Electric Motor Thermal Management




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National Renewable Energy Laboratory
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Overview

Timeline

Project Start Date: FY 2010

Project End Date: FY 2013

Percent Complete: 60%

Barriers and Targets

- **Cost**
- **Weight**
- **Performance & Life**

Budget

Total Project Funding:

DOE Share:$1,275K (FY10-FY12)

Funding Received in FY11: $450K

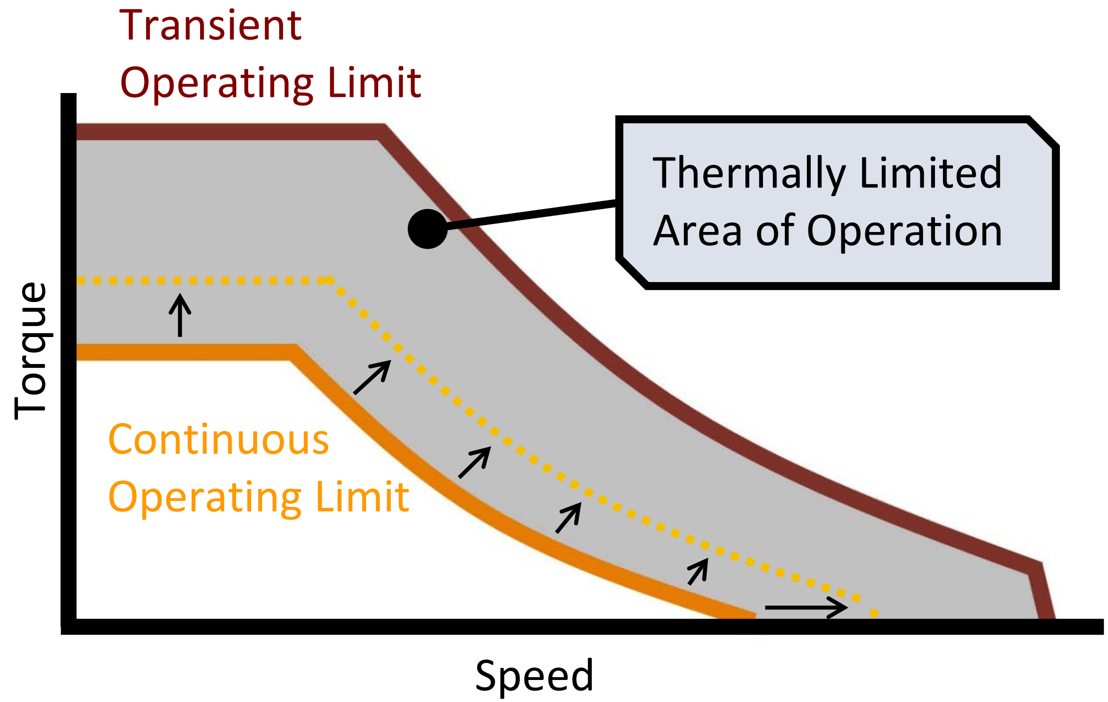
Funding for FY12: $425K

Partners

- Interactions / Collaborations
  - University of Wisconsin (UW) – Madison (Thomas M. Jahns)
  - Oak Ridge National Laboratory (ORNL)
  - Motor Industry Representatives
- Project Lead
  - National Renewable Energy Laboratory

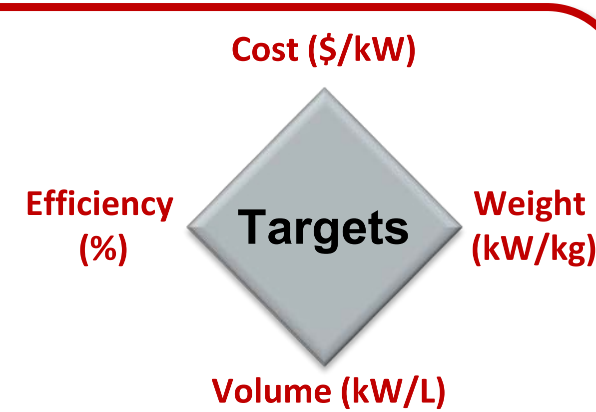
Relevance/Objectives

The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems.



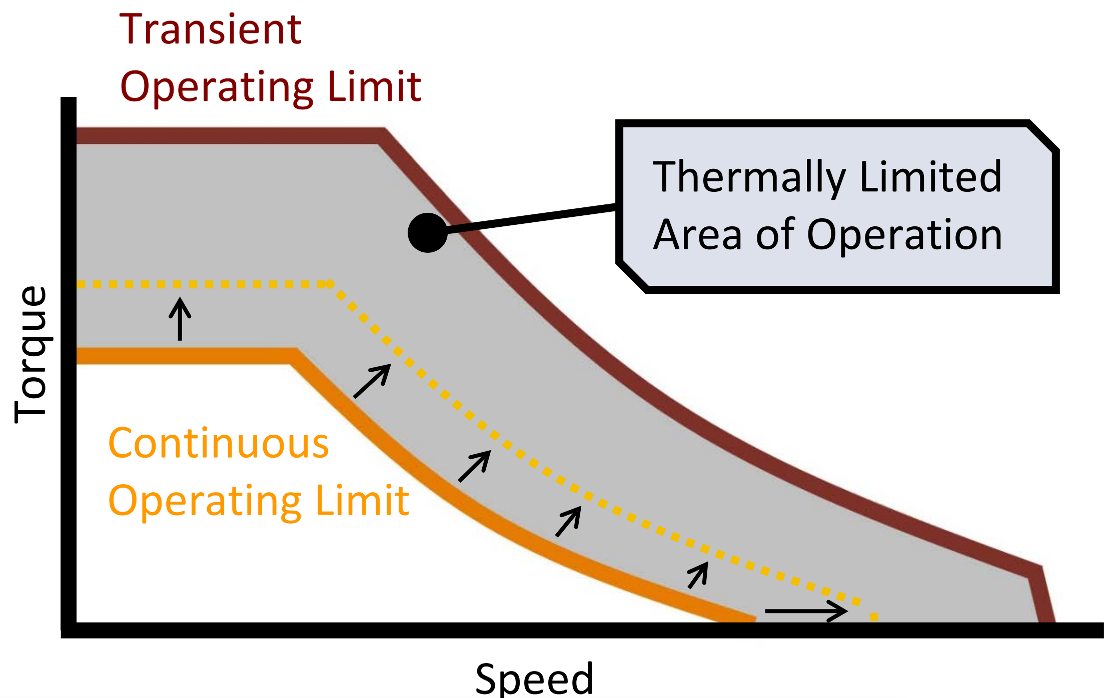
Thermal management is needed to reduce size and improve performance of electric motors.

- Meet/improve power capability within cost/efficiency constraints
- Reduce rare earth material costs (dysprosium)



Relevance/Objectives

The transition to more electrically dominant propulsion systems leads to higher-power duty cycles for electric drive systems.



Objectives

- Quantify opportunities for improving cooling technologies for electric motors
- Link thermal improvements to their impact on Advanced Power Electronics and Electric Motors (APEEM) targets
- Increase publicly available information related to motor thermal management

Addresses Targets

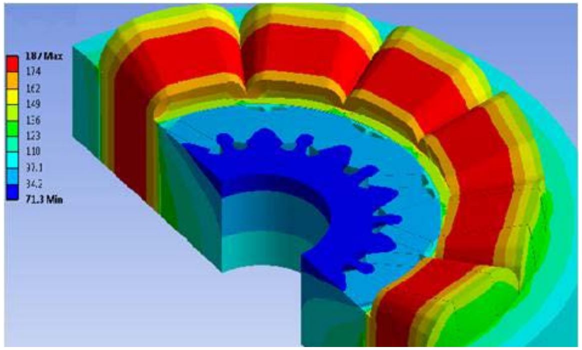
- Translates cooling performance improvements into impacts on program targets
- Prioritizes motor thermal management efforts based on areas of most impact

Milestones

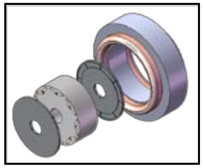
Date	Milestone or Go / No-Go Decision Point
Oct. 2011	Milestone report • Analytical and 3D finite element analysis (FEA) models for determining effective conductivity of composite materials as applied specifically to motor slot windings • Results of initial thermal property testing of motor lamination materials • Method of evaluating loss distributions within the electric motor for different operating conditions (in collaboration with University of Wisconsin – Madison) • Development of stator thermal model validated against published data • Parameter sensitivity study of thermal design factors for motor stator cooling
Jan. 2012	Go/No-Go • Completed selected motor lamination material thermal property tests • Decided to not expand material tests at this time Milestone (intermediate) • Completed thermal sensitivity analysis for interior permanent magnet (IPM) motor stator and rotor utilizing test data provided by ORNL
Jul. 2012	Go/No-Go • Thermal sensitivity analysis shows significant impact common to multiple motor configurations leading to future project proposals for specific cooling enhancements
Sept. 2012	Milestone report • Lamination material thermal properties, motor thermal sensitivity analysis, and oil heat transfer experimental data

Approach/Strategy

- Complete thermal FEA and lumped parameter thermal models for cooling parameter sensitivity analysis (UW, NREL)
- Complete material thermal property tests (NREL)



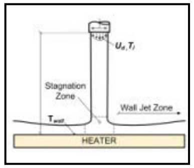
Courtesy of T. M. Jahns / S. McElhinney, UW - Madison

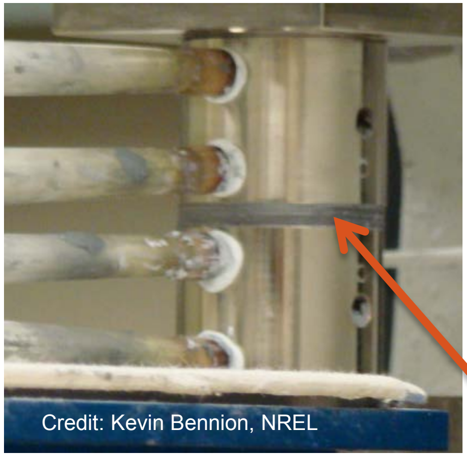


Package Mechanical Design

Thermal Design Targets

Cooling Technology Selection





Credit: Kevin Bennion, NREL

Lamination Stack

- Characterize fundamental oil-cooling heat transfer performance
- Initiate experiments to identify cooling limitations (durability)

Approach/Strategy

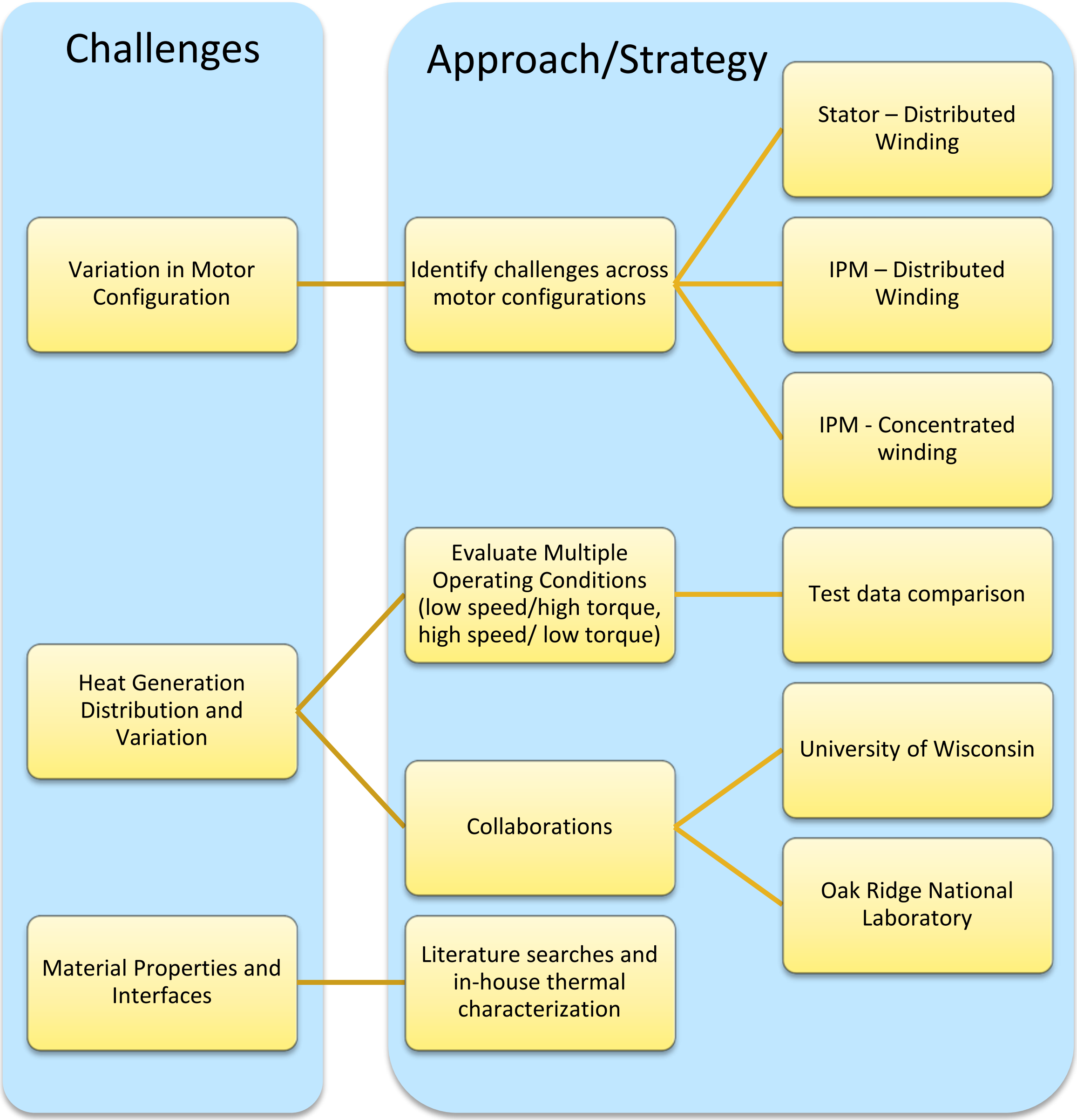
Motor thermal analysis is a challenge

- Complicated
- Many unknowns

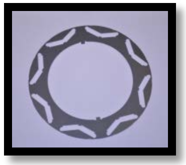
Absolute results of analysis could change, but the goal is to identify trends for improvements in motors

Try to make intelligent choices to ensure quality:

- Results not focused on single motor design
- Assumptions and results compared to published literature
- Model results compared against test data
- Collaborations with motor designers
- Component testing



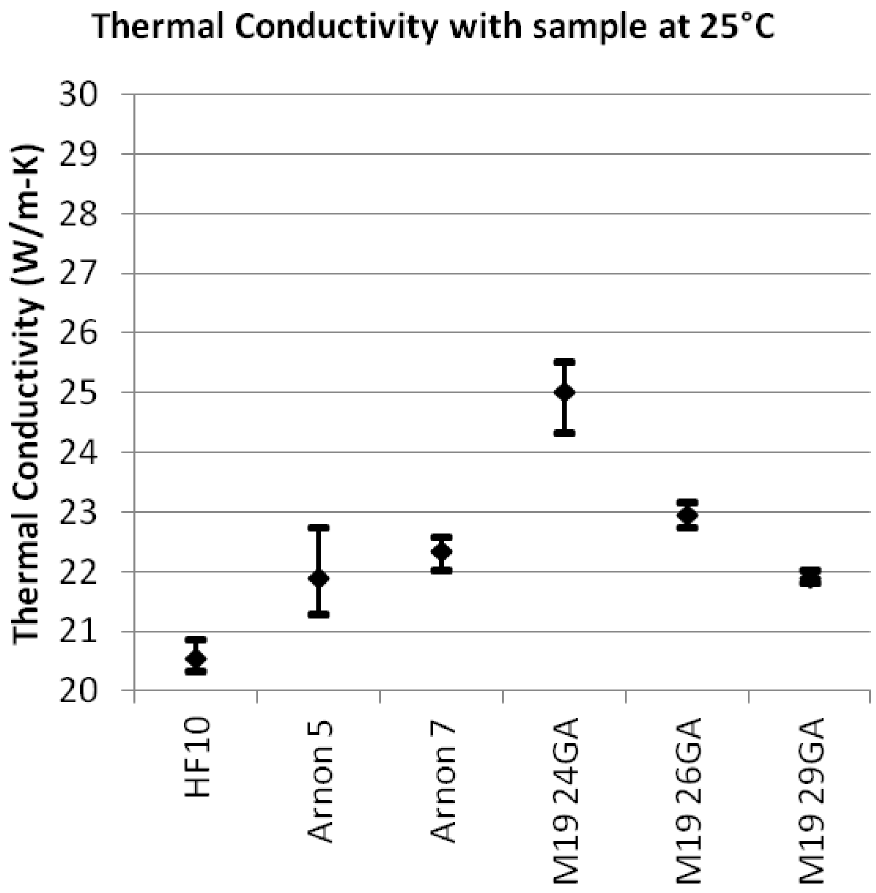
Technical Accomplishments and Progress



Lamination
Material Tests

Measured bulk thermal conductivity of lamination materials

- Tests performed with Xenon Flash equipment
- Four samples of each material tested
- General data for silicon steels lists the thermal conductivity to be between 20-30 W/m-K [1].

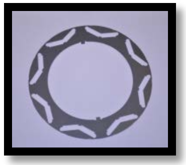


Data range from four samples of each material

[1] J. R. Hendershot and T. J. E. Miller, "Design of brushless permanent-magnet motors." *Magna Physics Pub.*, 1994.

All Images - Credit: Kevin Bennion, NREL

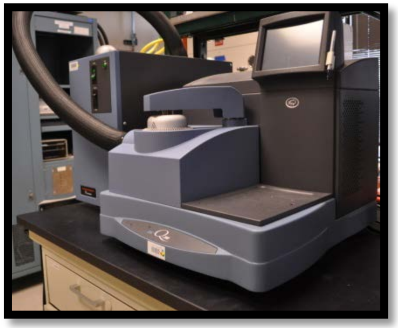
Technical Accomplishments and Progress

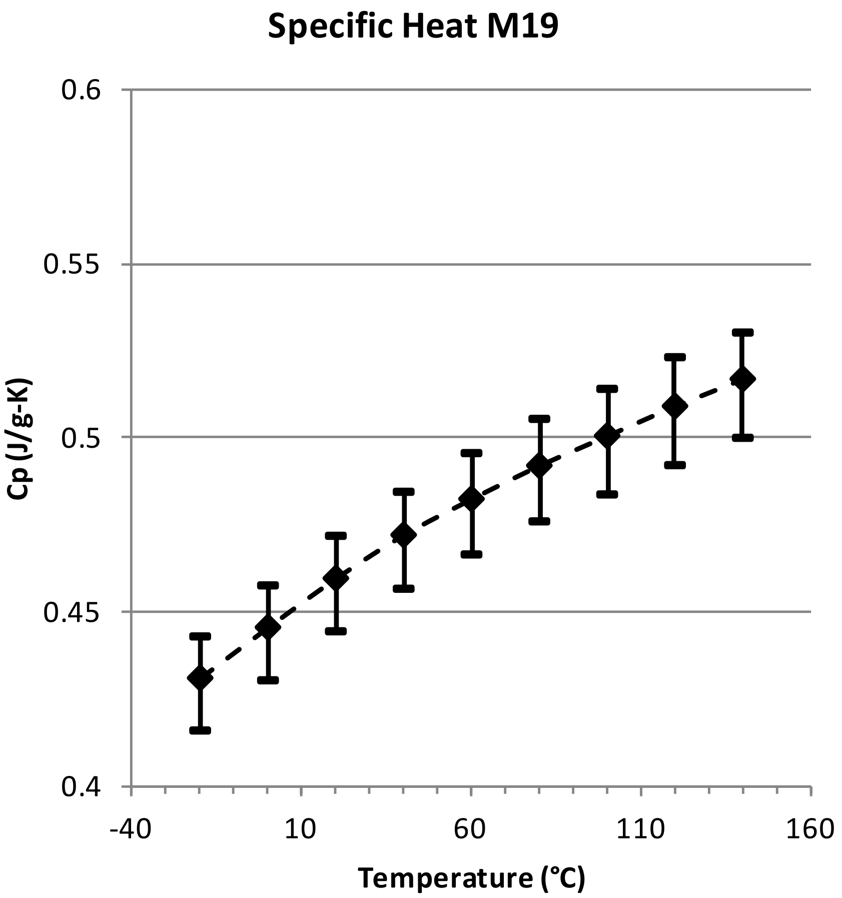


Lamination
Material Tests

Measured specific heat of lamination materials

- Tests performed with differential scanning calorimeter
- Two samples of each material tested
- Provides data for specific heat over a range of temperatures
- Generally available data for silicon steels list the specific heat to be 0.49 J/(g-K) [1].





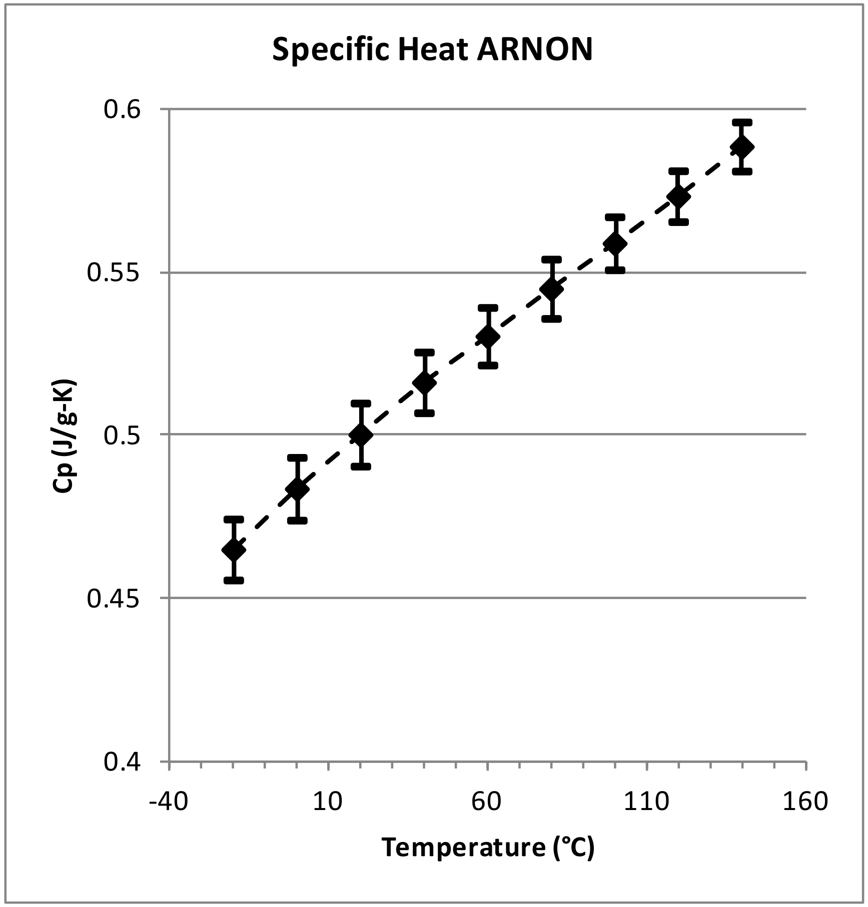
Data range from two samples of each material (two of each thickness)

[1] J. R. Hendershot and T. J. E. Miller, "Design of brushless permanent-magnet motors." *Magna Physics Pub.,* 1994.

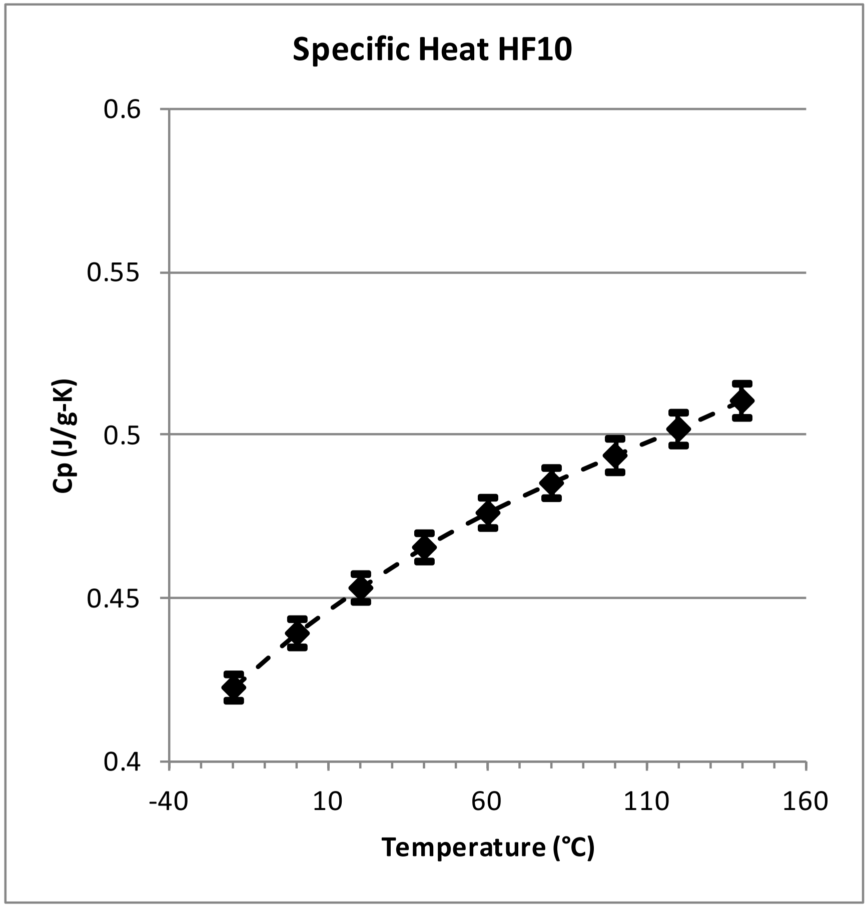
All Images - Credit: Kevin Bennion, NREL

Technical Accomplishments and Progress

Additional specific heat measurements for sample materials



Data range from two samples of each material

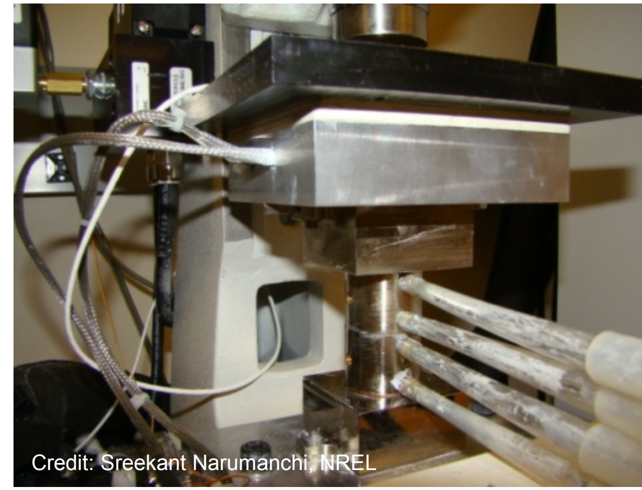


Data range from two samples of each material

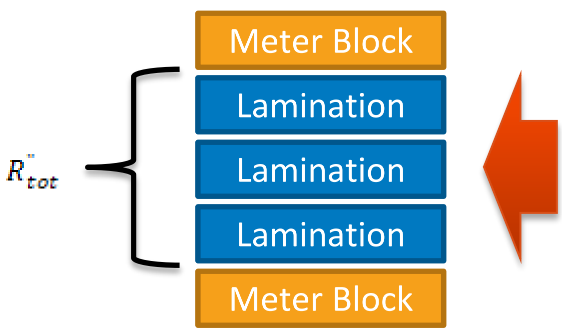
Technical Accomplishments and Progress

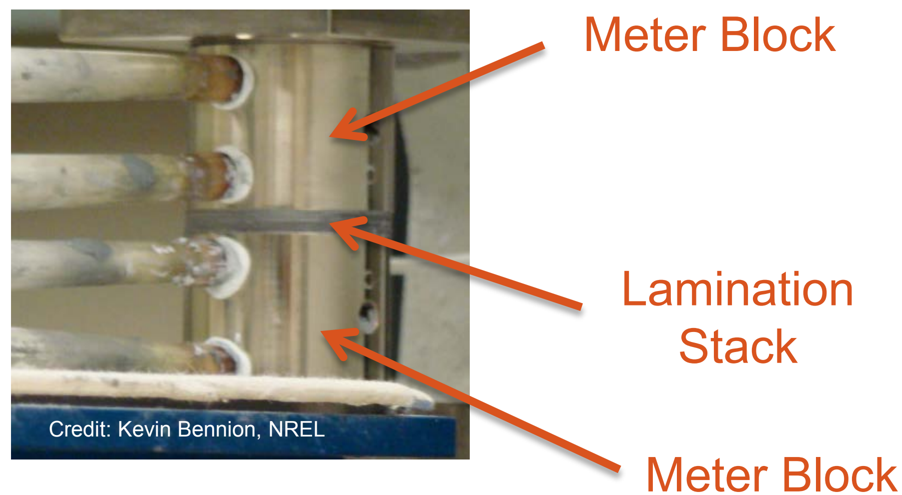
Quantified thermal contact resistance between laminations

- Tests performed with ASTM interface test stand
- Tested at multiple pressures and lamination layer counts
- Data used to approximate effective cross lamination thermal conductivity
- Data support modeling activities
- Expands publicly available data



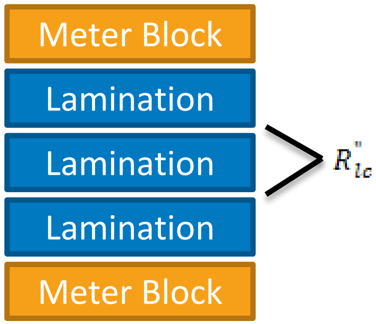
Measure total thermal resistance of lamination stack

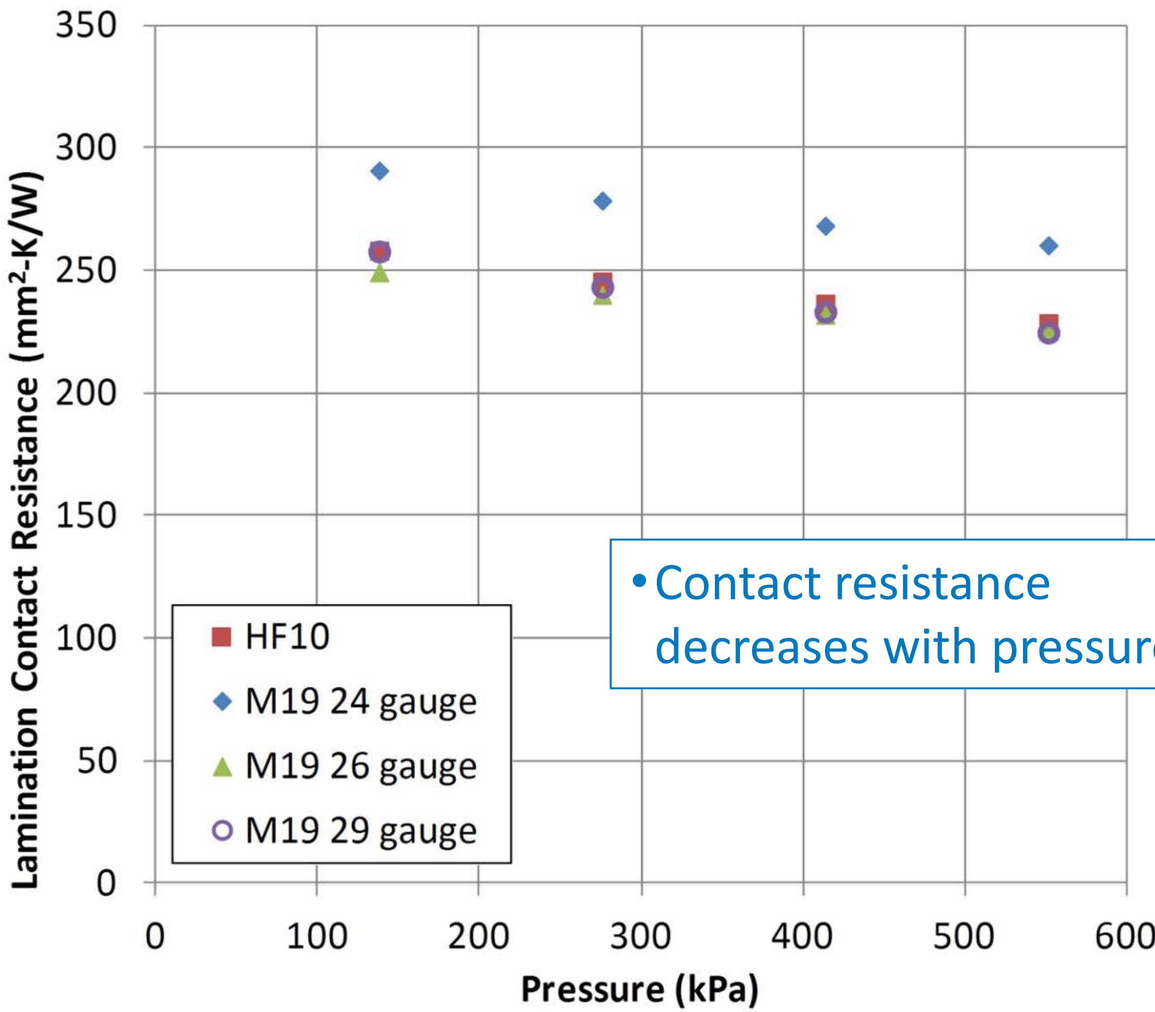




Technical Accomplishments and Progress

Calculated contact resistance from measured bulk material properties and lamination stack resistance measurements

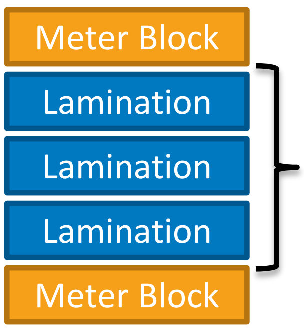


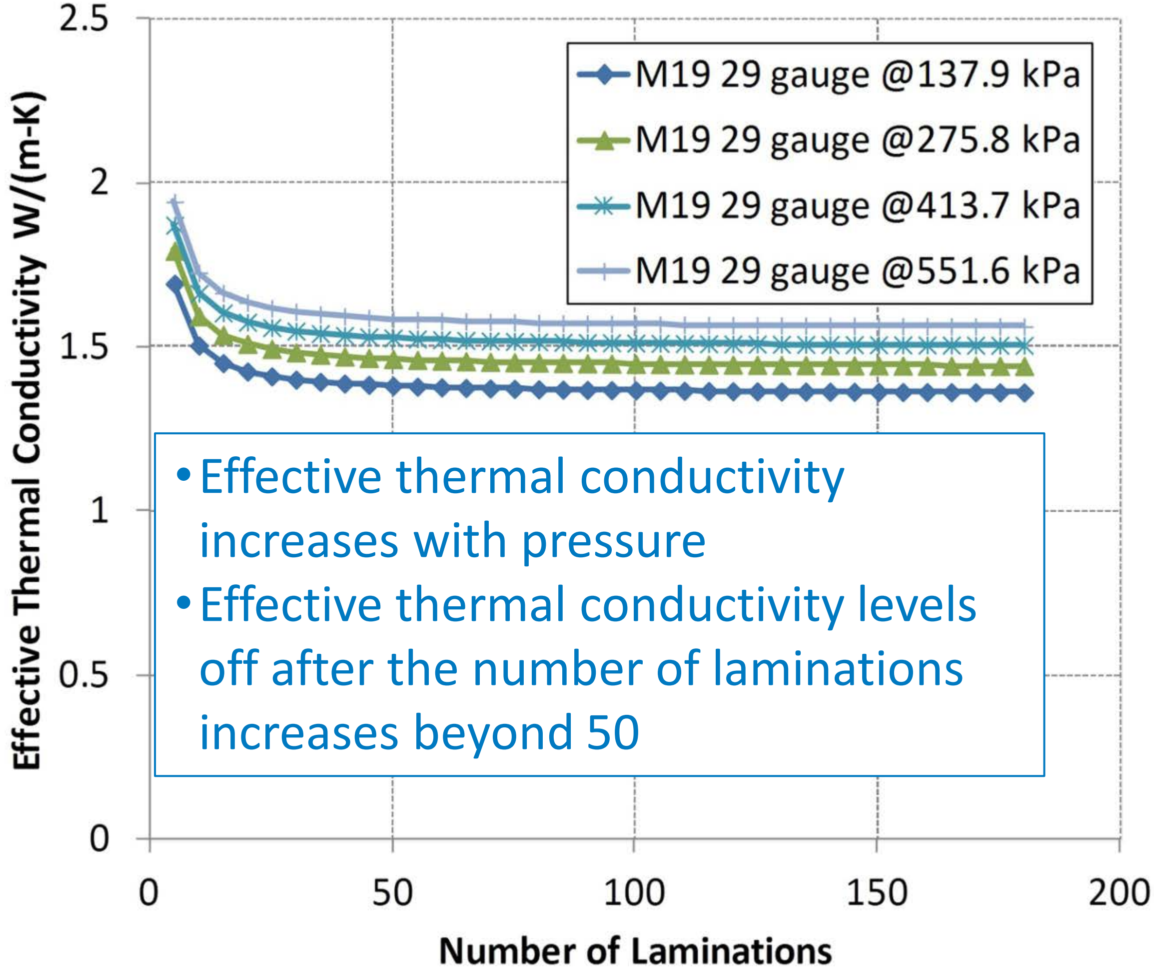


- Contact resistance decreases with pressure

Technical Accomplishments and Progress

Calculated effective conductivity from measured bulk material properties and lamination-to-lamination contact resistance



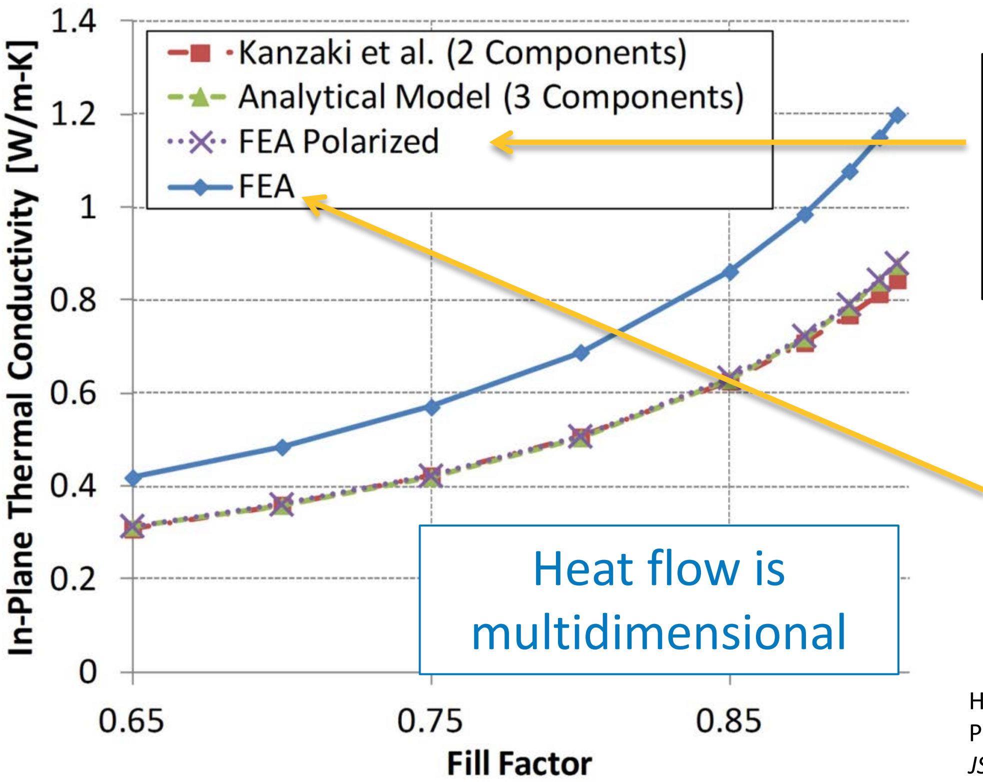


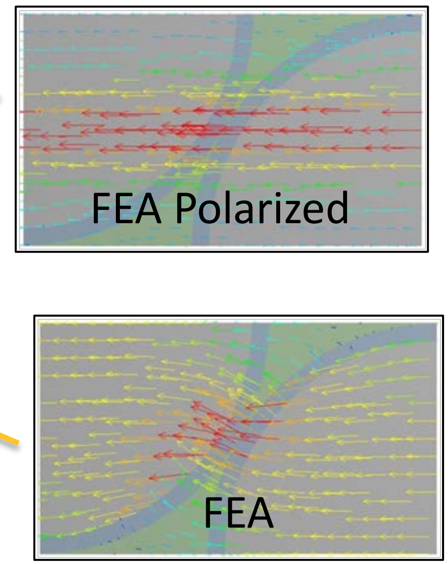
- Effective thermal conductivity increases with pressure
- Effective thermal conductivity levels off after the number of laminations increases beyond 50

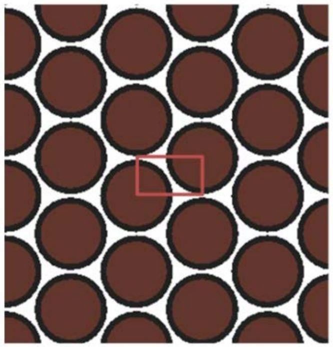
Technical Accomplishments and Progress

Quantified thermal properties for slot windings

- Expanded on published analytical methods to include wire, filler material, and insulation material (3-component analytical model)
- Developed parametric FEA modeling capabilities to characterize multi-dimensional heat spreading effect across slot windings
- Supports motor thermal modeling activities







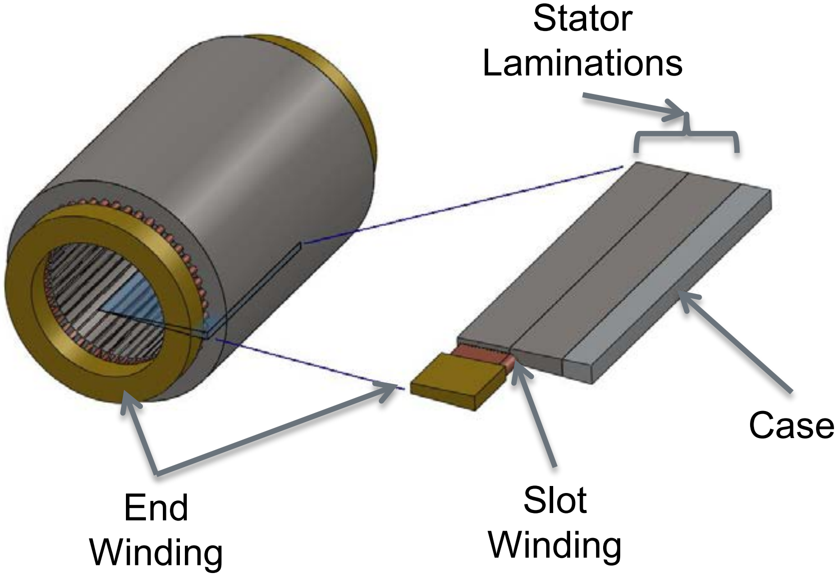
H. Kanzaki, K. Sato, and M. Kumagai, "A Study of an Estimation Method for Predicting the Equivalent Thermal Conductivity of an Electric Coil," *Trans. JSME*, 56 (526), 1990, 1753-1758.

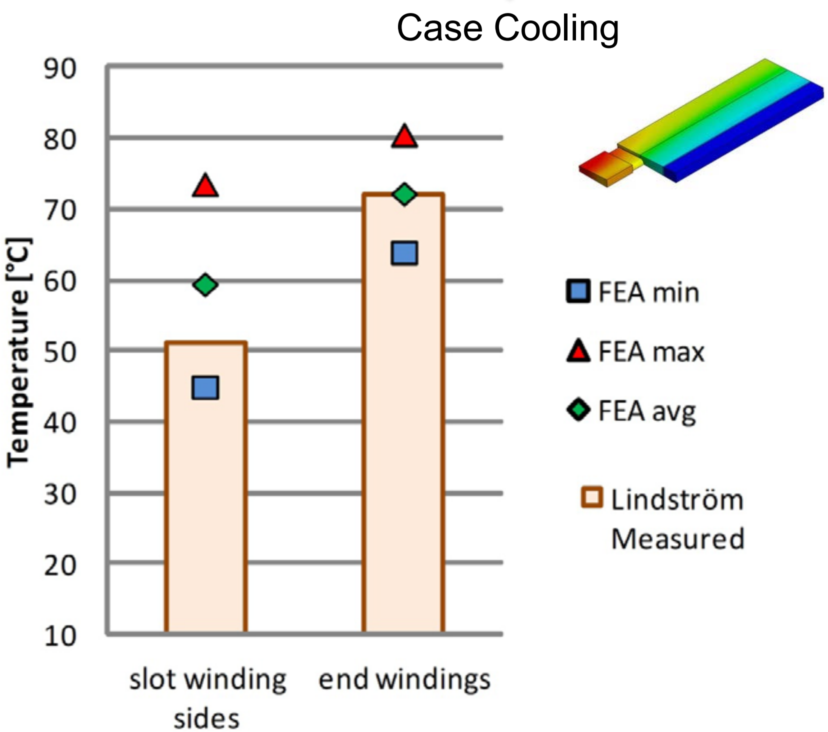
Technical Accomplishments and Progress

Completed thermal sensitivity analysis of surface permanent magnet motor stator

- Developed 3D thermal model
- Validated model against published data
- Confirmed thermal property (material/contact) and boundary condition assumptions

Validation of model assumptions

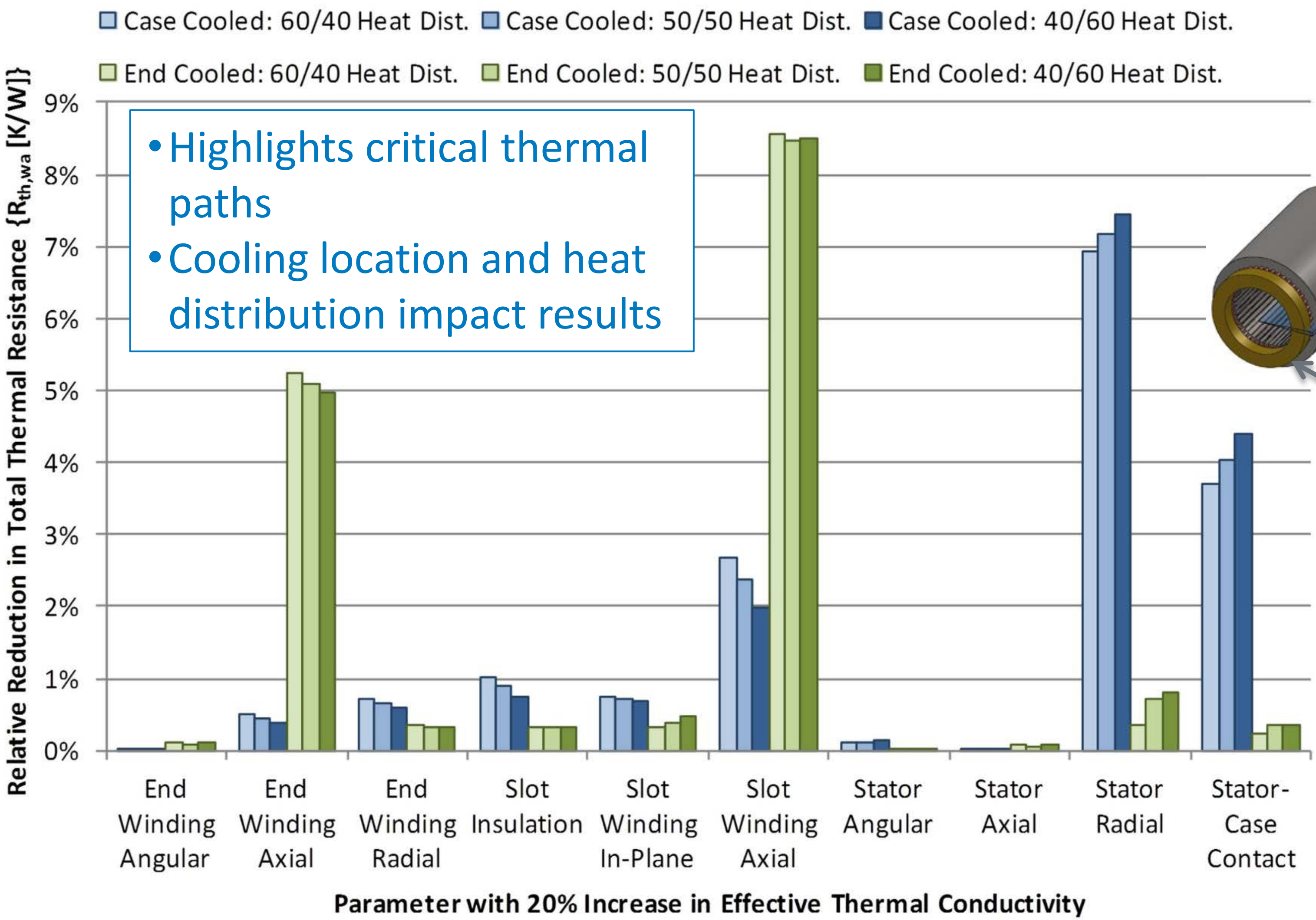




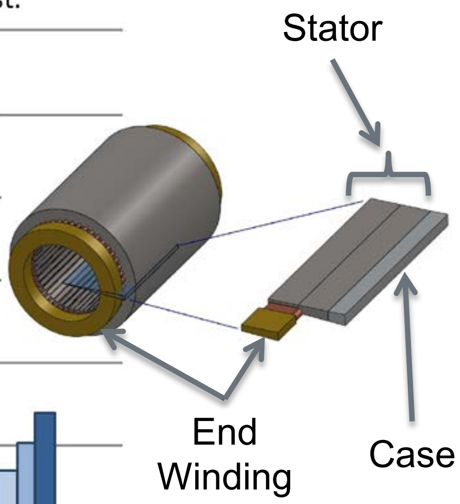
J. Lindström, "Thermal Model of a Permanent-Magnet Motor for a Hybrid Electric Vehicle," Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 1999.

Technical Accomplishments and Progress

Cooling sensitivity analysis with different winding/core heat distributions at fixed heat exchanger performance



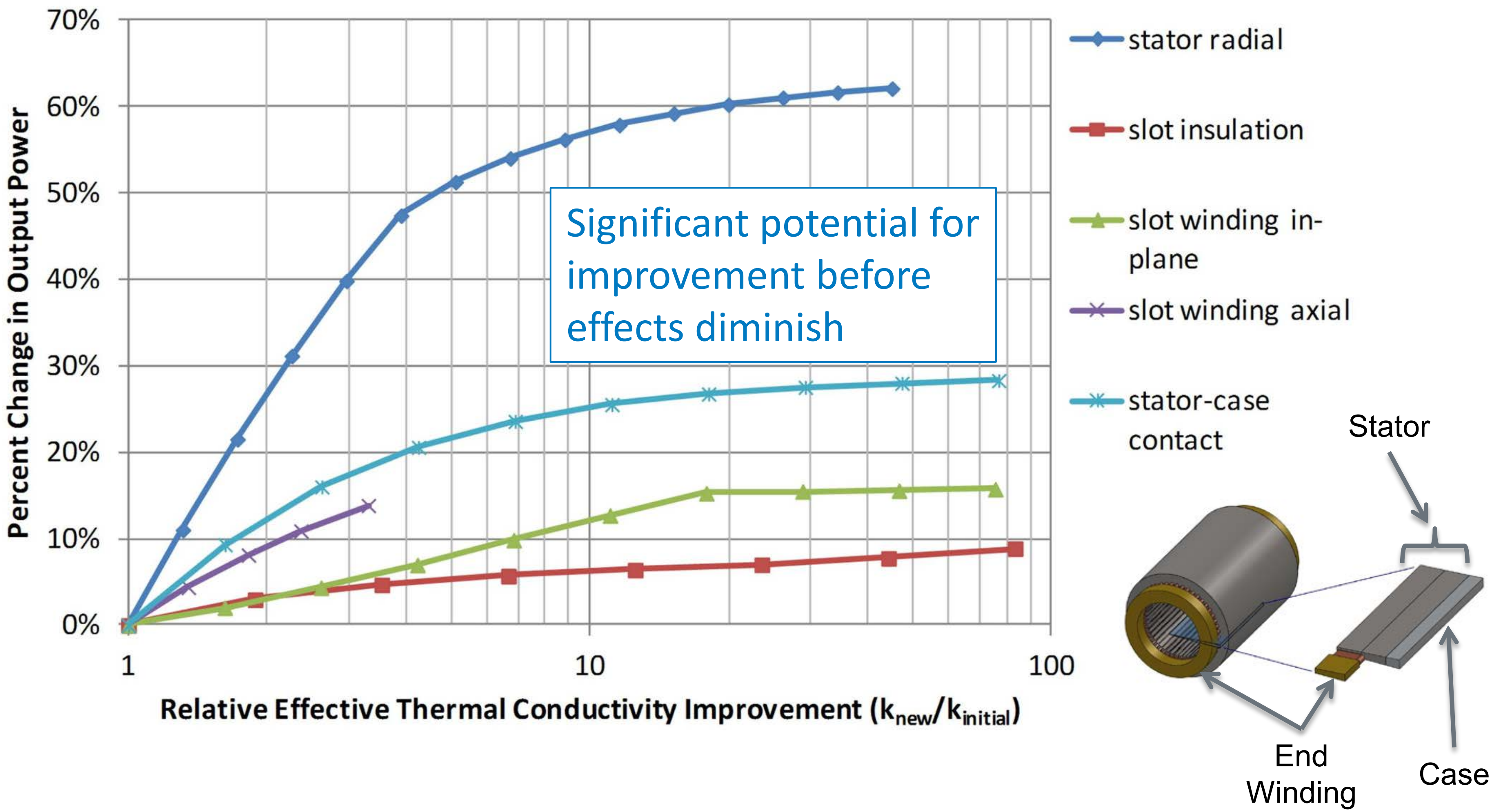
- Highlights critical thermal paths
- Cooling location and heat distribution impact results



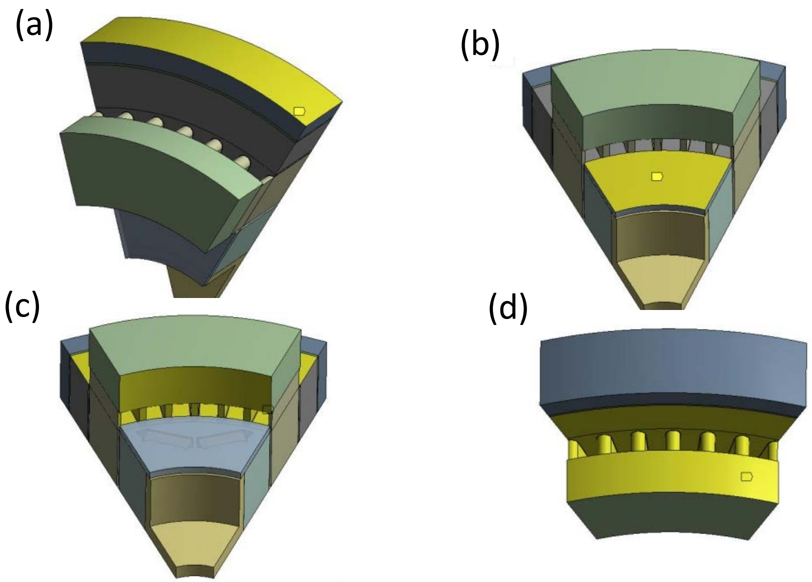
Note:
Axial direction is along the length of the motor

Technical Accomplishments and Progress

Change in available power output versus relative change in effective thermal conductivity for case-cooled configuration



Technical Accomplishments and Progress



Convection coefficients, shown in yellow, applied to the (a) case, (b) rotor face, and (c) & (d) end windings.

Operating Point				Loss Distribution	
Dataset	Power	Speed	Torque	Core Loss	Winding Loss
	[W]	[RPM]	[Nm]	[W]	[W]
1	25,000	5,000	47.75	87%	13%
2	33,500	3,000	106.6	70%	30%
3	33,500	3,000	106.6	70%	30%
4	33,000	5,000	63.03	83%	17%
5	33,000	5,000	63.03	83%	17%
6	33,500	7,000	45.70	85%	15%
7	50,000	5,000	95.49	76%	24%
8	50,000	5,000	95.49	76%	24%

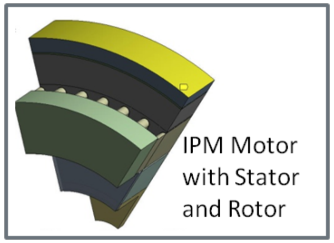
Completed thermal sensitivity analysis for interior permanent magnet motor application (stator and rotor)

- Developed 3D thermal model of permanent magnet motor stator and rotor
- Validated model against test data provided by ORNL
- Dataset with longest run time selected for estimation of boundary conditions
- Remaining data sets used for model validation

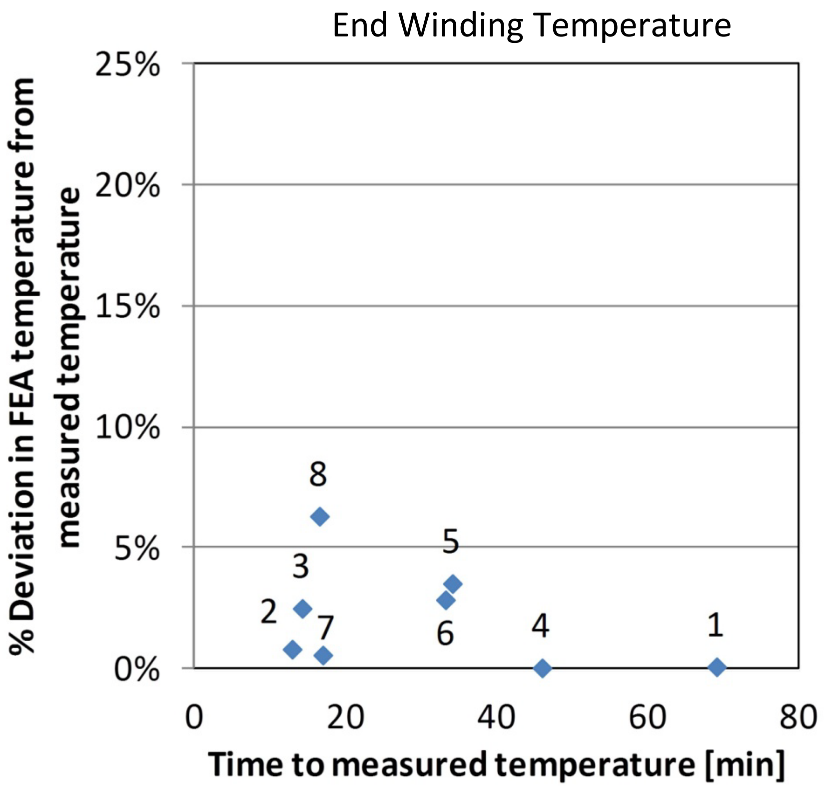
- Builds on previous stator model parameter assumptions and validation
- Expands analysis to include rotor

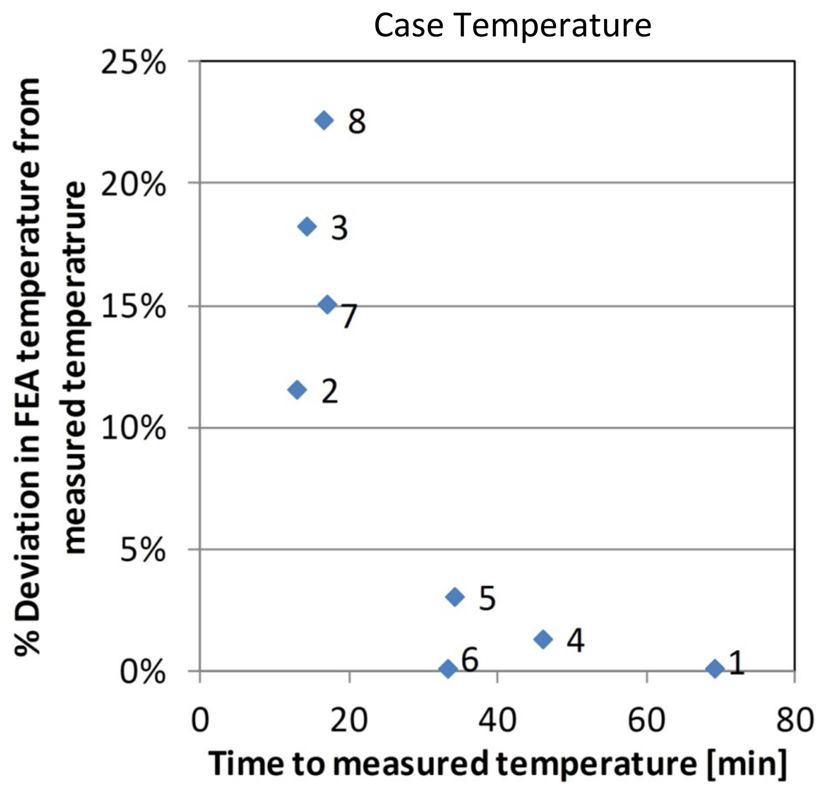
Technical Accomplishments and Progress

Model comparison to experimental data



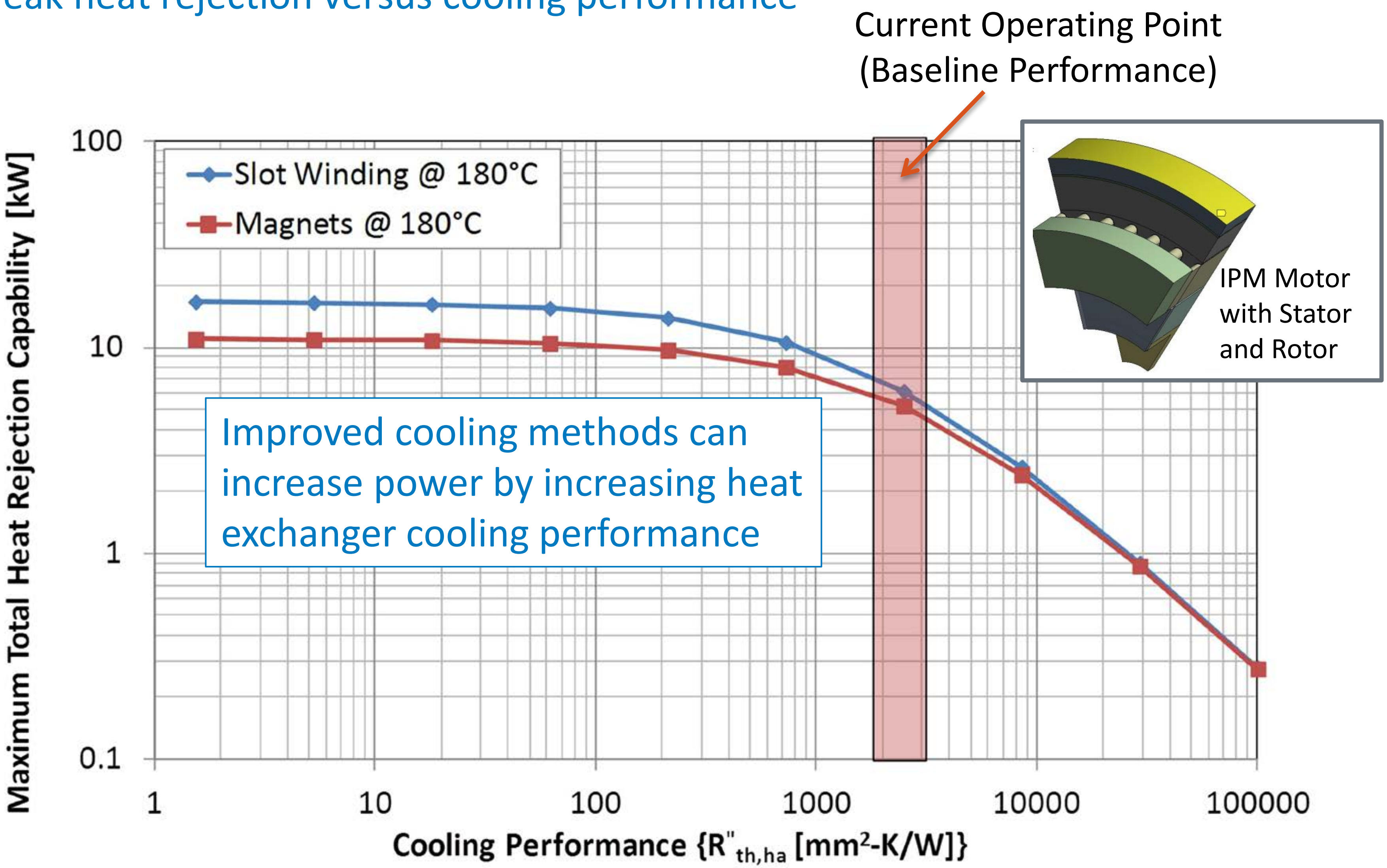
- Model performance is comparable to test data
- Shorter duration tests show less agreement in case temperature because steady-state temperatures have not been reached





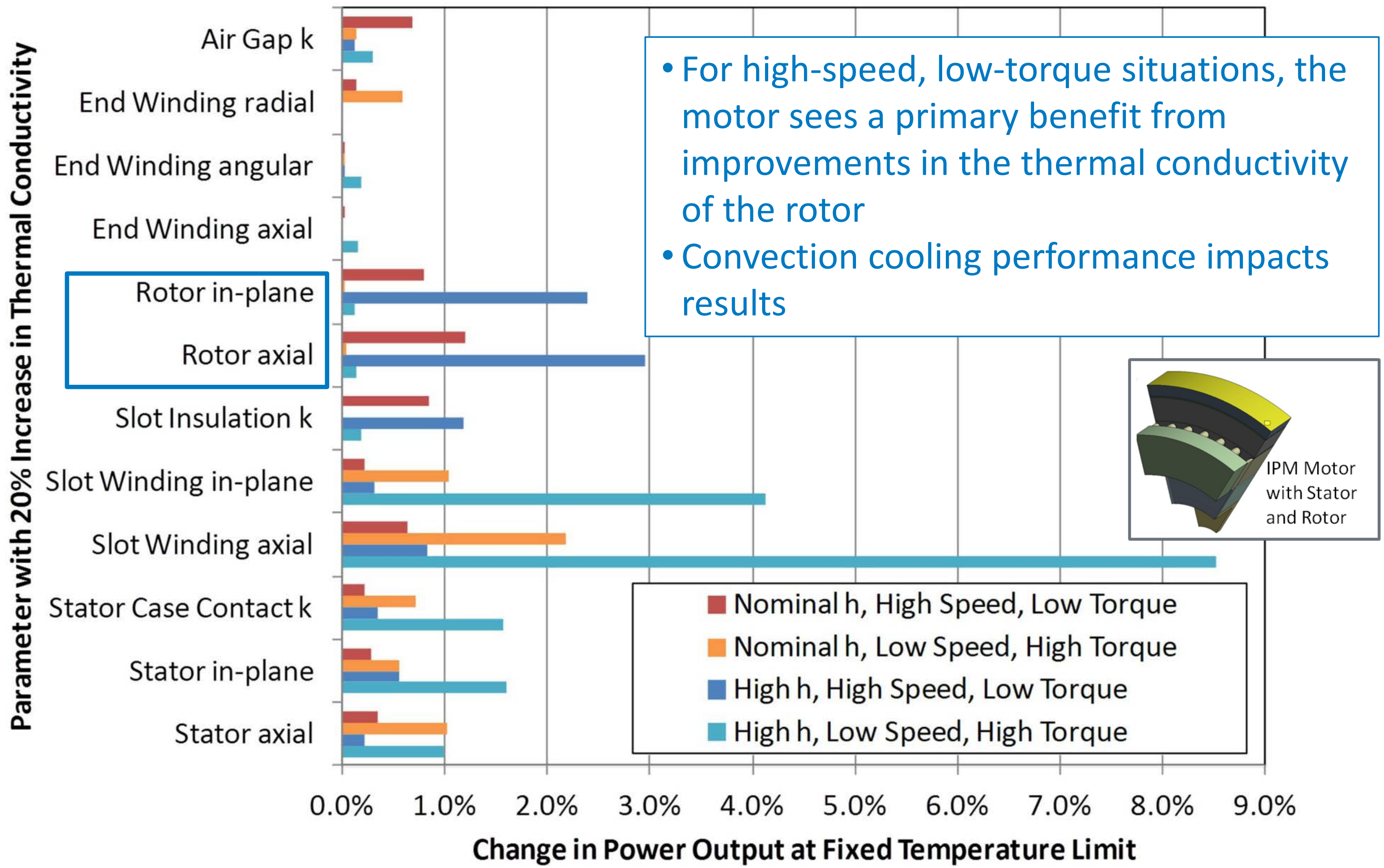
Technical Accomplishments and Progress

Peak heat rejection versus cooling performance



Technical Accomplishments and Progress

Sensitivity in power output capability for 20% increase in material thermal conductivity



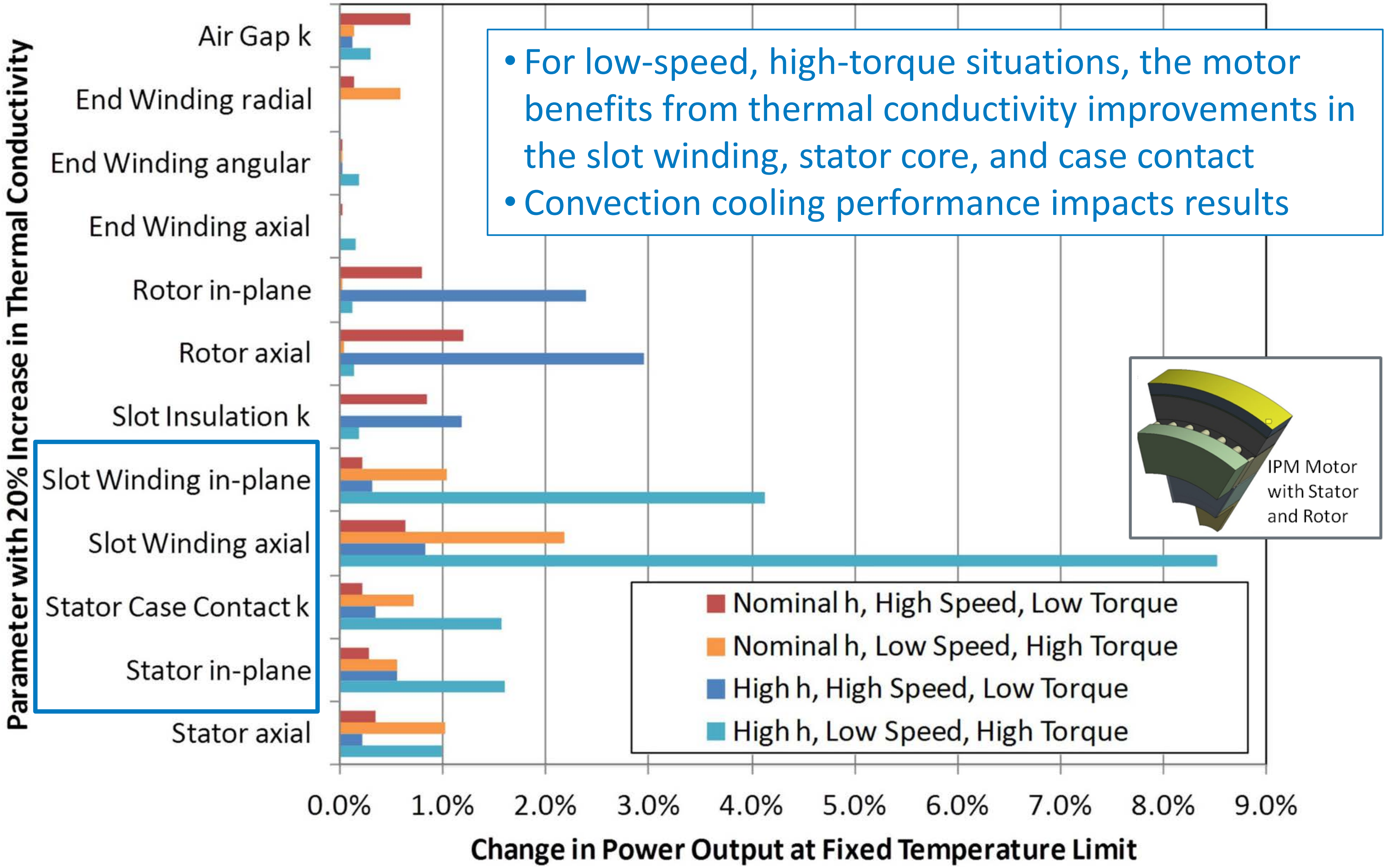
- For high-speed, low-torque situations, the motor sees a primary benefit from improvements in the thermal conductivity of the rotor
- Convection cooling performance impacts results

Note: “Nominal h” refers to the baseline cooling performance, “High h” represents an aggressive cooling condition

Technical Accomplishments and Progress

Sensitivity in power output capability for 20% increase in material thermal conductivity

- For low-speed, high-torque situations, the motor benefits from thermal conductivity improvements in the slot winding, stator core, and case contact
- Convection cooling performance impacts results

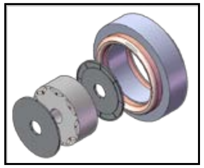


Note: “Nominal h” refers to the baseline cooling performance, “High h” represents an aggressive cooling condition

Collaboration and Coordination

- **University**
  - UW – Madison (Thomas M. Jahns)
    - Support with electric motor expertise
- **Industry**
  - Motor industry suppliers, end users, and researchers
    - Input on research and test plans
- **Other Government Laboratories**
  - ORNL
    - Support from benchmarking activities
    - Ensure thermal design space is appropriate and modeling assumptions are consistent with other aspects of APEEM research
  - Other VTP areas
    - Collaborate with VTP cross-cut effort for combined cooling loops

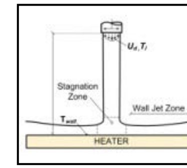
Proposed Future Work



Package Mechanical Design

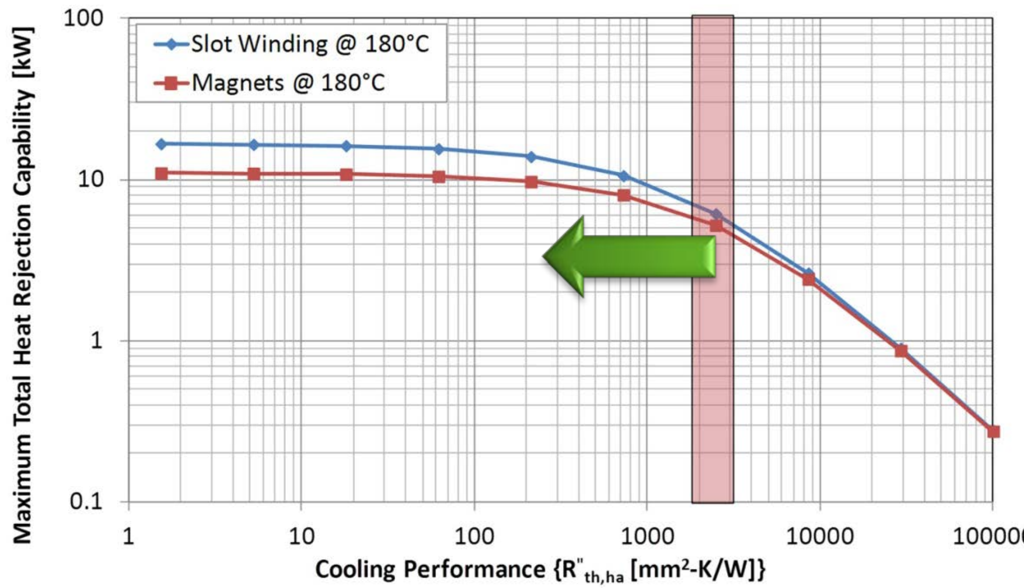
Thermal Design Targets

Cooling Technology Selection

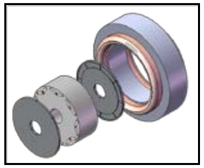


Cooling Technology Selection

- Characterize oil-cooling heat transfer coefficients
- Initiate cooling durability tests (winding insulation)
- Go/No-Go for FY13
  - If improvement in cooling performance shows impact on total thermal performance, pursue efforts to characterize improved oil-cooling approaches
  - Continue cooling durability tests



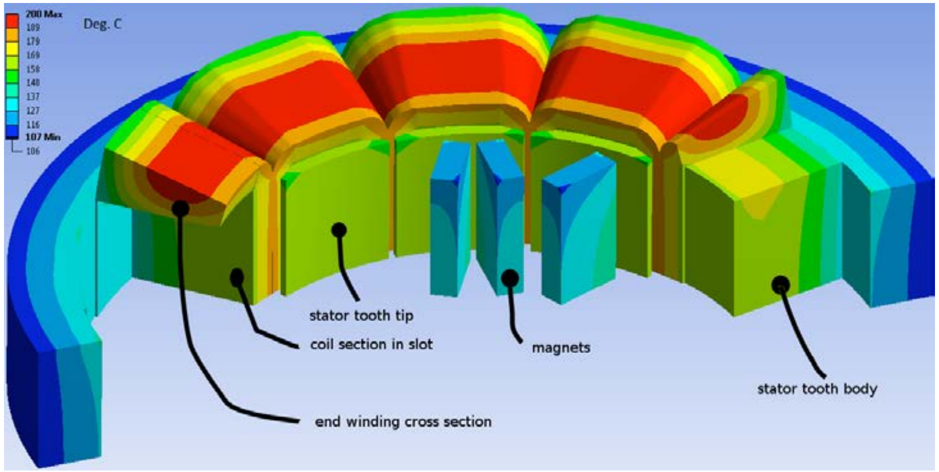
Proposed Future Work



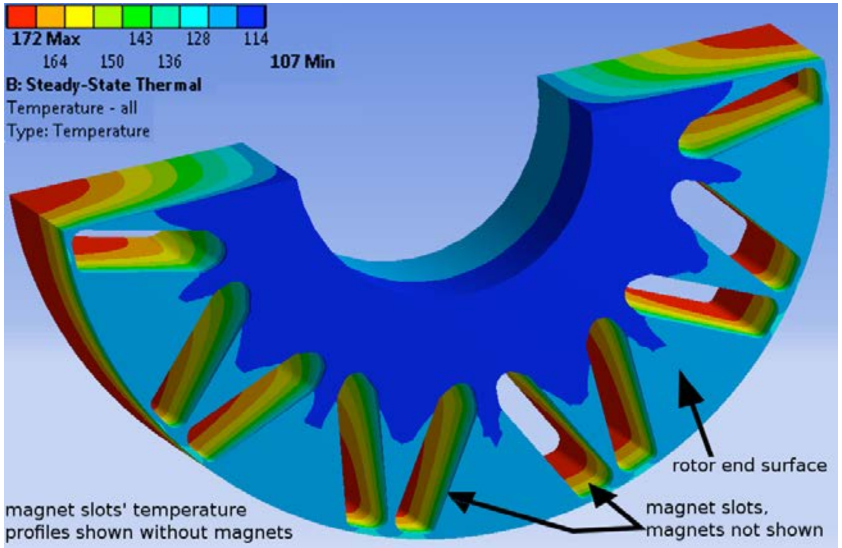
Package Mechanical Design

Package Mechanical Design

- Complete thermal sensitivity analysis and model validation for concentrated winding motor with University of Wisconsin (FEA and lumped parameter thermal analysis)
- Quick look at methods to enhance internal heat spreading
- Go/No-Go for FY13
  - If motor cooling sensitivity analysis shows common areas for thermal improvement, initiate R&D on critical factors



Courtesy of T. M. Jahns / S. McElhinney, UW - Madison



Courtesy of T. M. Jahns / S. McElhinney, UW - Madison

Summary

Relevance

- Impacts the transition to more electrically dominant propulsion systems with higher continuous power requirements
- Enables improved performance of non-rare earth motors
- Supports lower cost through reduction of rare earth materials used to meet temperature requirements (dysprosium)
- Applies experimental and analytical capabilities to quantify and optimize the selection and design of effective motor cooling approaches

Approach/Strategy

Developed process to meet challenges of motor thermal management

- Identify thermal improvements across a range of motor configurations
- Evaluate multiple operating conditions (loss distributions)
- Engage in collaborations with motor design experts
- Perform in-house characterization of material and interface thermal properties

Summary

Technical Accomplishments

- Measured bulk thermal conductivity of lamination materials
- Measured specific heat of lamination materials
- Quantified thermal contact resistance between laminations
- Quantified thermal properties for slot windings
- Completed thermal sensitivity analysis for surface permanent magnet motor stator
- Completed thermal sensitivity analysis for interior permanent magnet motor application (stator and rotor)

Collaborations

- Collaborations established with research and development partners
  - University of Wisconsin – Madison
  - Oak Ridge National Laboratory
  - Motor industry representatives: Manufacturers, researchers, and end users (light duty and heavy duty)

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Acknowledgments:

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Tim Burress, Oak Ridge National
Laboratory

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