

# Electric Motor Thermal Management R&D



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National Renewable Energy Laboratory  
2016 Annual Merit Review  
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**EDT064  
NREL/PR-5400-66046**

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# Overview

## Timeline

- Project Start Date: FY2014
- Project End Date: FY2017
- Percent Complete: 65%

## Budget

- Total Project Funding:
  - DOE Share: \$1,575K
- Funding for FY2016: \$500K

## Barriers

- Cost
- Performance (Power Density)
- Life

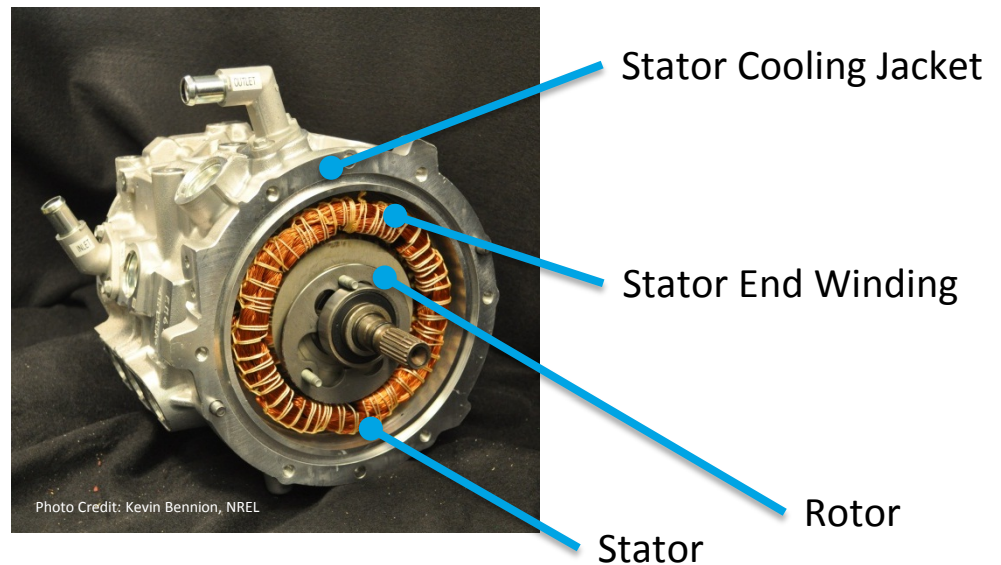
## Partners

### (Interactions/Collaborations)

- Motor Industry – R&D Input and Application of Research Results
  - Suppliers, end users, and researchers
- Oak Ridge National Laboratory (ORNL) – Motor R&D Lead
  - Tim Burress (ORNL) – EDT062
  - Andy Wereszczak (ORNL) – PM054
- Ames Laboratory – Magnet Materials
  - Iver Anderson
- National Renewable Energy Laboratory (NREL) – Thermal Project Lead

# Relevance – Why Motor Cooling?

- **Thermal management enables more efficient and cost-effective motors.**
- **Current Density**
  - Size, Weight, Cost
- **Material Cost**
  - Magnets
  - Price variability
  - Rare-earth materials
- **Reliability**
- **Efficiency**



# Relevance – Research Objective

Problem



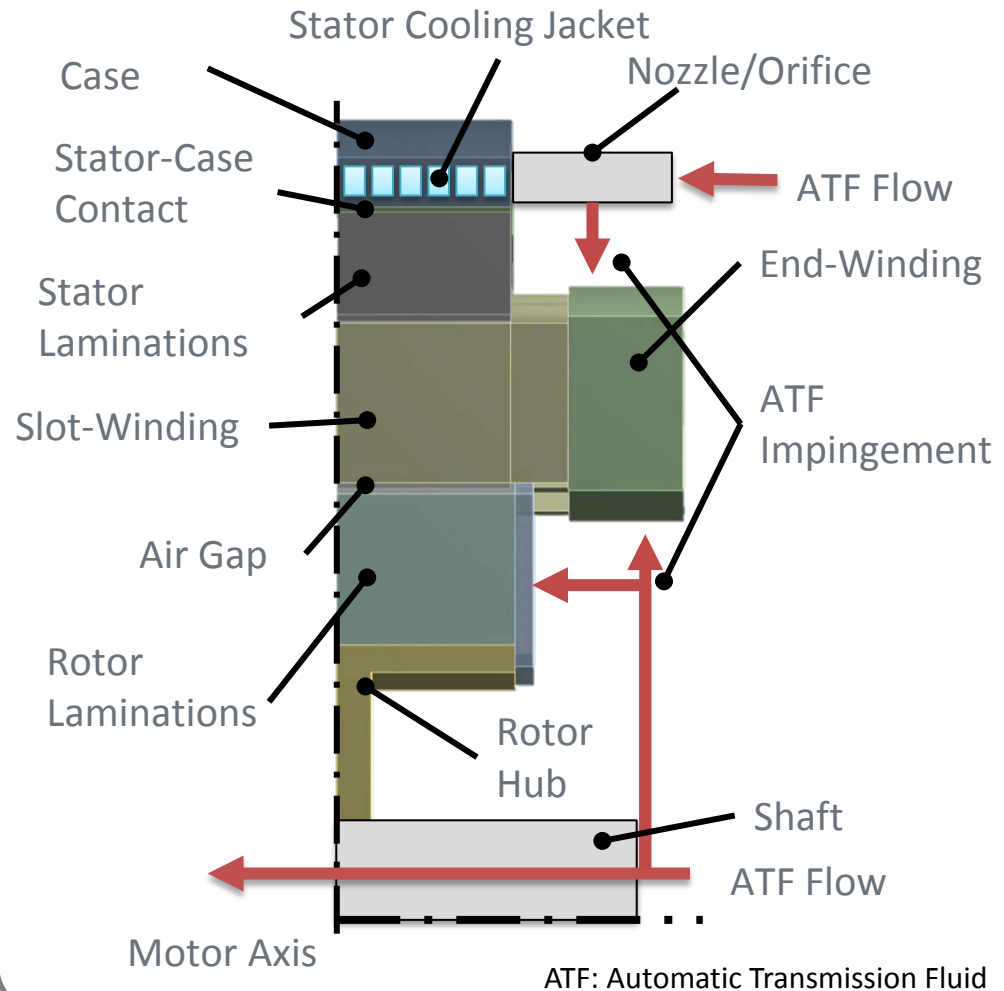
Core Thermal Capabilities  
and Research Tasks



Objective

Support broad industry demand for data, analysis methods, and experimental techniques to improve and better understand motor thermal management

## Motor Cooling Section View



# Milestones

Date	Description
December 2014 (Complete)	Milestone <ul style="list-style-type: none"><li>Design test bench setup for measurement of ATF jet impingement on representative motor end windings.</li></ul>
March 2015 (Complete)	Milestone <ul style="list-style-type: none"><li>Perform thermal measurements on passive thermal materials in collaboration with ORNL.</li></ul>
June 2015 (Complete)	Go/No-Go <ul style="list-style-type: none"><li>Select potting material for bench-level testing on representative motor components in collaboration with ORNL.</li></ul>
September 2015 (Complete)	Milestone <ul style="list-style-type: none"><li>Publish end-winding jet impingement heat transfer data and share with industry.</li></ul>
December 2015 (Complete)	Go/No-Go <ul style="list-style-type: none"><li>Select alternative motor winding configurations and flow conditions for ATF experiments, and select passive stack materials for characterization in collaboration with ORNL.</li></ul>
March 2016 (Complete)	Milestone <ul style="list-style-type: none"><li>Complete preliminary measurements of ATF heat transfer coefficients on motor end windings.</li></ul>
June 2016 (in progress)	Milestone <ul style="list-style-type: none"><li>Complete design to incorporate motor rotor cooling and effects on cooling end windings.</li></ul>
September 2016 (in progress)	Milestone <ul style="list-style-type: none"><li>Measure ATF heat transfer coefficients on motor end windings and passive stack thermal resistance measurements. Prepare report to summarize project results.</li></ul>

# Approach/Strategy – Problem

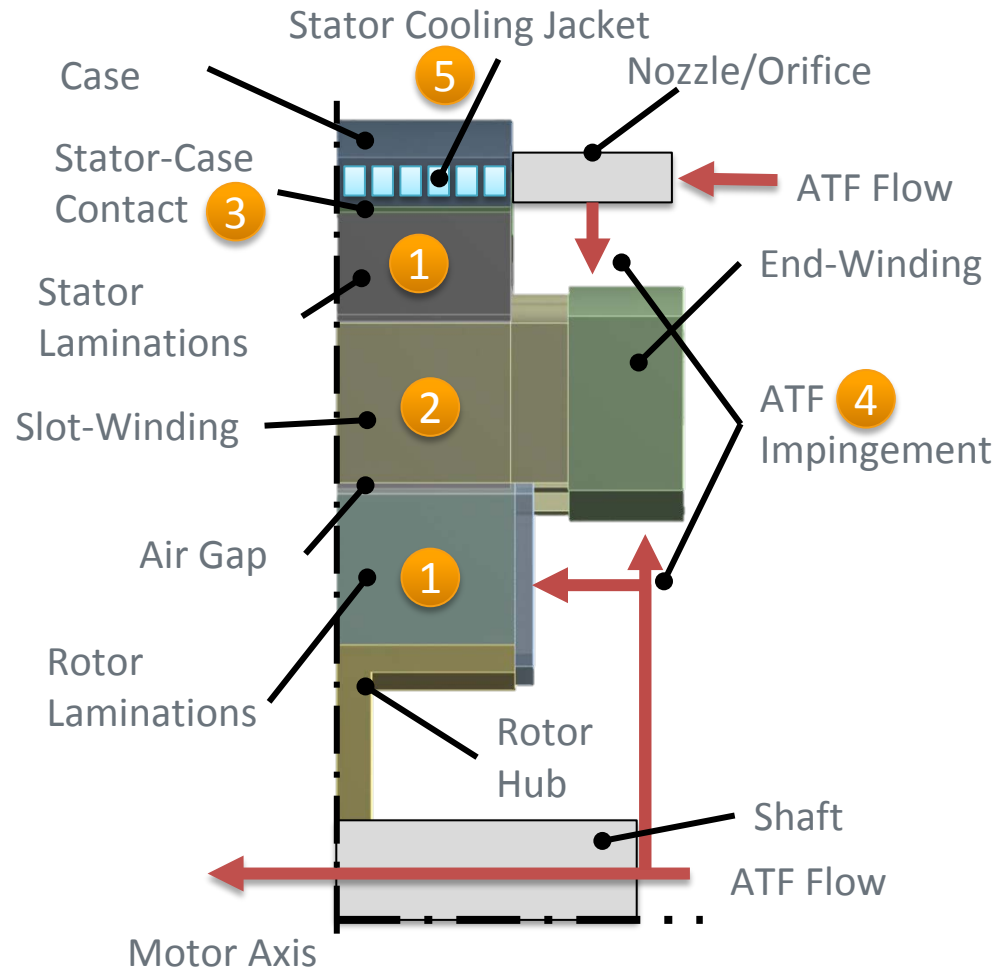
## Problem

- Multiple factors impacting heat transfer are not well quantified or understood.

## Contributing Factors

1. Direction-dependent thermal conductivity of lamination stacks
2. Direction-dependent thermal conductivity of slot windings and end windings
3. Thermal contact resistances (stator-case contact, slot-winding interfaces)
4. Convective heat transfer coefficients for ATF cooling
5. Cooling jacket performance

## Motor Cooling Section View



ATF: Automatic Transmission Fluid

# Approach/Strategy – Focus

Core Capabilities

Apply core thermal experimental and modeling capabilities.

Tasks

- Measure convective heat transfer coefficients for ATF cooling of end windings.
- Measure interface thermal resistances and orthotropic thermal conductivity of materials with ORNL.
- Support property measurements of magnet materials for Ames-led magnet efforts.

Objective

Support broad industry demand for data to improve and better understand motor thermal management.

*Automatic Transmission Fluid Heat Transfer*



*Material and Thermal Interface Testing*

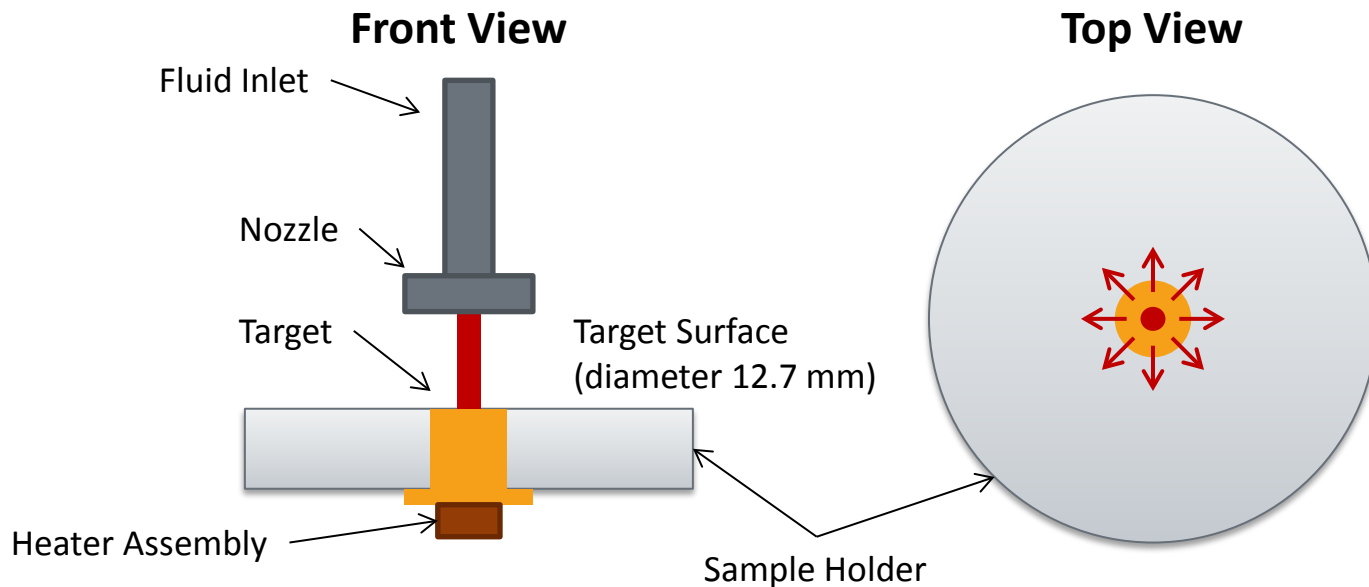


Material Sample Provided by ORNL



# Technical Accomplishments

- Prior ATF heat transfer measurements performed with orifice jet



All of the fluid from the nozzle impinges onto the target surface and flows radially outward.

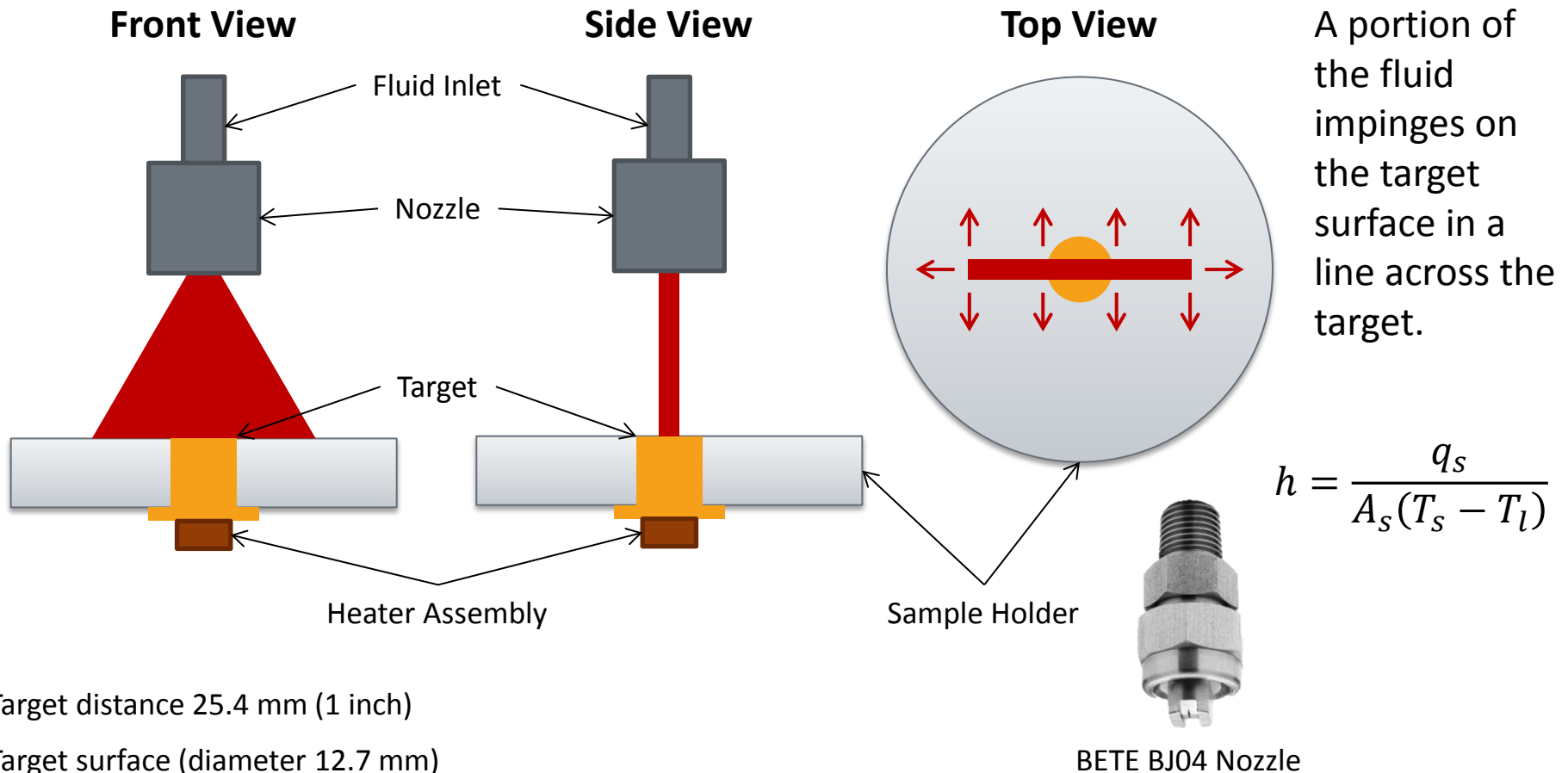
$$h = \frac{q_s}{A_s(T_s - T_l)}$$

Reference:  
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.



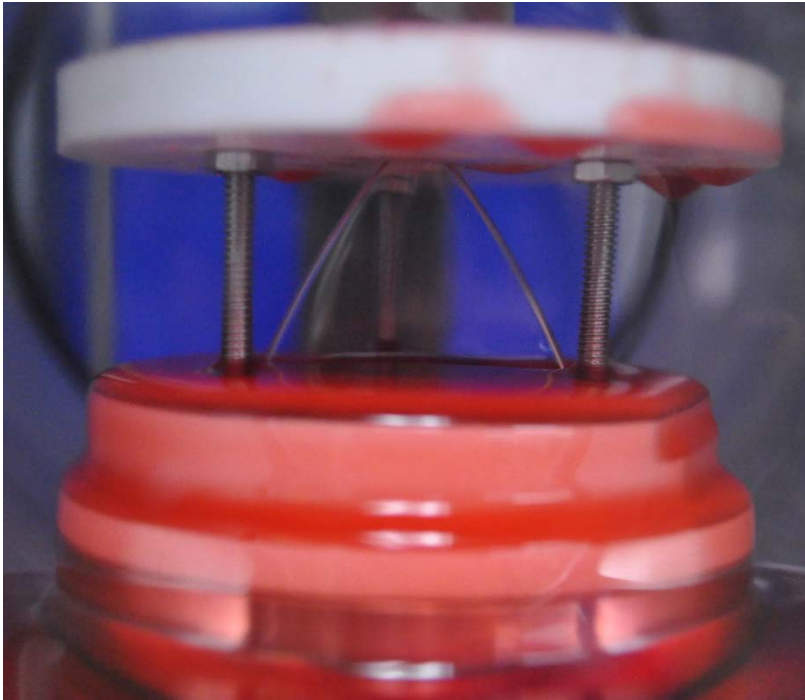
# Technical Accomplishments

- ATF heat transfer for flat fan jet

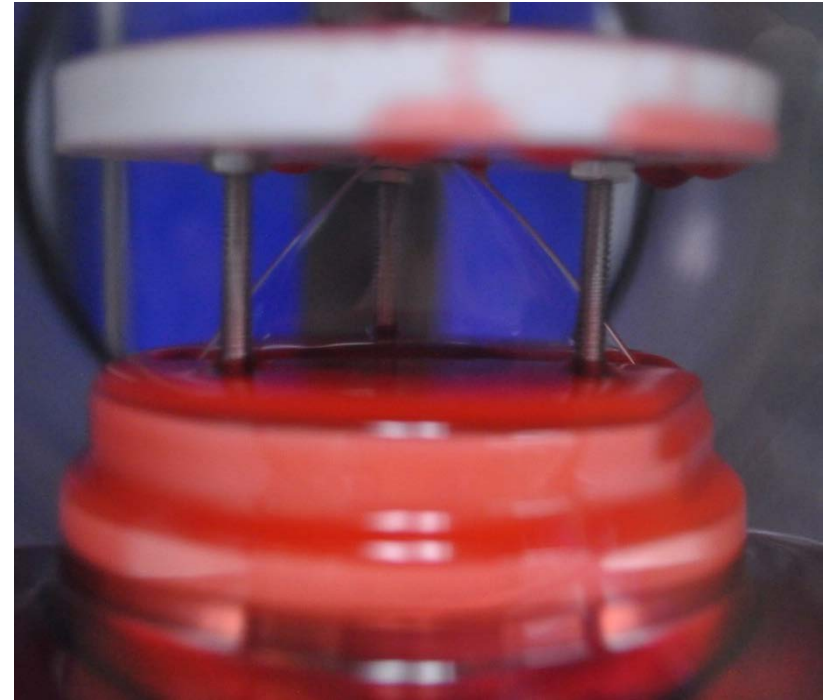


# Technical Accomplishments

- ATF heat transfer for flat fan jet



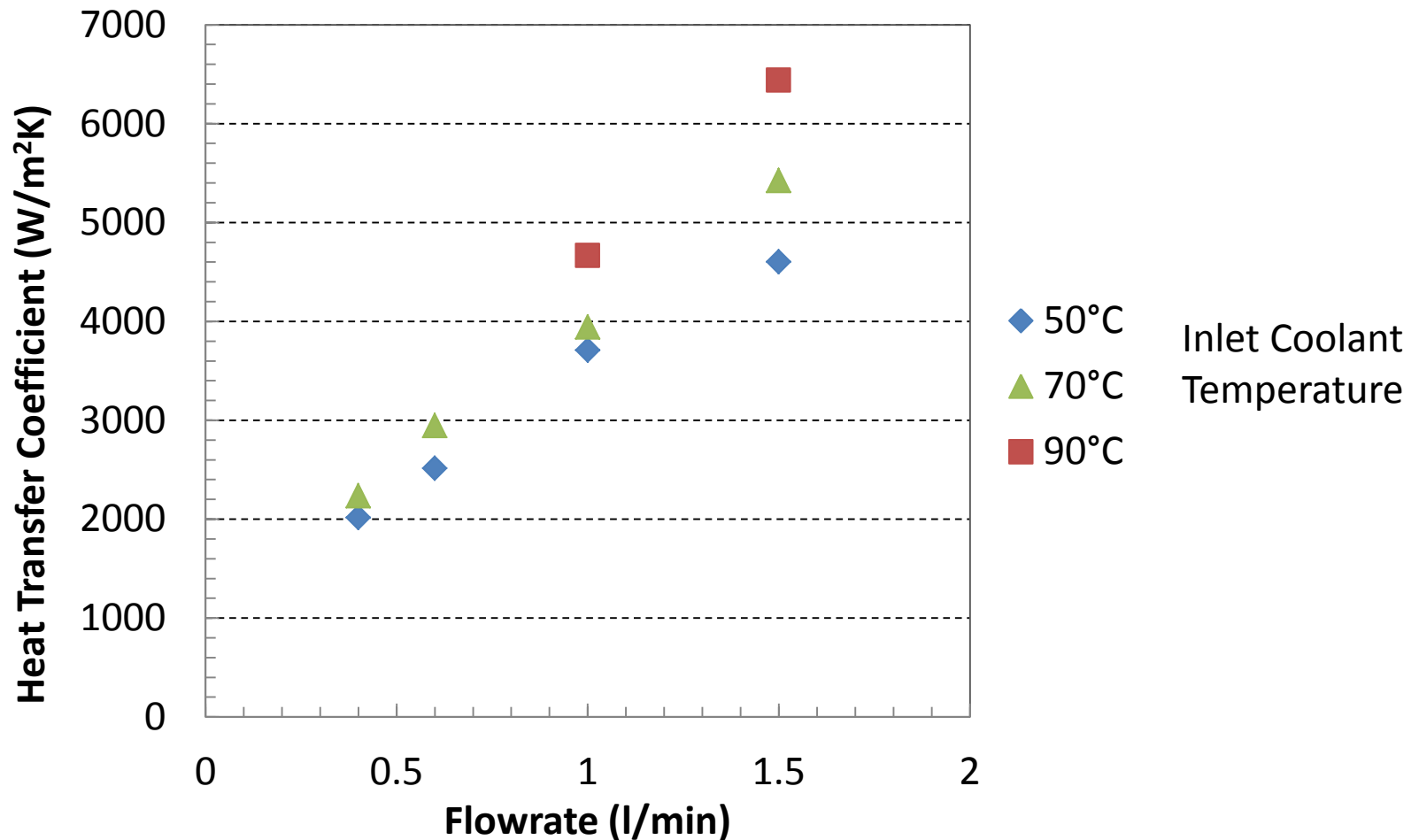
*Flowrate of 0.6 l/min led to  
58° spray angle*



*Flowrate of 1.0 l/min led to  
78° spray angle*

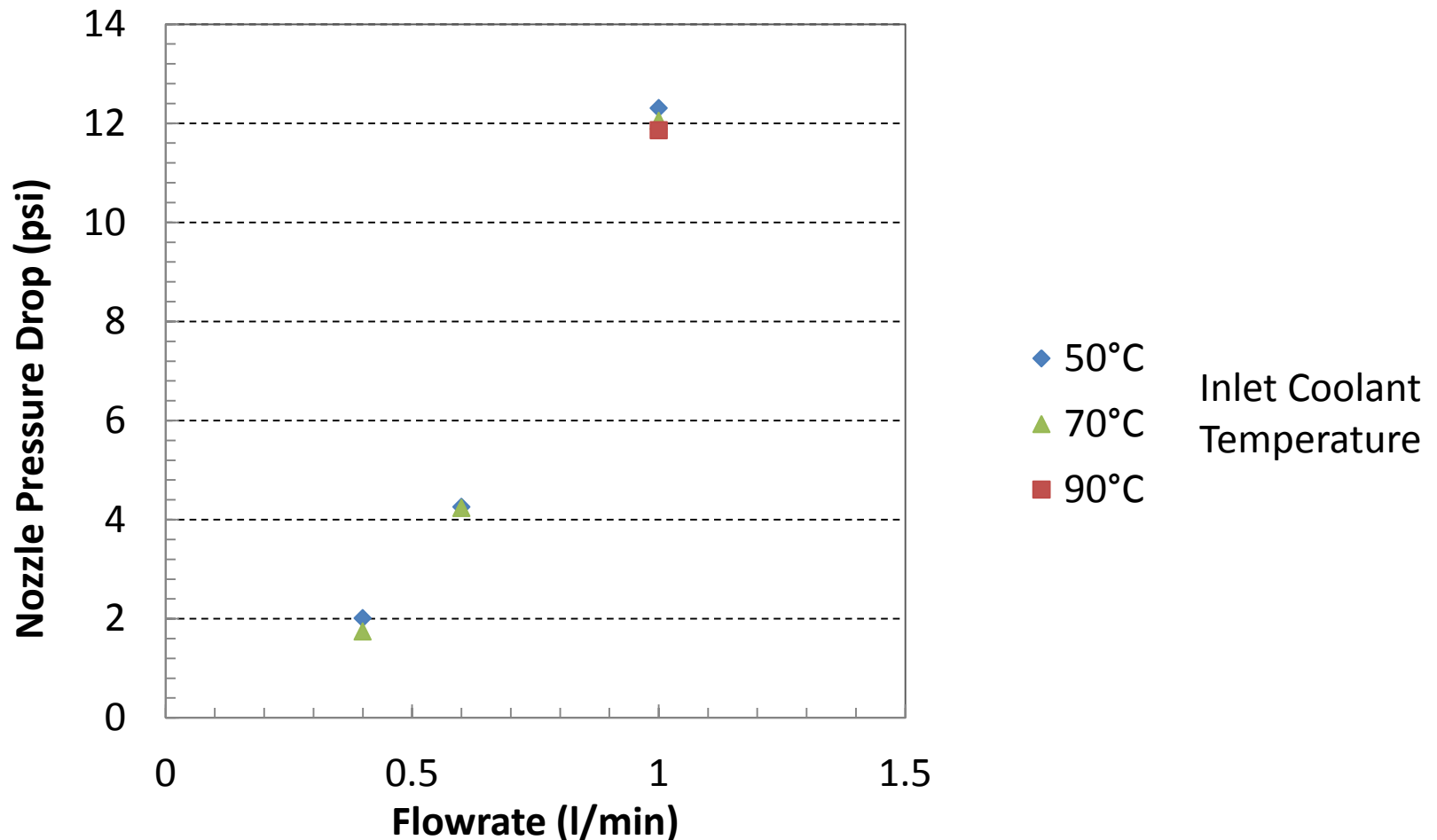
# Technical Accomplishments

- ATF heat transfer for flat fan jet



# Technical Accomplishments

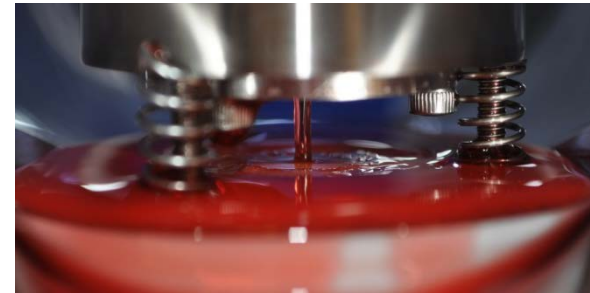
- ATF pressure drop measurements for fan jet



# Technical Accomplishments

- For motor applications, the jet performance depends on more than the heat transfer coefficient over a small target surface
  - The following research is needed
    - Cooling tradeoffs with pressure drop
    - Additional nozzle configurations
    - Local versus large-scale heat transfer coefficients

*Orifice Jet*



*Fan Jet*

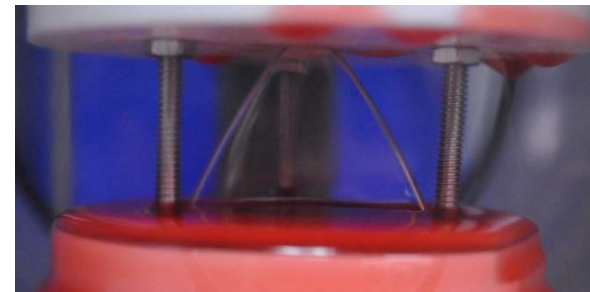


Photo Credit: Jana Jeffers and Xuhui Feng, NREL

# Technical Accomplishments

- **Spatial mapping of large-scale end-winding convective heat transfer with direct ATF cooling**

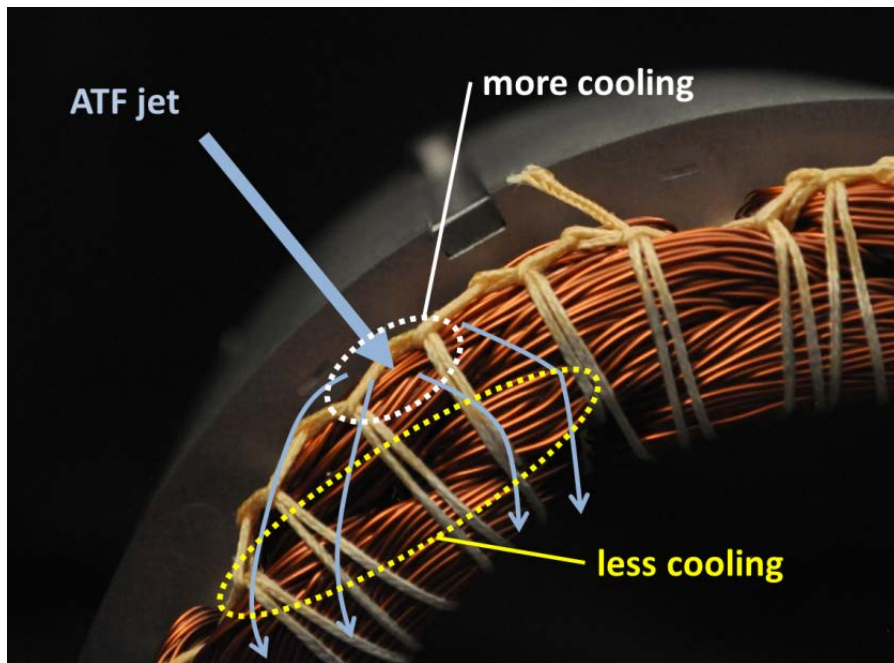


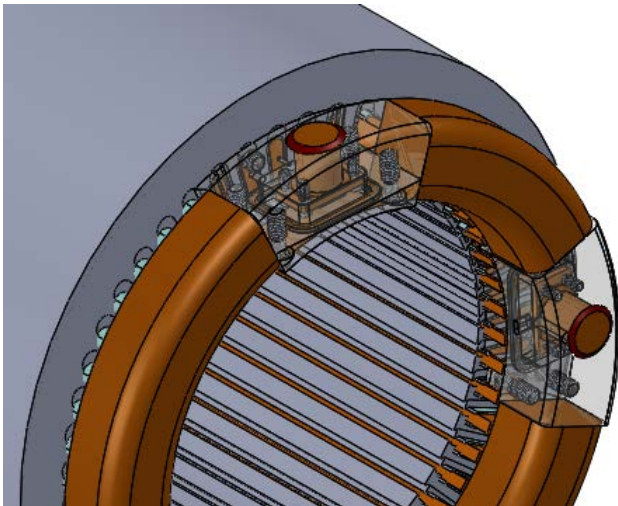
Photo Credit: Kevin Bennion, NREL

- Study effects of:
  - Oil jet placement
  - Nozzle type
  - ATF free flow over end-winding surfaces
  - Jet interactions
- Assumptions:
  - Flat surface with texture of wires

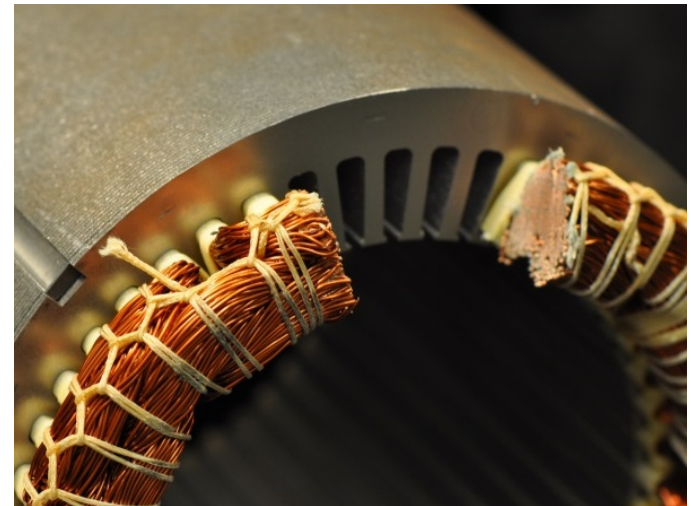
# Technical Accomplishments

- **Designed and built sensor packages to install in motor end winding for measuring heat transfer coefficients**

*3D drawing of stator with sensor packages installed*



*Stator winding removed for sensor package*

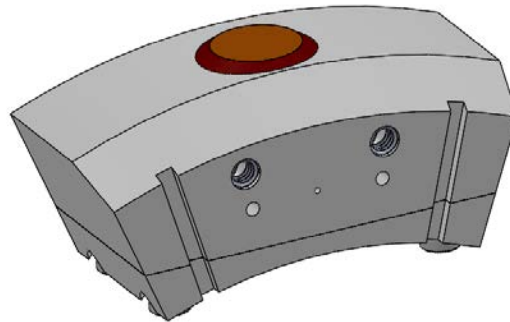




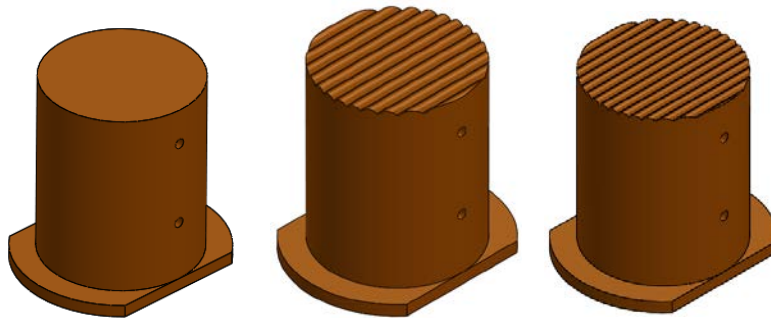
# Technical Accomplishments

- **Sensor package construction**

Sensor Package



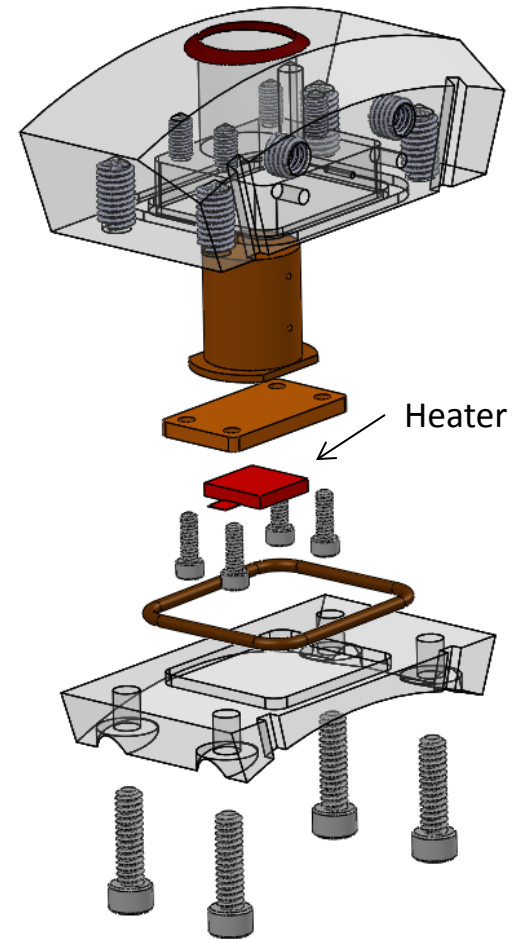
Targets



Flat

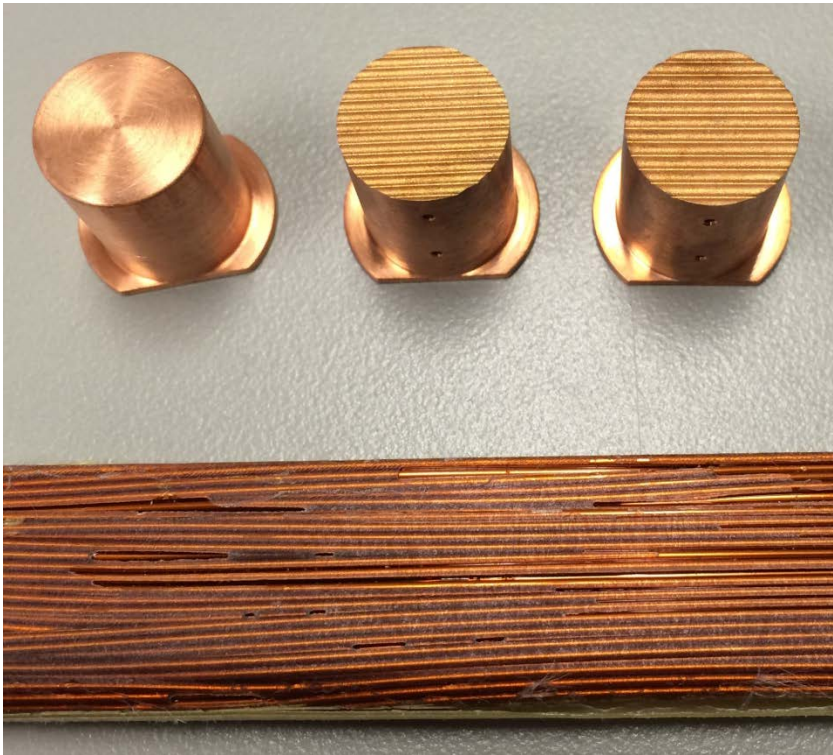
18 AWG

20 AWG

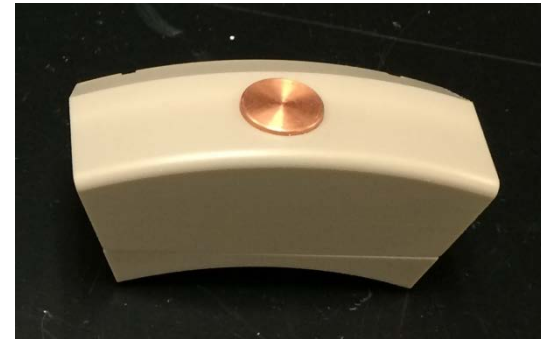


Exploded View

# Technical Accomplishments



*Target surfaces built to represent wire surface with different wire sizes*



*Assembled test fixture for outer diameter heat transfer measurement*

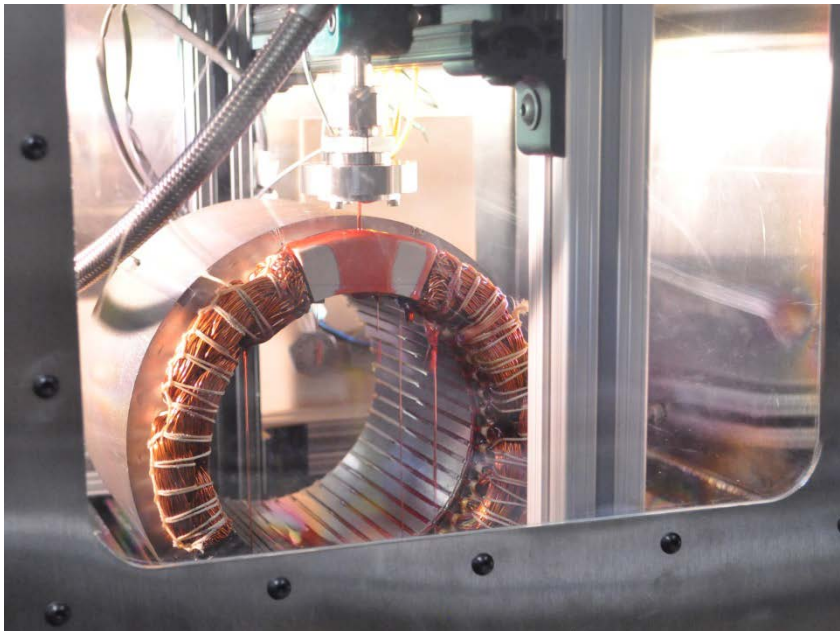


*Assembled test fixture for end-surface heat transfer measurement*

# Technical Accomplishments

- **Enclosure allows direct impingement on motor for heat transfer measurements and flow visualization**

*Enclosure with stator and ATF cooling*



*Jet impingement on target surface*

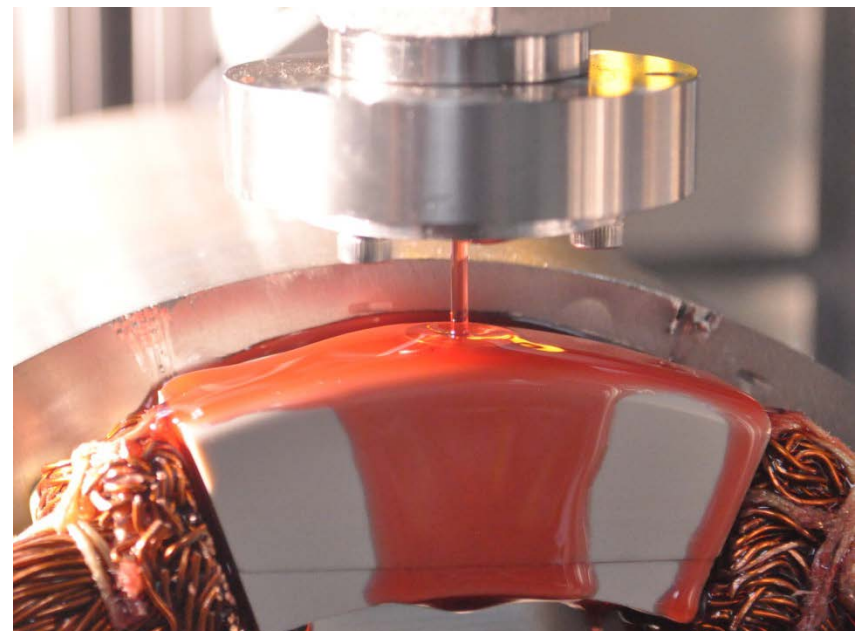
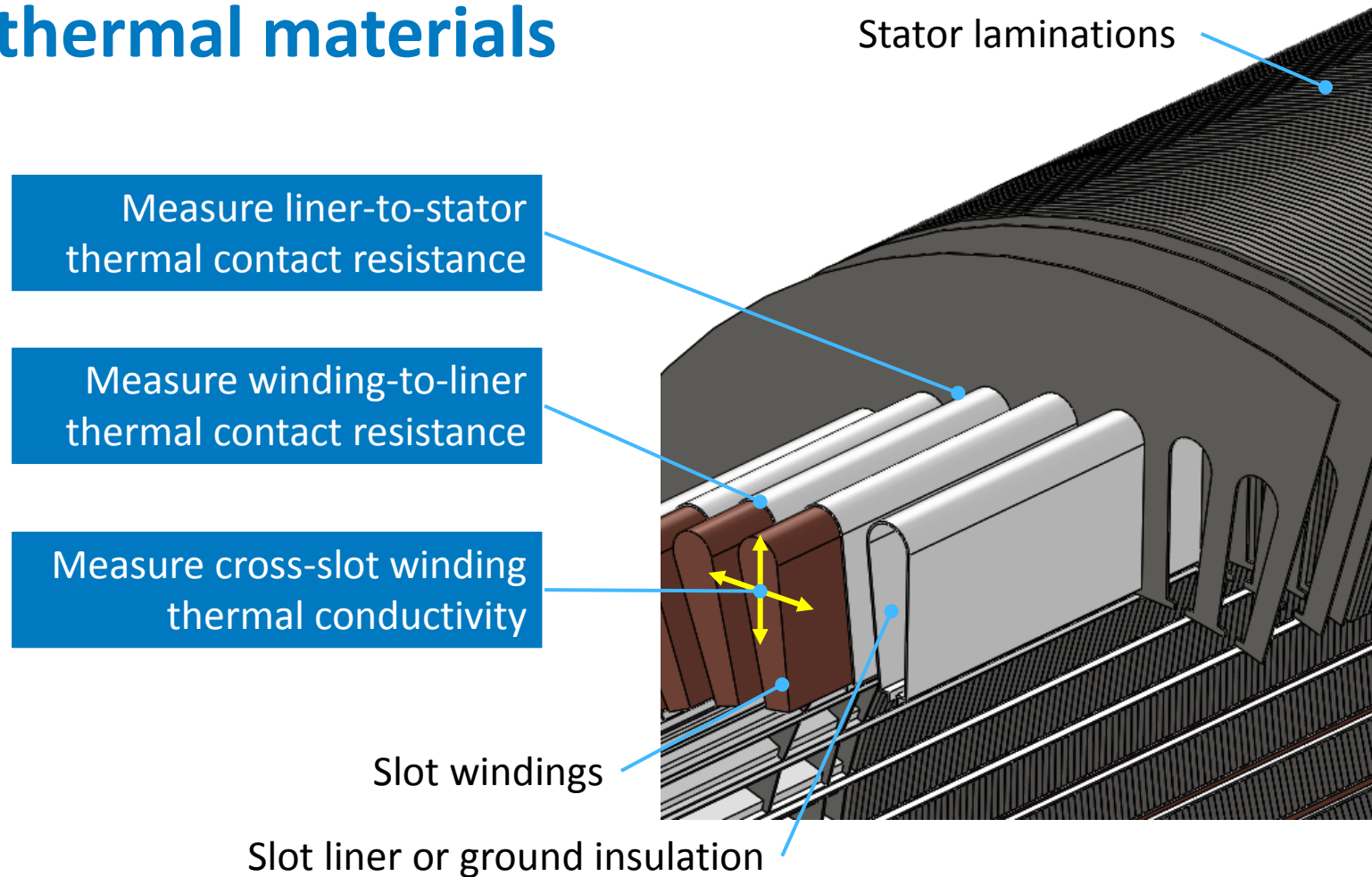


Photo Credit: Kevin Bennion, NREL

# Technical Accomplishments

- **Performing thermal analysis on passive thermal materials**

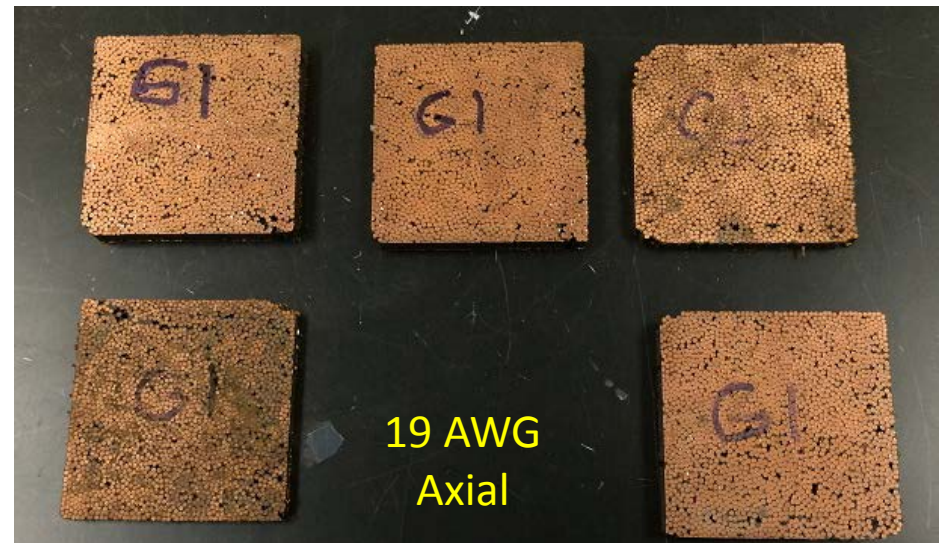




# Technical Accomplishments

- **Performing thermal analysis on passive thermal materials**

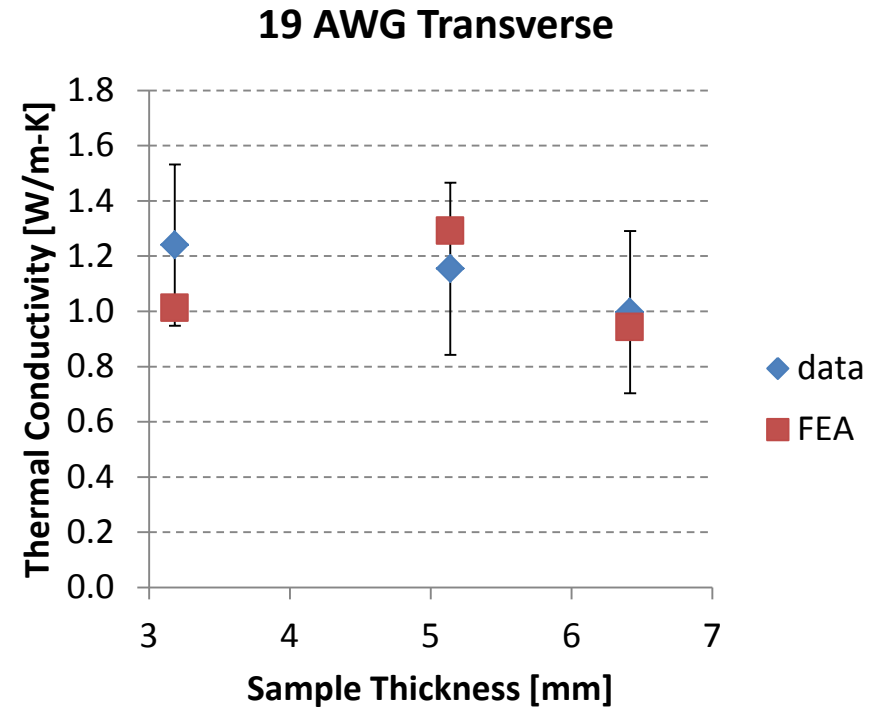
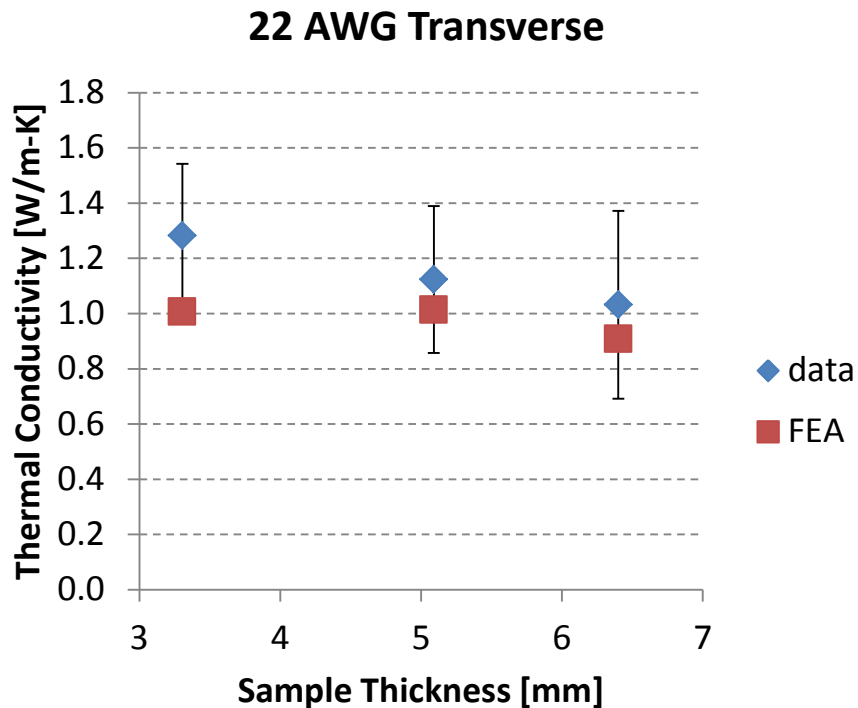
- ORNL prepared slot-winding samples with variations for:
  - Wire size (19 AWG, 22 AWG)
  - Sample thickness
- Collaborating with ORNL on thermal conductivity measurement techniques



*Winding sample blocks prepared by ORNL*

# Technical Accomplishments

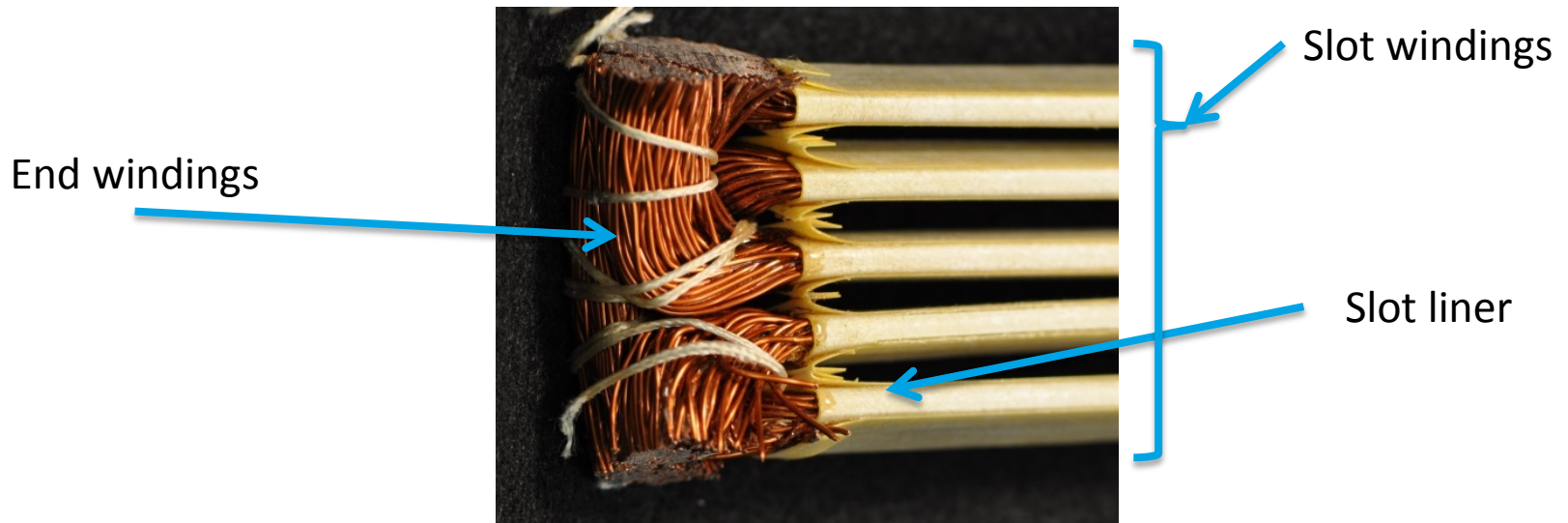
- **Transverse winding results**



- Error bars represent 95% measurement uncertainty (U95)
- Finite element analysis (FEA) model result based on measured sample copper fill factor
- FEA assumes hexagonal or closed-pack wire pattern

# Technical Accomplishments

- Performing thermal analysis on passive thermal materials

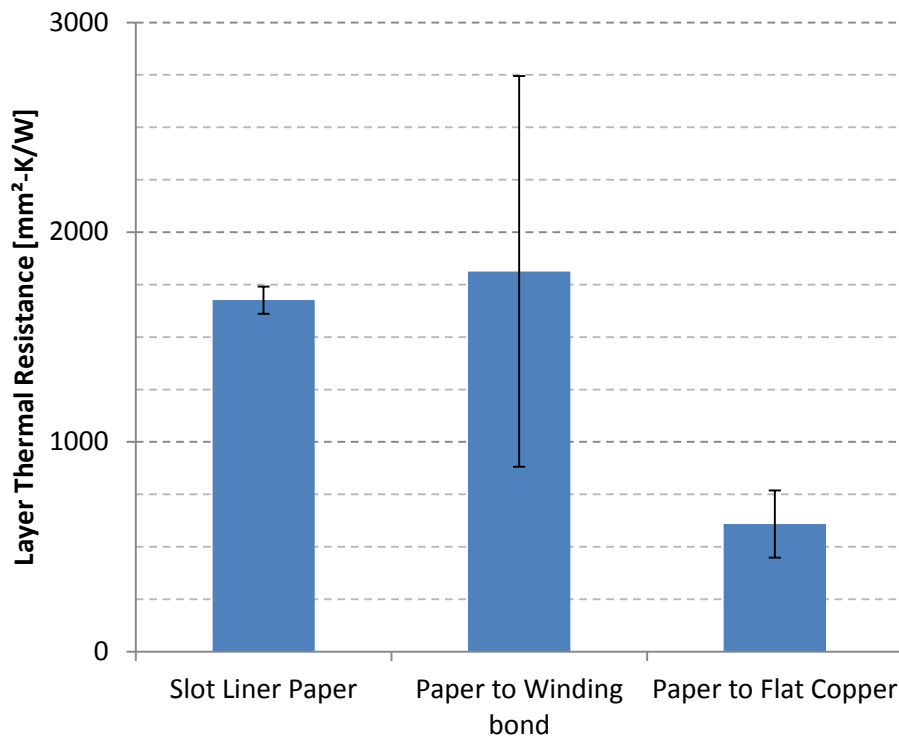




# Technical Accomplishments

- **Measured passive thermal materials and interfaces**

*Slot Liner Paper and Thermal Interfaces*



- Limited sample size for measurements
- Slot liner paper thermal conductivity of  $0.175 \text{ W/m-K}$  (thickness  $0.294 \text{ mm}$ )
- Winding thermal conductivity measured to be  $0.88 \pm 0.11 \text{ W/m-K}$  ( $U_{95}$ )
- FEA estimate of thermal conductivity is  $0.99 \text{ W/m-K}$  for measured copper fill factor

# Response to Previous Year Reviewers' Comments

- **Reviewers thought the passive material measurements and heat transfer coefficients were important and the data is valuable. It was suggested that it would be great to publish and present results.**
  - *This past year, we have published and presented results related to prior work, and we are working with ORNL on publishing our data on winding thermal measurements. We will work to focus on publishing results.*
- **Reviewer said it would be good to include more details that make the testing more realistic to what takes place in a real motor. Another reviewer mentioned or highlighted an interest in bar wound stators.**
  - *We have constructed a new test setup allowing thermal testing on more representative motor and stator geometries. This should also enable potential collaborative work related to bar-wound stators and other geometries.*
- **The reviewer's analysis was that there is potential for increased collaboration, exchange of data/comparison with GE, the other group that is testing end winding impingement cooling. The reviewer suggested considering collaborating with universities as well.**
  - *We have tried to increase our collaborations as suggested.*

# Collaboration and Coordination with Other Institutions

- **Industry**

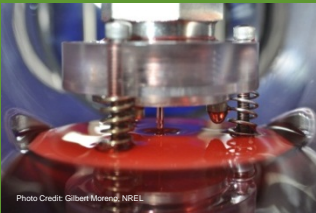
- Motor industry suppliers, end users, and researchers
  - Sharing experimental data, modeling results, and analysis methods
  - Companies providing research comments, requesting data, or supplying data or motor material information include: Ford, FCA, GM, Tesla, UQM Technologies, GE Global Research, Remy/BorgWarner, John Deere, Oshkosh, motor material manufacturers

- **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 Barriers

## Cooling Technology Development



- 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)

## Passive Thermal Stack and Reliability



- Thermal tests of interfaces between slot insulation and laminations, and slot insulation and slot windings
- Irregular structure of certain end windings present a challenge to measure thermal conductivity

# Proposed Future Work

## FY2016

- Continue ongoing collaboration with ORNL material developments and motor research.
- Measure passive stack thermal interfaces and orthotropic thermal properties of materials in collaboration with ORNL. Publish results with ORNL.
- Measure physical properties as a function of temperature for Ames Laboratory on new magnet materials developed at Ames.
- Measure large-scale variation in ATF impingement heat transfer coefficients within a stator - supporting fourth-quarter milestone.
- Share and publish fan jet heat transfer results.

## FY2017

- Characterize alternative ATF cooling sprays and end-winding geometry in motor-scale thermal measurements.
- Continue collaborative efforts with ORNL and Ames on material measurements representative of motor materials.
- Initiate efforts on rotor thermal management in collaboration with research partners.

# 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

- Completed measurement of fan jet nozzle for ATF heat transfer in motor application in collaboration with industry partner.
- Built experimental apparatus to measure large-scale variation in convective heat transfer coefficients.
- Collaborating 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:

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## Team Members:

Emily Cousineau (NREL)  
Doug DeVoto (NREL)  
Xuhui Feng (NREL)  
Charlie King (NREL)  
Gilbert Moreno (NREL)  
Tim Burress (ORNL)  
Andy Wereszczak (ORNL)  
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