new project with no reviewer comments

Collaboration and Coordination

- Other Government Laboratories
 - ORNL
 - Collaboration on motor designs and material thermo-mechanical properties
 - NREL support for computational fluid dynamics for fluid flow and heat transfer analysis
 - Ames
 - NREL supporting material thermo-mechanical property measurements
 - Sandia
 - NREL supporting material thermo-mechanical property measurements
- Industry
 - Motor industry suppliers, end users, and researchers
 - NREL providing
 - Experimental data, modeling results, analysis methods
 - Industry providing
 - Information on materials, boundary conditions for experimental and analytical work, and application information

Remaining Challenges and Barriers

- Research enabling compact, reliable, low-cost, 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

- Material thermal conductivity
- Methods to quantify thermal interfaces
- Data for interface thermal resistance
- Reliability measurements to support increased lifetime targets

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

Proposed Future Research

- FY 2019

Winding



Wire size, Type, Insulation,
Impregnation Material

Slot Liner/Ground Insulation



Materials for Wide-Bandgap
(WBG) Inverters

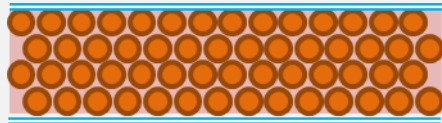
Slot Liner/Ground Insulation to Lamination Interface



Proposed Future Research

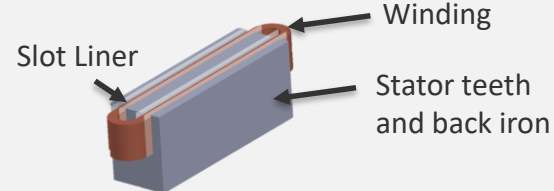
- Beyond FY 2019

Slot Winding Bonded to Slot Liner



Slot Liner to Winding Interface

Motorette



Slot Liner to Stator Interface,
System Validation



Thermal Measurements and Reliability

Temperature Cycles

Vibration Cycles

Voltage Cycles

Photo Credit: Doug DeVoto, NREL

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

Summary

Relevance

- Supports research enabling compact, reliable, low-cost, 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, Ames and Sandia to provide motor thermal analysis support, reliability evaluation, and material measurements on related motor research at National Laboratories
- Develop and document thermal and mechanical characterization methods of material and interface properties

Technical Accomplishments

- Developed experimental hardware for low-thermal-conductivity materials capable of characterization up to 200°C.

Collaborations

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

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Thank You

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