ELECTRIC MOTOR THERMAL MANAGEMENT FOR ELECTRIC TRACTION DRIVES

Kevin Bennion, Justin Cousineau, Gilbert Moreno
National Renewable Energy Laboratory

SAE 2014 Thermal Management Systems Symposium
September 22–24, 2014
Denver, CO

14TMSS-0086

SAE INTERNATIONAL

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL/PR-5400-62919

Relevance – Why Motor Cooling?

- **Current Density**
- **Magnet Cost**
    - Price variability
    - Rare-earth materials
- **Material Costs**
- **Reliability**
- **Efficiency**

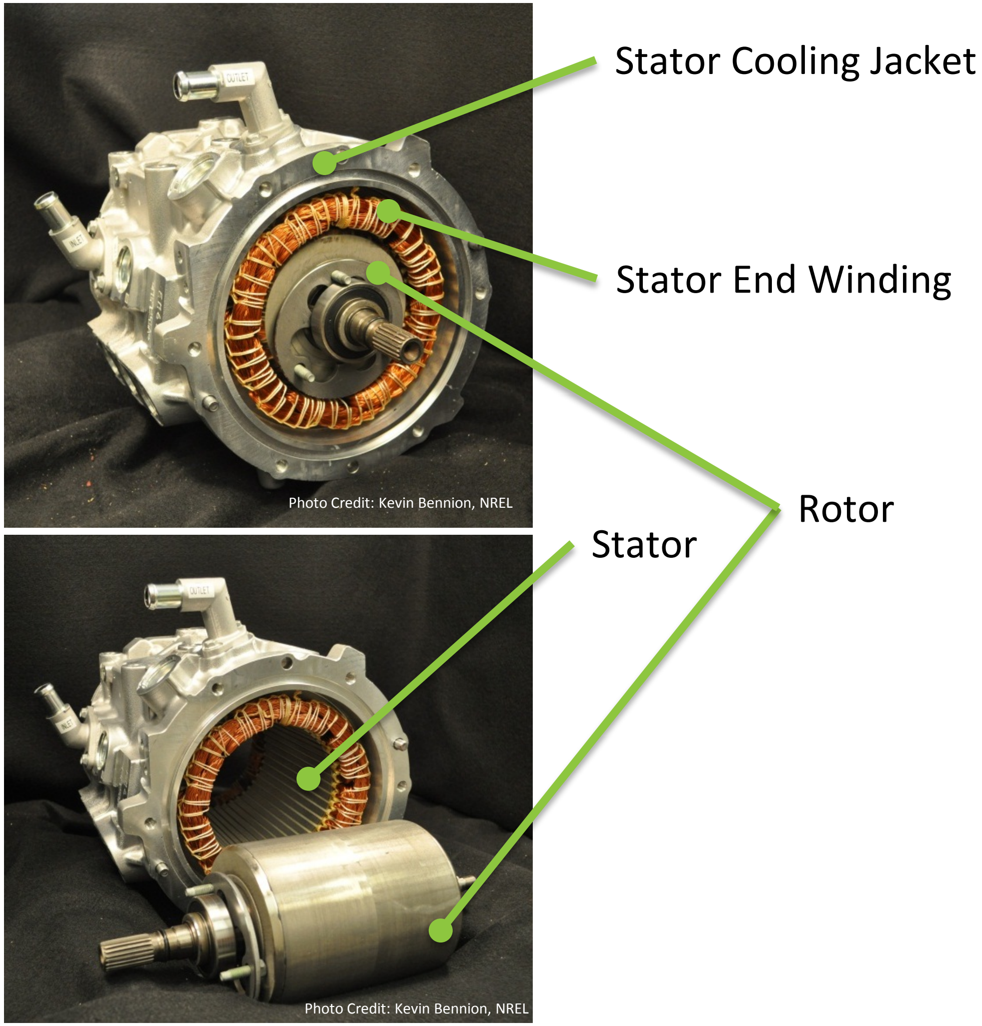


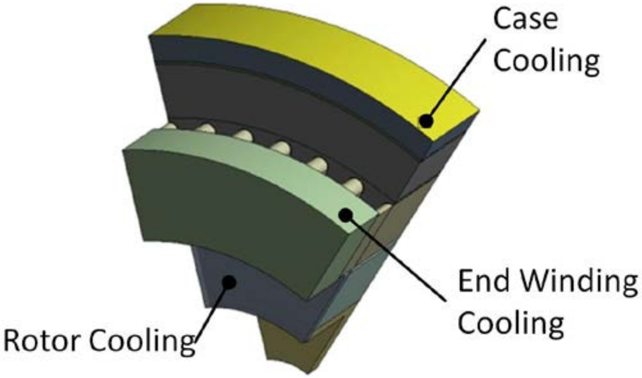
Photo Credit: Kevin Bennion, NREL

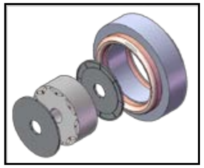
Photo Credit: Kevin Bennion, NREL

Sample electric traction drive motor.

Motor Thermal Management – Passive and Active Cooling

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

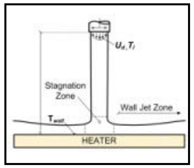


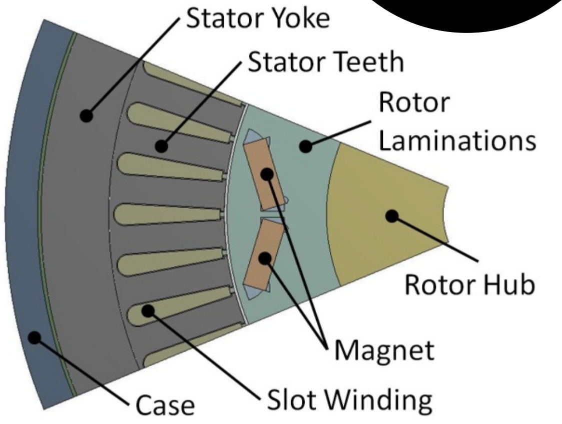


Passive Thermal Design

Motor Thermal Management

Active Convective Cooling





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

Background –
Motor Thermal Management Challenges

Problem

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

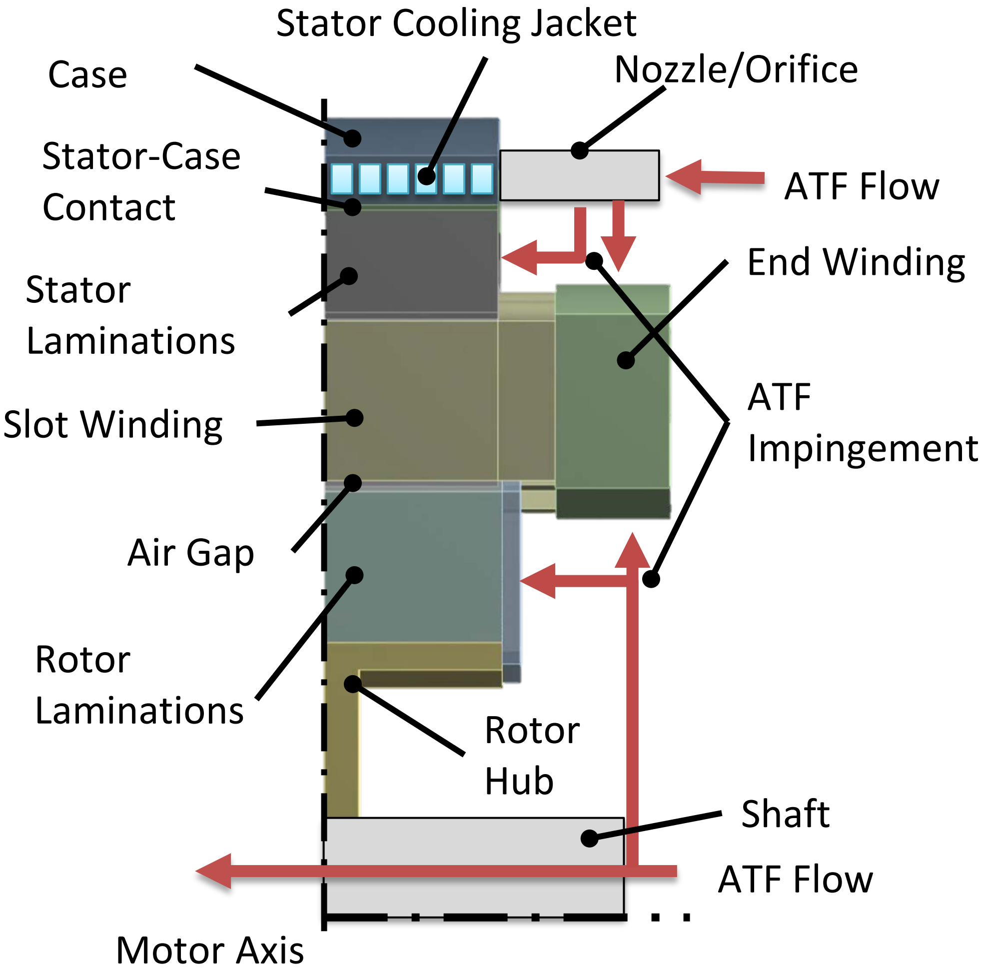
Example

4 to 9 kW of heat could be produced with an 80-kW motor operating with an efficiency between 90% and 95% [1].

[1] S. Oki, S. Ishikawa, and T. Ikemi, "Development of High-Power and High-Efficiency Motor for a Newly Developed Electric Vehicle," SAE International, 2012-01-0342, Apr. 2012.

ATF: Automatic Transmission Fluid

Motor Cooling Section View



Background –
Motor Thermal Management Challenges

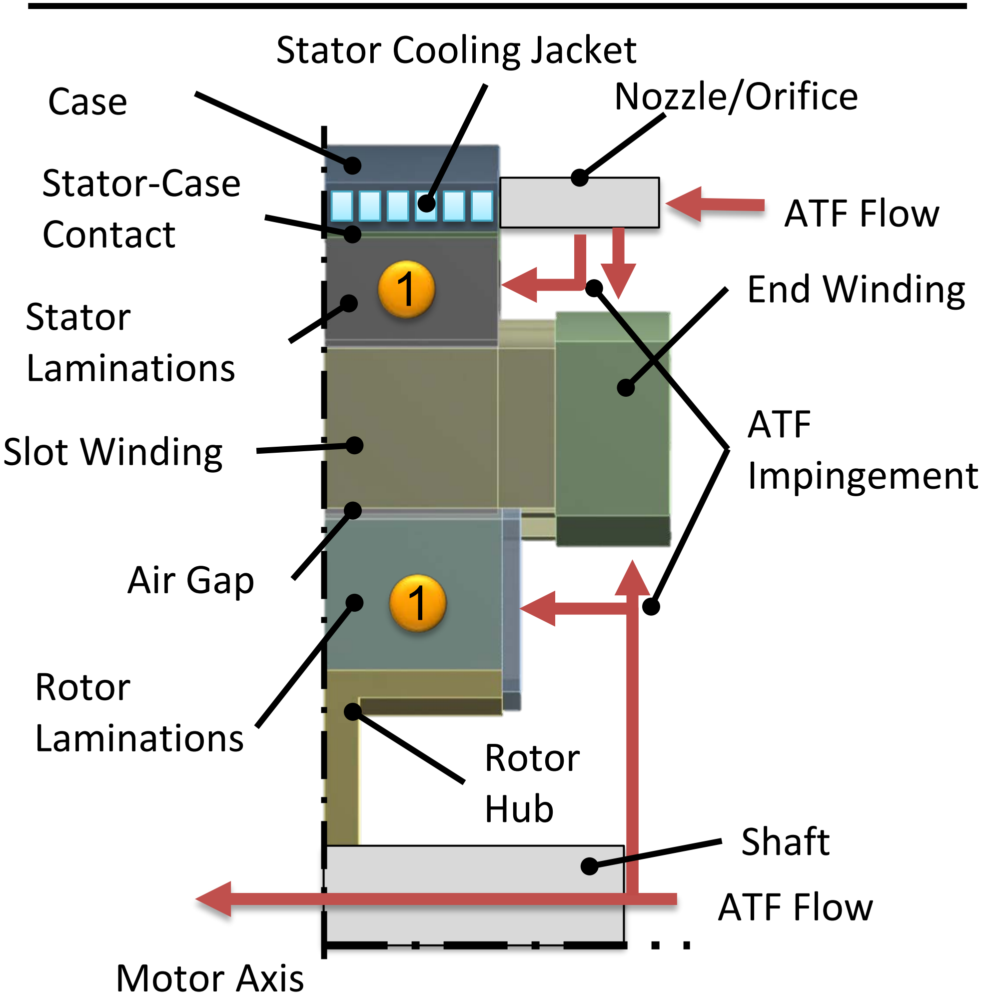
Problem

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

Challenges

1. Orthotropic (direction dependent) thermal conductivity of lamination stacks

Motor Cooling Section View



Background –
Motor Thermal Management Challenges

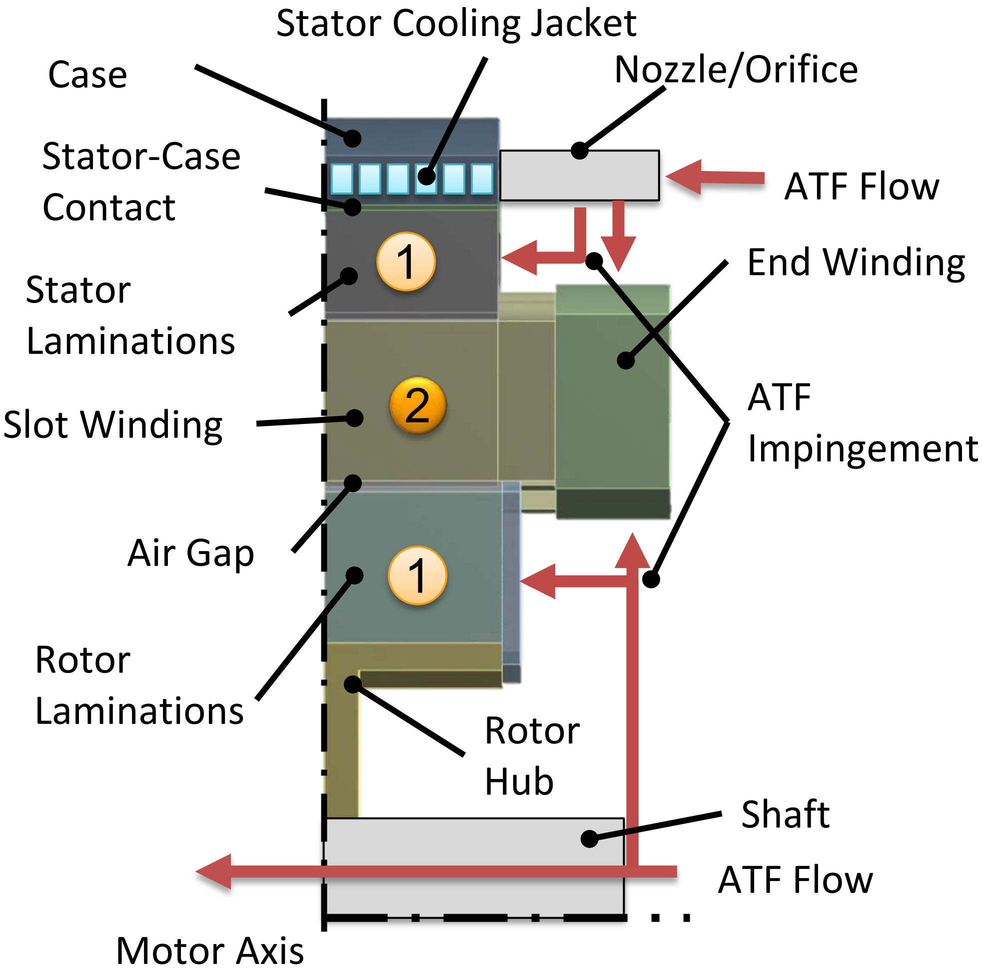
Problem

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

Challenges

1. Orthotropic (direction dependent) thermal conductivity of lamination stacks
2. Orthotropic thermal conductivity of slot windings

Motor Cooling Section View



Background –
Motor Thermal Management Challenges

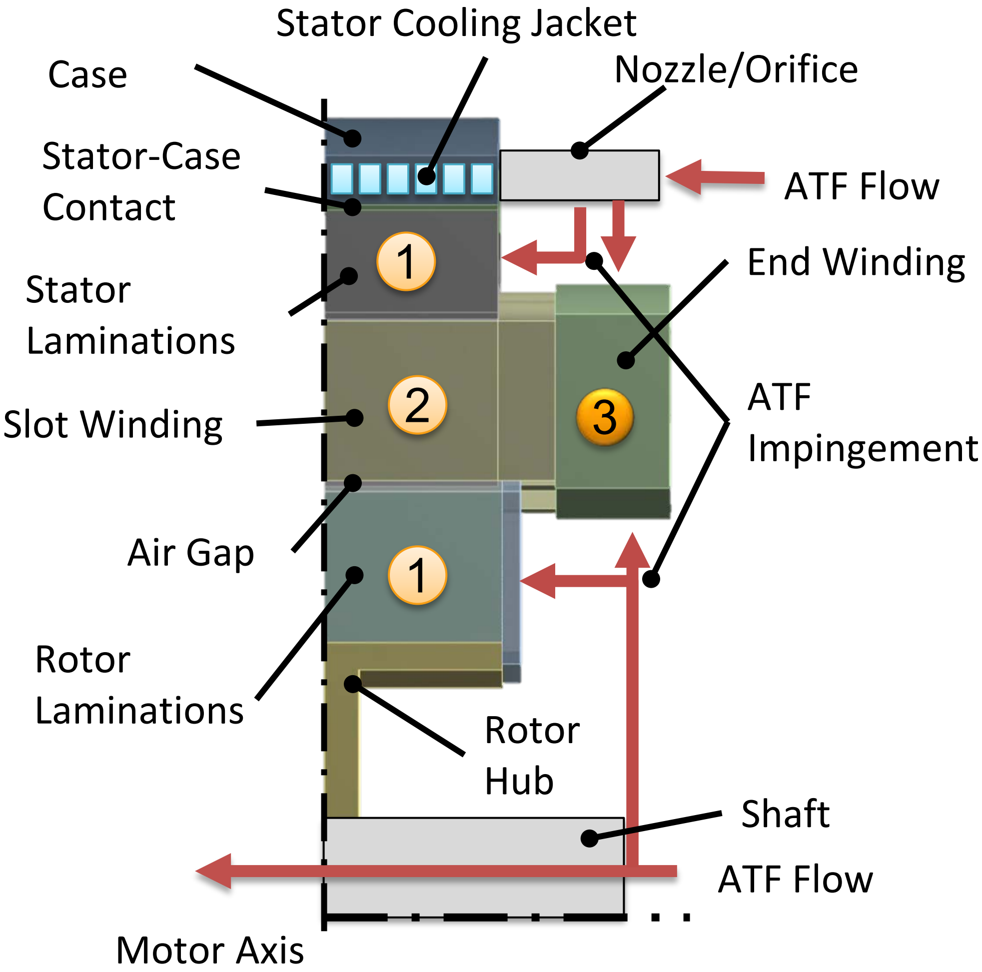
Problem

Extracting heat from within the motor to protect 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

Motor Cooling Section View



Background –
Motor Thermal Management Challenges

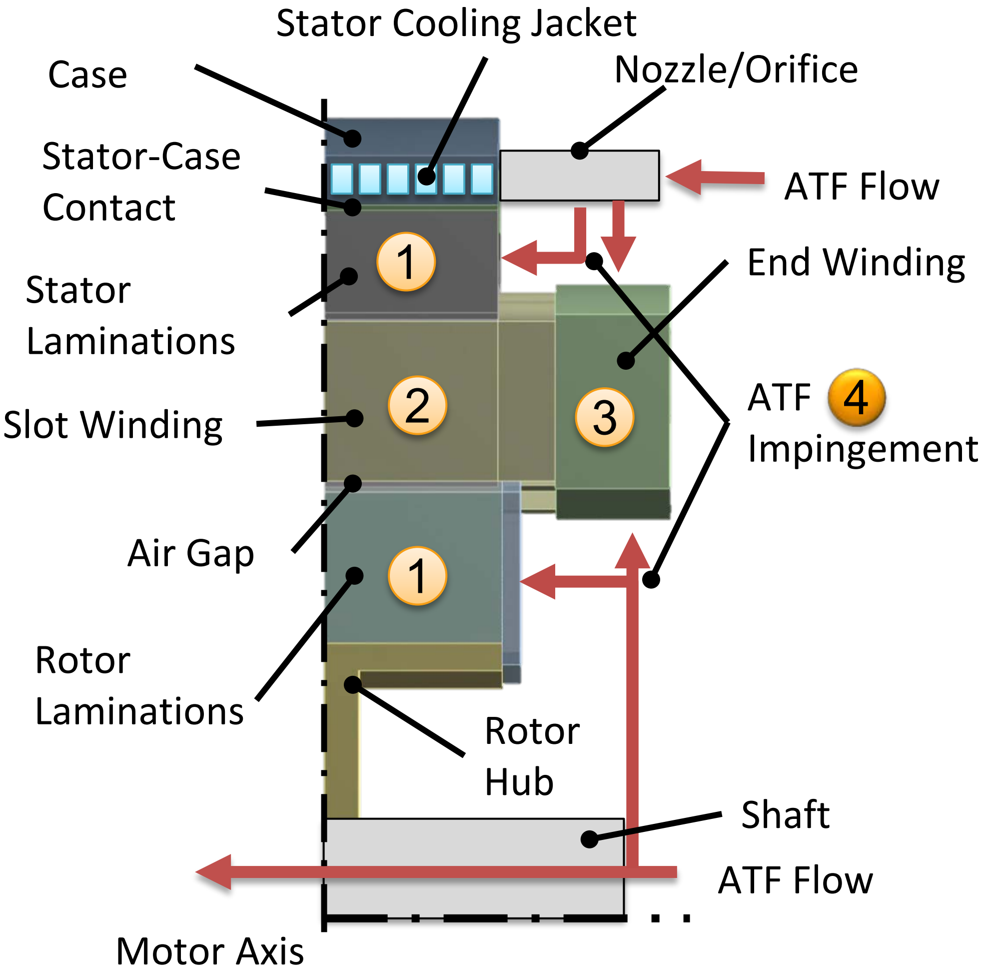
Problem

Extracting heat from within the motor to protect 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

Motor Cooling Section View



Background –
Motor Thermal Management Challenges

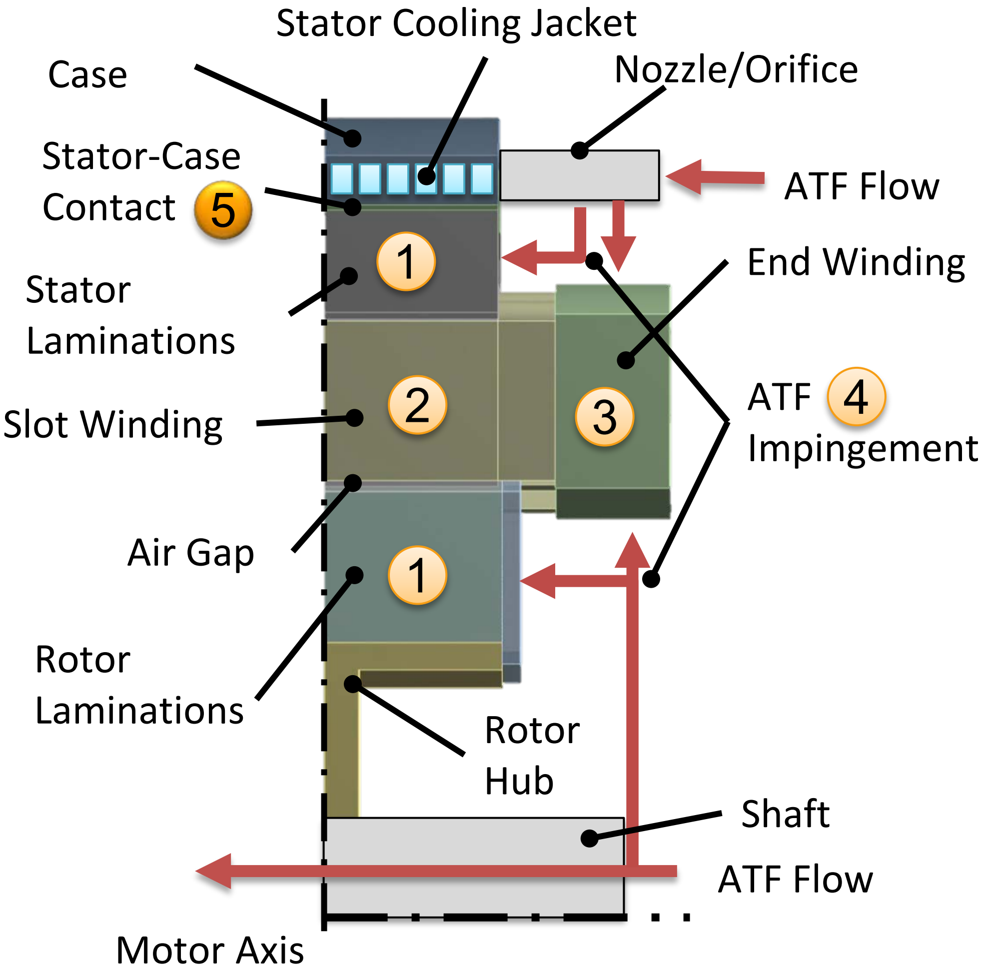
Problem

Extracting heat from within the motor to protect 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

Motor Cooling Section View



Background – Motor Thermal Management Challenges

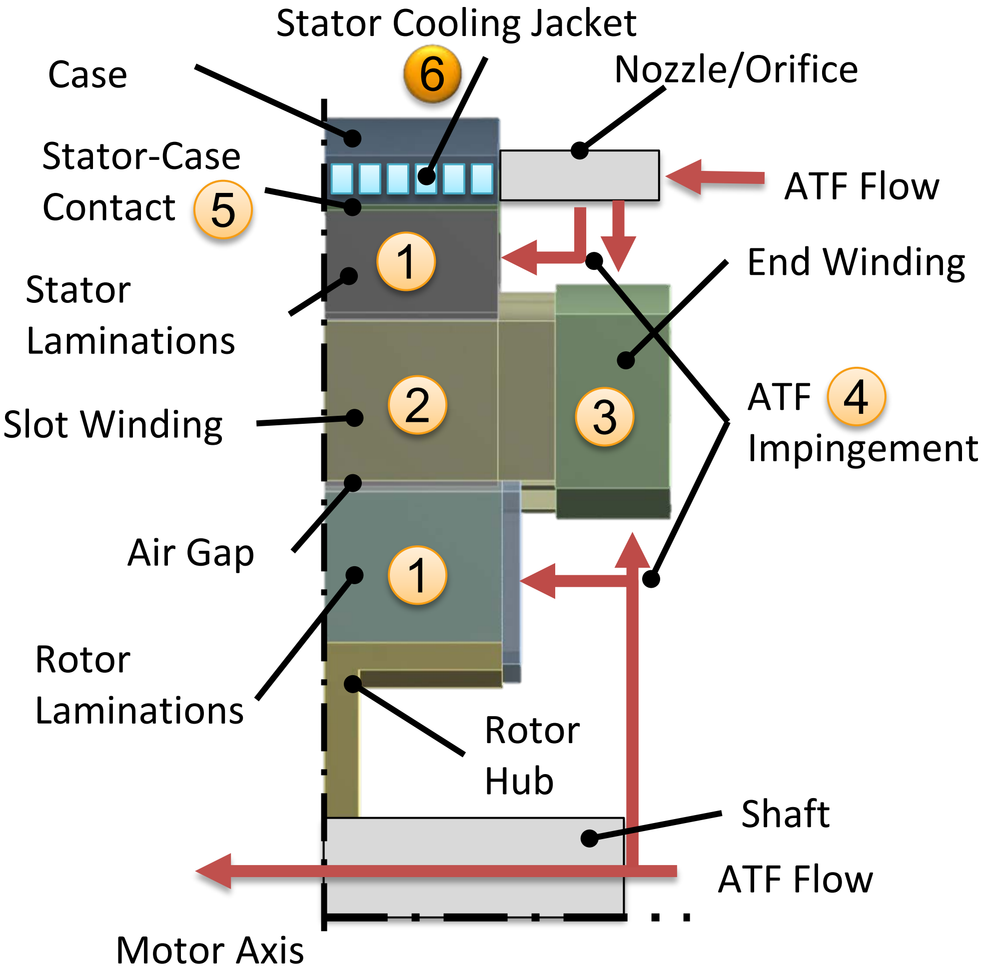
Problem

Extracting heat from within the motor to protect 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



Research Objective

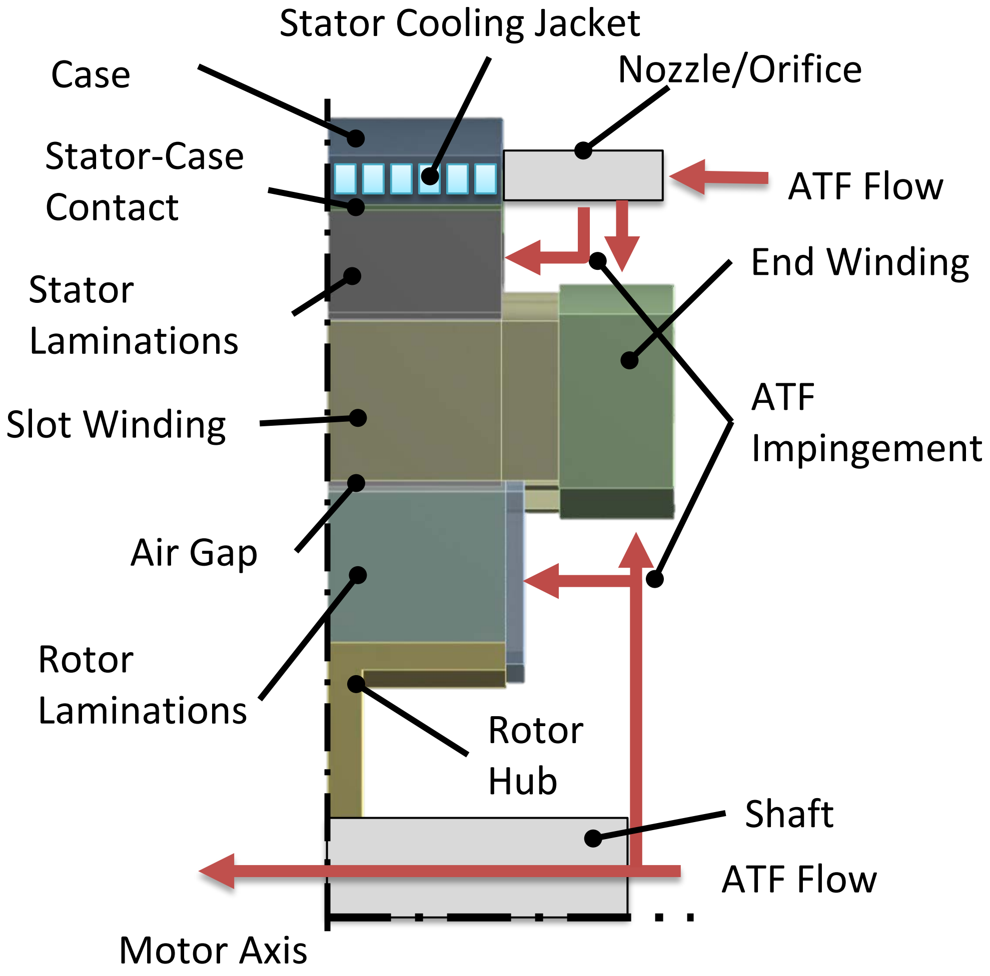
Problem

Research Tasks

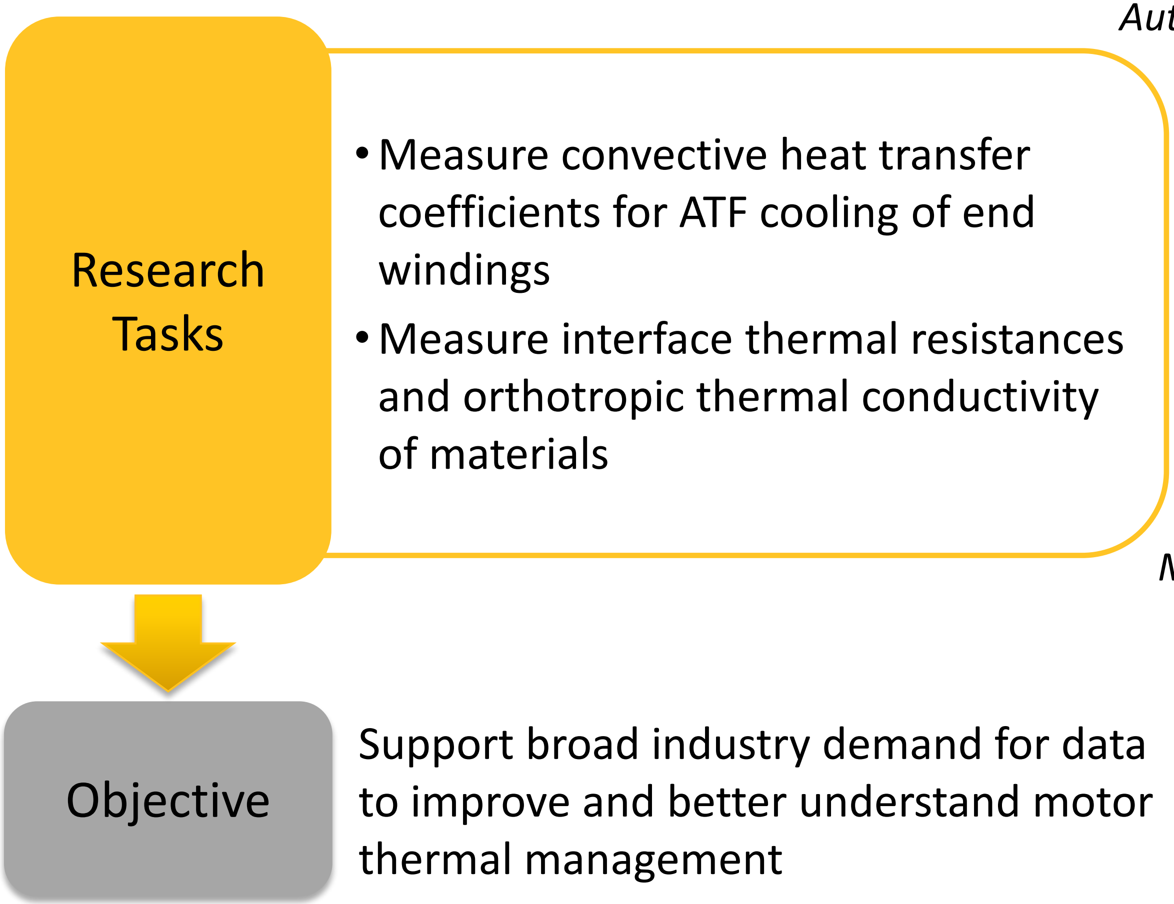
Objective

Support broad industry demand for data, analytical 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

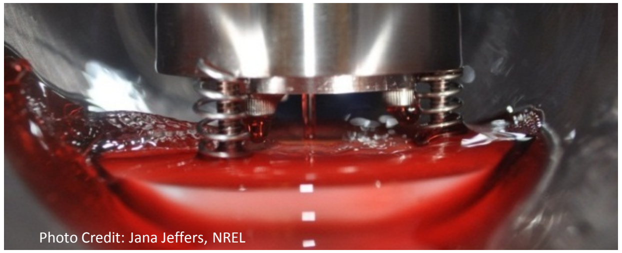


Photo Credit: Jana Jeffers, NREL

Material and Thermal Interface Testing

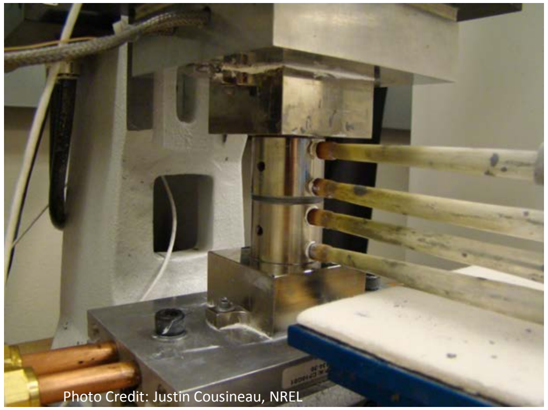


Photo Credit: Justin Cousineau, NREL

Active Convective Cooling – ATF Heat Transfer Coefficients

- Measure convective heat transfer coefficients for ATF cooling of end windings

Direct impingement on target surfaces

Impingement on motor end windings

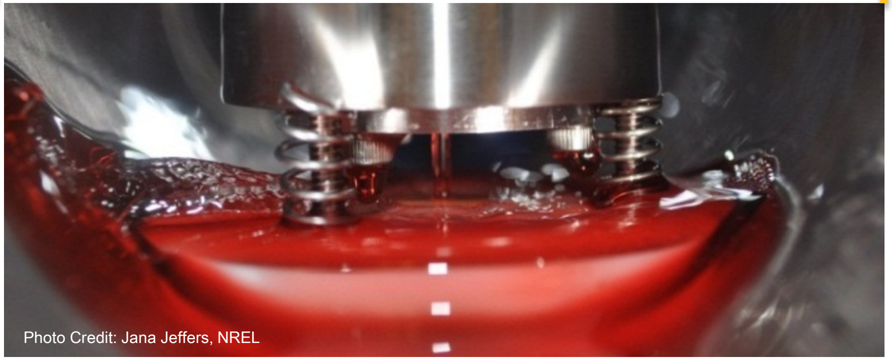


Photo Credit: Jana Jeffers, NREL

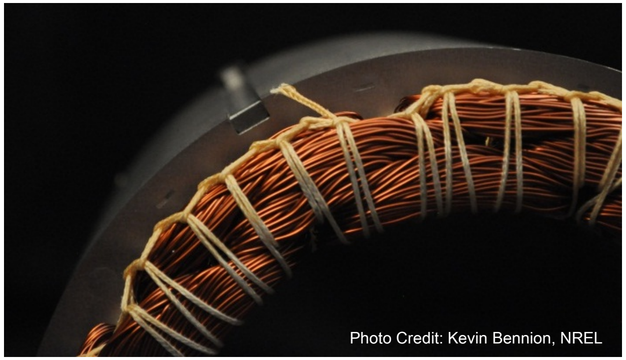
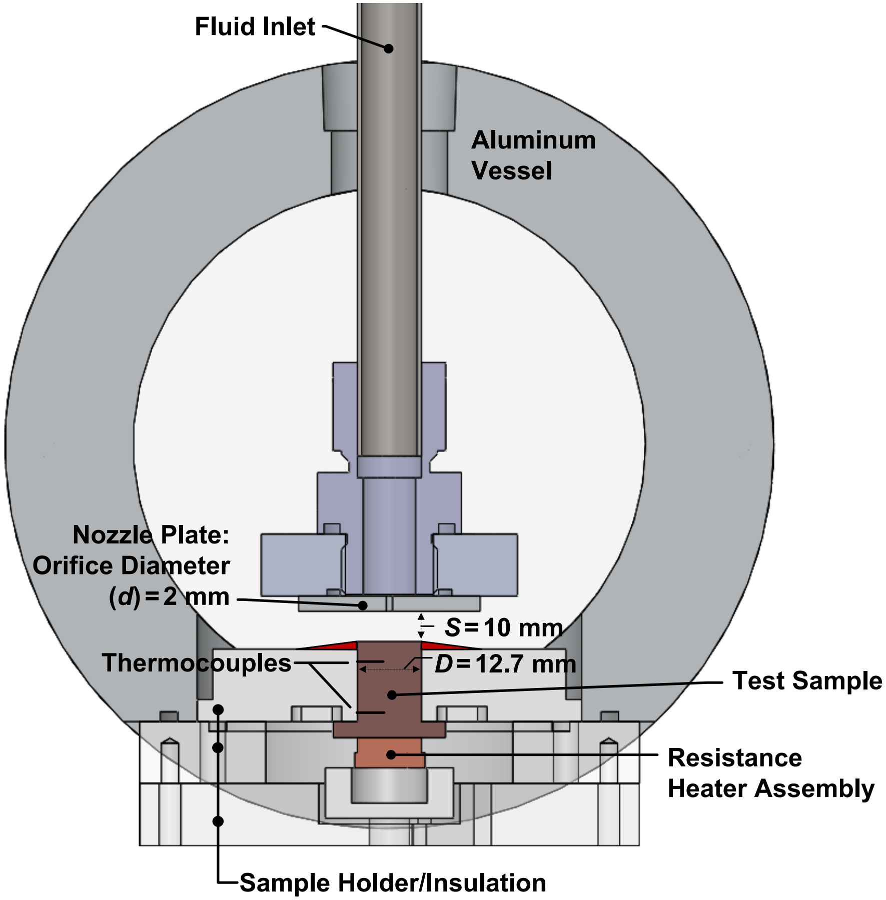


Photo Credit: Kevin Bennion, NREL

ATF Impingement Test Section



Oil Impingement Test Section Schematic

D (mm)	d (mm)	S (mm)	S/d	D/d
12.7	2.06	10	5	6.2

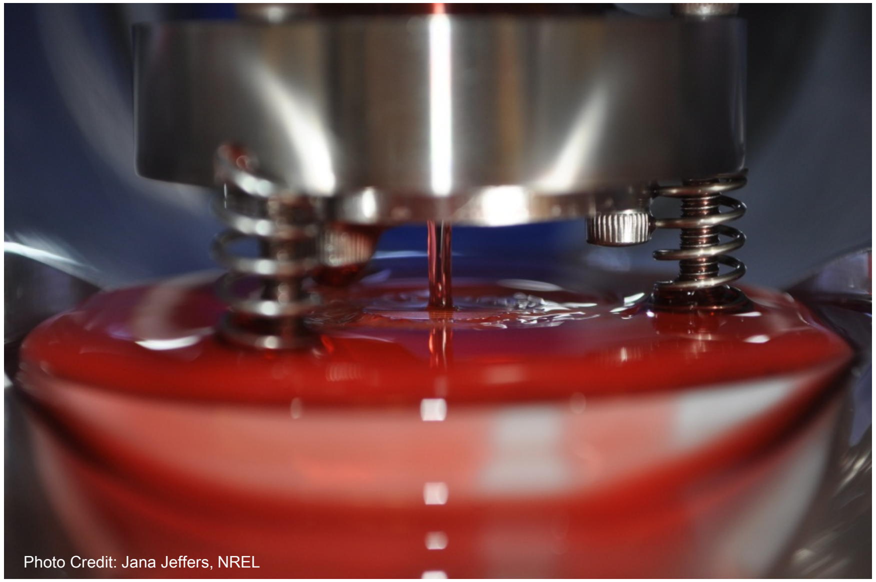
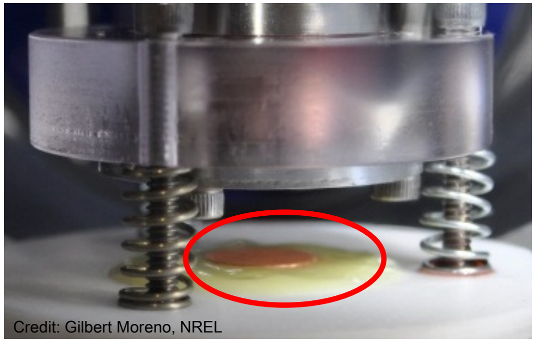


Photo Credit: Jana Jeffers, NREL

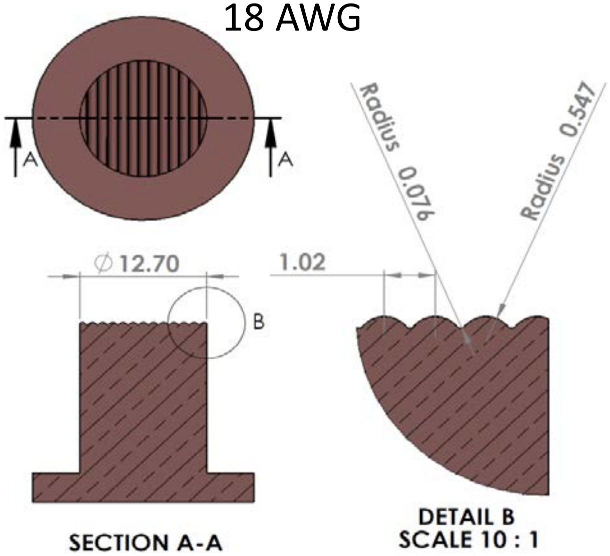
Photo During Operation

ATF Impingement Target Surfaces

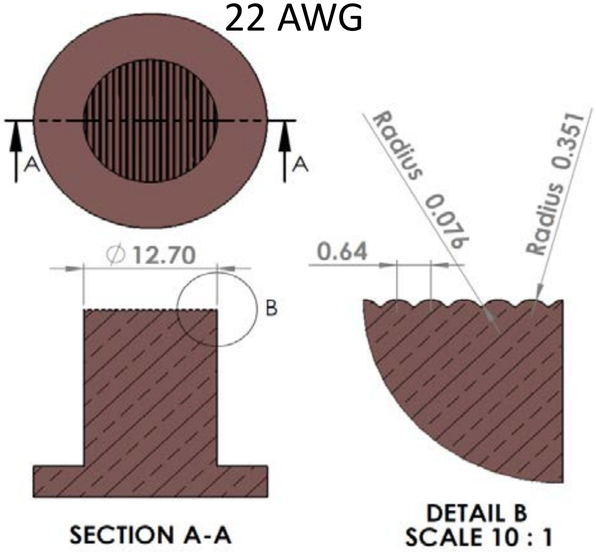

Credit: Gilbert Moreno, NREL

	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

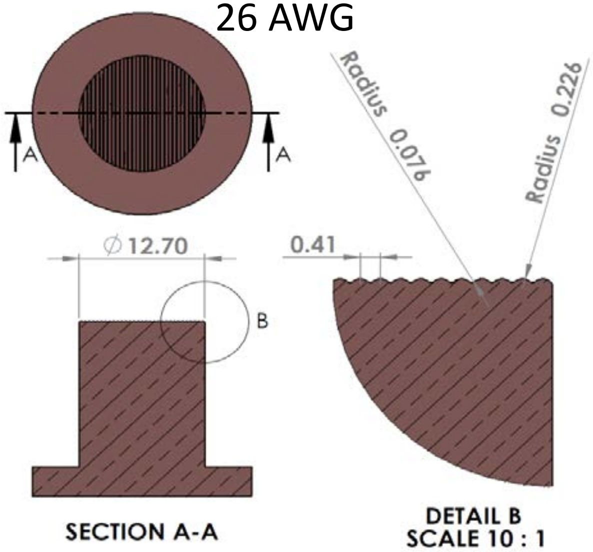
18 AWG



22 AWG

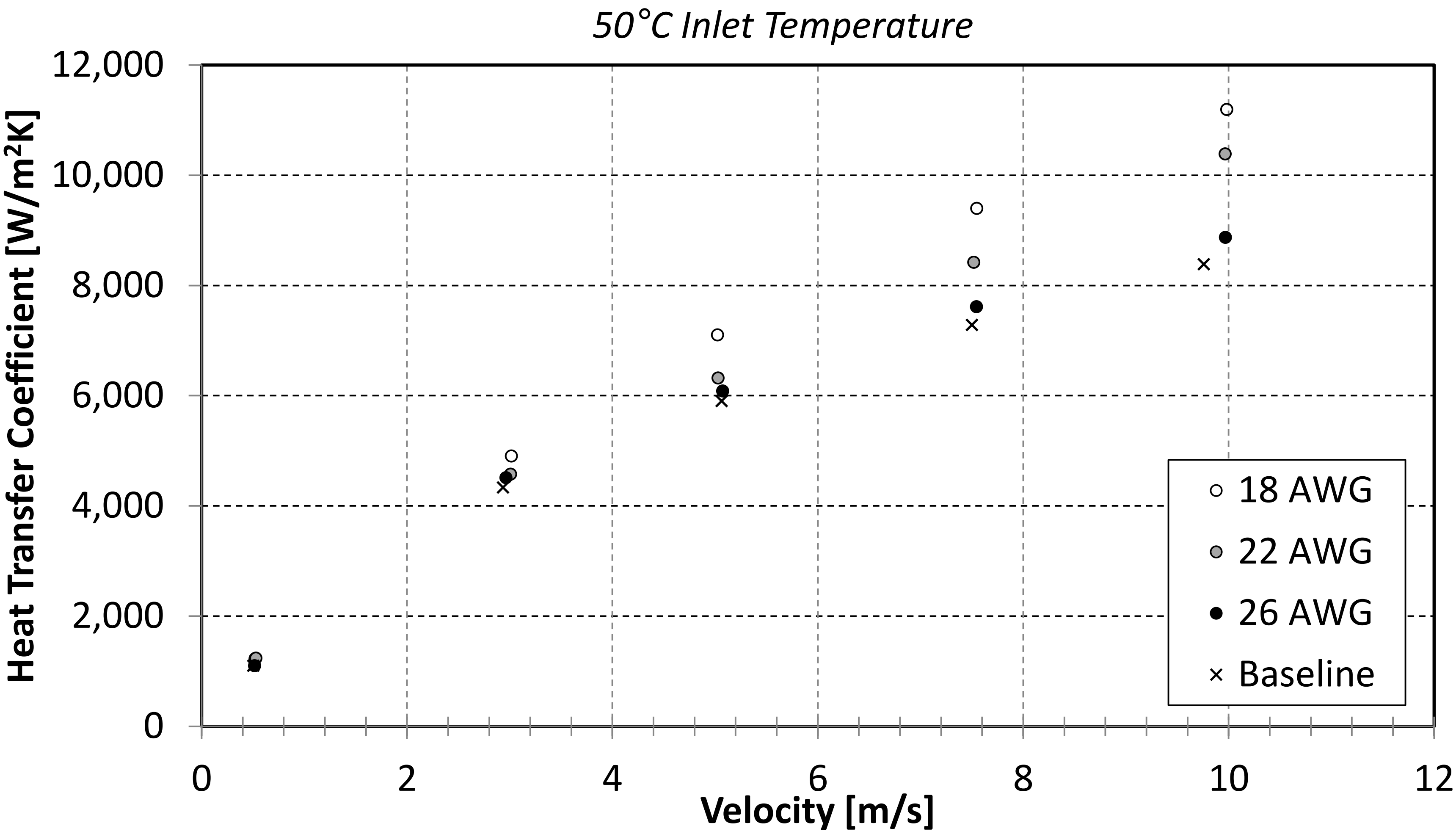


26 AWG



AWG = American Wire Gauge

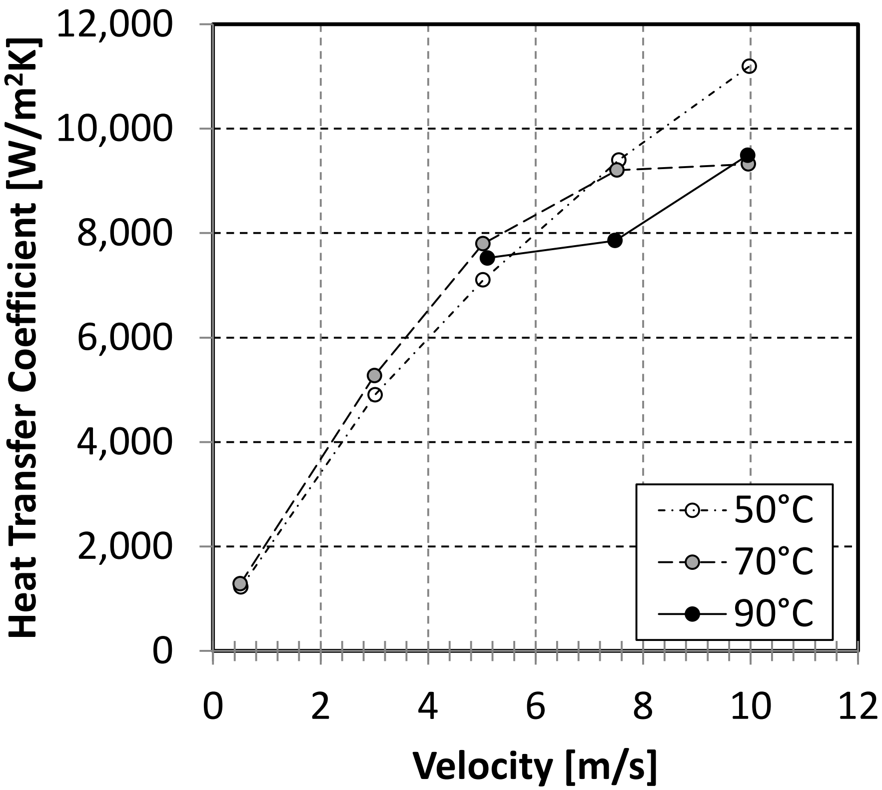
ATF Heat Transfer Coefficients



Note: Heat transfer coefficient calculated from the base projected area (not wetted area)

ATF Heat Transfer Coefficients

18 AWG sample data for all inlet temperatures



ATF flowing over surface

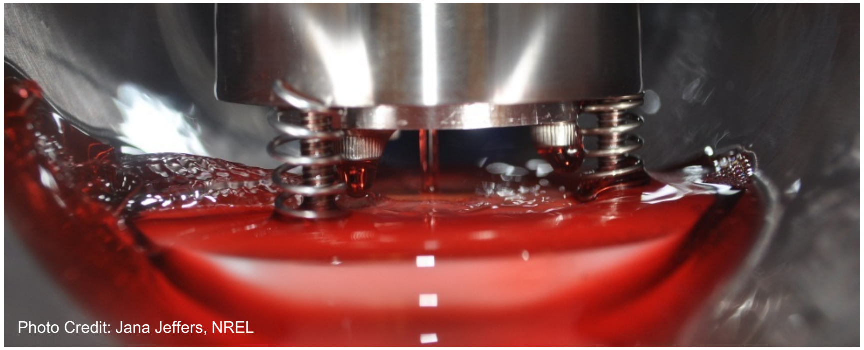


Photo Credit: Jana Jeffers, NREL

ATF deflecting off surface

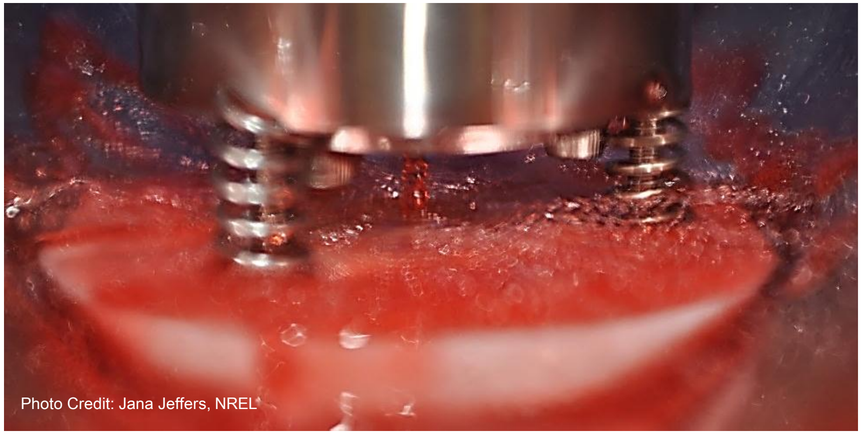


Photo Credit: Jana Jeffers, NREL

Note: ATF viscosity decreases as temperature increases

Passive Thermal Design – Material and Interface Thermal Measurements

- Measure interface thermal resistances and orthotropic thermal conductivity of materials

- Stacked lamination thermal conductivity
- Slot windings

Effective thermal properties for motor design and simulation

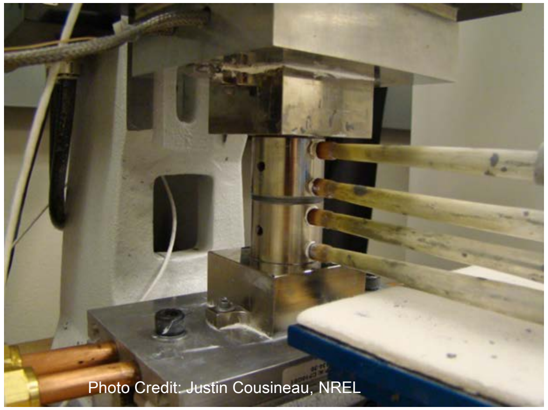


Photo Credit: Justin Cousineau, NREL

Photo Credit: Kevin Bennion, NREL

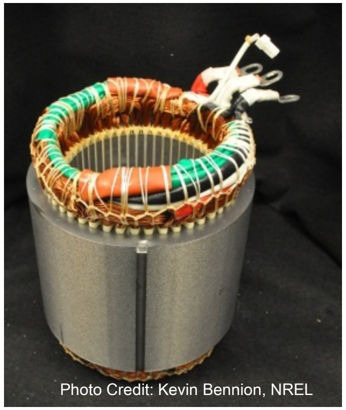
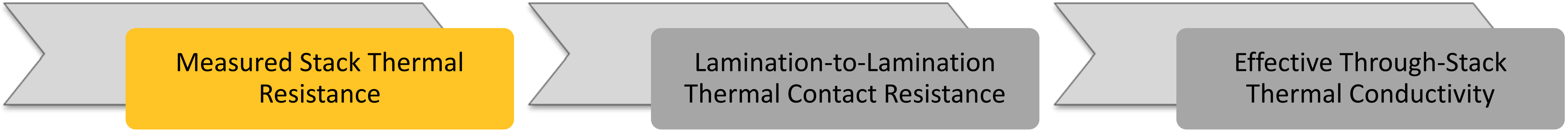


Photo Credit: Kevin Bennion, NREL

Passive Thermal Design –
Effective Through-Stack Thermal Conductivity



Measured Stack Thermal Resistance

Lamination-to-Lamination Thermal Contact Resistance

Effective Through-Stack Thermal Conductivity

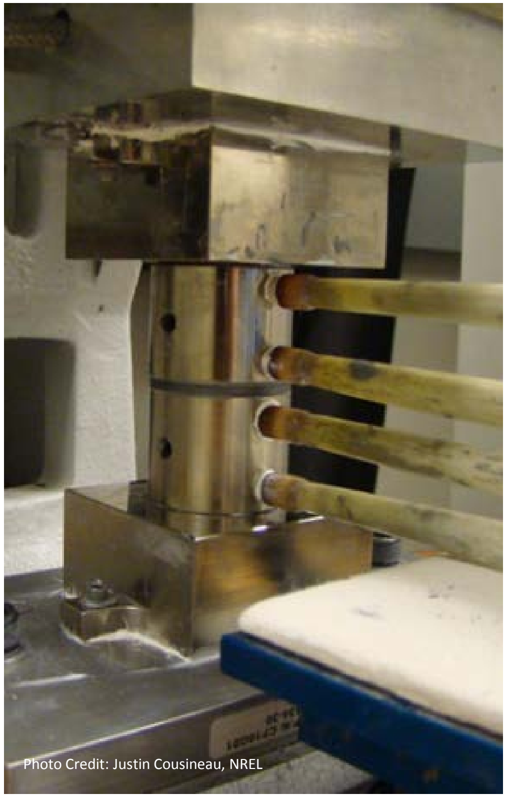
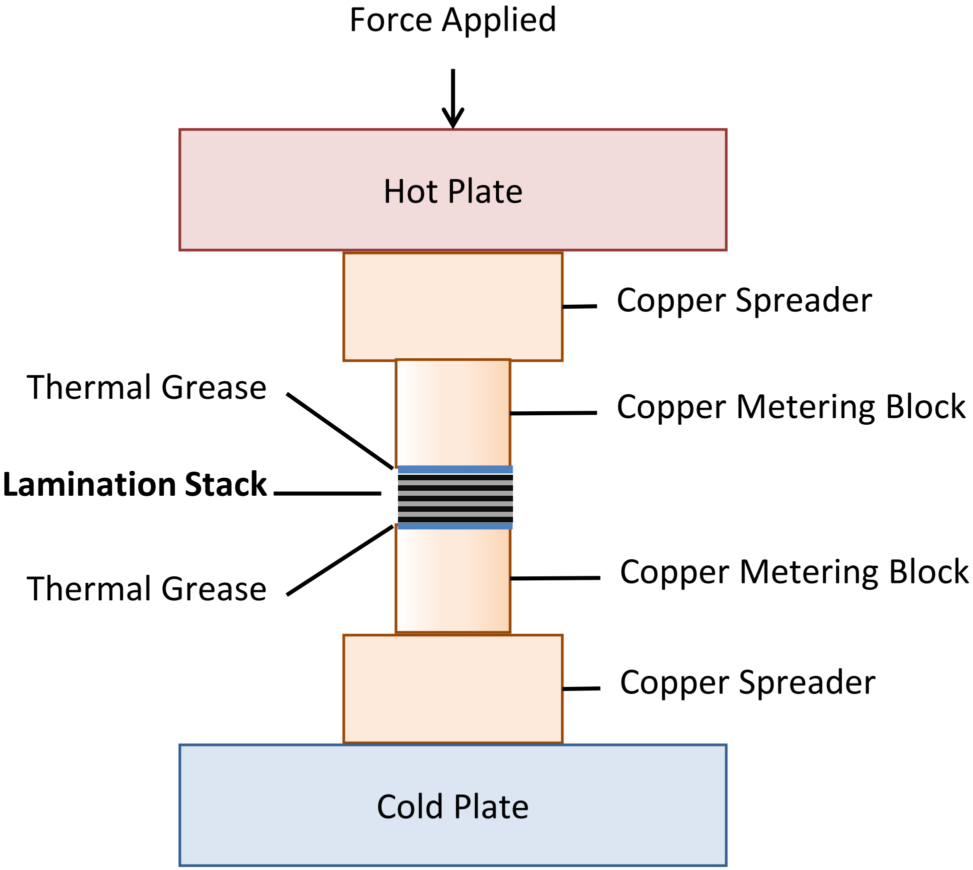


Photo Credit: Justin Cousineau, NREL

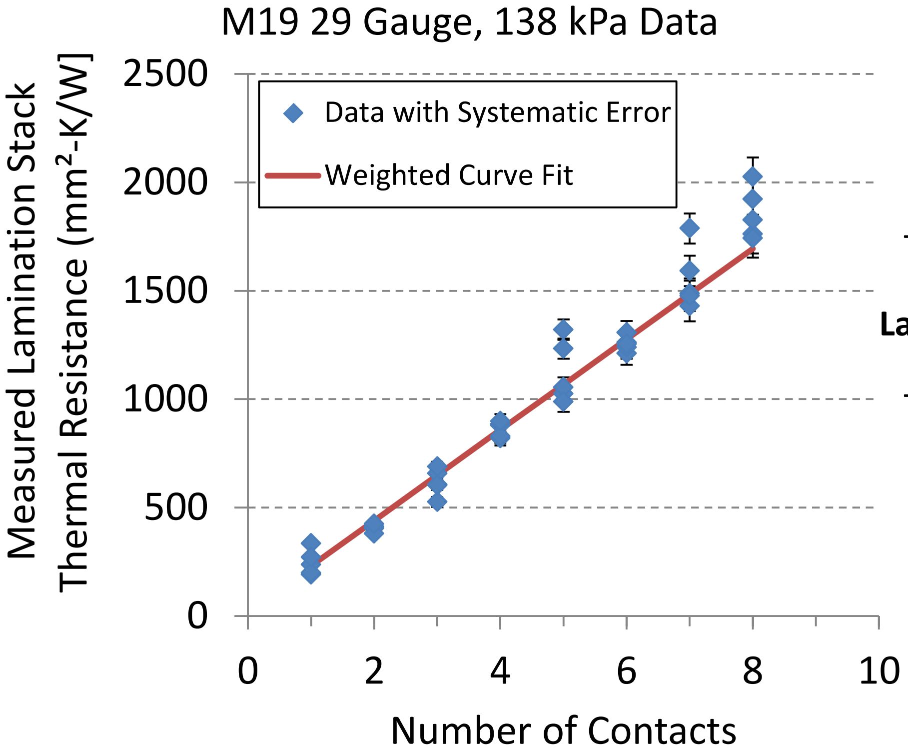


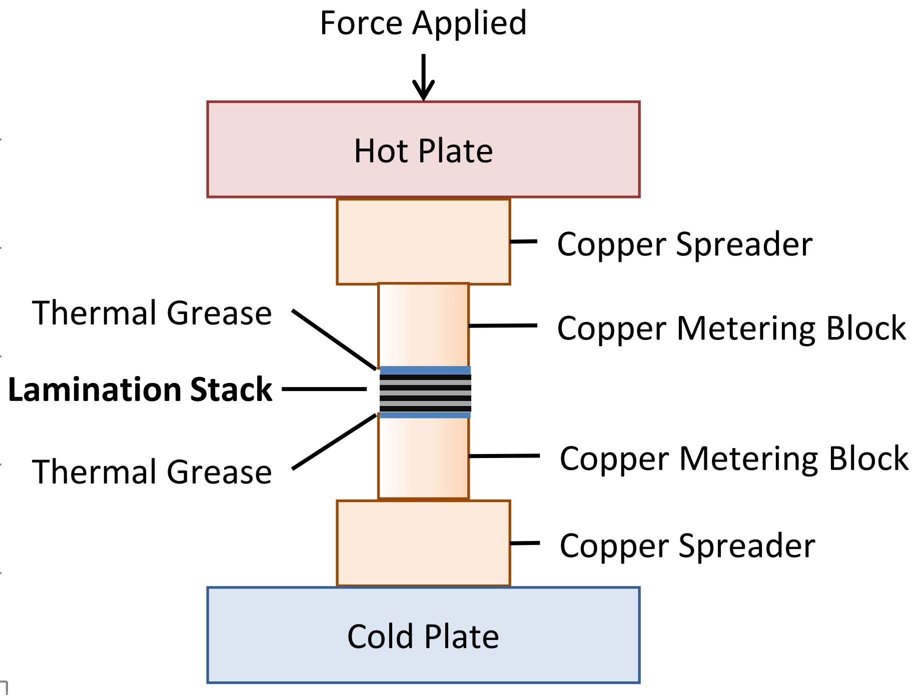
Passive Thermal Design –
Effective Through-Stack Thermal Conductivity

Measured Stack Thermal Resistance

Lamination-to-Lamination Thermal Contact Resistance

Effective Through-Stack Thermal Conductivity





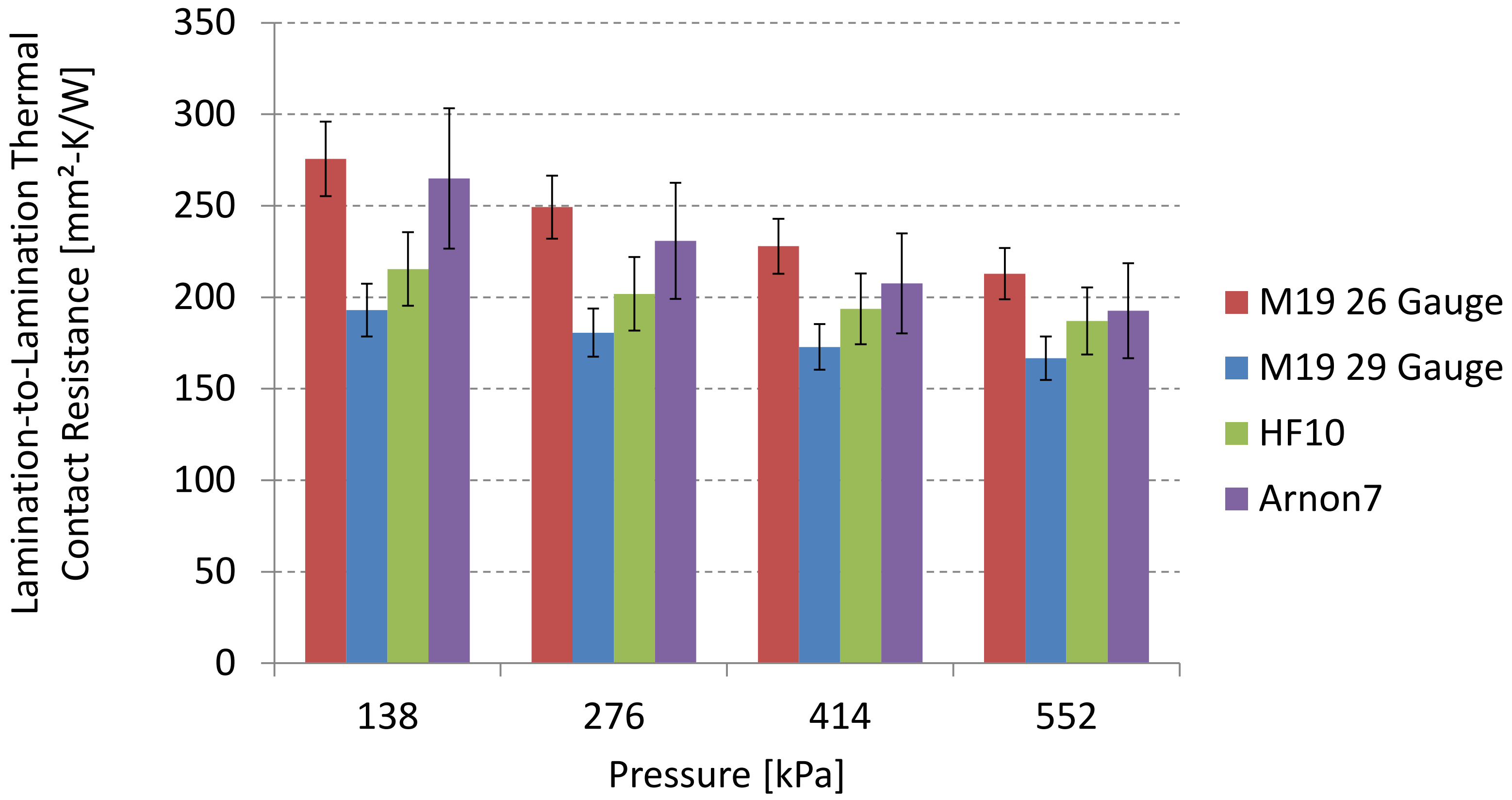
Error bars represent 95% confidence level

Passive Thermal Design - Effective Through-Stack Thermal Conductivity

Measured Stack Thermal Resistance

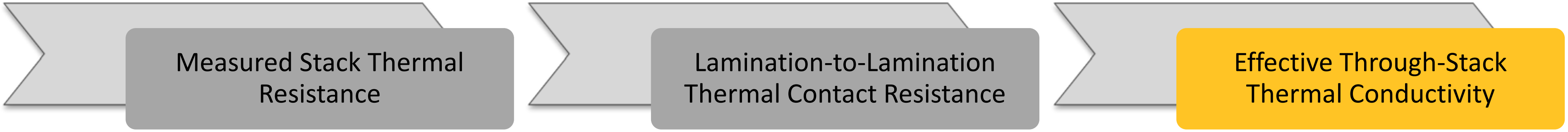
Lamination-to-Lamination Thermal Contact Resistance

Effective Through-Stack Thermal Conductivity



Error bars represent 95% confidence level

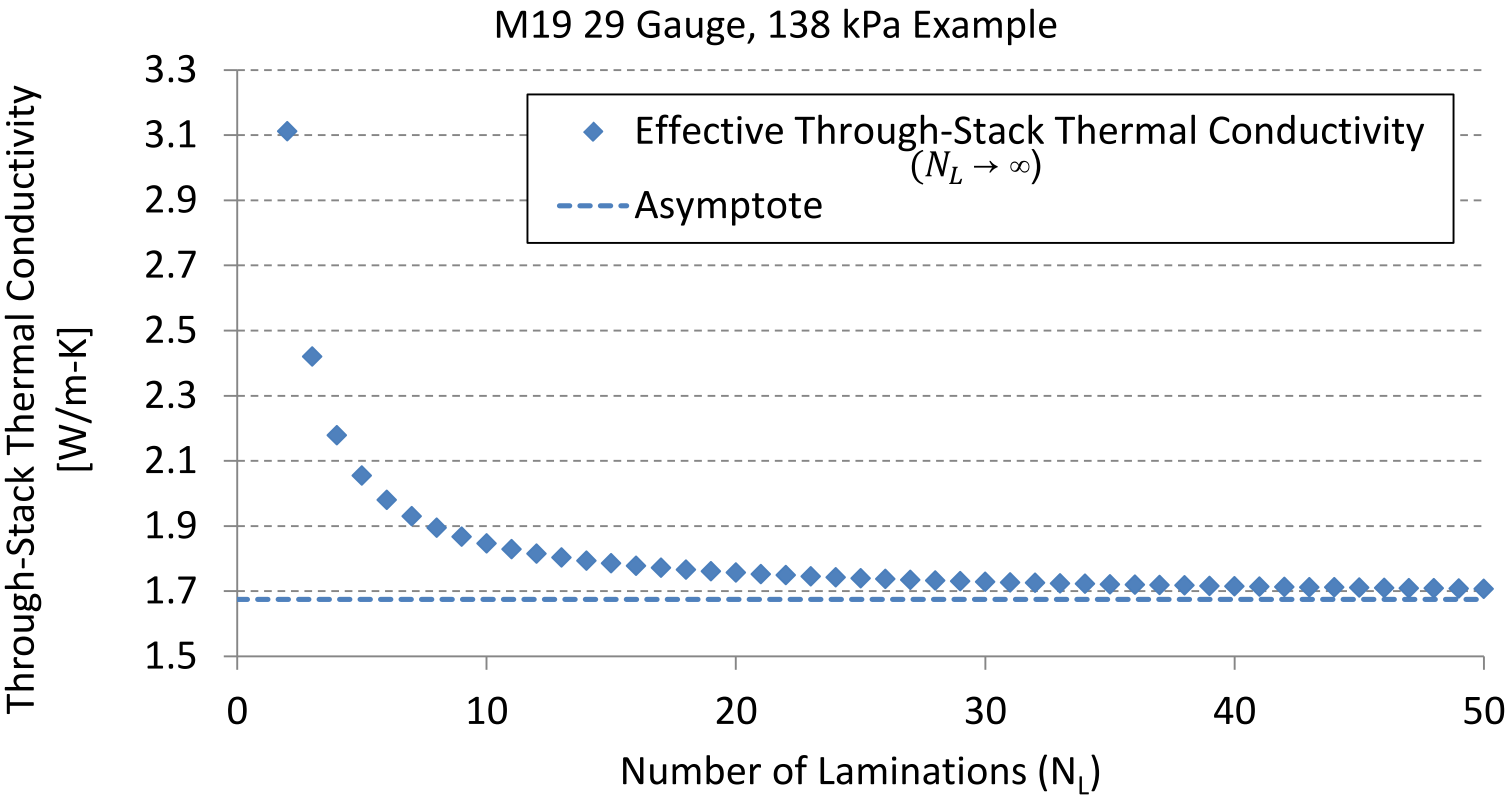
Passive Thermal Design – Effective Through-Stack Thermal Conductivity



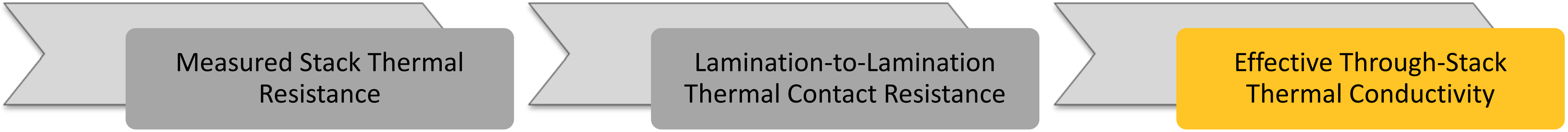
Measured Stack Thermal Resistance

Lamination-to-Lamination Thermal Contact Resistance

Effective Through-Stack Thermal Conductivity



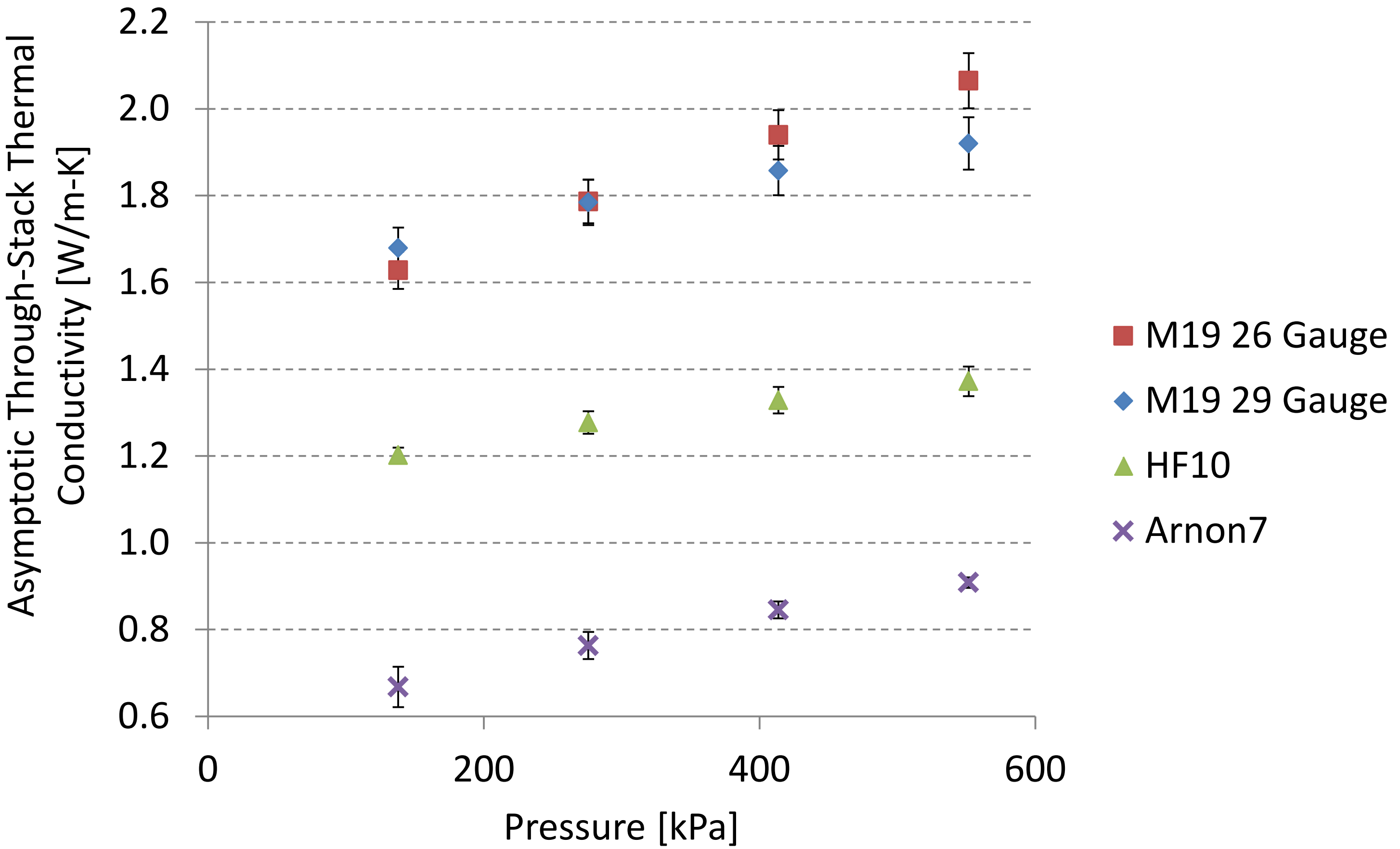
Passive Thermal Design – Effective Through-Stack Thermal Conductivity



Measured Stack Thermal Resistance

Lamination-to-Lamination Thermal Contact Resistance

Effective Through-Stack Thermal Conductivity



Error bars represent 95% confidence level

Passive Thermal Design –
Effective In-Plane Lamination Stack Thermal Conductivity

- Measured in-plane thermal conductivity of lamination stacks provided by Oak Ridge National Laboratory (ORNL)

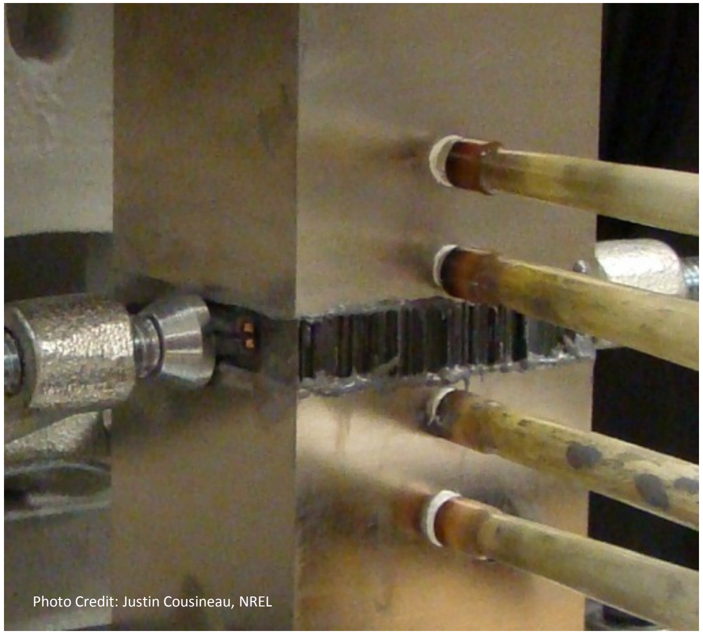
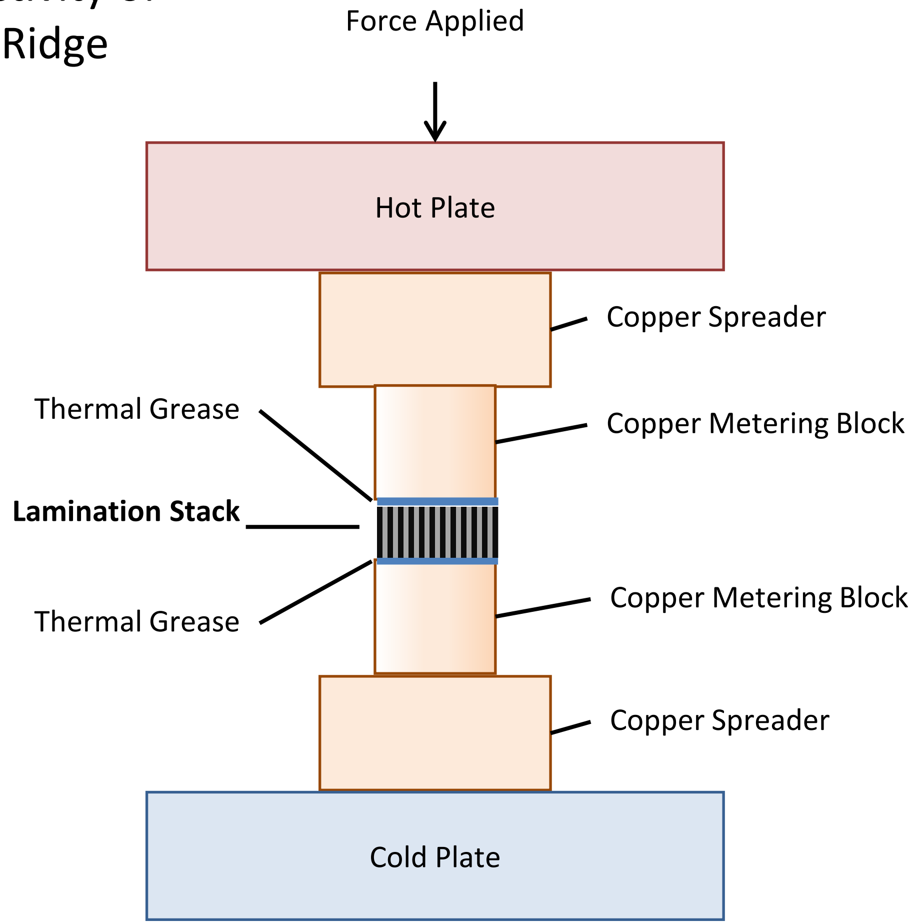
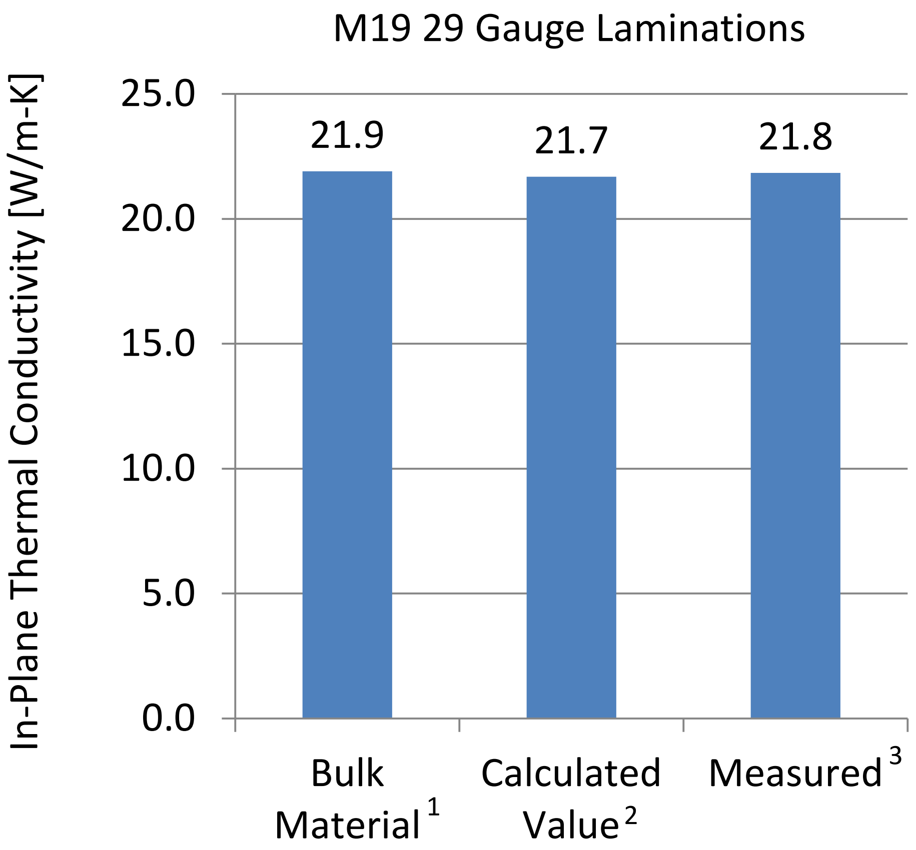


Photo Credit: Justin Cousineau, NREL



Passive Thermal Design –
Effective In-Plane Lamination Stack Thermal Conductivity



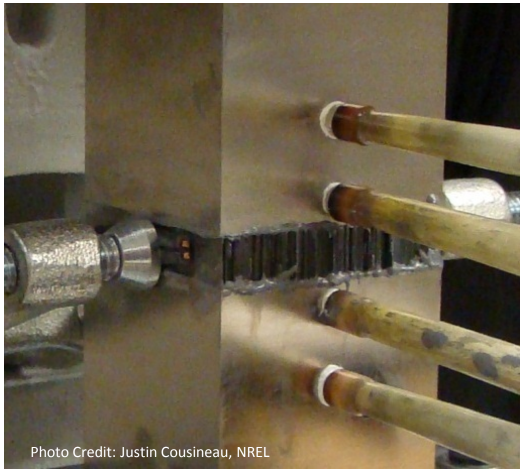


Photo Credit: Justin Cousineau, NREL

- 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

Passive Thermal Design –
Effective Wire Bundle Cross-Slot Thermal Conductivity

- Measured cross-slot thermal conductivity of wire bundles prepared and provided by ORNL

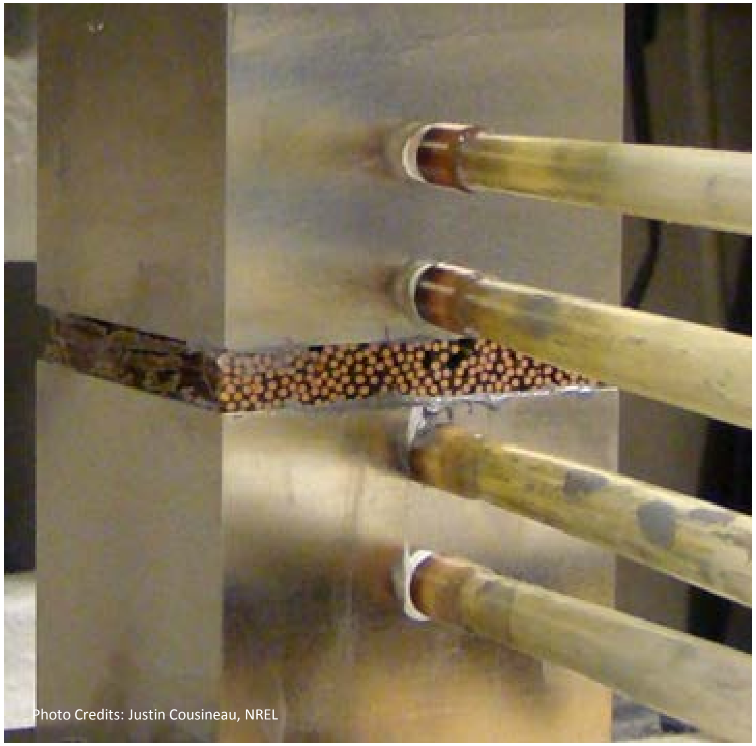
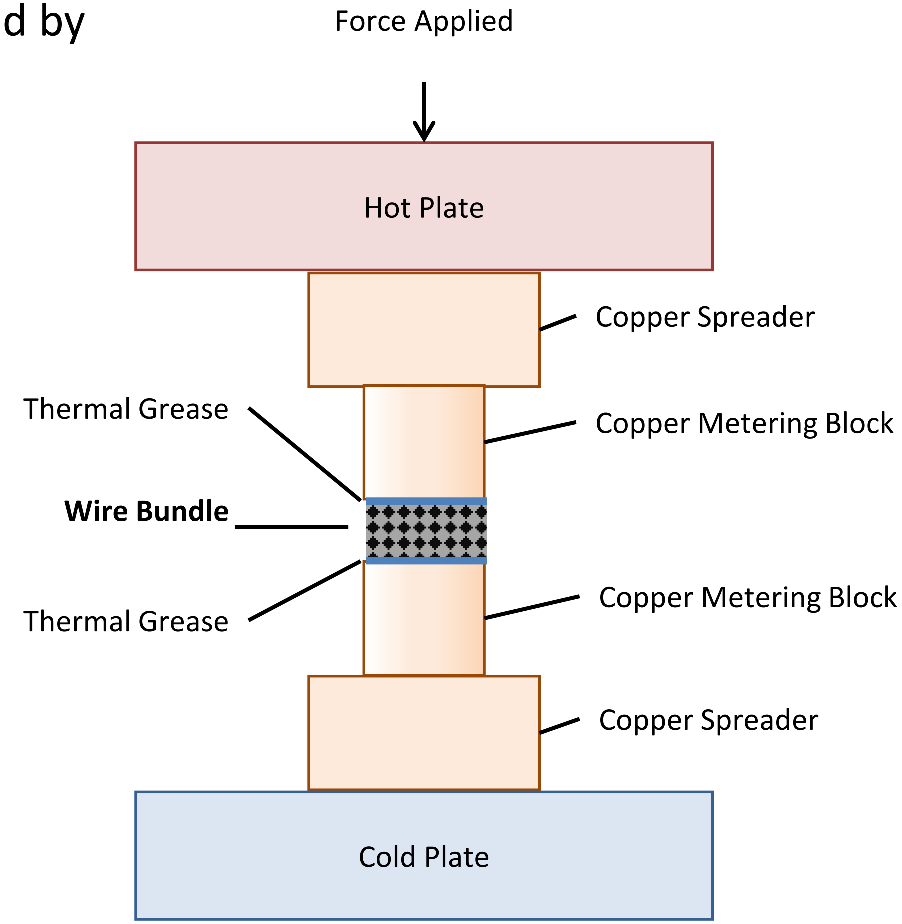


Photo Credits: Justin Cousineau, NREL



Passive Thermal Design – Effective Wire Bundle Cross-Slot Thermal Conductivity

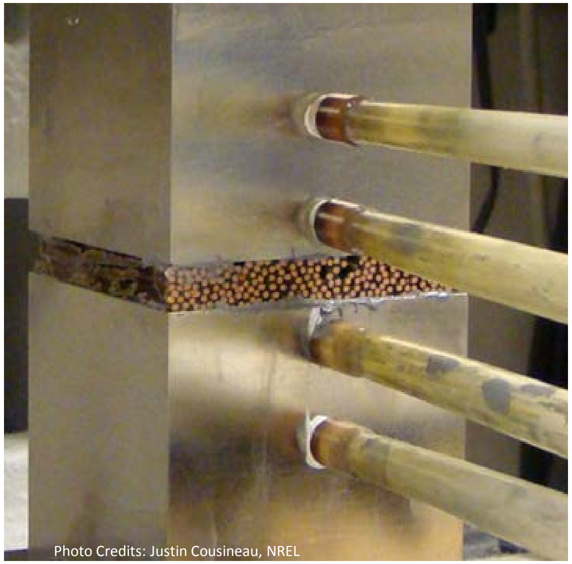
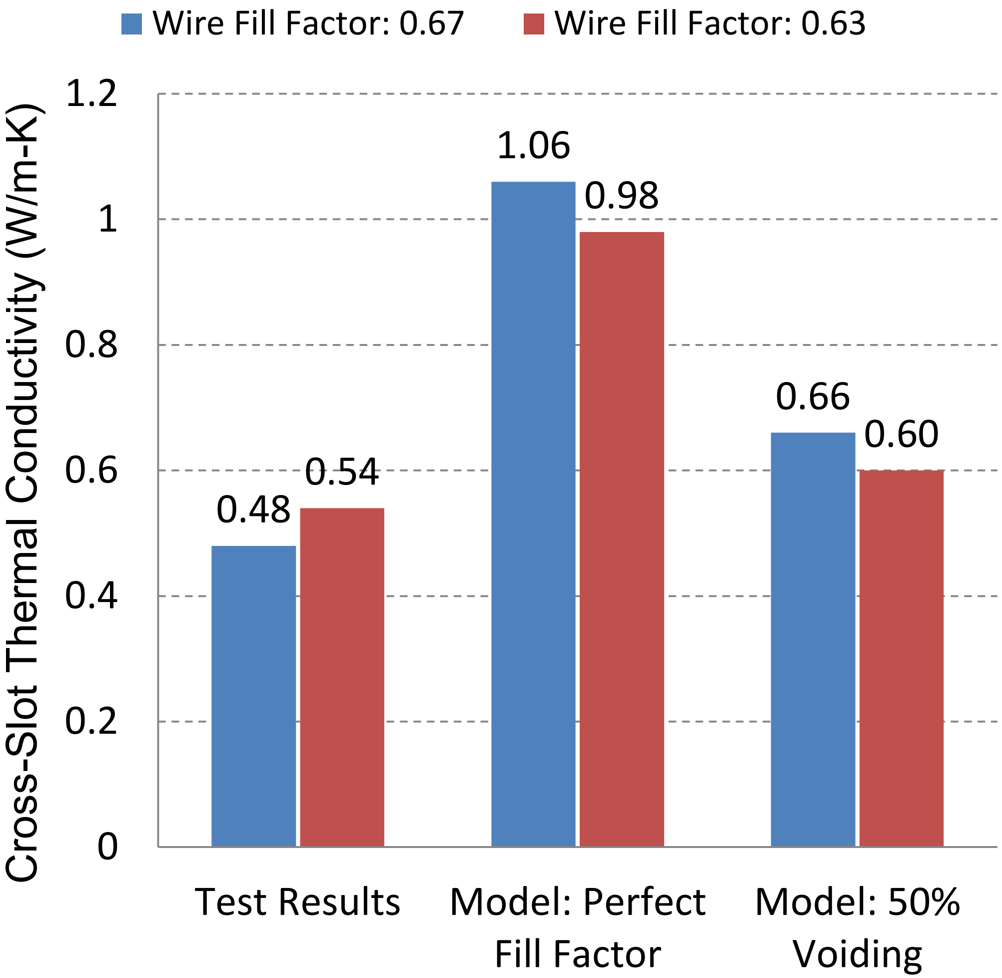


Photo Credits: Justin Cousineau, NREL

- The agreement between model and experimental results depends on assumptions for fill factor, voiding, and thermal contact resistance
- Modeling approach appears to match, but additional testing is needed



Note: Wire fill factor includes copper and insulation

Conclusion

Relevance

- Supports transition to more electric-drive vehicles 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)

Technical Accomplishments

- Received sample motor materials from ORNL and measured orthotropic thermal conductivity
- Completed expanded lamination thermal tests
- Measured ATF heat transfer convection coefficients on target surfaces
- Received ATF fluid property data from Ford Motor Company to support future work to develop correlations and computational fluid dynamics models

Collaborations

- Motor industry representatives: manufacturers, researchers, and end users (light-duty and medium/heavy-duty applications)
- Oak Ridge National Laboratory

Acknowledgments:

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

Team Members:

Justin Cousineau (NREL)
Jana Jeffers (NREL)
Charlie King (NREL)
Gilbert Moreno (NREL)
Tim Burress (ORNL)
Andy Wereszczak (ORNL)

For more information, contact:

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

APEEM Task Leader:

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