Electric Motor Thermal Management

Kevin Bennion
National Renewable Energy Laboratory
June 2, 2020

DOE Vehicle Technologies Program
2020 Annual Merit Review and Peer Evaluation Meeting

Project ID: ELT214

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2023
- Percent complete: 30%

Budget

- Total project funding: $500K
  - DOE share: $500K
  - Contractor share: $0
- Funding for FY 2019: $250K
- Funding for FY 2020: $250K

Barriers

- Cost, Power Density, Life

Partners

- National Renewable Energy Laboratory (NREL)
  - Lead for thermal and reliability research
- Oak Ridge National Laboratory (ORNL)
  - Motor development, modeling, and material research
- Ames Laboratory
  - Motor material research
- Sandia National Laboratories (SNL)
  - Motor and materials research
- Georgia Institute of Technology
  - Motor thermal management technologies

Relevance

- This project is part of the Electric Drive Technologies (EDT) Consortium and focuses on NREL's role under Keystone 2

Keystone 1

- Power Electronics

Keystone 2

- Electric Motors

Keystone 3

- Traction Drive System

- 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]

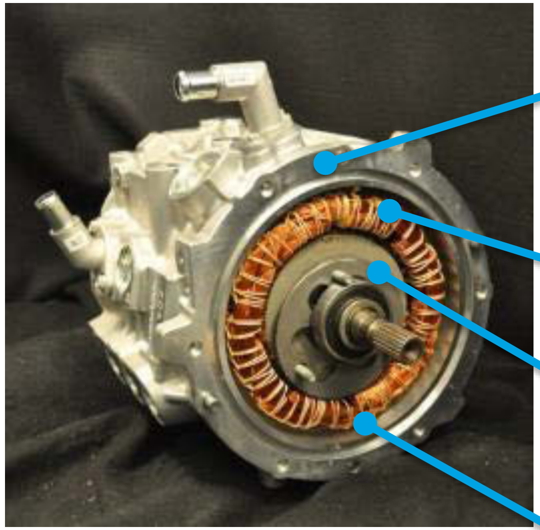
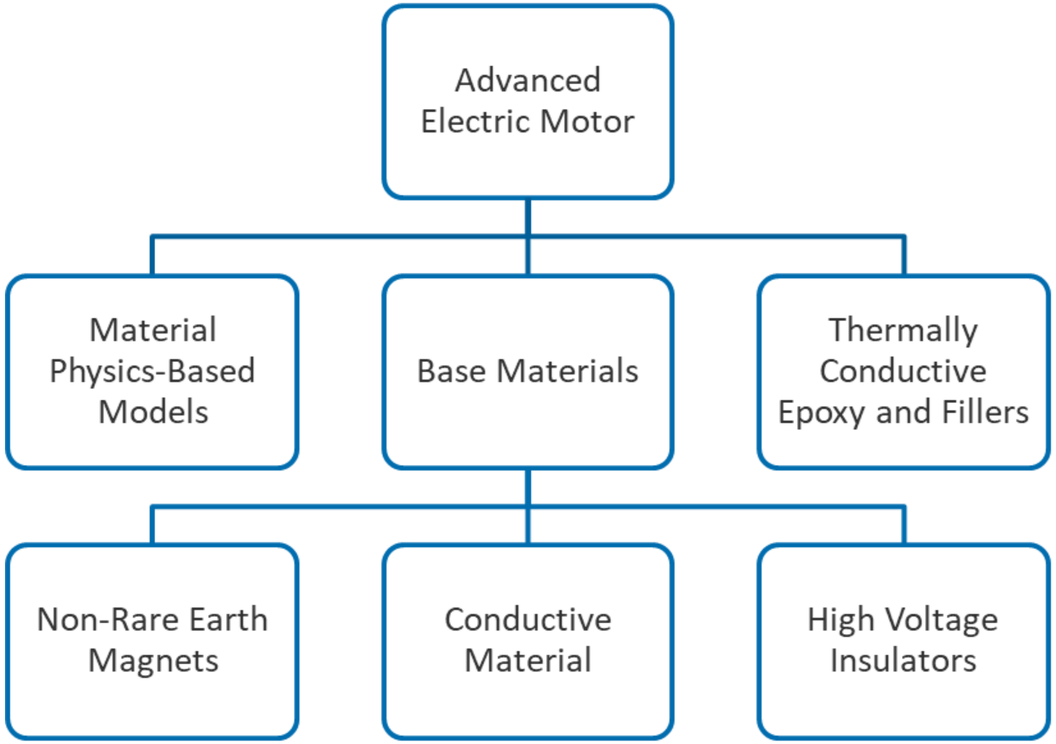


Photo Credit: Kevin Bennion, NREL

[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.

Milestones

Date	Description
December 2019 (Complete)	Milestone • Draft journal paper detailing advancements in ASTM D5470 setup for measuring low thermal conductivity materials such as electric machine winding materials and insulating materials
March 2020 (Complete)	• Preliminary thermal design analysis of initial version of ORNL-led motor development efforts
June 2020 (In Progress)	• Thermal design analysis of revised ORNL-led motor • Preliminary measurements of SNL motor material sample
September 2020 (In Progress)	Milestone • Prepare report on research results

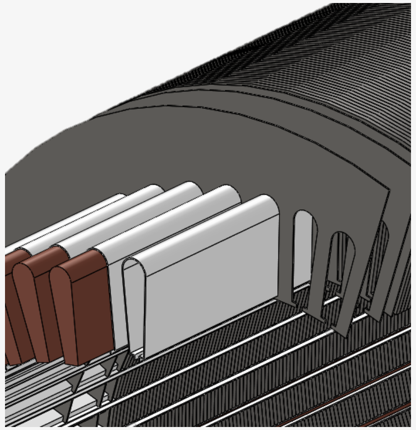
Approach

Electric Drive Technologies Consortium Team Members

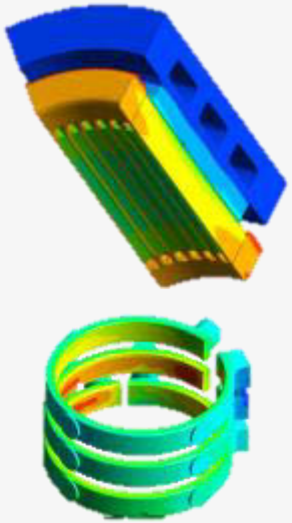
NREL-Led Thermal Management Research

Material and Interface Thermal and Mechanical Characterization


a



Motor System Thermal Analysis Support




b

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

Approach

Material and Interface Thermal and Mechanical Characterization

Setup for material and interface characterization up to 200°C

Photo Credit: Emily Cousineau, NREL

Slot Insulation

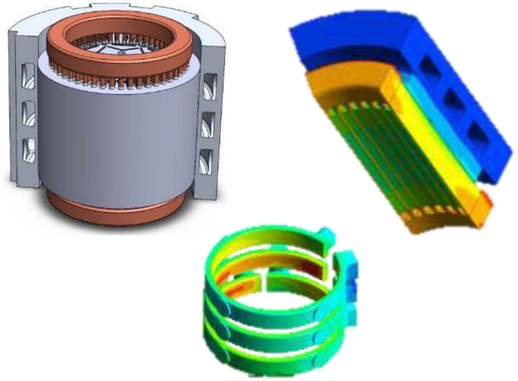
- Bulk property measurements of slot-liner materials
  - Thermal conductivity between 50°C–200°C
- Unbonded interface thermal contact resistance (50°C–200°C)

- Collaboration with Sandia National Laboratories to support mechanical and thermal measurements of new motor materials

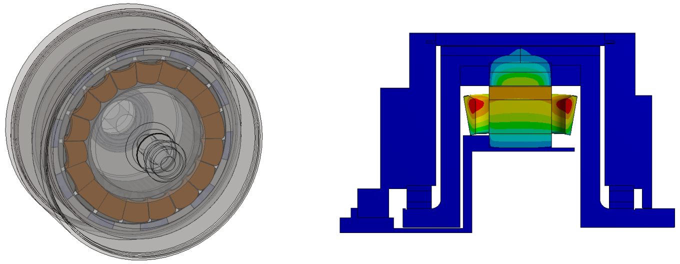
*Note: Measurement equipment design and approach summarized in FY 2019 Annual Merit Review presentation.

Approach

Motor System Thermal Analysis Support



- Collaboration with Georgia Institute of Technology to support research efforts at Georgia Institute of Technology for advanced convective heat-transfer technologies for electric machines
  - NREL providing technical support, geometry data, thermal modeling data, and experimental data to support evaluations of advanced cooling impacts



- Collaboration with Oak Ridge National Laboratory (ORNL) to support motor thermal analysis and thermal design of advanced machine design led by ORNL
  - Providing thermal design support to support iterative electric machine design process led by ORNL

Photo Credit: Gilbert Moreno and Emily Cousineau, NREL

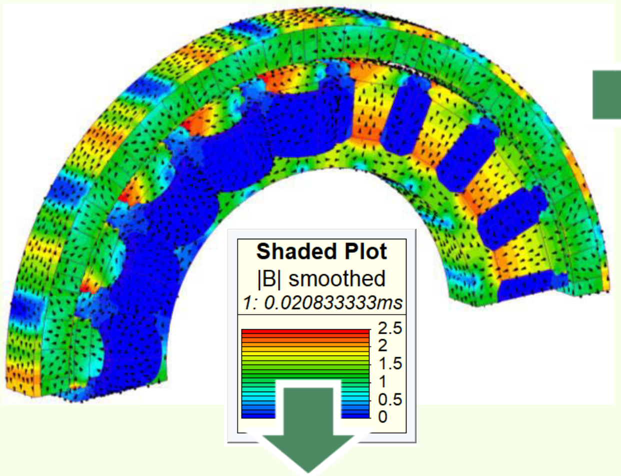
Technical Accomplishments and Progress

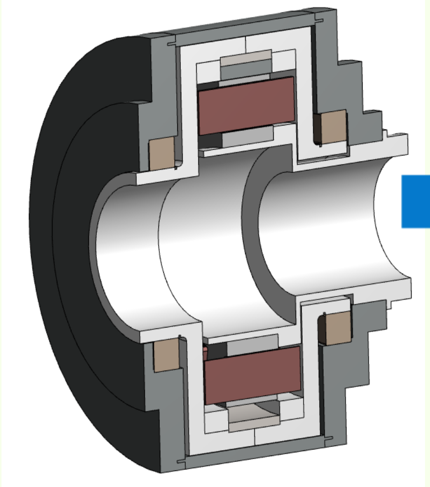
Electromagnetic, Mechanical and Thermal Design

ELT212 ORNL

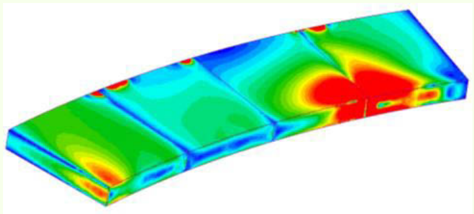
Mechanical assembly design

Electromagnetic design

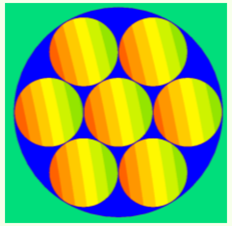




Loss evaluation



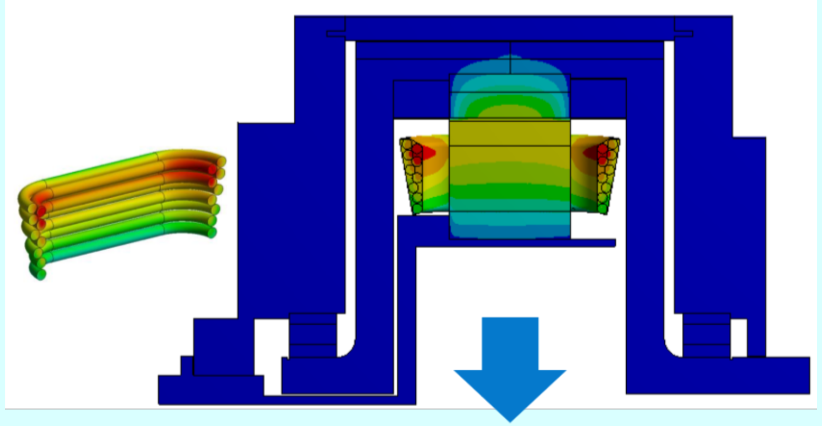
PM eddy current loss



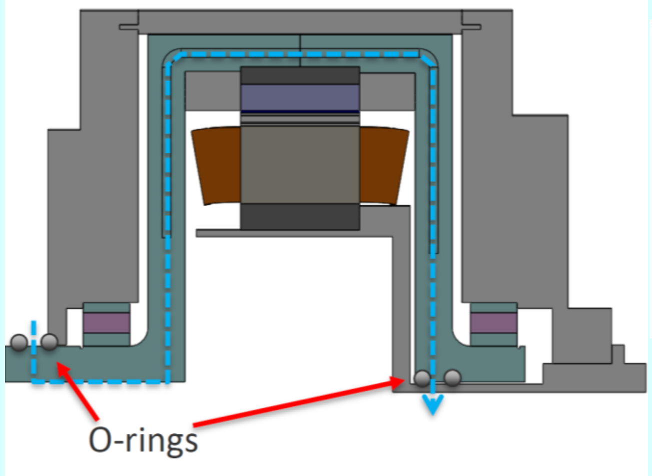
AC loss in Litz wire winding

ELT214 NREL

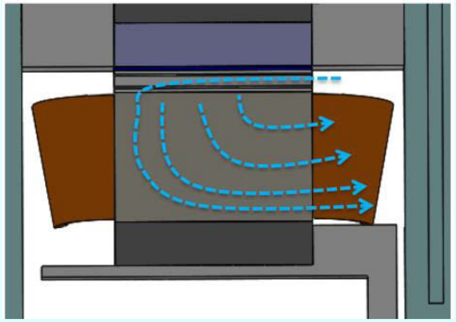
Thermal modeling



Cooling design



Rotor cooling

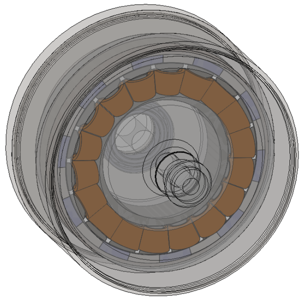


Slot heat exchanger

Technical Accomplishments and Progress

Motor Electromagnetic Analysis and Design (ORNL)

Motor Mechanical Analysis and Design (ORNL)



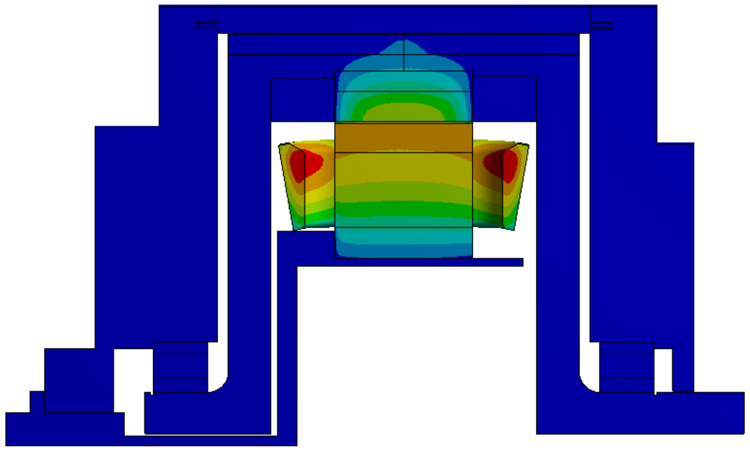
Materials, Geometry, Heat Loads, and Temperature Limits

Motor Thermal Analysis and Design (NREL)

1. Preliminary thermal analysis to quantify critical thermal hot spots versus machine operating conditions

2. Quantify impacts and tradeoffs of alternative material selections
   - Potting materials
   - Lamination materials

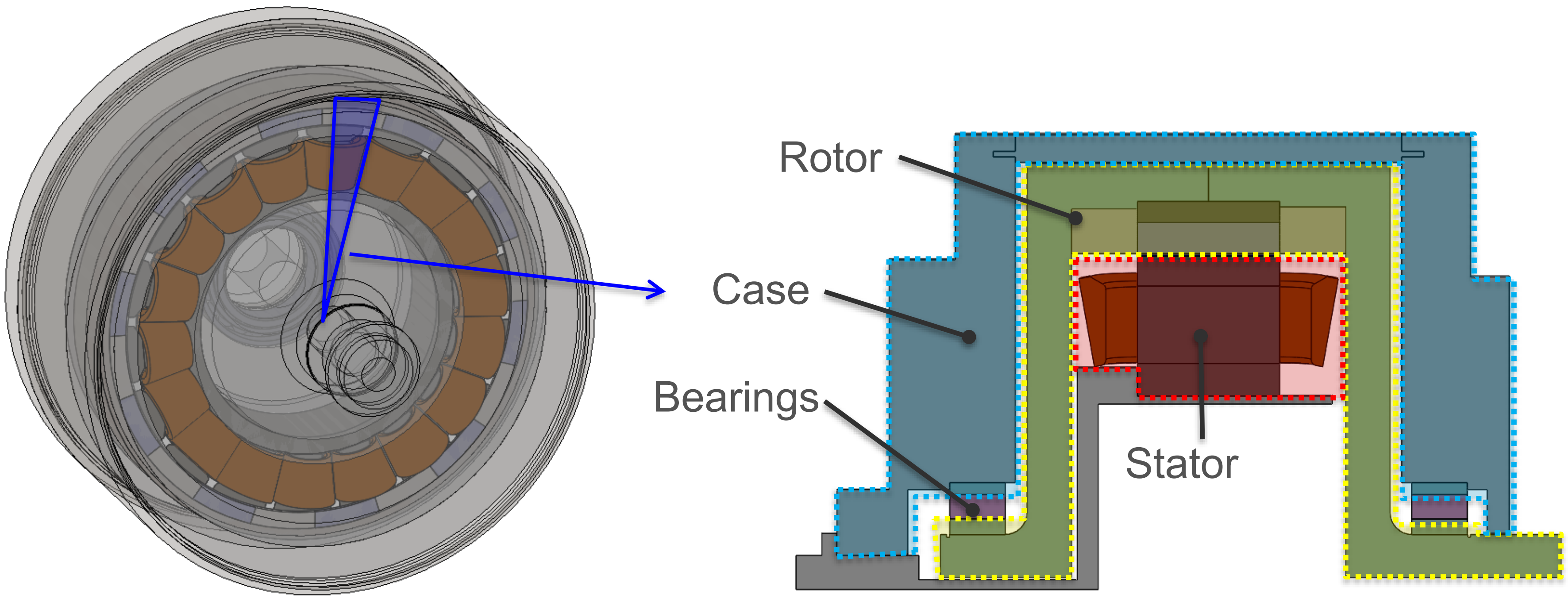
3. Quantify active cooling performance requirements to mitigate critical hot spots and operating conditions
   - Cooling location
   - Heat transfer coefficient



Thermal analysis tradeoff studies

Technical Accomplishments and Progress

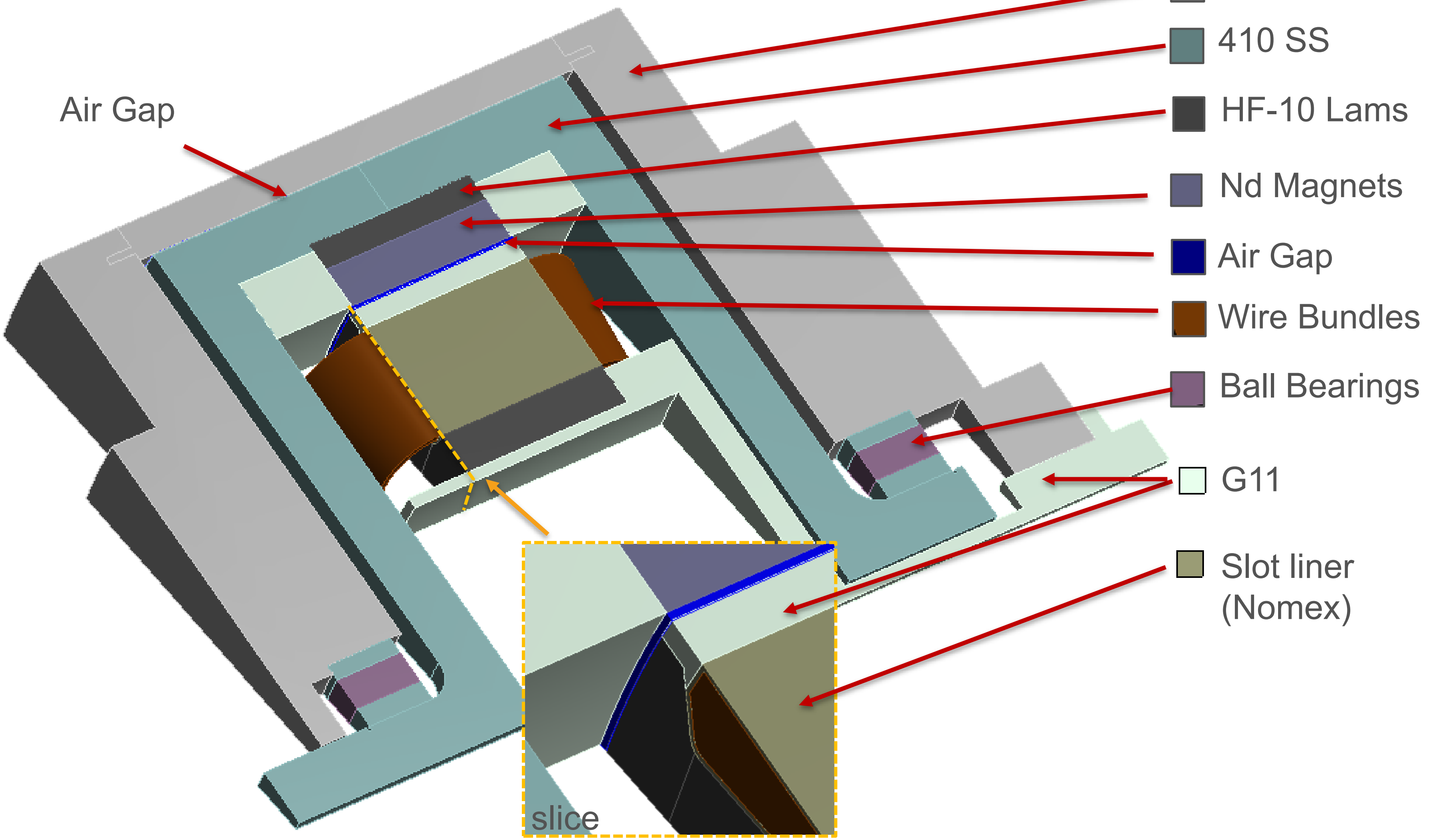
Outer Rotor Motor Description (Version 1)



- Design led by Oak Ridge National Laboratory (ORNL)
- Maximum rated speed 20,000 rpm
  - 55-kW continuous power
  - 100-kW peak power
- NREL supporting thermal analysis and design research

Technical Accomplishments and Progress

Model Materials (Version 1)



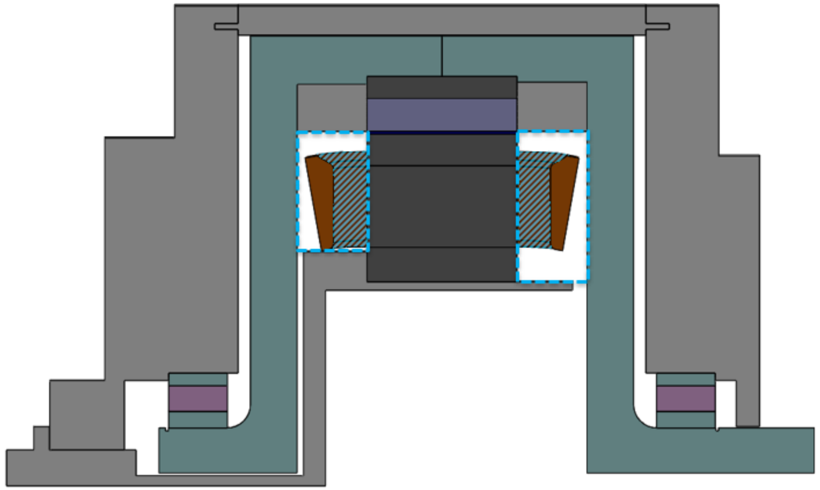
Technical Accomplishments and Progress

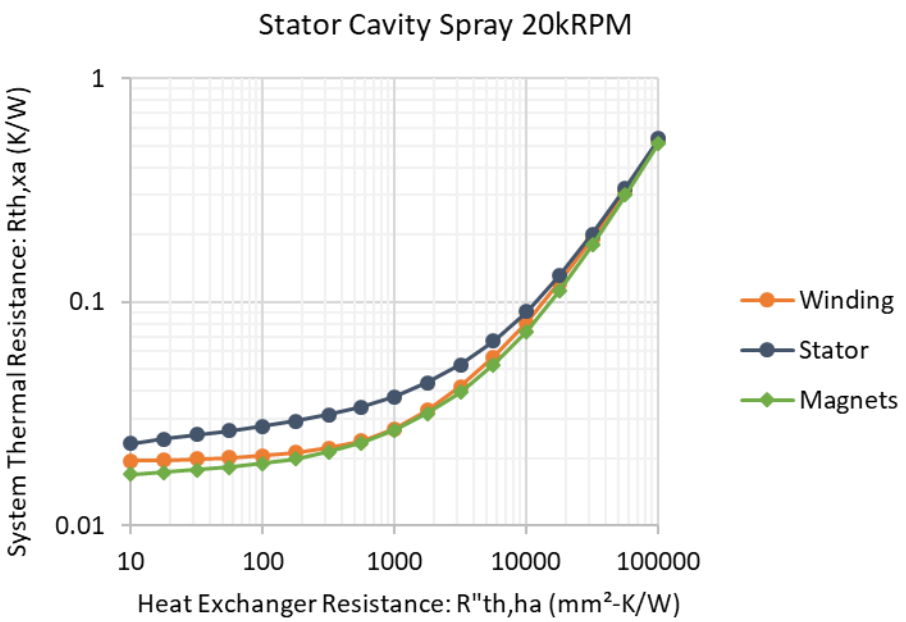
Preliminary Thermal Analysis (Version 1)

- Stator cavity cooling
  - Simulates impingement cooling on all surfaces of stator cavity around the end winding
  - Intended to reveal hot spots in the motor

- Plot shows component (x) to ambient (a) thermal resistance (Rth,xa) versus heat exchanger (R"th,ha) thermal resistance
  - System performance gains reduce when heat exchanger performance reaches 111 mm²·K/W

Stator Cavity Cooling



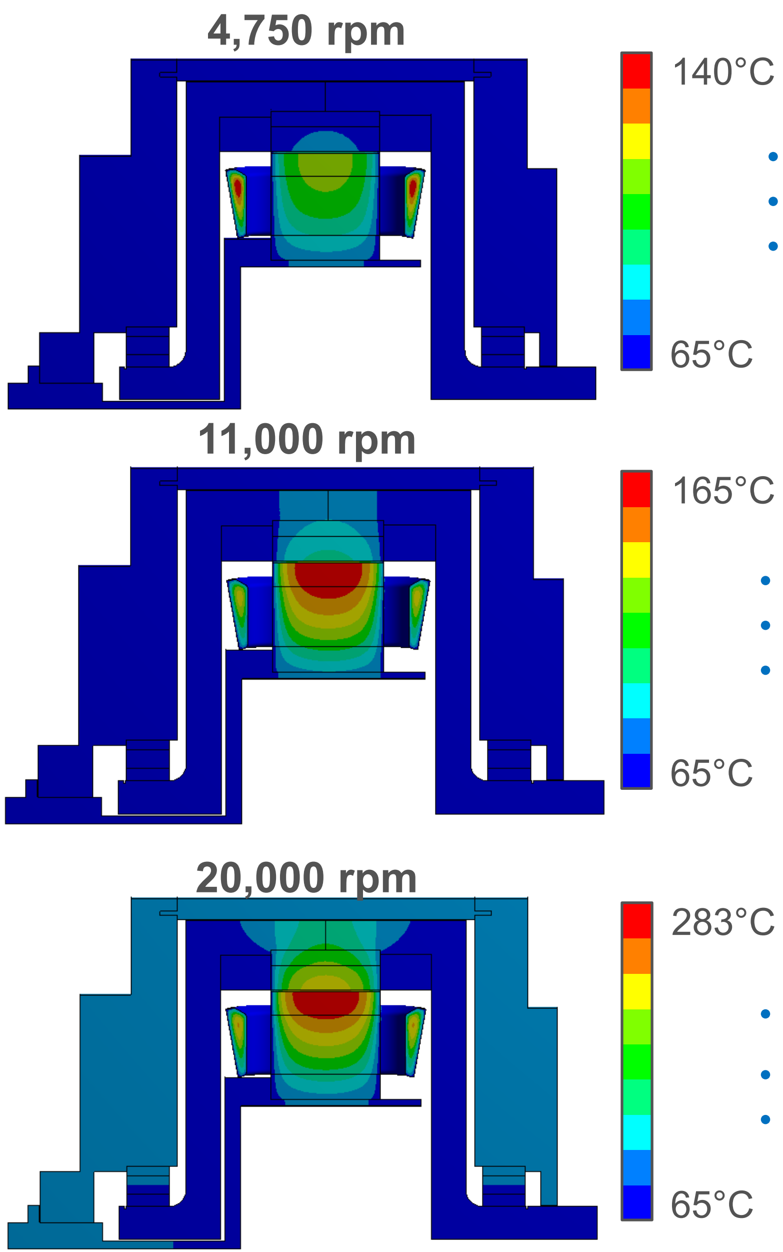


Technical Accomplishments and Progress

Preliminary Thermal Analysis (Version 1)

- Stator cavity cooling with Rth”,ha = 111 mm²·K/W (very aggressive impingement cooling), 65°C coolant temperature
- Analyzed motor at 6 speeds (3 shown)
- 20,000 rpm results in highest heat loads and temperatures for all components
- Hot spots in motor identified in windings and stator shoe

- A combination of passive and active thermal management approaches needed
  - Winding hot spot requires effective passive thermal design or direct cooling
  - Rotor requires direct cooling
  - Stator shoe hot spot requires novel thermal management solution



Maximum Temperatures

4,750 rpm:
- Magnets: 75.3°C
- Stator: 110°C
- Windings: 140°C

11,000 rpm:
- Magnets: 101°C
- Stator: 165°C
- Windings: 139°C

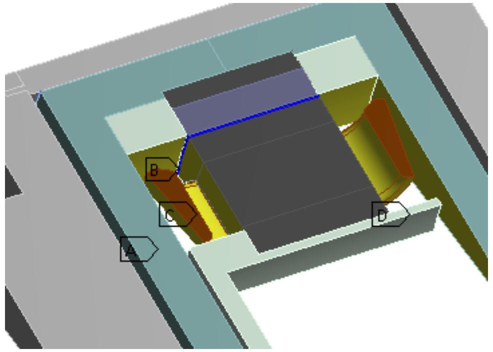
20,000 rpm (Exceed Temperature Requirements):
- Magnets: 234°C
- Stator: 283°C
- Windings: 240°C

Technical Accomplishments and Progress

Preliminary Thermal Analysis (Version 1)

- Winding potting materials
  - Using a commercially available, high-performance (k = 3 W/m·K) potting compound for the winding reduces winding to ambient temperature rise by 40%

- Lamination materials
  - ORNL performed electromagnetic analysis of alternative lamination types to obtain losses
  - NREL performed thermal analysis
    - Thinner lamination materials reduced stator core losses, and Arnon 7 was found to reduce the core losses by 50% compared to the baseline material (HF-10)

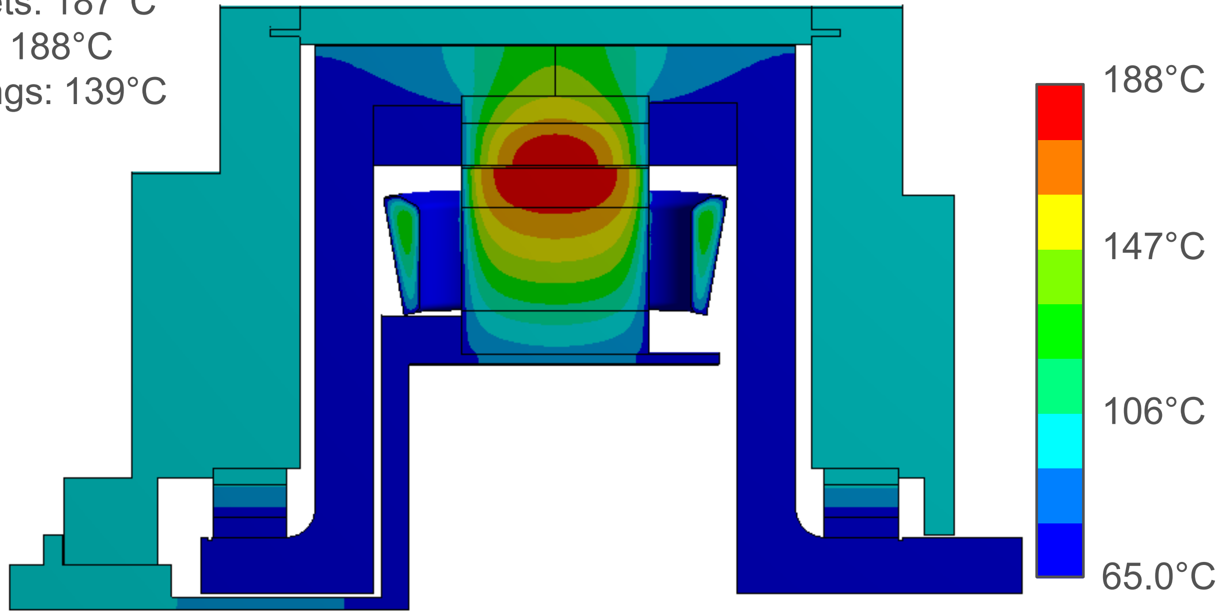


Stator Cavity Cooling

- 20,000 rpm
- Stator cavity cooling
- High-performance potting compound
- Arnon 7 laminations
- Stator cavity cooling with Rth",ha = 111 $mm^2 \cdot K/W$ @ 65°C (highlighted yellow surfaces)

Maximum Temperatures:

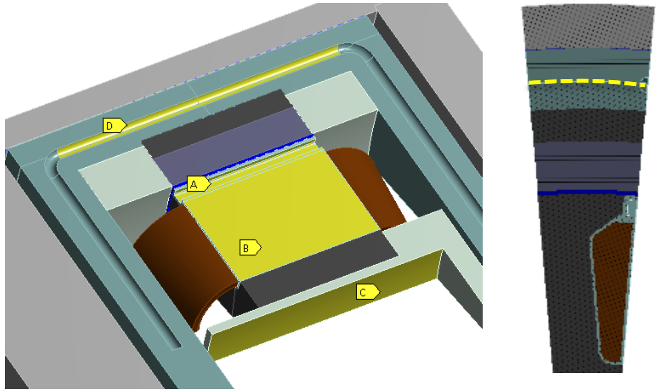
- Magnets: 187°C
- Stator: 188°C
- Windings: 139°C



Technical Accomplishments and Progress

Preliminary Thermal Analysis (Version 1)

- Multiple approaches for machine cooling
  - Oil cooling through the rotor
  - Interior cooling of the stator
  - In-slot cooling for winding and stator teeth
  - High-performance potting compound
  - Arnon 7 laminations

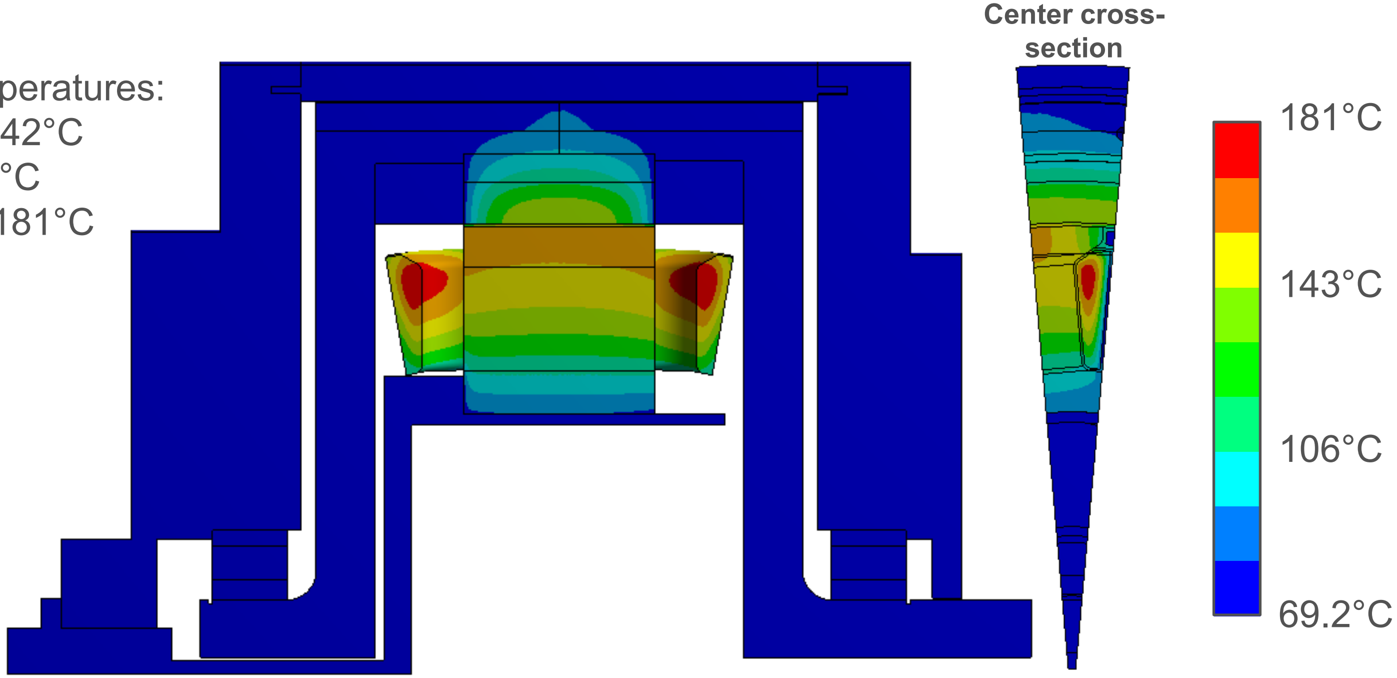


Modified Cooling Approach

Convection Coefficient: 3,000 W/m²·K (333 mm²·K/W) @ 65°C (highlighted yellow surfaces)

Maximum Temperatures:

- Magnets: 142°C
- Stator: 159°C
- Windings: 181°C



- Except for the windings, this design performs better than the aggressive (9,000 W/m²·K) cavity spray cooling technique

Responses to Previous Year Reviewers' Comments

- The reviewer said that it sounds like the collaboration is happening, but it would be nice to see more evidence in the material.
    - *We included more information specific to work with project collaborators in the presentation materials for this year.*

- This reviewer stated that so far, the work is very general. Studying the heat transfer measurement between different materials is explored. While some of these findings can help motor designers to model their motor more accurately, there is much more involved in motor thermal management.
    - *We are working to develop and demonstrate material and interface characterization techniques to better understand material and interface properties that can be applied to a wide range of electric machine designs. In addition to the material and interface characterization techniques, we are working with collaborating partners to support thermal management research and development efforts.*

- This reviewer stated that optimized motor design will require knowing the correct thermal properties of design materials. This work looks to be very well aligned with that need and will provide methods and maybe eventually data on material properties to help designers.
    - *The comment matches the focus in the U.S. DRIVE Electrical and Electronics Technical Team Roadmap. For this reason, we are working to develop confidence in material and interface properties to support optimized electric machine designs*

Collaboration and Coordination

- Other Government Laboratories
  - ORNL
    - —NREL collaborating on electric motor design efforts led by ORNL
    - —NREL supporting thermal modeling and simulation analysis for motor and material performance tradeoff studies
  - Sandia National Laboratories (SNL)
    - —NREL supporting material thermal and mechanical property measurements for material research efforts led by SNL
  - Ames Laboratory
    - —NREL continuing discussions with Ames to support material characterization efforts led by Ames Laboratory
- Universities
  - Georgia Institute of Technology
    - —NREL collaborating with Georgia Institute of Technology to support research efforts at Georgia Institute of Technology for advanced convective heat transfer technologies for electric machines
    - —NREL providing technical support, geometry data, thermal modeling data, and experimental data to support evaluations of advanced cooling impacts.

Remaining Challenges and Barriers

Electric Drive Technologies Consortium Team Members

NREL-Led Thermal Management Research

Material and Interface Thermal and Mechanical Characterization	Motor System Thermal Analysis Support
• Material thermal conductivity • Methods to quantify thermal interfaces • Data for interface thermal resistance • Reliability measurements to support increased lifetime targets	• Cooling approaches to support hot-spot cooling within electric motor design with ORNL

Proposed Future Research

- FY 2020
  - Bulk property measurements of slot-liner materials
    - —Thermal conductivity between 50°C–200°C

Slot Insulation

  - Unbonded interface thermal contact resistance (50°C–200°C)

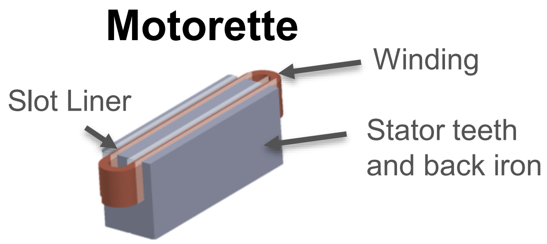
  - Complete thermal measurements for SNL-developed materials

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

Proposed Future Research

- Beyond FY 2020
  - Bonded interface thermal contact resistance (50°C–200°C)
    - — Typically varnish infiltrates into the slot liner and often into the laminations, impacting the contact resistance between these parts

  - System thermal validation and reliability
    - — Slot Liner to Stator Interface, System Validation



Temperature Cycles

Vibration 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 SNL 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

- NREL collaborating with Sandia National Laboratories to support mechanical and thermal measurements of new motor materials
- NREL providing technical support, geometry data, thermal modeling data, and experimental data to Georgia Institute of Technology to support evaluations of advanced cooling impacts
- NREL providing thermal design support to support iterative electric machine design process led by ORNL

Collaborations

- Oak Ridge National Laboratory
- Ames Laboratory
- Sandia National Laboratories
- Georgia Institute of Technology

Acknowledgments

Susan Rogers, U.S. Department of Energy

NREL EDT Task Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: 303-275-4062

Team Members

Emily Cousineau, Doug DeVoto, Xuhui Feng, Bidzina Kekelia, Josh Major, Jeff Tomerlin (NREL)

Tsarafidy Raminosoa, Randy Wiles (ORNL)

Iver Anderson, Matt Kramer (Ames Laboratory)

Todd Monson (SNL)

Sebastien Sequeira, Yogendra Joshi, Satish Kumar (Georgia Institute of Technology)

For more information, contact:

Principal Investigator
Kevin Bennion
Kevin.Bennion@nrel.gov
Phone: 303-275-4447

Thank You

www.nrel.gov

NREL/PR-5400-76670

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL Transforming ENERGY