NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Electric Motor Thermal Management




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National Renewable Energy Laboratory
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Project ID: APE030

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Overview

Timeline

Project Start Date: FY 2010
Project End Date: FY 2013
Percent Complete: 80%

Budget

Total Project Funding:
DOE Share:$1,900K (FY10-FY13)

Funding Received in FY12: $550K

Funding for FY13: $500K

Barriers and Targets

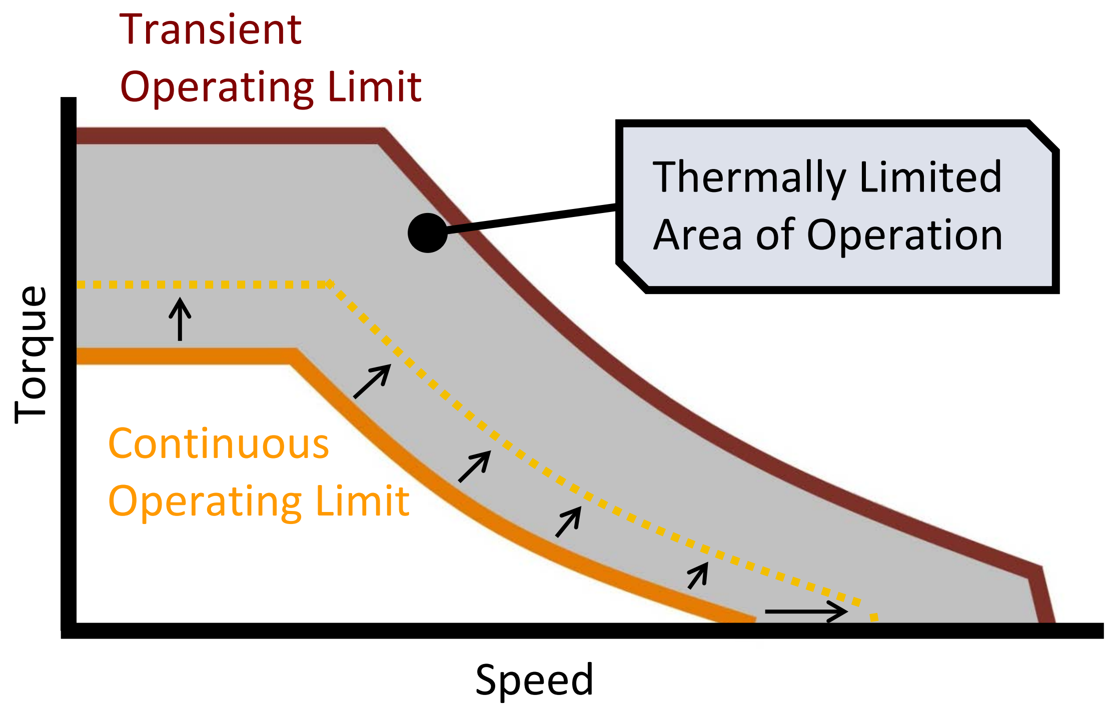
- Cost
- Weight
- Performance & Life

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

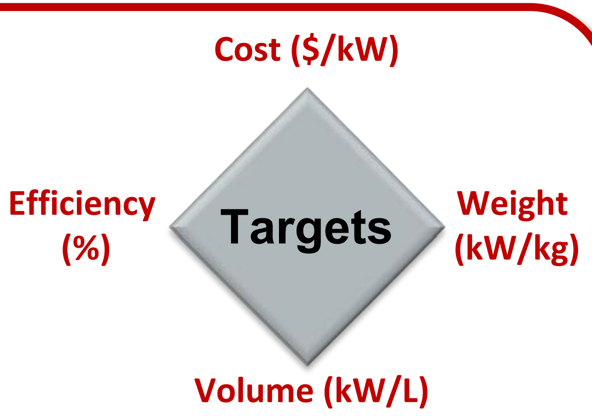
Relevance/Objectives

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

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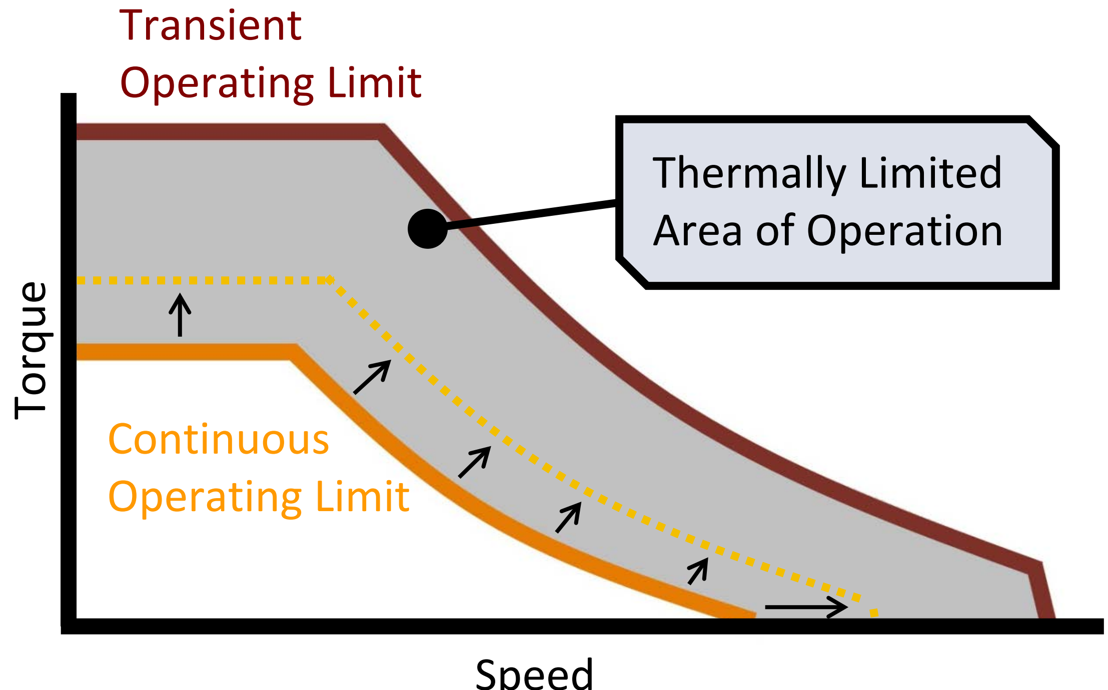


Objectives

- 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 information related to motor thermal management in open literature

Addresses Targets

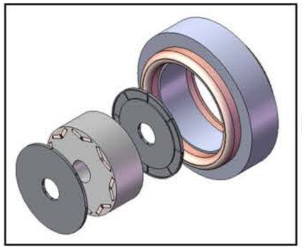
- Translates cooling performance improvements into impacts on program targets
- Prioritizes motor thermal management efforts based on areas of most impact

Milestones

Date	Description
January 2012	Go/No-Go • Completed selected motor lamination material thermal property tests • Decided to not expand material tests at this time
July 2012	Go/No-Go • Thermal sensitivity analysis showed significant impact common to multiple motor configurations leading to future project proposals for specific convective cooling enhancements and passive stack thermal improvements
September 2012	Milestone report • Lamination material thermal properties and motor thermal sensitivity analysis
December 2012	Milestone (internal) • Completed transmission oil test bench for oil cooling experiments
September 2013	Milestone report • Final project summary report on lamination material thermal properties, motor thermal sensitivity analysis, and oil heat transfer experimental data • Summarize collaborative motor cooling efforts with Oak Ridge National Laboratory (ORNL)

Approach/Strategy

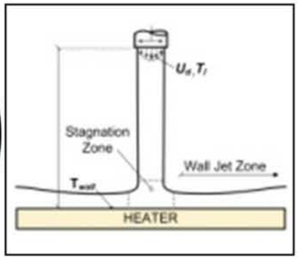
FY13 Focus

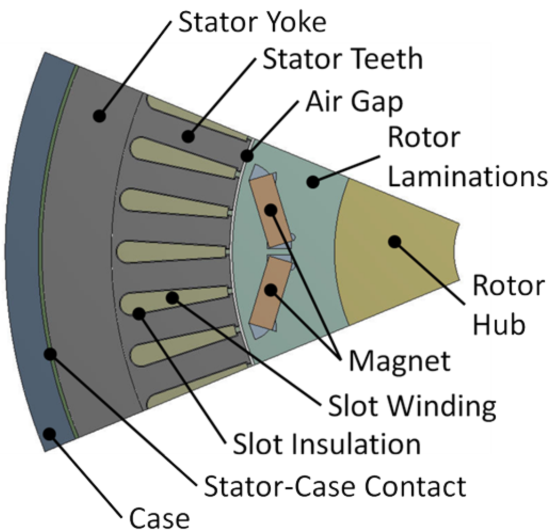


Passive Thermal Design

Integrated Thermal Impacts

Cooling Technology Selection

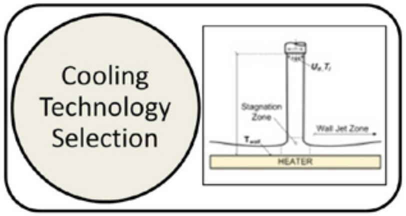




Interior Permanent Magnet (IPM) Model Cross Section

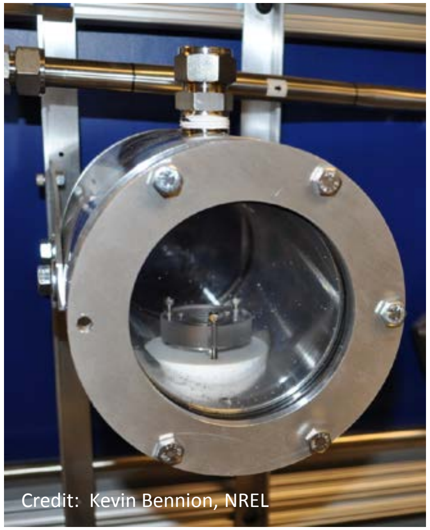
Transmission Oil Heat Transfer Experimental Setup

Approach/Strategy

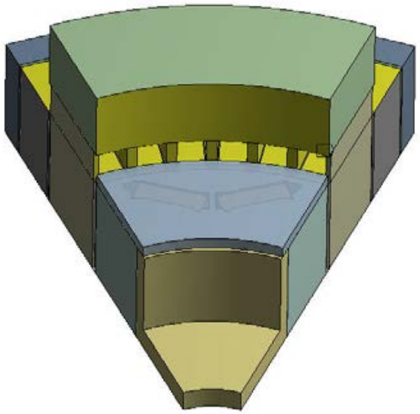


Cooling Technology Selection

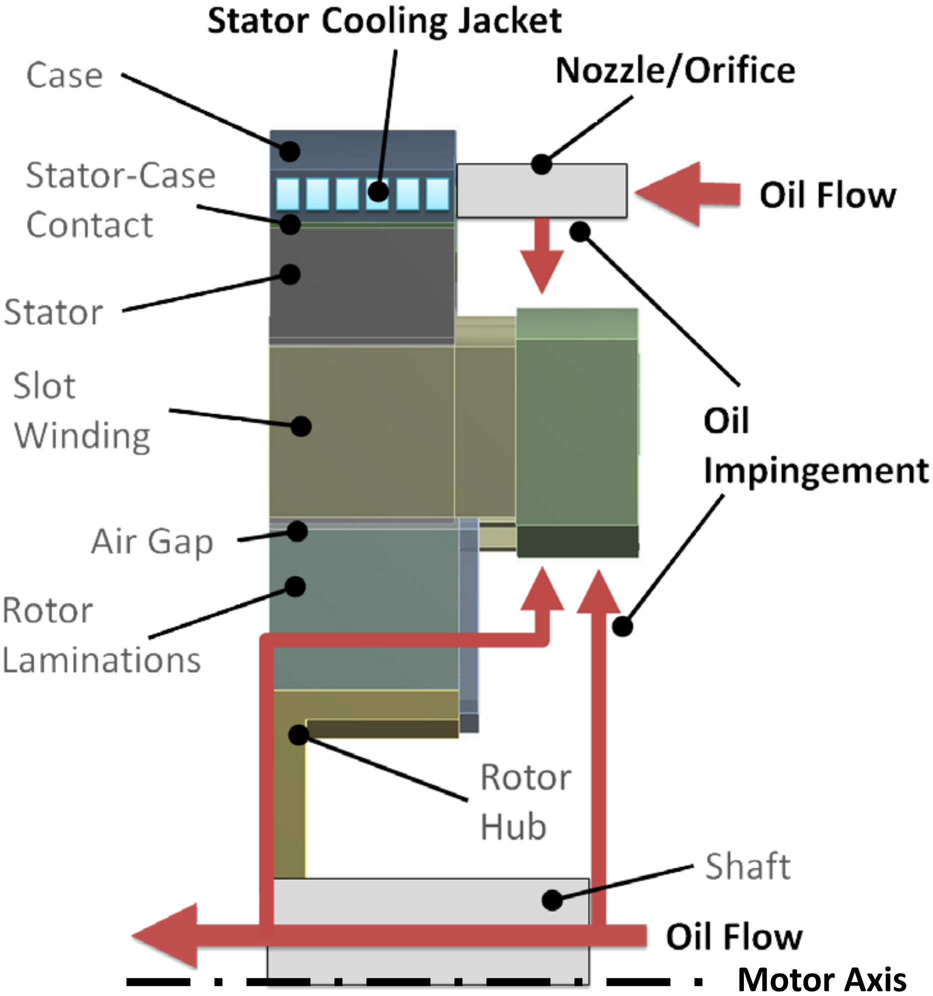
- Characterize heat transfer coefficients of oil impingement cooling
- Investigate wire insulation reliability
  - Oil cooling impingement
  - High-potential breakdown voltage tests



Oil Impingement Test Chamber

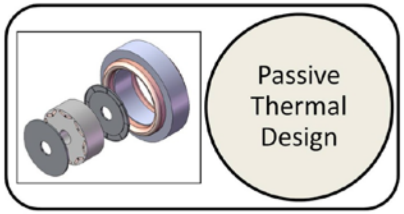


IPM Motor Model



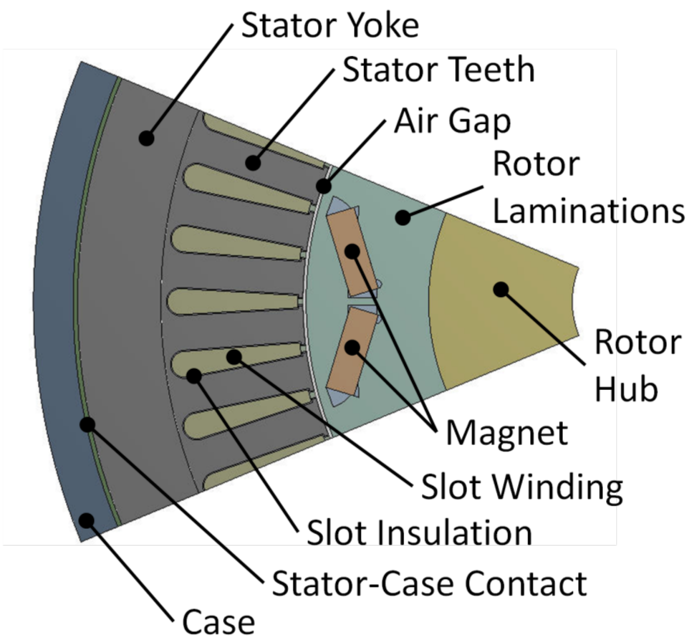
IPM Motor Cooling Schematic

Approach/Strategy



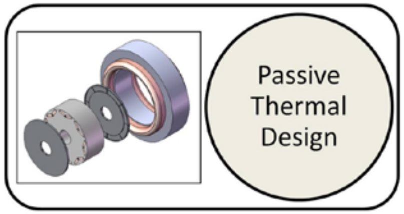
Passive Thermal Design

- Thermal interfaces between contacting components provide significant resistance to heat flow.
- Interfaces are often difficult to characterize experimentally.
- Manufacturing variability increases the uncertainty of the interface thermal resistance.



IPM Motor Model Cross Section

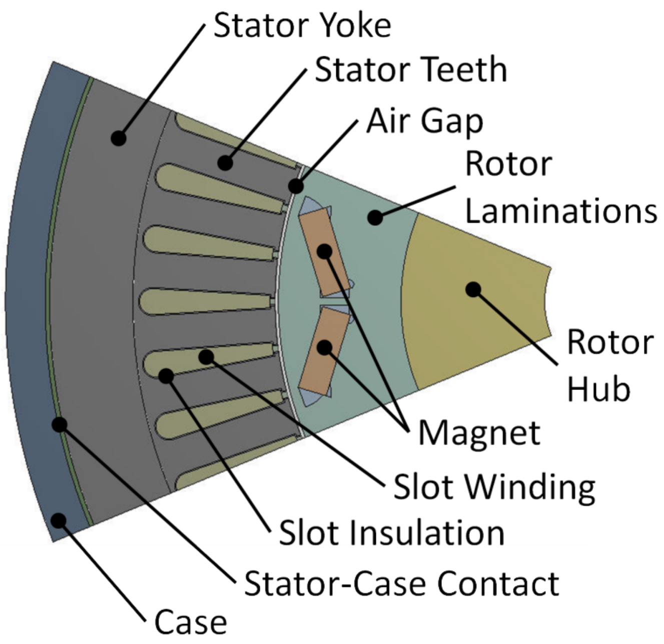
Approach/Strategy



Passive Thermal Design

- Thermal interfaces between contacting components provide significant resistance to heat flow.
- Interfaces are often difficult to characterize experimentally.
- Manufacturing variability increases the uncertainty of the interface thermal resistance.

- Develop baseline performance data from analytical and experimental methods.
- Investigate concepts to enhance or improve effective component thermal properties.
- Improve cooling methods to reduce heat flow through critical or variable interfaces.



IPM Motor Model Cross Section

Approach/Strategy

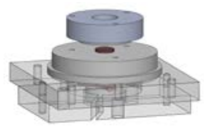
2012			2013								
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Complete transmission oil loop construction and preliminary testing

Milestone

Final Project Report

Heat transfer measurements of transmission oil jets/sprays and winding insulation reliability

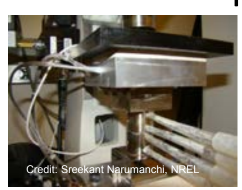


Go/ No-Go

Obtain Baseline Data for Potential Future Focus Areas

Continue baseline measurements of passive thermal design elements

- Slot Windings
- Laminations
- Contact Interfaces



Collaboration with ORNL

- Thermal analysis and design support of motor developments conducted at ORNL

ORNL Induction Motor

Legend

Complete

In Progress

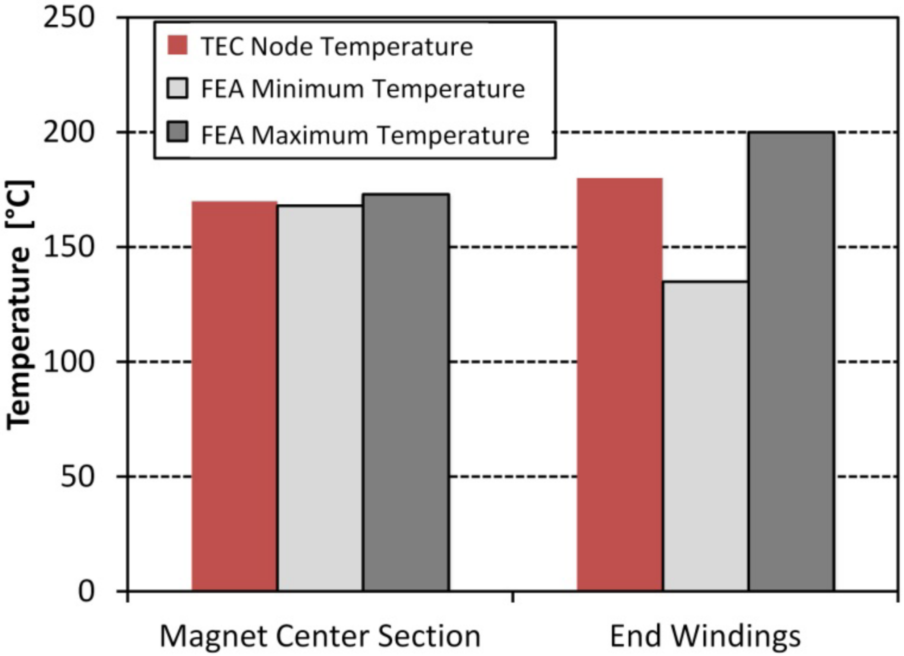
Technical Accomplishments and Progress

Completed phase one of partnership with the University of Wisconsin – Madison

- Review of thermal analysis and cooling techniques for traction drive motors
- Developed a computationally efficient technique for estimating the loss components in IPM motors as a function of the motor's operating point
- Developed a 3D finite element analysis (FEA) thermal model for a concentrated winding stator motor configuration
- Developed a thermal equivalent circuit (TEC) model for an IPM concentrated winding motor

Concentrated winding motor

Preliminary thermal FEA showing temperature drop across slot liner for case cooled machine and thermal gradients in winding

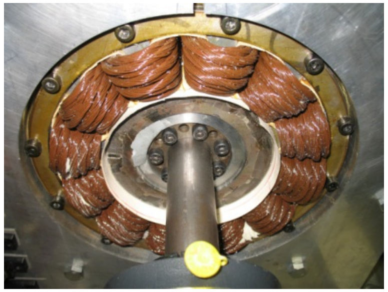


Comparison of TEC model with FEA temperature predictions

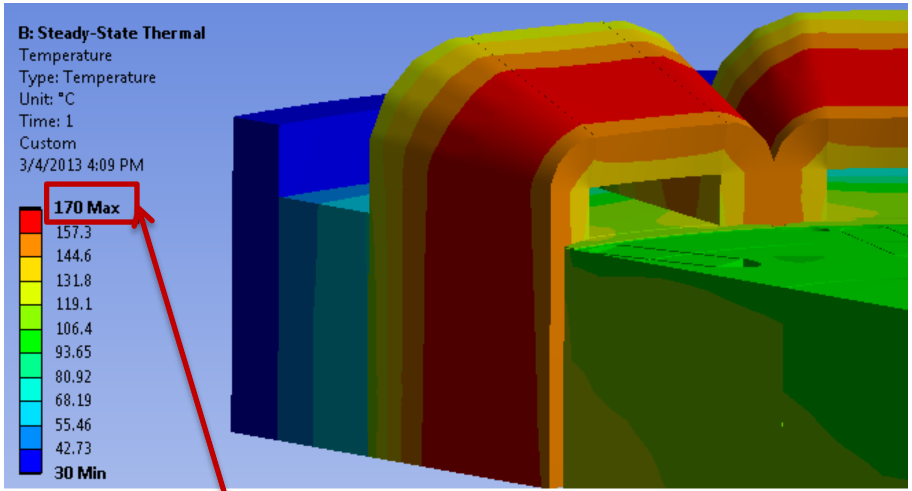
Technical Accomplishments and Progress

Initiated phase two of partnership with the University of Wisconsin – Madison

- Model experimental validation and improvement
- Investigating improved heat spreading methods

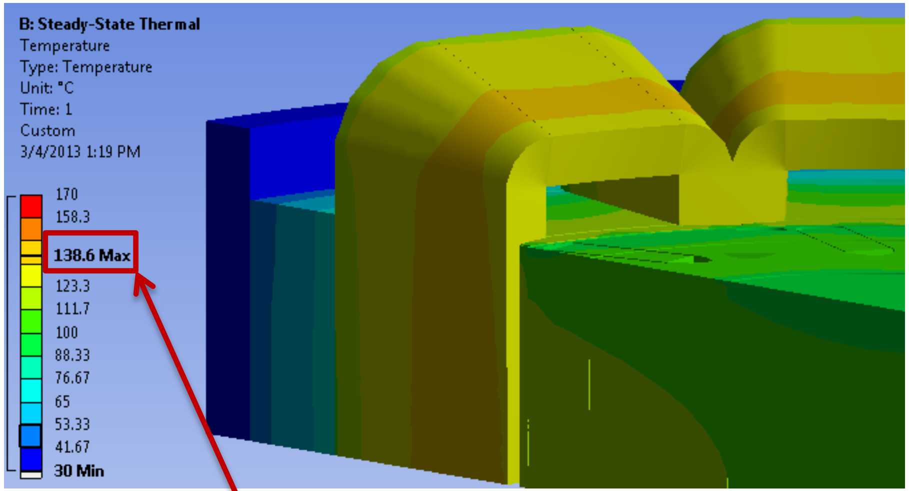


Untwisted Wire Bundles



170°C Maximum Temperature

Litz Type 1 Twisted Wire Bundles



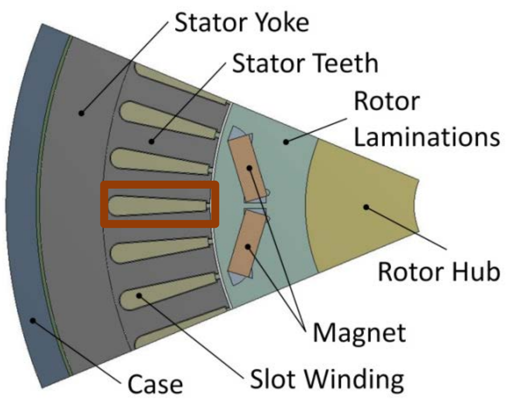
139°C Maximum Temperature (Same Scale)

Preliminary analysis of twisted wire bundles show a hot spot temperature reduction of 30°C at rated torque and power

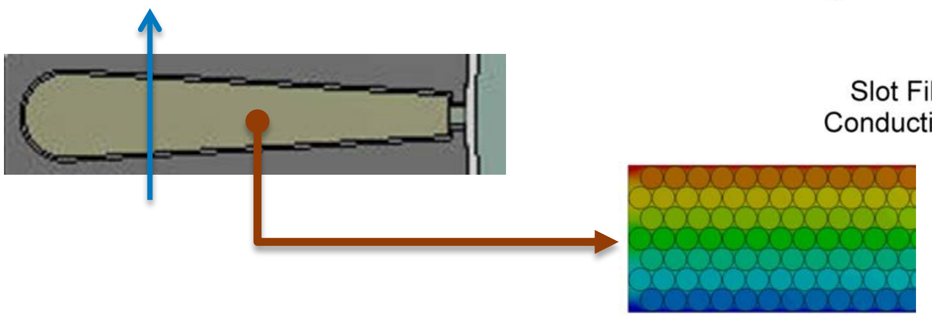
All Images - Credit: Thomas M. Jahns, Seth McElhinney (UW–Madison)

Technical Accomplishments and Progress

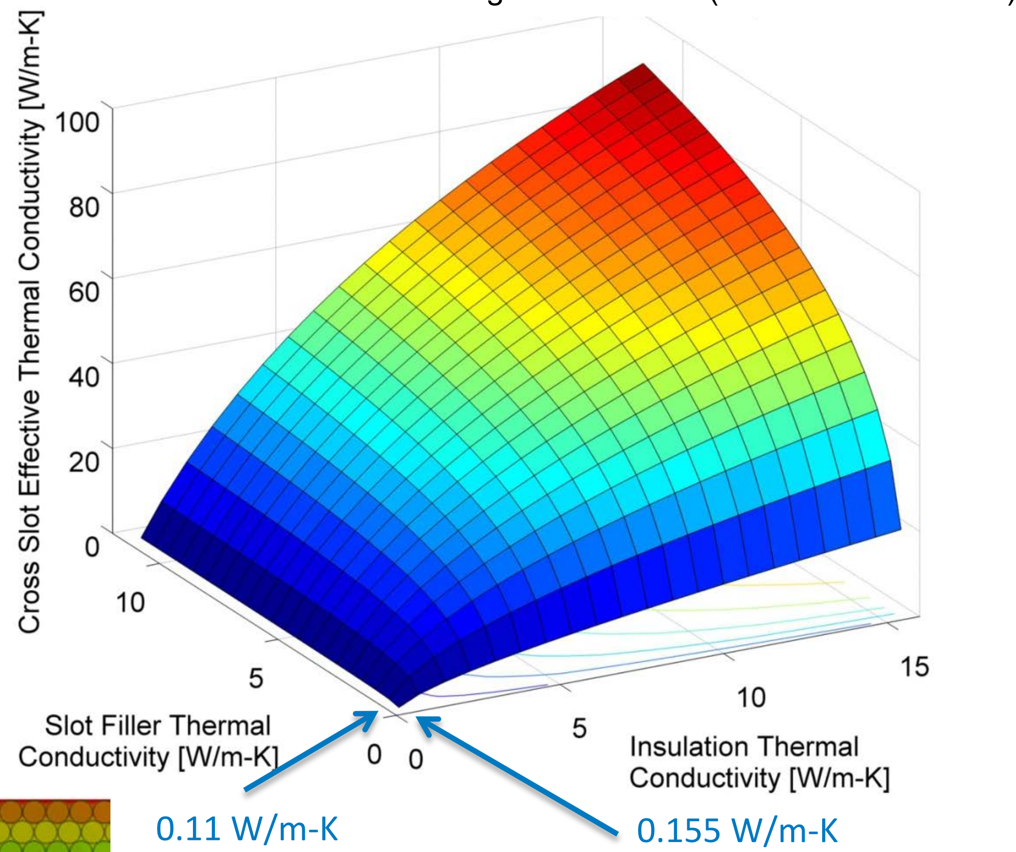
Slot Winding Thermal Conductivity



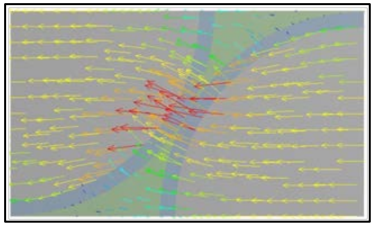
Cross Slot Thermal Conductivity



78% Fill Factor with 20 Gauge Round Wire (Maximum Fill Factor)

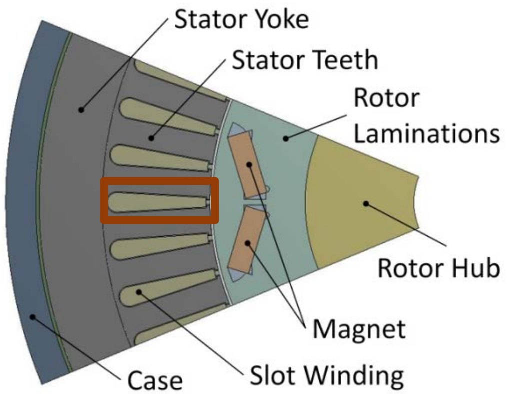


- Improvements to the slot filler material have little impact without improvements to the wire insulation thermal conductivity.

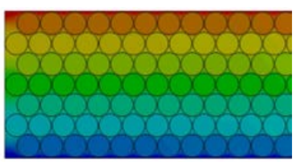


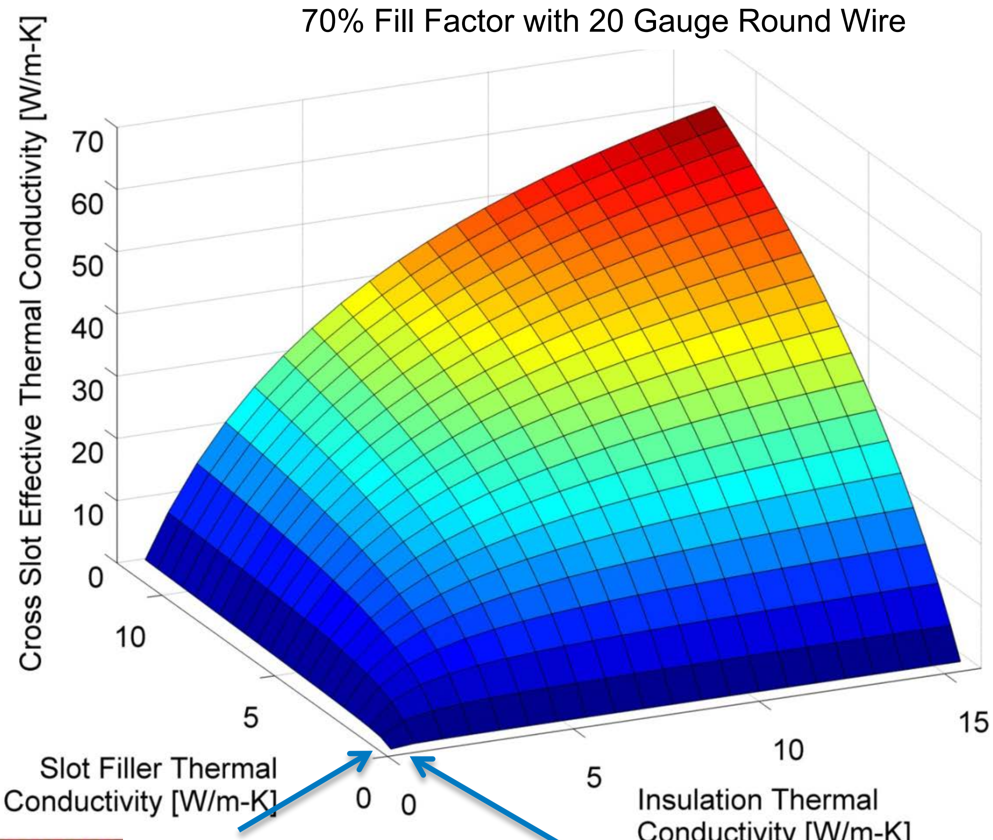
Technical Accomplishments and Progress

Slot Winding Thermal Conductivity

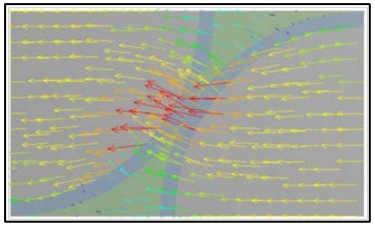


Cross Slot Thermal Conductivity



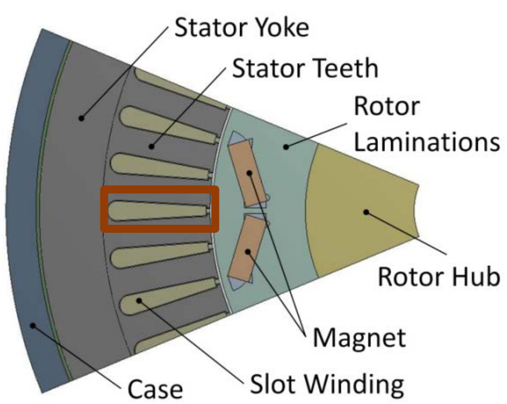


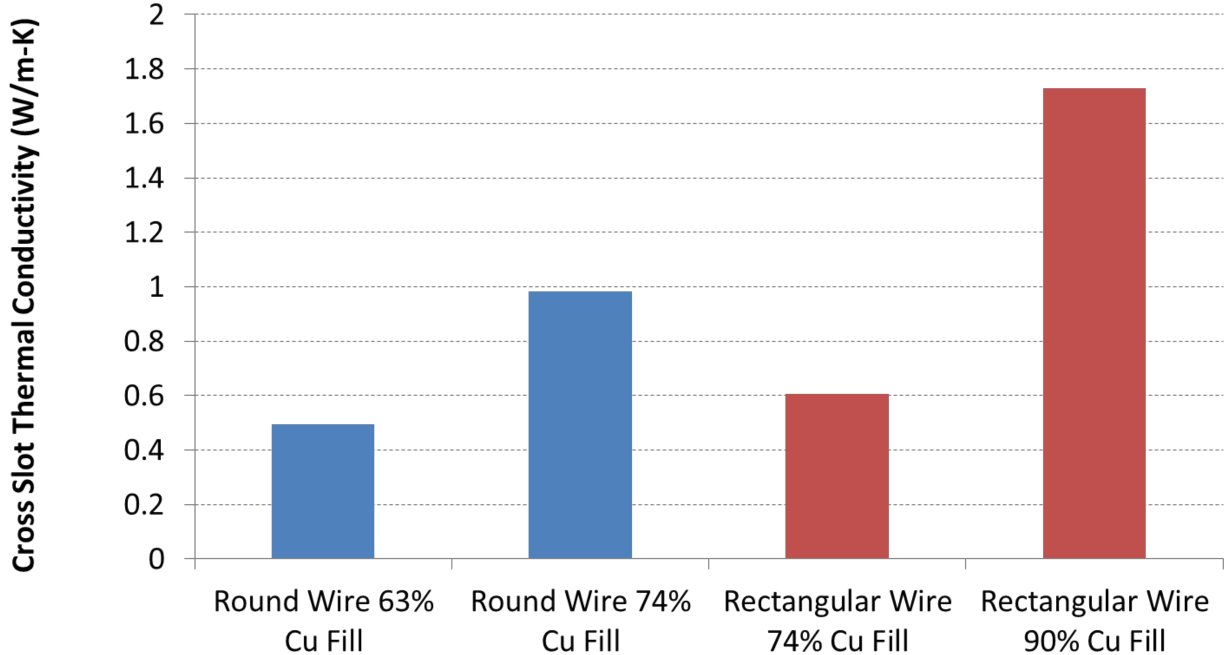
- Improvements to the slot filler material and wire insulation are needed for reduced fill factors.



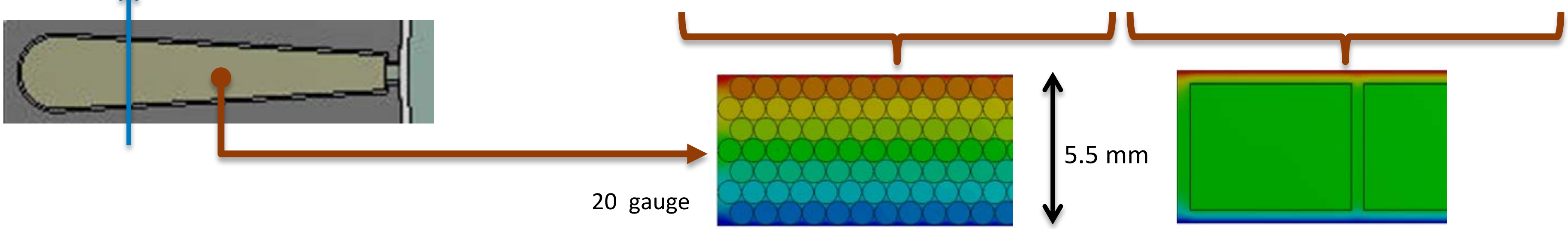
Technical Accomplishments and Progress

Slot Winding Wire Shape





Cross Slot Thermal Conductivity

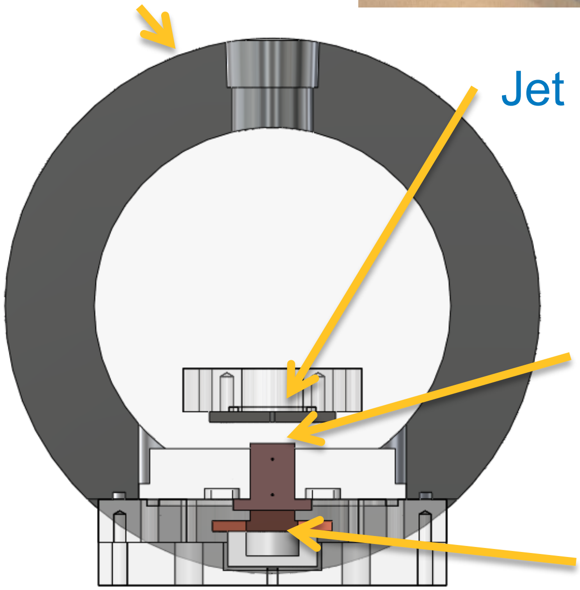


- Rectangular wire shows lower thermal conductivity at the same fill factor because of the lower conductivity filler material.
- Benefit of rectangular wire is seen if the thickness of the filler material boundaries are reduced.

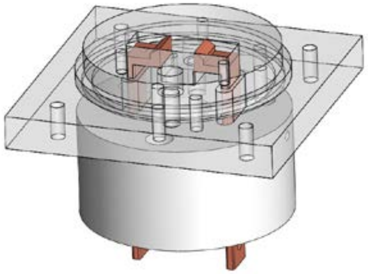
Technical Accomplishments and Progress

Oil Loop Experimental Setup

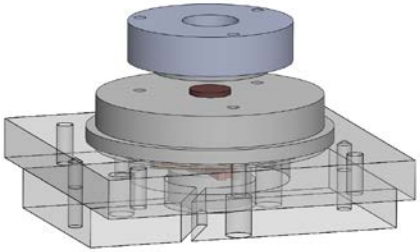
- Mercon LV Transmission Fluid
- Initial heat transfer tests focused on jet impingement on target surface
- Future work
  - Alternative heat transfer coefficient measurement techniques
  - Expand number of jets, target size, and target surface
  - Wire insulation impacts



Alternative Convection Coefficient Measurement Methods

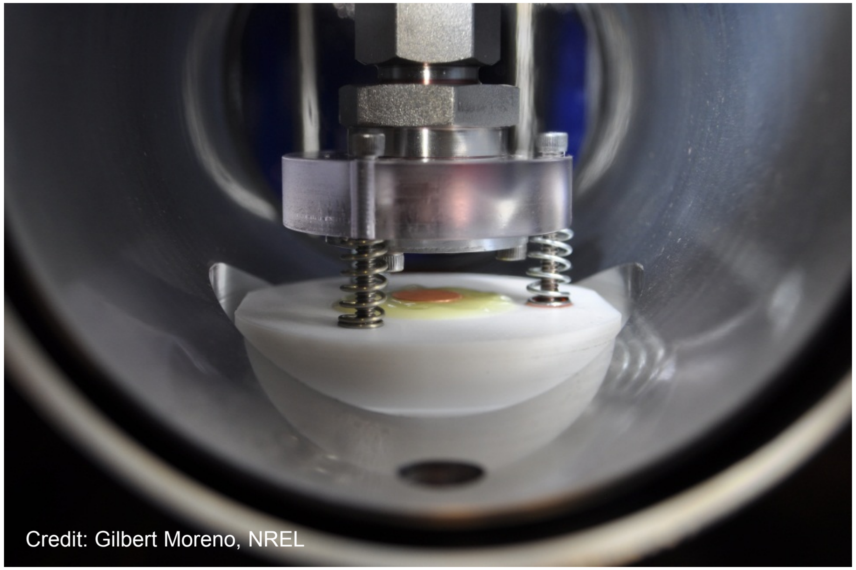


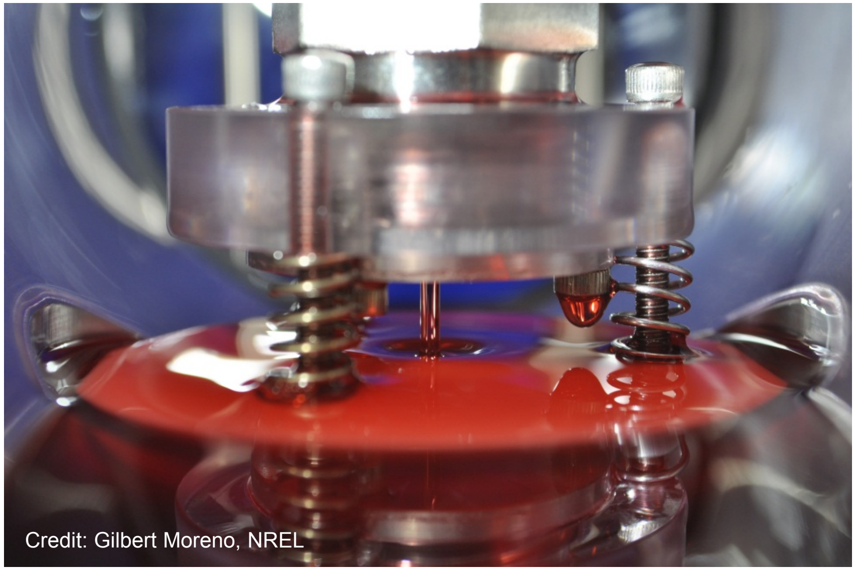
Thermochromic Liquid Crystal

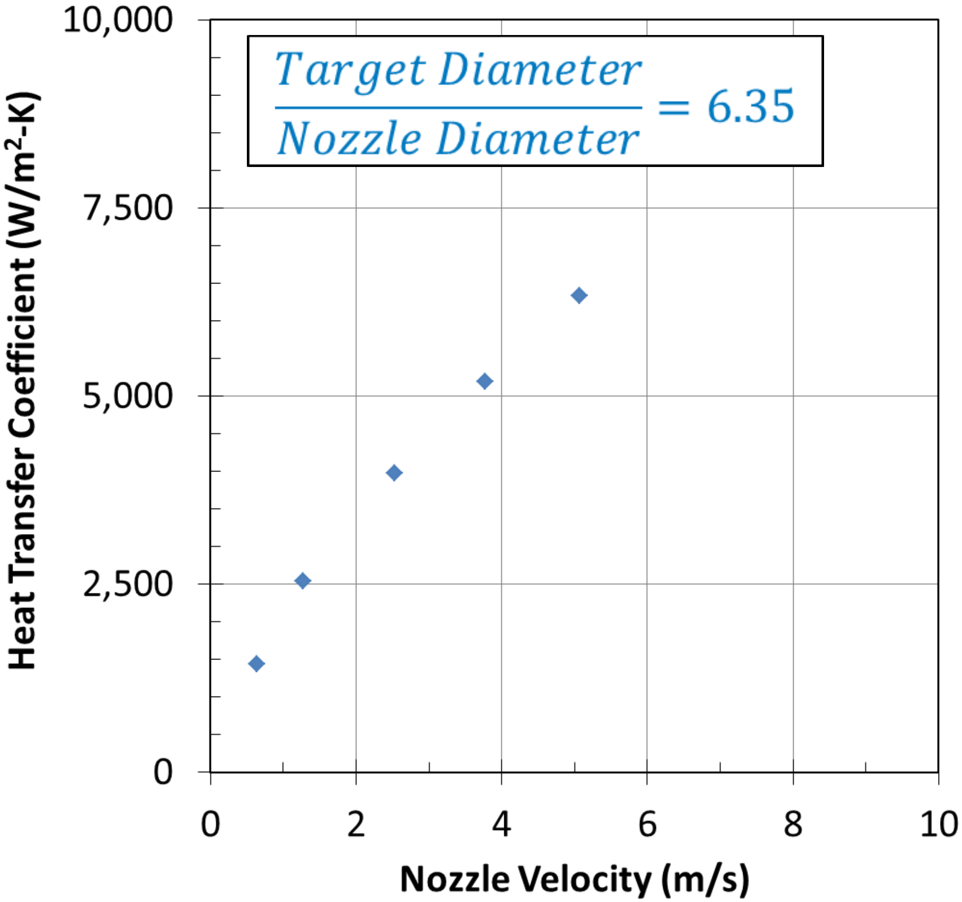


Thermocouple Surface Temperature Estimate

Technical Accomplishments and Progress





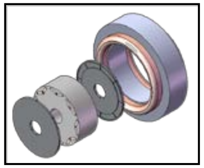


Area averaged heat transfer coefficient at 50°C fluid temperature

Collaboration and Coordination

- **University**
  - University of Wisconsin – Madison
    - Support with electric motor expertise
- **Industry**
  - Motor industry suppliers, end users, and researchers
    - Input on research and test plans
- **Other Government Laboratories**
  - Oak Ridge National Laboratory
    - Support from benchmarking activities
    - Ensure thermal design space is appropriate and modeling assumptions are consistent with other aspects of APEEM research
    - Collaboration on motor designs to reduce or eliminate rare-earth materials
  - Other Vehicle Technology Office (VTO) areas
    - Collaborate with VTO cross-cut effort for combined cooling loops

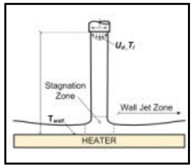
Future Work

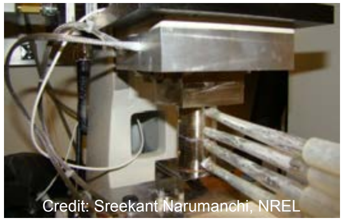


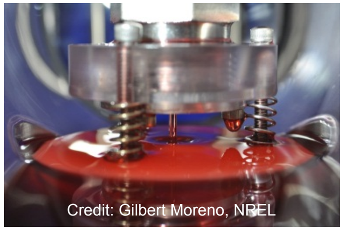
Package Mechanical Design

Thermal Design Targets

Cooling Technology Selection







ORNL Induction Motor

Package Mechanical Design

- Thermal tests of interfaces and materials

Cooling Technology Selection

- Characterization of oil-cooling heat transfer coefficients
- Oil cooling reliability tests (winding insulation)

Motor Thermal Design Targets

- Collaboration with ORNL
- Thermal analysis and design support of motor developments conducted at ORNL

Summary

Relevance

- Impacts the transition to more electrically dominant propulsion systems with higher continuous power requirements
- Enables improved performance of non-rare earth motors and supports lower cost through reduction of rare earth materials used to meet temperature requirements (dysprosium)

Approach/Strategy

- Engage in collaborations with motor design experts from industry, university, and national labs
- Perform in-house thermal characterization of materials, interface thermal properties, and cooling techniques
- Collaborating with ORNL to provide motor thermal analysis support on related motor research at ORNL

Technical Accomplishments

- Completed thermal sensitivity analysis for a range of motor configurations and over a range of operating conditions in collaboration with the University of Wisconsin – Madison
- Evaluated impact of winding material improvements leading to future experimental test plans
- Initiated heat transfer characterization tests involving transmission oil

Collaborations

- University of Wisconsin – Madison
- Oak Ridge National Laboratory
- Motor industry representatives: manufacturers, researchers, and end users (light duty and heavy duty)

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