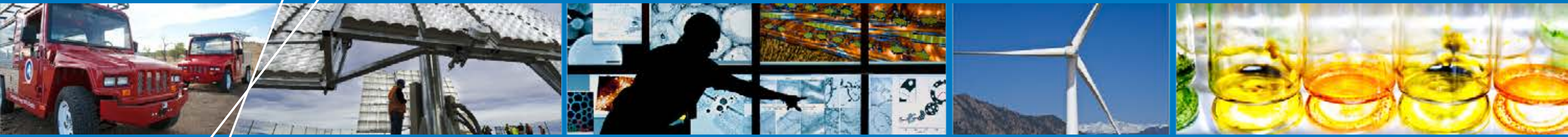
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Electric Motor Thermal Management R&D



Kevin Bennion
Organization: NREL
Email: kevin.bennion@nrel.gov
Phone: 303-275-4447

Team members/collaborators:
Justin Cousineau, Charlie King, Gilbert Moreno, Caitlin Stack (NREL)
Tim Burress, Andy Wereszczak (ORNL)

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

DOE Vehicle Technologies Office
Electric Drive Technologies
FY15 Kickoff Meeting

Oak Ridge National Laboratory
Oak Ridge, Tennessee
November 18 – 20, 2014

NREL/PR-5400-63004

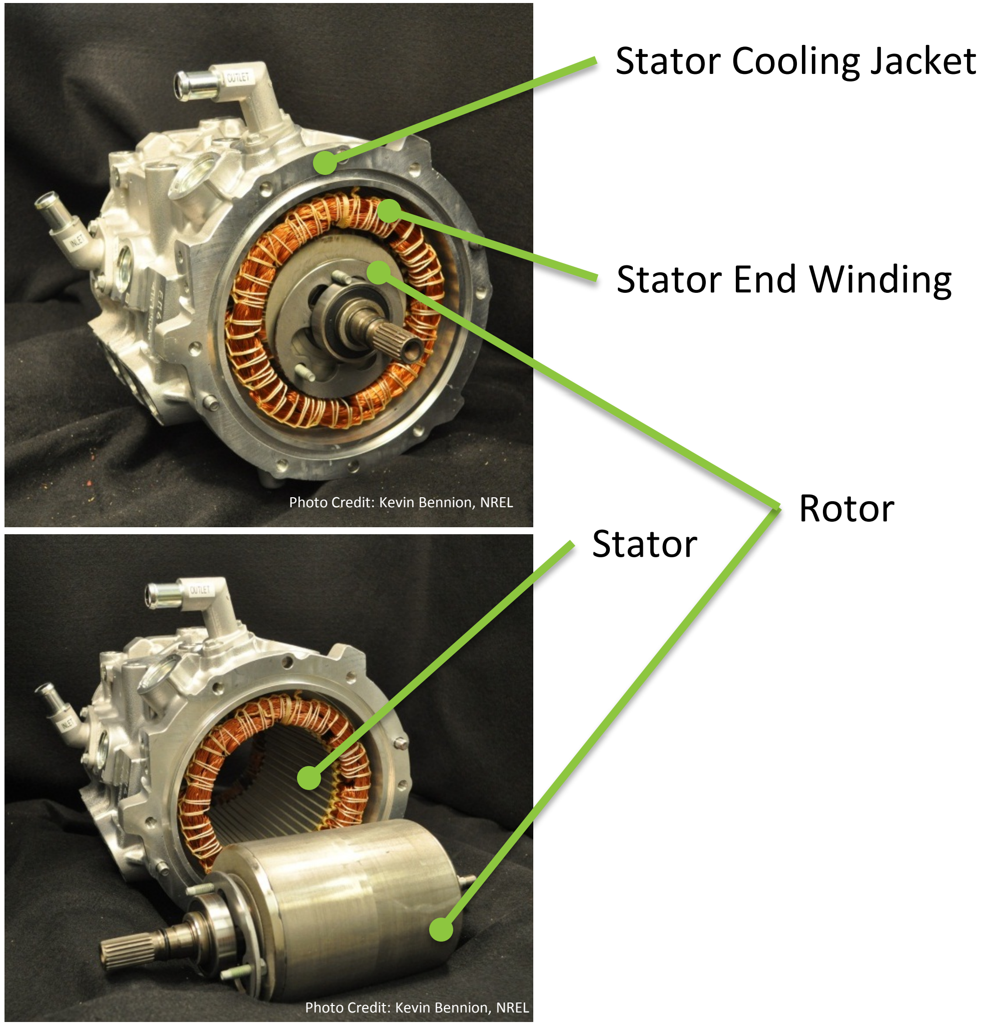
Thermal Management Enables More Efficient and Cost-Effective Motors

State of the Art

- Water-ethylene glycol stator cooling jacket
- Automatic transmission fluid (ATF) impingement on motor end windings

Why Motor Cooling

- Current Density
    - Size
    - Weight
    - Cost
- Material Costs
    - Magnets
    - Rare-earth materials
    - Price variability
- Reliability
- Efficiency



Passive and Active Cooling

Passive Thermal Stack
- Motor geometry
- Material thermal properties
- Thermal interfaces

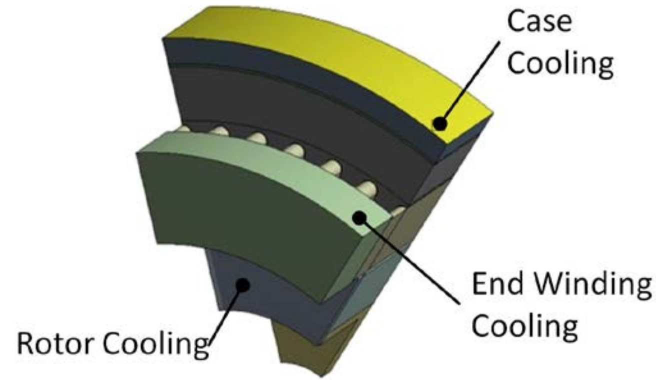
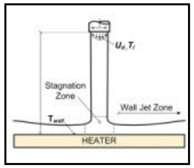
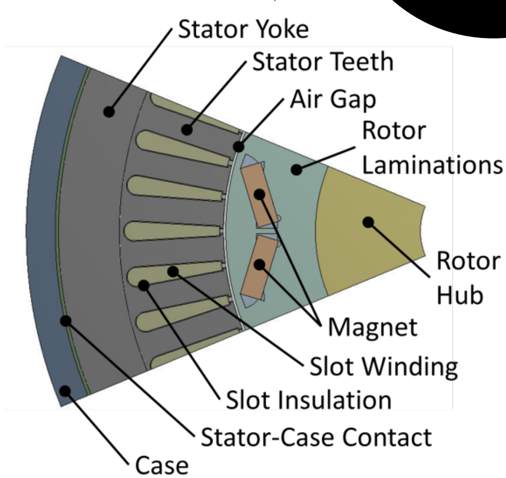


Photo Credit: Kevin Bennion, NREL

Passive Thermal Stack → Motor Thermal Management ← Active Convective Cooling





Active Convective Cooling
- Cooling location
- Heat transfer coefficients
- Available coolant
- Parasitic power

Challenges

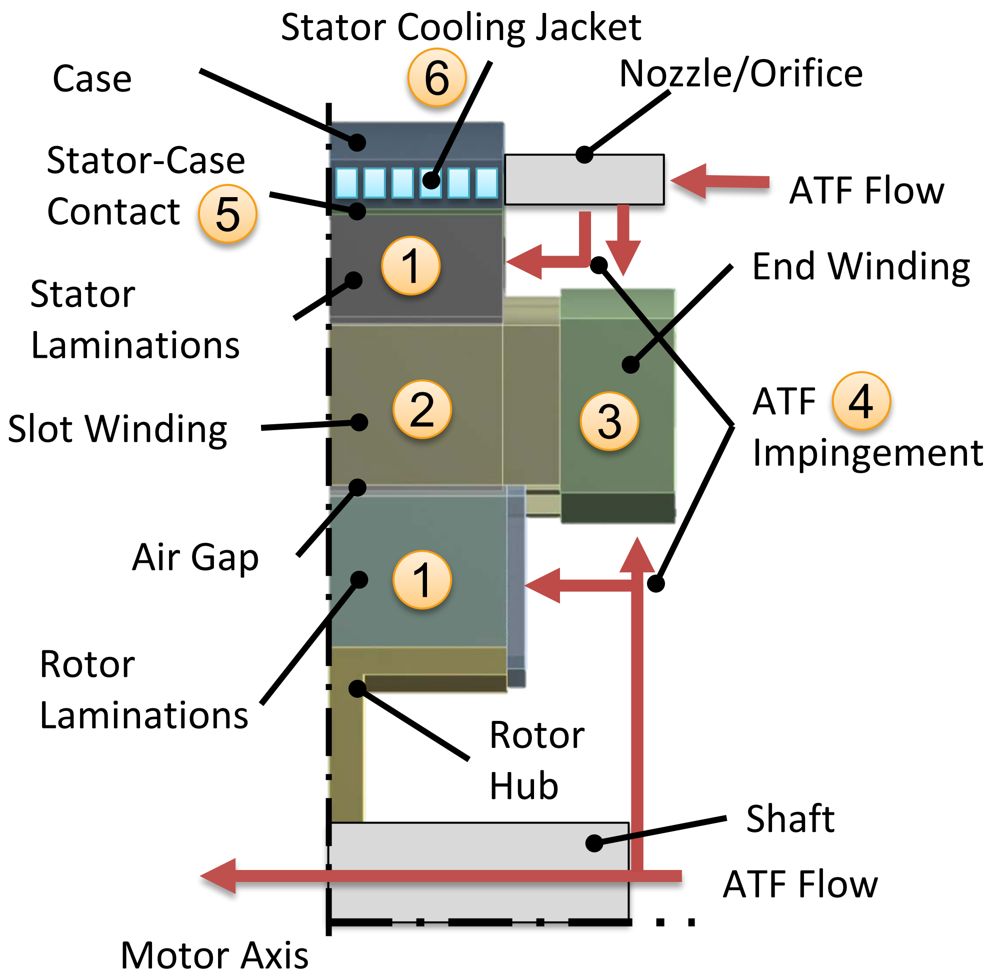
Problem

Extracting heat from within the motor to protect the motor and enable high power density

Challenges

1. Orthotropic (direction dependent) thermal conductivity of lamination stacks
2. Orthotropic thermal conductivity of slot windings
3. Orthotropic thermal conductivity of end windings
4. Convective heat transfer coefficients for ATF cooling
5. Thermal contact resistance of stator-case contact
6. Cooling jacket performance

Motor Cooling Section View



Proposed Research Objectives

Problem

↓

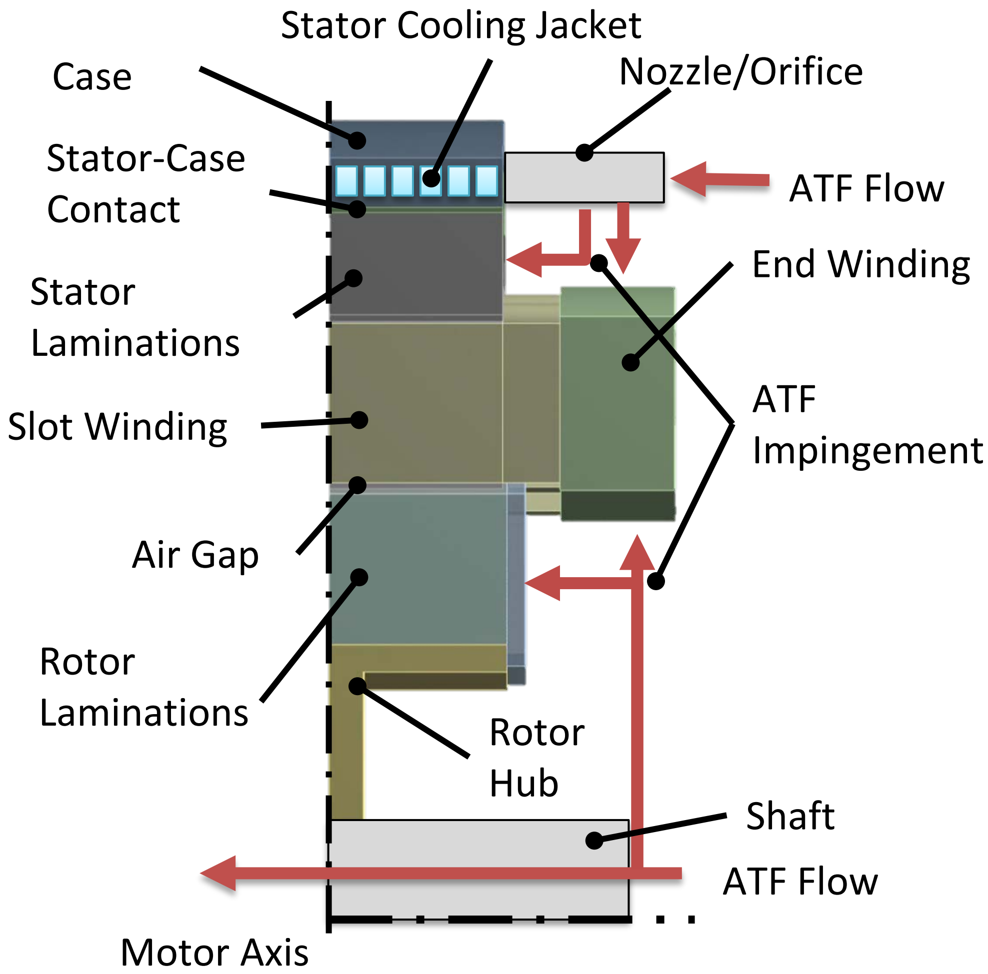
Core Thermal Capabilities and Research Tasks

↓

Objective

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

Motor Cooling Section View



Research Focus

Research Tasks

- Measure convective heat transfer coefficients for ATF cooling of end windings
- Measure interface thermal resistances and orthotropic thermal conductivity of materials

Objective

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

Automatic Transmission Fluid Heat Transfer

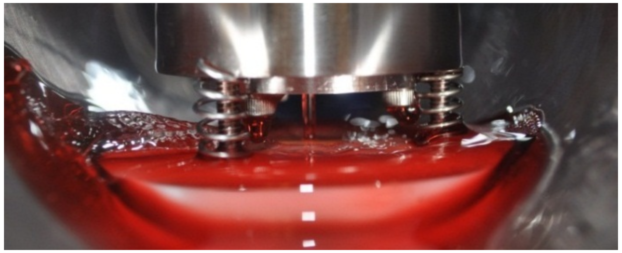


Photo Credit: Jana Jeffers, NREL

Material and Thermal Interface Testing

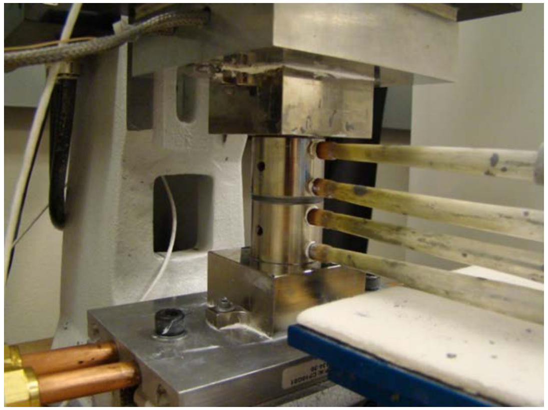


Photo Credit: Justin Cousineau, NREL

Active Cooling

Direct Impingement on Target Surfaces

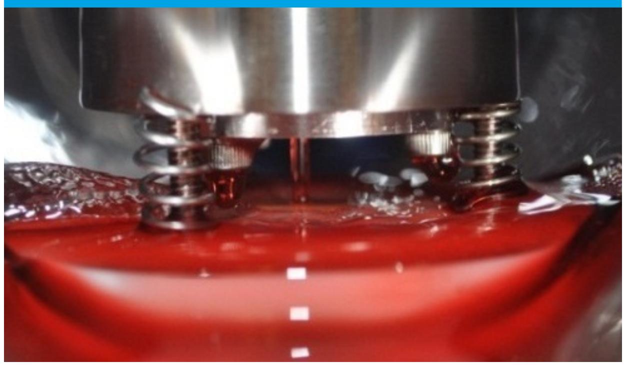


Photo Credit: Jana Jeffers, NREL

Measure heat transfer coefficients for ATF cooling of end windings

Impingement on Motor End Windings

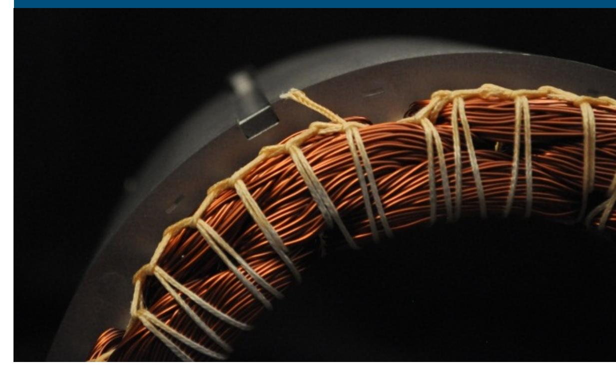


Photo Credit: Kevin Bennion, NREL

Average Heat Transfer Coefficients

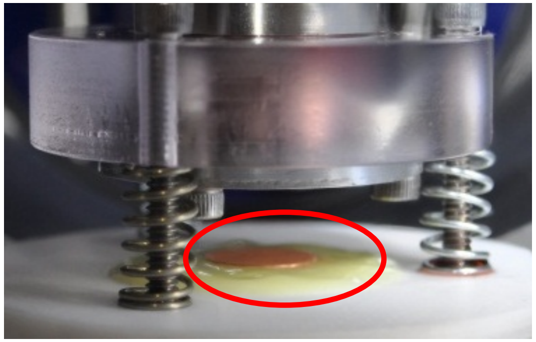
- Establish credibility of experiment and data through comparison of plain target surface results to existing correlations in literature
- Produce new data for textured surfaces representative of end-winding wire bundles

Spatial Mapping of Convective Heat Transfer Coefficient

- Jet local convective heat transfer
- Large-scale end-winding convective heat transfer mapping

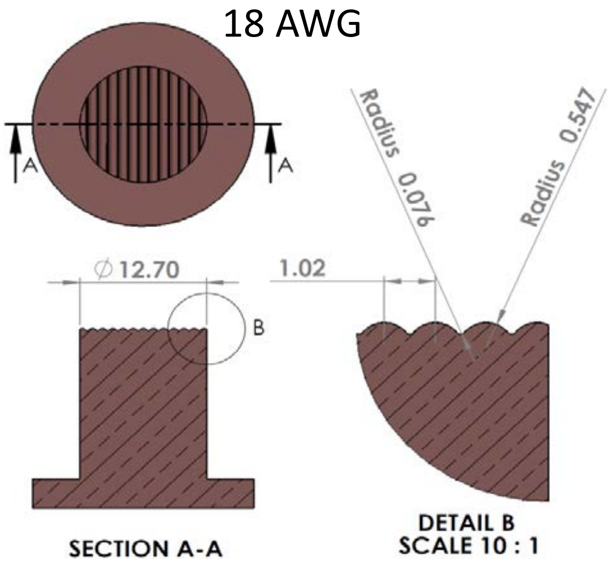
ATF Impingement Target Surfaces

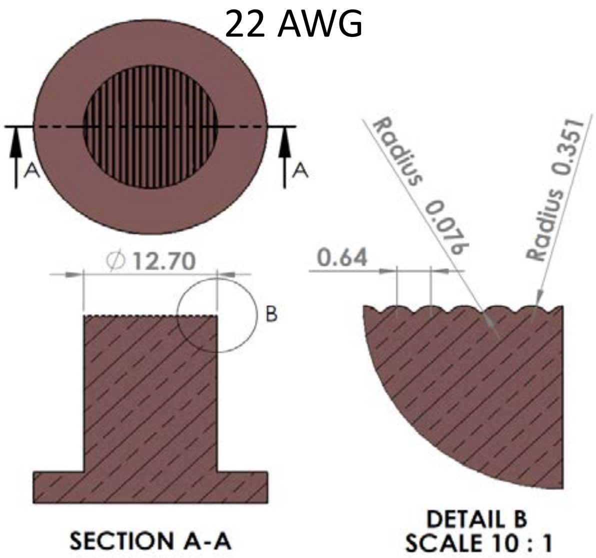
- ATF impingement baseline target is plain, polished copper with 600-grit sandpaper
- Additional targets mimic wire bundles with insulation (18, 22, and 26 AWG)

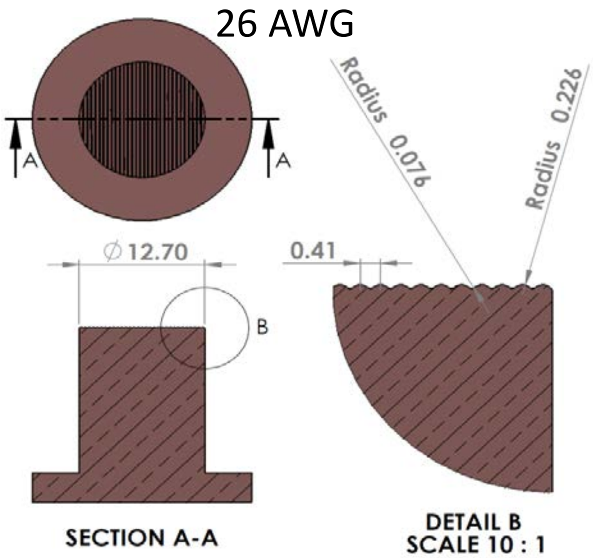


Credit: Gilbert Moreno, NREL

	Baseline	18 AWG	22 AWG	26 AWG
Radius (wire and insulation), mm	N/A	0.547	0.351	0.226
Total wetted surface area, mm^2	126.7	148.2	143.3	139.2



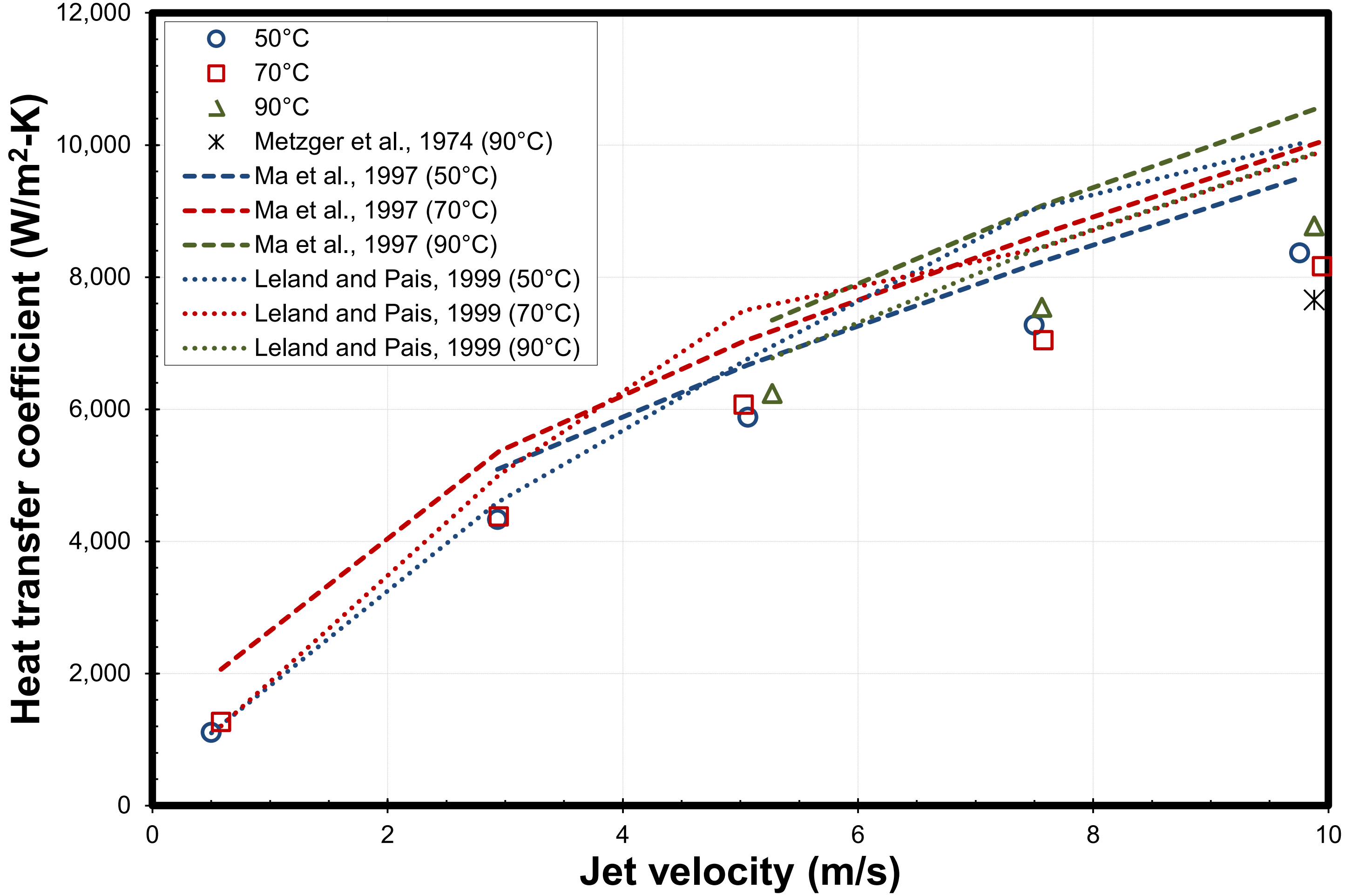




AWG = American Wire Gauge

Comparison to Plain Surface Correlations

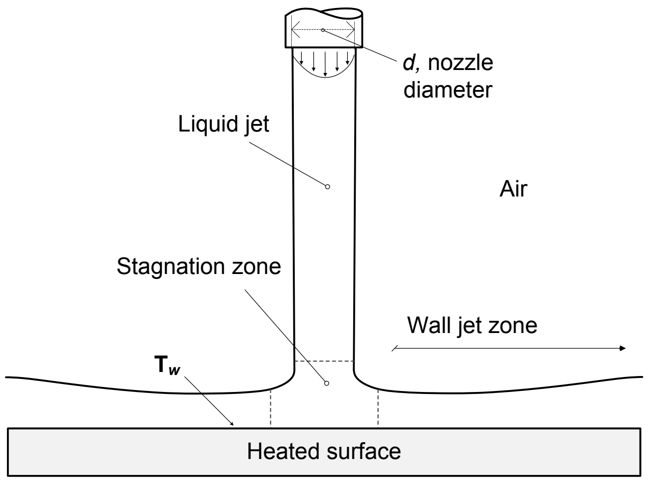
Comparison of test results to literature correlations on flat target surface

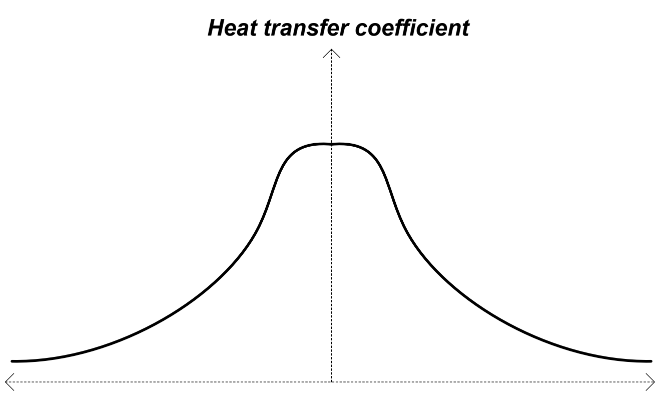


ATF fluid properties provided by Ford

Spatial Mapping of Heat Transfer

Local convective heat transfer coefficient

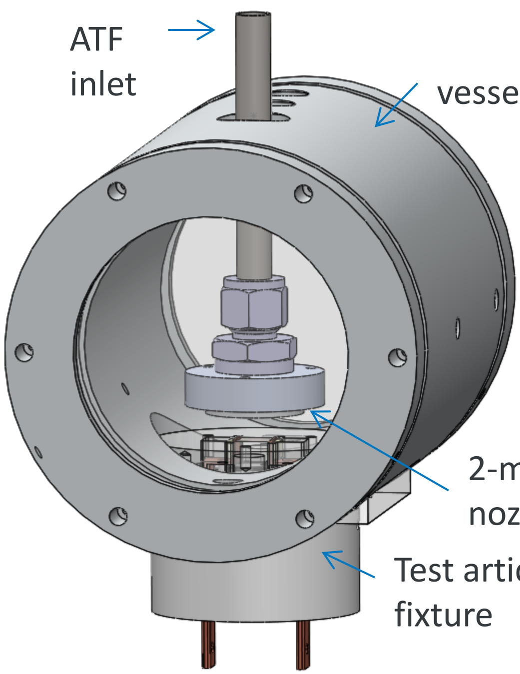




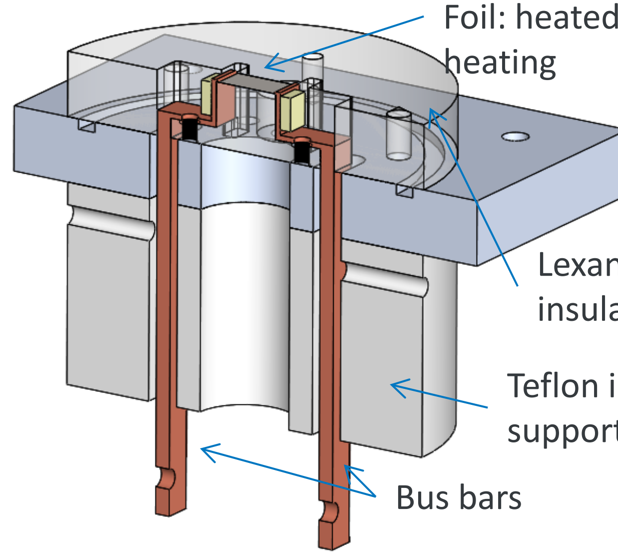
- Jet impingement heat transfer coefficients are not uniform over the entire cooled surface
- The highest heat transfer coefficients occur at the jet impact zone
- The rate of decrease in the heat transfer coefficient is unknown

TLC Experimental Apparatus

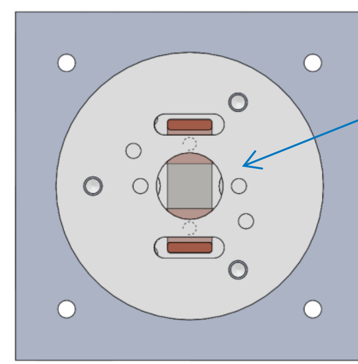
- Fabricated a test section to spatially measure jet impingement heat transfer coefficients on a discrete heat source.
- Initial tests will be conducted using thermochromic liquid crystals (TLCs), followed by infrared imaging

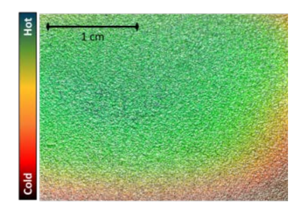


Test article cross-sectional view



Test article bottom view





Passive Thermal Stack

Accomplishments to Date – FY14

Material Measurements

Photo Credit: Justin Cousineau, NREL

Measure interface thermal resistances and orthotropic thermal conductivity of materials

Effective Thermal Properties for Motor Design and Simulation

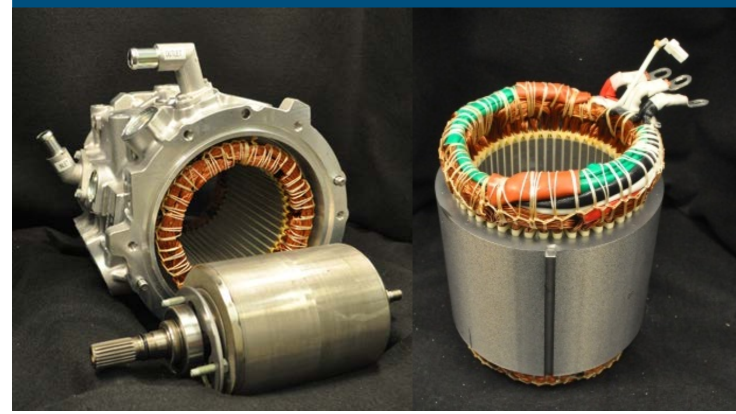


Photo Credit: Kevin Bennion, NREL

Stacked lamination thermal conductivity

- Quantified thermal contact resistance between motor laminations
- Supports improved thermal models for motor design and thermal analysis

Winding effective thermal properties

- Initiated work to measure orthotropic thermal properties
- Supports improved thermal models for motor design
- Enables analysis to improve thermal properties of motor materials

Case-to-stator thermal contact resistance

- Developed ability to measure case-to-stator thermal contact resistance

Through-Stack Thermal Conductivity

Measured Stack Thermal Resistance → Lamination-to-Lamination Thermal Contact Resistance → Effective Through-Stack Thermal Conductivity

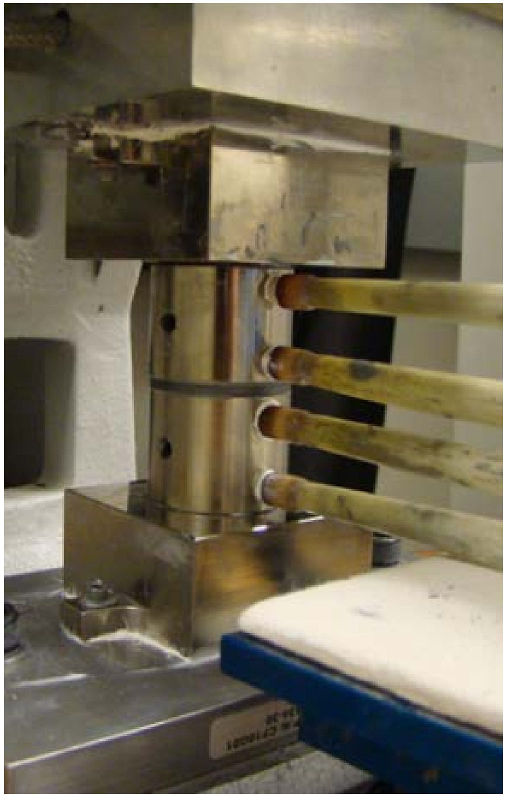
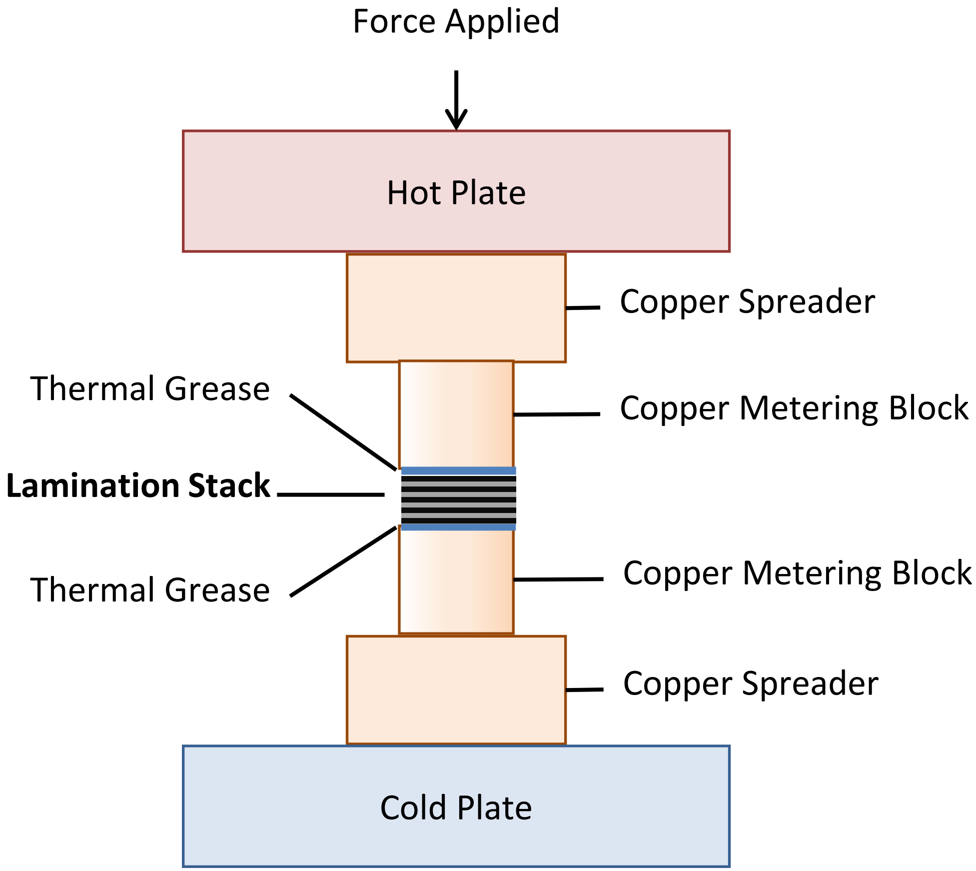
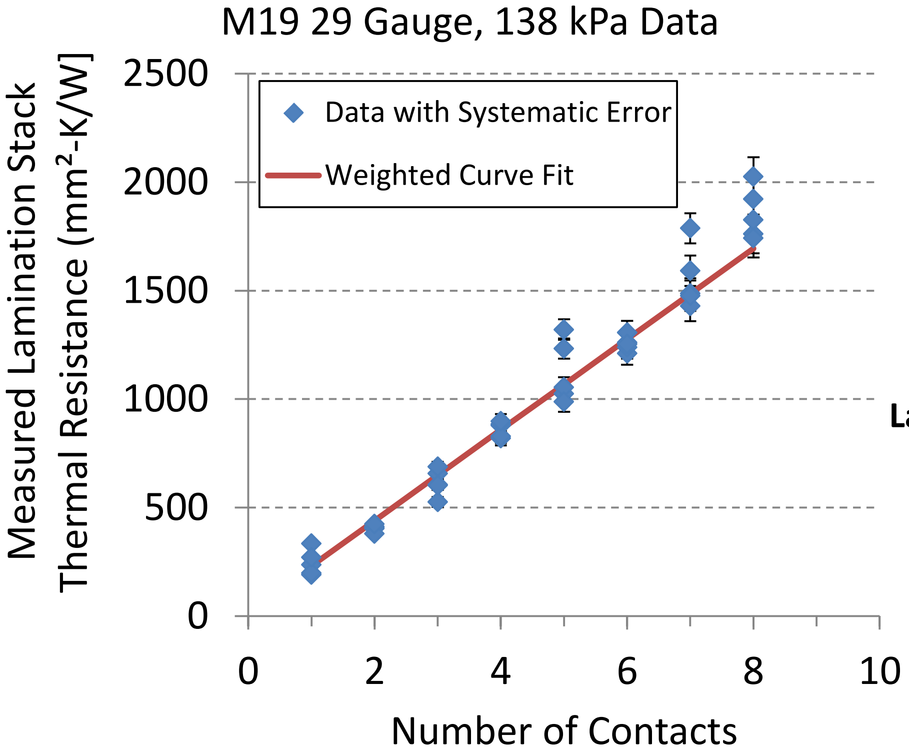


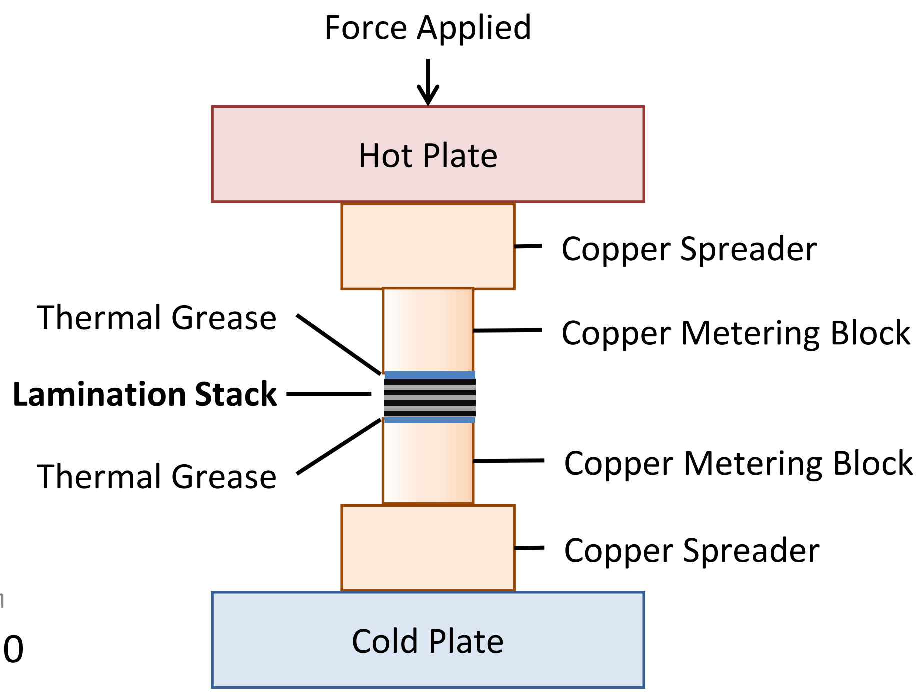
Photo Credit: Justin Cousineau, NREL



Through-Stack Thermal Conductivity

Measured Stack Thermal Resistance → Lamination-to-Lamination Thermal Contact Resistance → Effective Through-Stack Thermal Conductivity

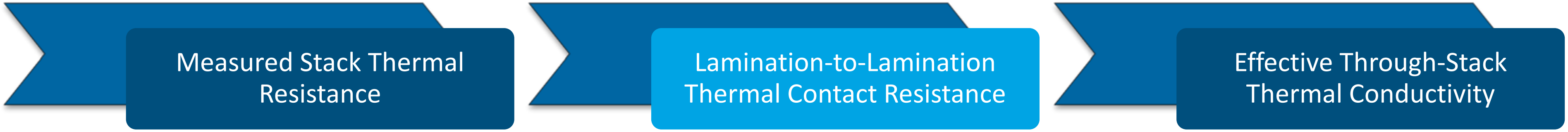


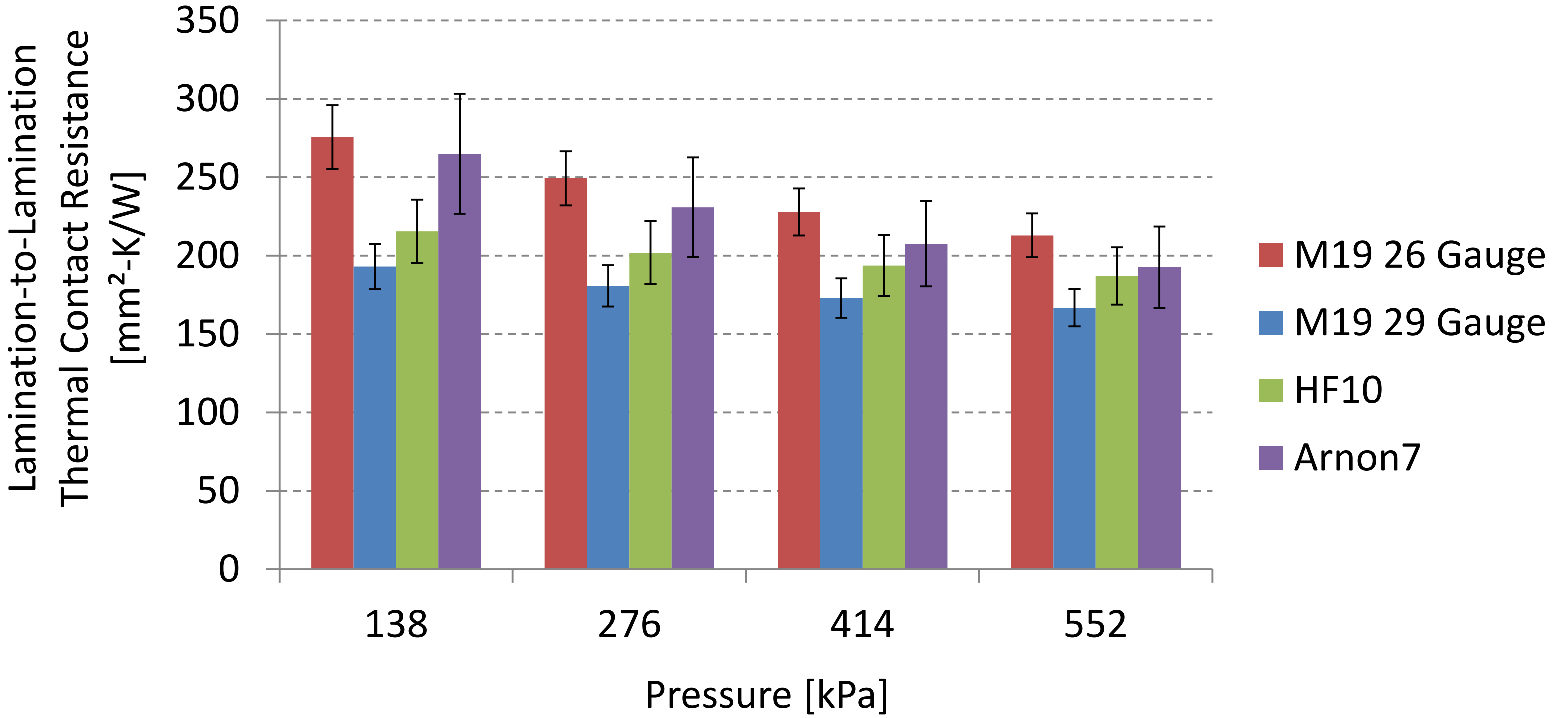


- Lamination-to-lamination thermal contact resistance calculated from slope of weighted curve fit

Error bars represent 95% confidence level

Through-Stack Thermal Conductivity



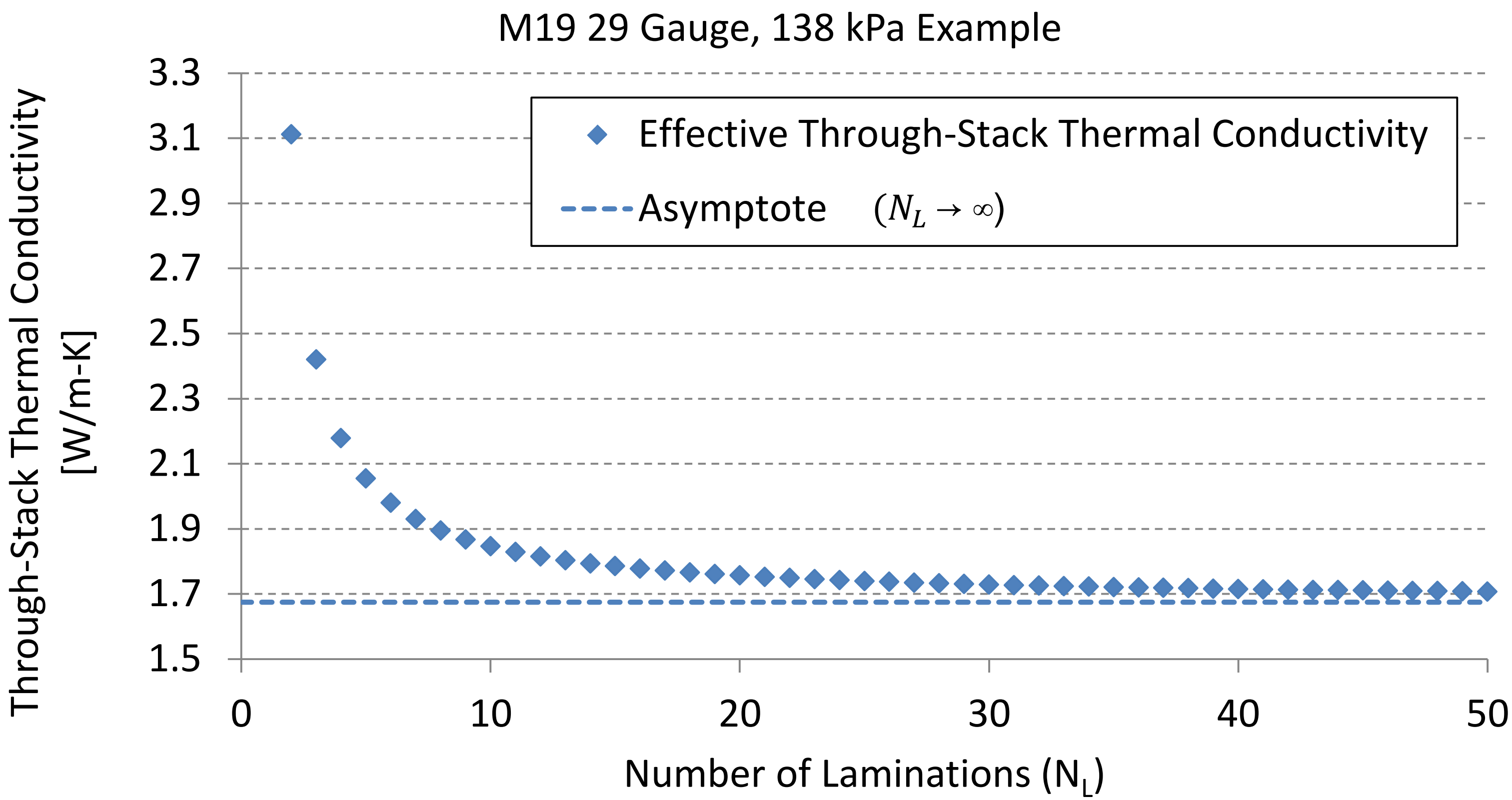


- The lamination-to-lamination thermal contact resistance is affected by the surface topography and contact pressure

Error bars represent 95% confidence level

Through-Stack Thermal Conductivity

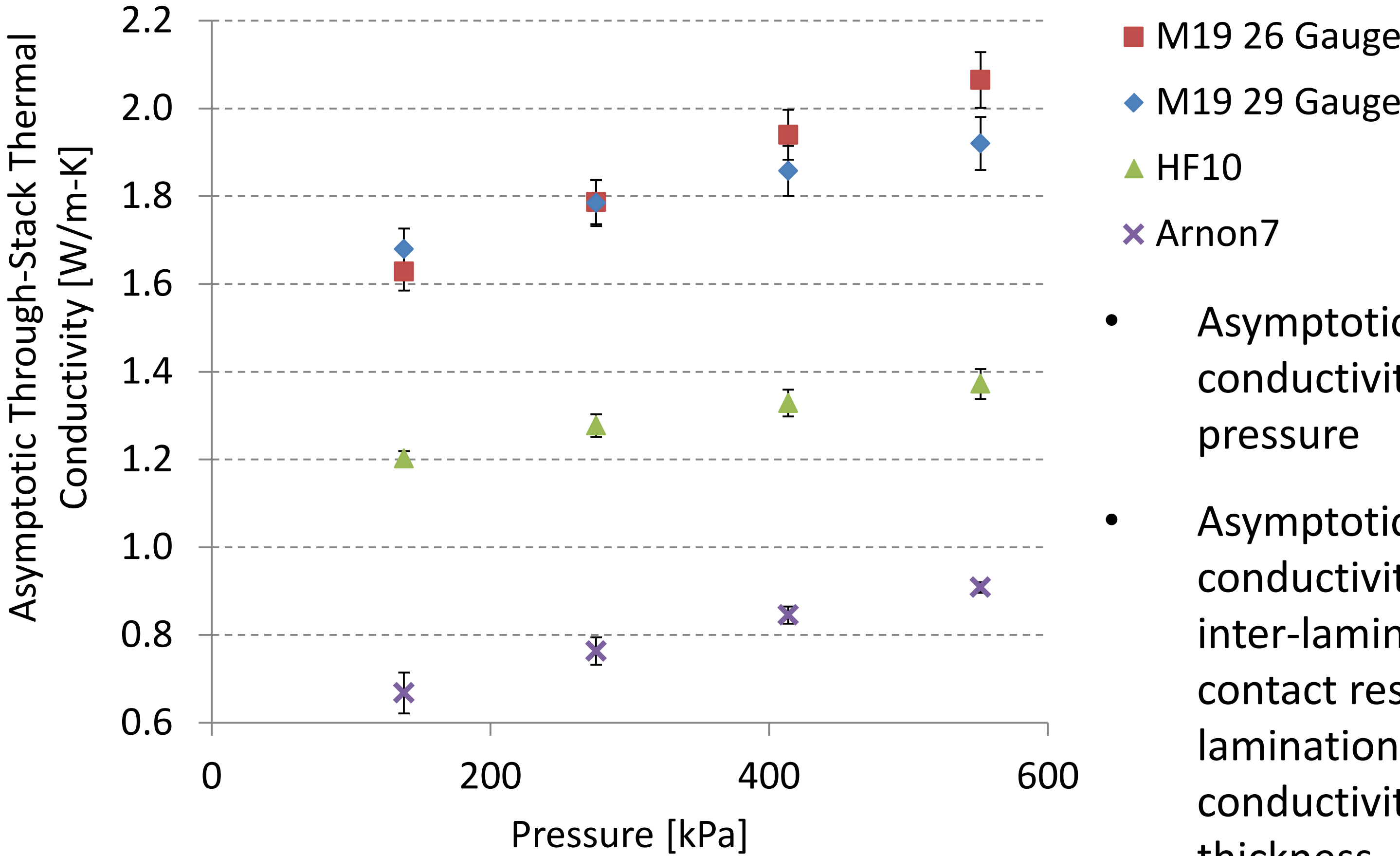
Measured Stack Thermal Resistance → Lamination-to-Lamination Thermal Contact Resistance → Effective Through-Stack Thermal Conductivity



- The effective through-stack thermal conductivity approaches the asymptote within 30–50 laminations

Through-Stack Thermal Conductivity

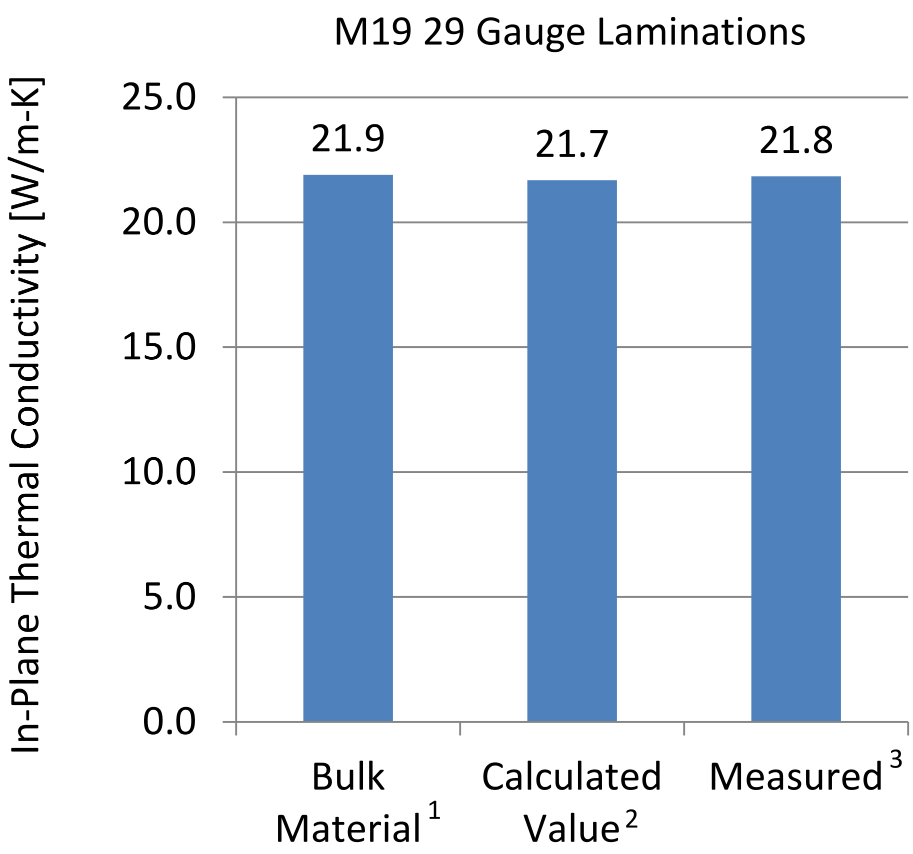
Measured Stack Thermal Resistance → Lamination-to-Lamination Thermal Contact Resistance → Effective Through-Stack Thermal Conductivity



- Asymptotic thermal conductivity increases with pressure
- Asymptotic thermal conductivity depends on inter-lamination thermal contact resistance, lamination thermal conductivity, and lamination thickness

Error bars represent 95% confidence level

In-Plane Lamination Thermal Conductivity



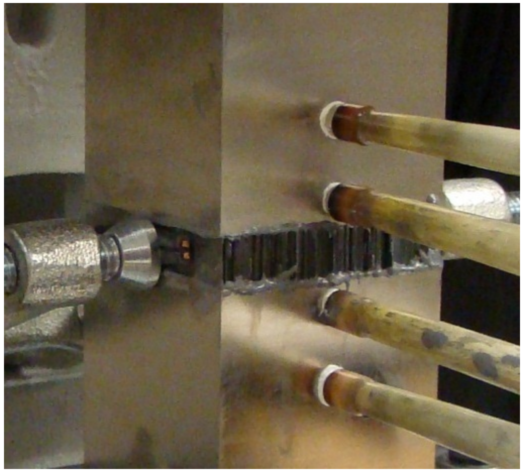


Photo Credit: Justin Cousineau, NREL

- Confirmed in-plane thermal conductivity is close to bulk material thermal conductivity

1. Based on measured thermal conductivity of similar material
2. Calculated assuming 99% stacking factor
3. Average of measured orthotropic property in setup shown in figure

FY15 Tasks to Achieve Key Deliverable

2014 Oct	Nov	Dec	2015 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Publications for End-Winding Heat Transfer

Deliverable

ATF impingement experiments to measure variation in local convective heat transfer coefficients

End-winding spatial mapping of ATF convective heat transfer coefficients on end-winding features

Thermal measurements of passive thermal stack elements in collaboration with Oak Ridge National Laboratory (ORNL)

- Winding thermal properties
- Contact interfaces
- Thermal analysis support in collaboration with ORNL motor research

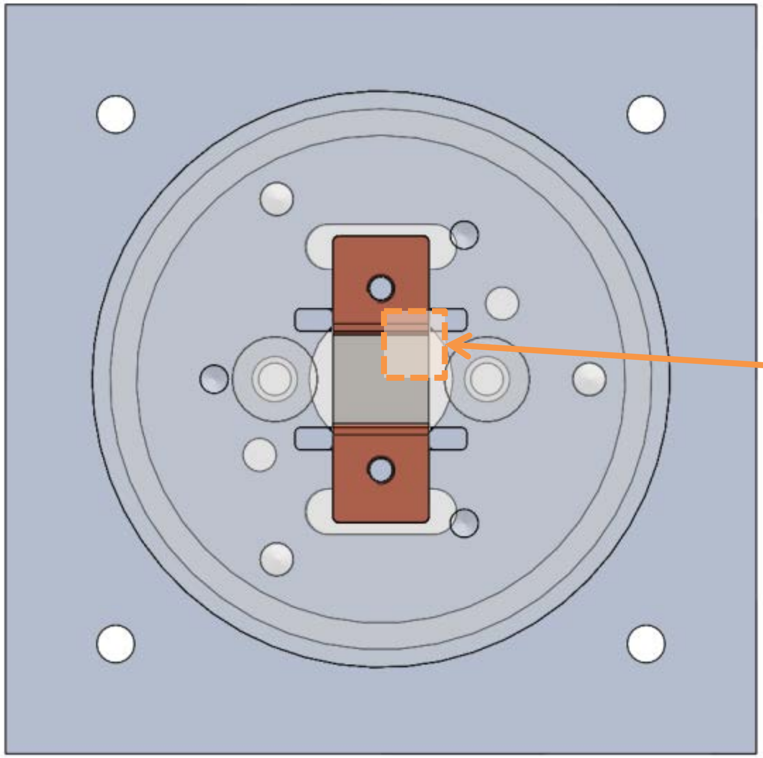
Go/ No-Go

Select passive thermal materials for bench-level testing in partnership with ORNL

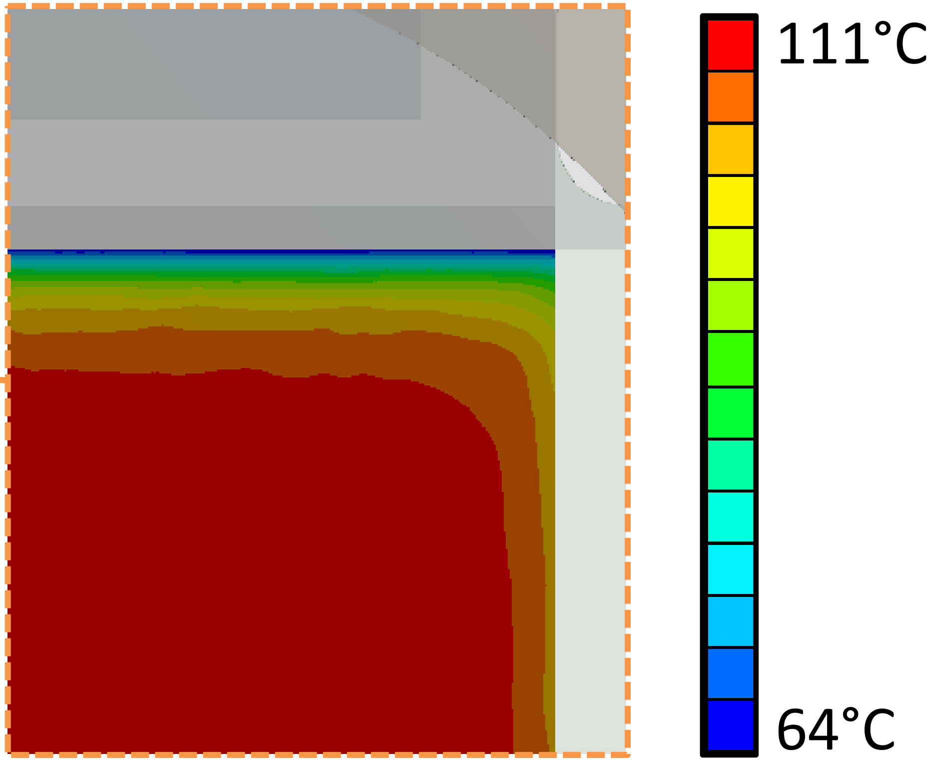
Local ATF Jet Heat Transfer Mapping

Spatially measure jet impingement heat transfer coefficients on a discrete heat source.

Bottom view of test article



Heated foil temperature distribution



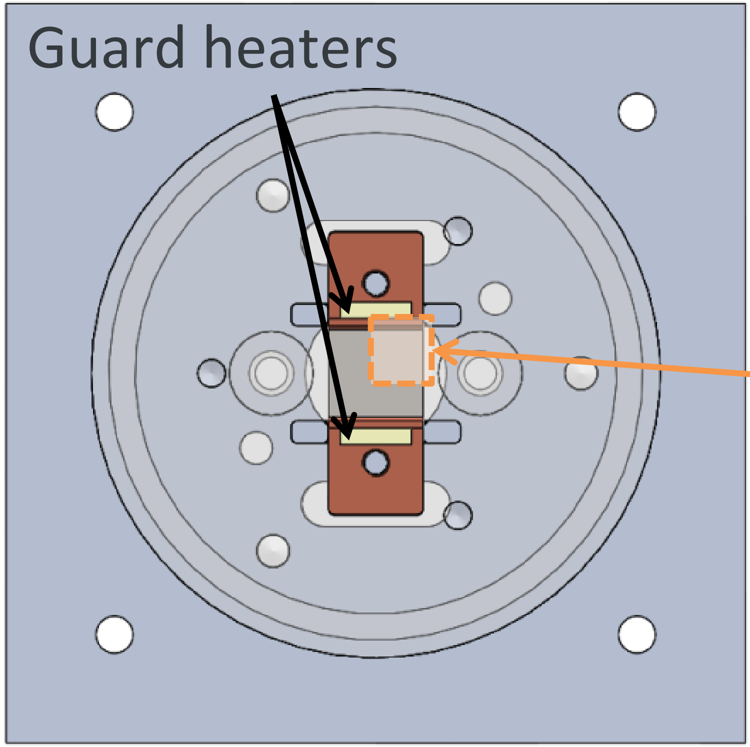
Thermal-electrical finite element analysis (FEA) reveals edge effects mostly associated with copper bus bars

- ΔT across foil 47°C (most of heat loss to copper bars)
- 85% of foil heater power dissipated by jet

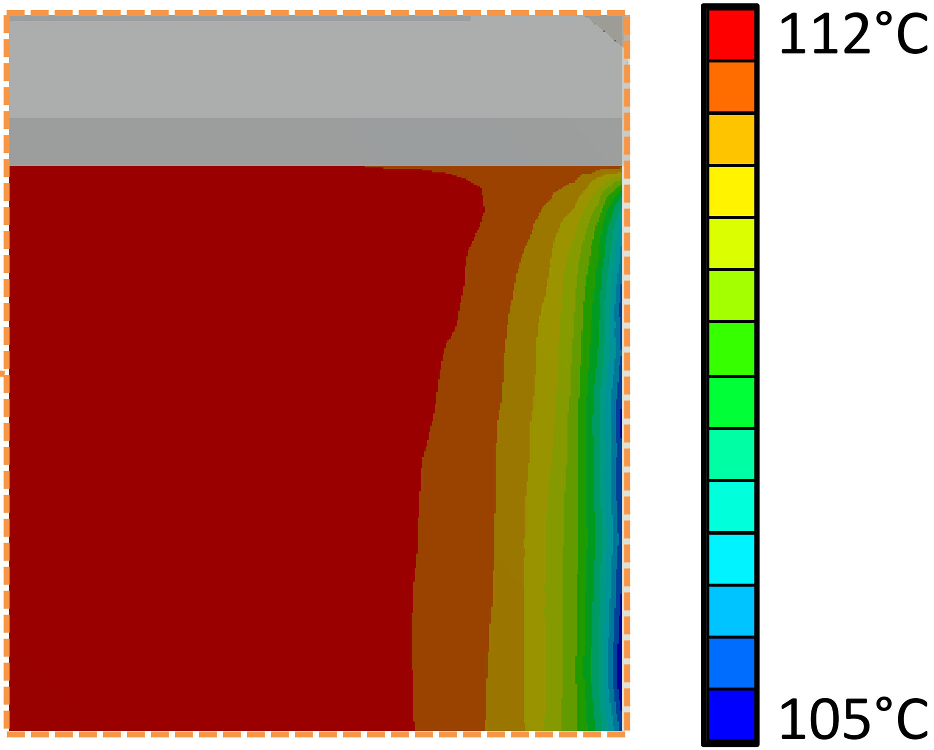
Local ATF Jet Heat Transfer Mapping

Spatially measure jet impingement heat transfer coefficients on a discrete heat source.

Bottom view of test article



Heated foil temperature distribution



Use of guard heaters minimize edge effects through the use of guard heaters

- ΔT across foil 7°C (heat loss to copper decreased)
- 98% of foil heater power dissipated by jet

Spatial Mapping of Heat Transfer

Large-scale end-winding convective heat transfer mapping

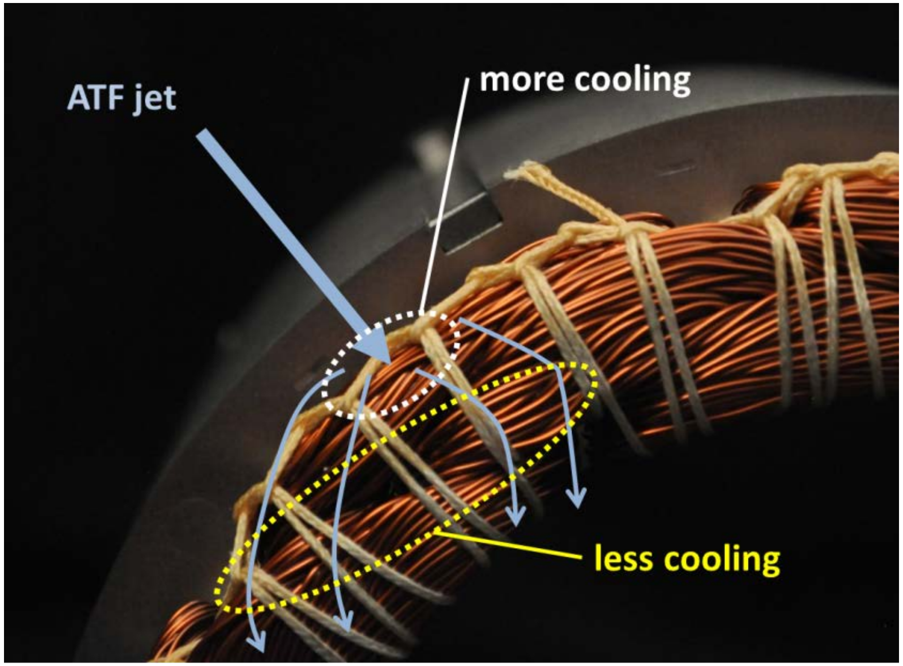
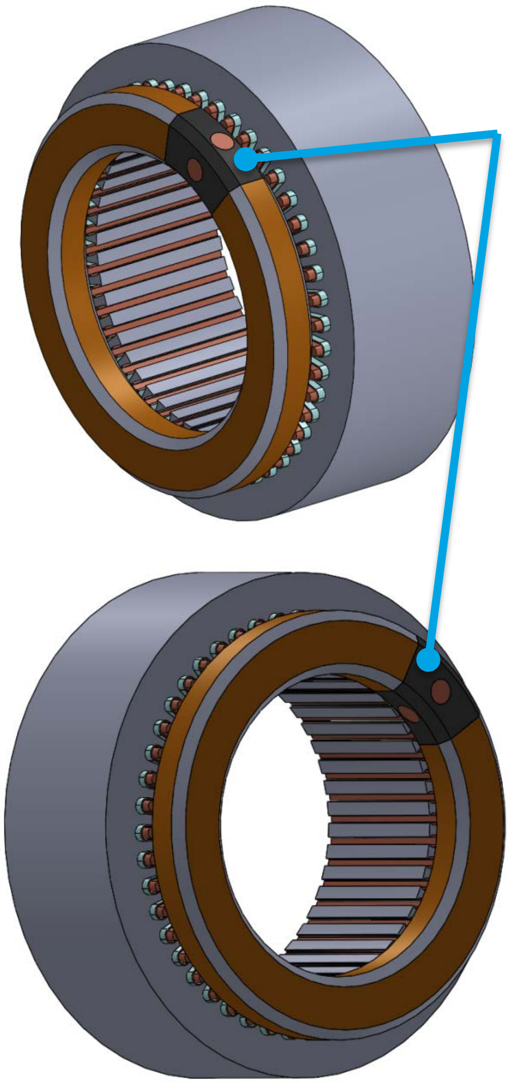


Photo Credit: Kevin Bennion, NREL

- Map the large-scale spatial distribution of the heat transfer coefficients over motor end windings
- Study effects of
  - Oil jet placement
  - ATF free flow over end-winding surfaces
  - Jet interactions

Spatial Mapping of Heat Transfer

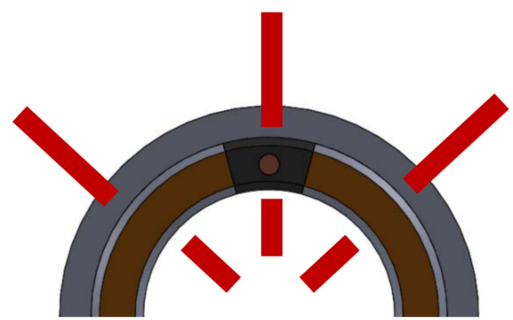
Large-scale end-winding convective heat transfer mapping



Custom heat transfer sensor package in end winding

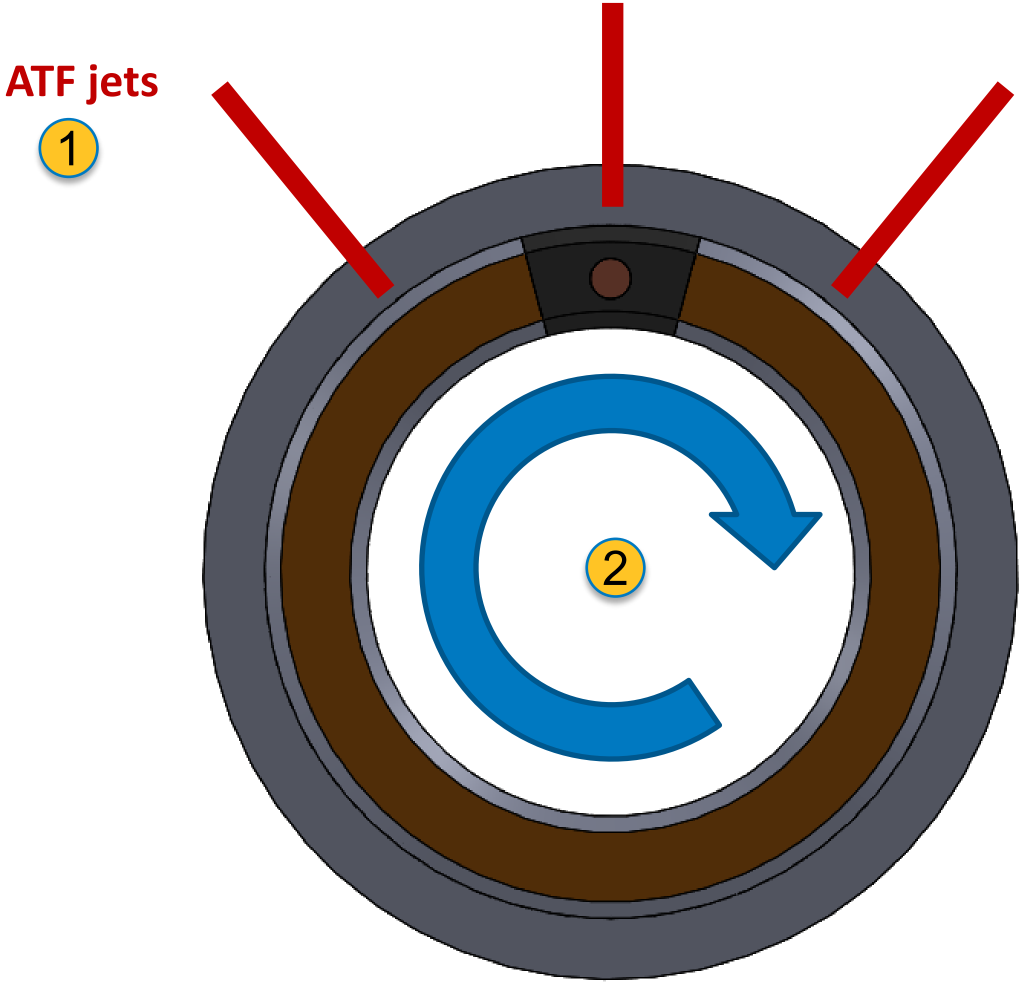
- Target surfaces installed on three surfaces to measure heat transfer coefficients
  - Outside diameter surface
  - Inside diameter surface
  - Axial end surface

Example ATF jets



Spatial Mapping of Heat Transfer

Large-scale end-winding convective heat transfer mapping

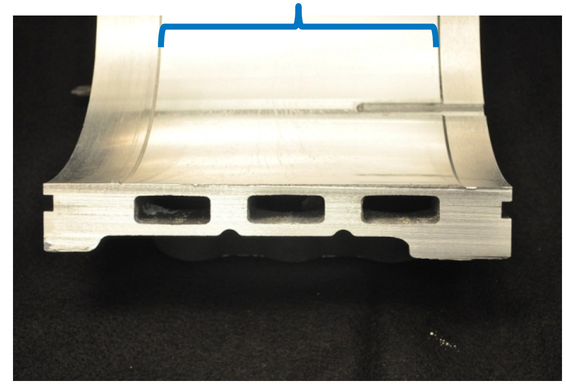


1. Fluid Jet Geometry
   - Location and orientation of ATF fluid jets
   - Nozzle type/geometry
   - System flow rate
   - Jet velocity
   - Parasitic power
2. Relative positon between measured heat transfer and jet location
   - Impact of gravity and free fluid flow
   - Fluid interactions between jets

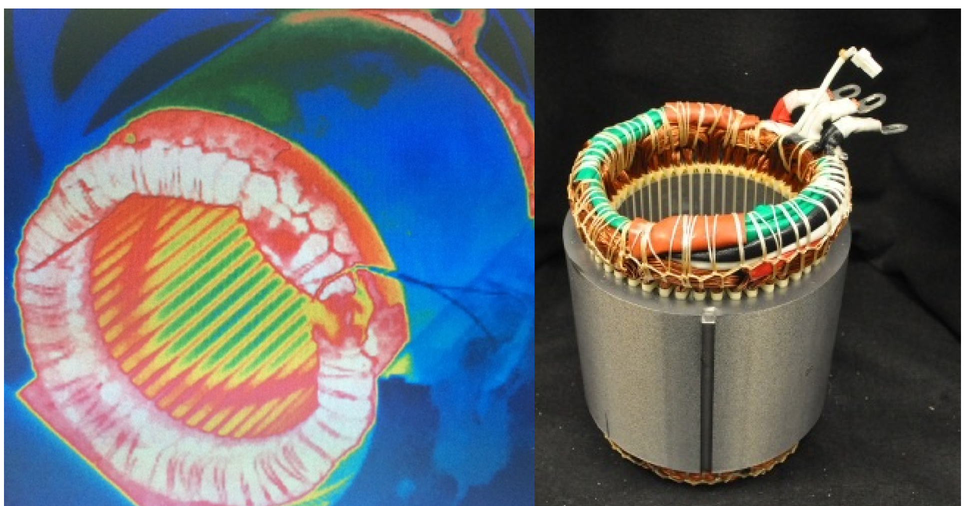
Passive Thermal Stack

- Case thermal contact resistance
  - Case surface characteristics
- Slot and end-winding effective thermal conductivity
- Potting materials for end-winding cooling

Sample Case-Stator Contact Surface for Motor Cooling



Sample Motor End Windings



Example Interference Fit with Stator and Cooling Jacket Case

Photo Credits Kevin Bennion, NREL

Project Summary

Project Duration: FY14–FY16 **Overall Objective: Provide data to support broad Industry demand for improving motor thermal management**
FY14 Focus: Characterized ATF impingement average heat transfer coefficients and completed lamination-to-lamination thermal contact resistance measurements
Deliverable: Completed measurement of average convective heat transfer coefficients with ATF and compared results of plain surface data to correlations in the open literature. Completed lamination-to-lamination thermal contact measurements and stack effective thermal conductivity
Go/No-Go: Developed test apparatus to measure local impingement heat transfer results with ability to measure local heat transfer coefficients. Developed test hardware design and plan for representative wire bundle geometries
FY15 Focus: Spatially map ATF impingement convective heat transfer coefficients and measure passive thermal stack thermal resistances
Deliverable: Publish end-winding heat transfer performance data
Go/No-Go: In collaboration with ORNL select passive thermal stack materials for bench-level thermal testing
FY16 Focus: Confirm convective heat transfer performance on in-situ motor thermal performance tests.
Deliverable: Report heat transfer performance and model validation
Go/No-Go: Complete in-situ motor thermal tests for ATF cooling

Publications:

K. Bennion and J. Cousineau, “Sensitivity Analysis of Traction Drive Motor Cooling,” in *IEEE Transportation Electrification Conference and Expo (ITEC)*, 2012, pp. 1–6.

Technology-to-Market Plan

- This research impacts industry needs because …
  - The heat flow, temperature distribution, and fluid dynamics for motor thermal management are complex problems
  - Data on cooling convective heat transfer coefficients and heat spreading within the motor are needed to improve motor performance within cost, efficiency, and reliability constraints

- This research is on the path to commercialization because …
  - The research is reviewed by and shared with industry experts
  - The data are used by industry experts in the analysis and design of electric motors

Partners/Collaborators

- **Industry**
  - Motor industry suppliers, end users, and researchers
    - Input on research and test plans
    - Sharing of experimental data, modeling results, and analysis methods
    - Companies providing research input, requesting data, or supplying data include: Ford, Chrysler, GM, Tesla, UQM Technologies, Remy, Magna, John Deere, Oshkosh

- **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
      - Potting materials for end windings for improved heat transfer
      - Slot winding materials

NATIONAL RENEWABLE ENERGY LABORATORY

Acknowledgments:

Susan Rogers and Steven Boyd
U.S. Department of Energy

For more information, contact:

Principal Investigator

Kevin Bennion
Kevin.Bennion@nrel.gov
Phone: (303)275-4447

Team Members:

Justin Cousineau
Charlie King
Gilbert Moreno
Caitlin Stack
Tim Burress (ORNL)
Andy Wereszczak (ORNL)

APEEM Task Leader:

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