Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines

InterPACK Conference
San Francisco, CA
July 6-9, 2015

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NREL/PR-5400-63864
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Outline

- **Background**
- **Approach**
- **Results**
  - Bulk thermal conductivity
  - Contact resistance between laminations
  - Effective through-stack thermal conductivity
  - In-plane thermal conductivity
- **Conclusions**

Background

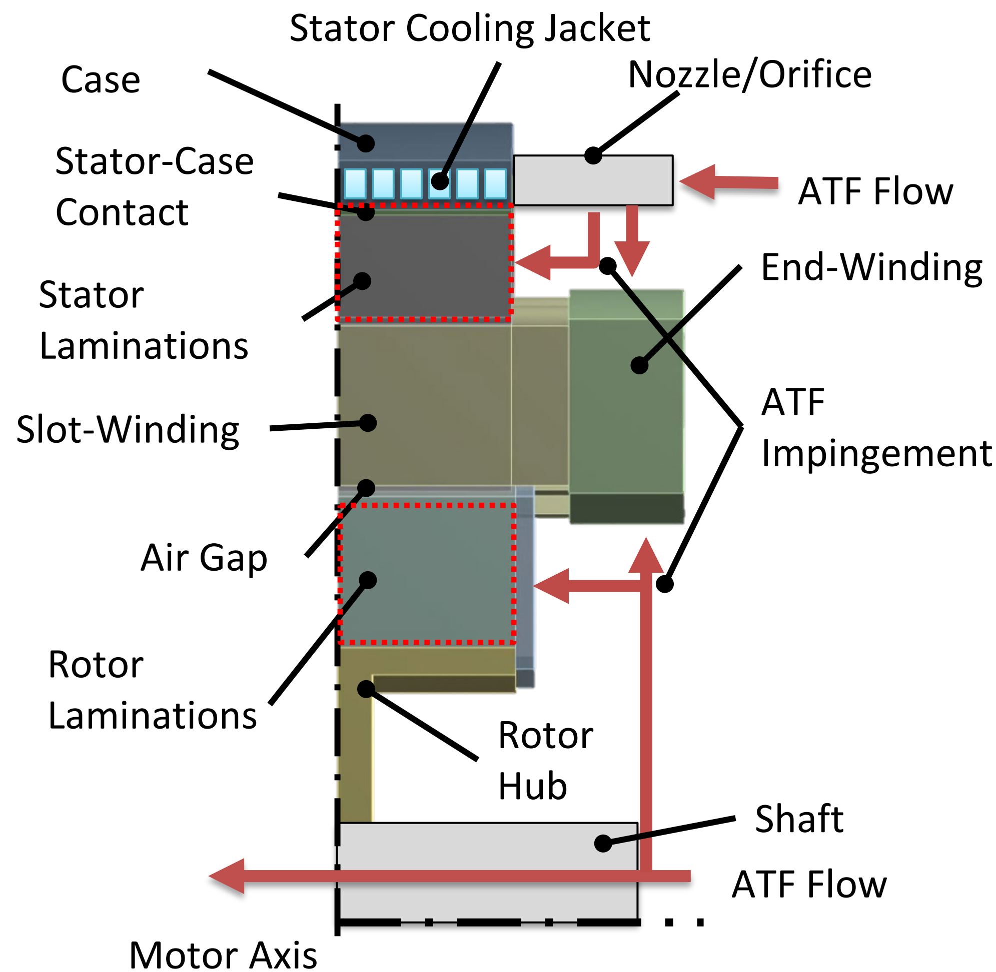
Problem

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

Laminations make up a large portion of the stator and rotor

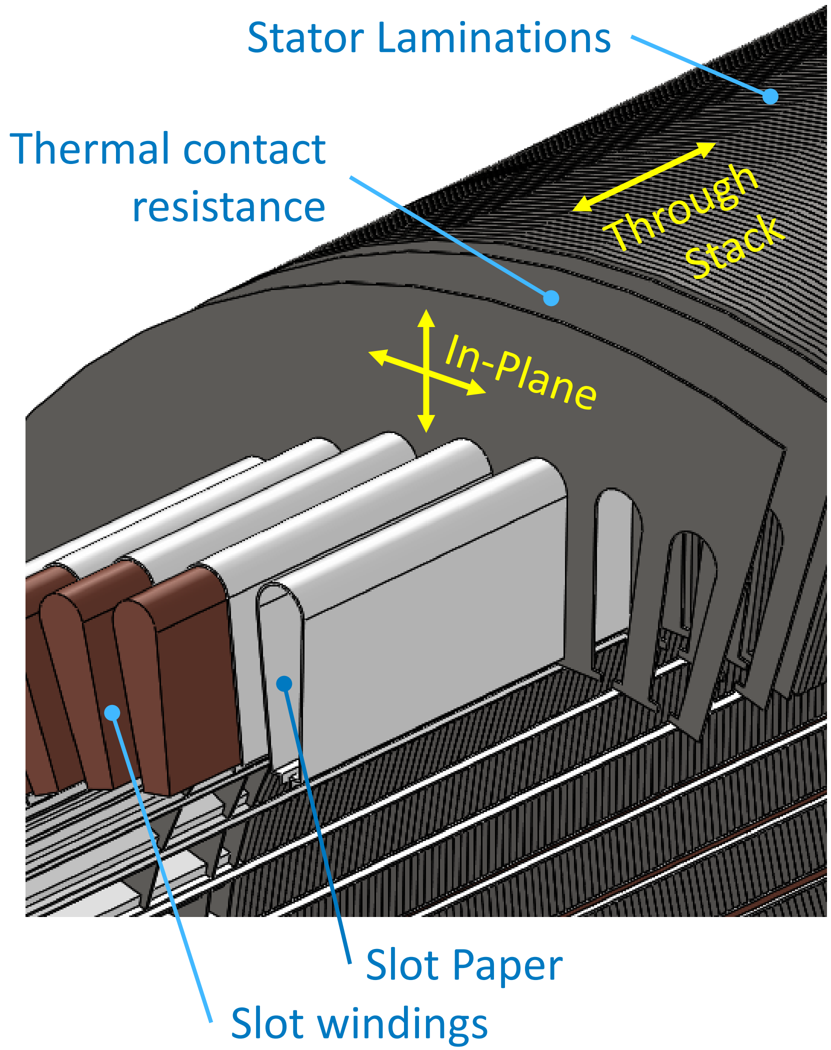
- Significant portion of thermal pathway to remove heat from motor
- Greater knowledge of factors affecting thermal conductivity can improve motor design models
- Currently a lack of public literature

Motor Cooling Section View



ATF: Automatic Transmission Fluid

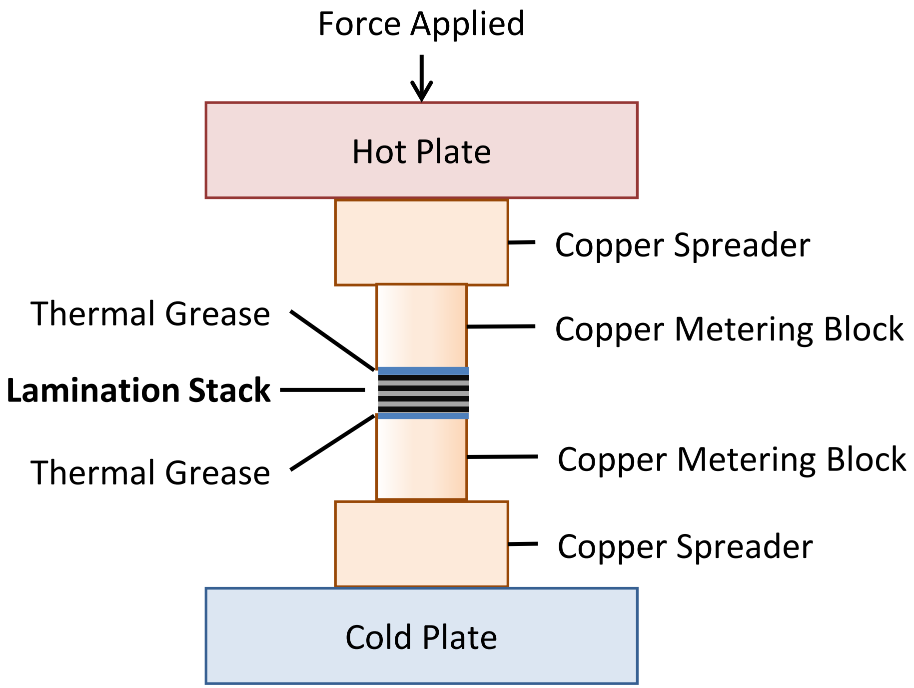
Overview



- Transversely isotropic thermal properties
  - Bulk properties in-plane
  - Effective properties through-stack

Approach

- Lamination bulk thermal conductivity measured with xenon flash equipment
- Through-stack thermal conductivity measured on test apparatus built in accordance with ASTM D5470-12 steady state technique
- Tested at multiple sample pressures



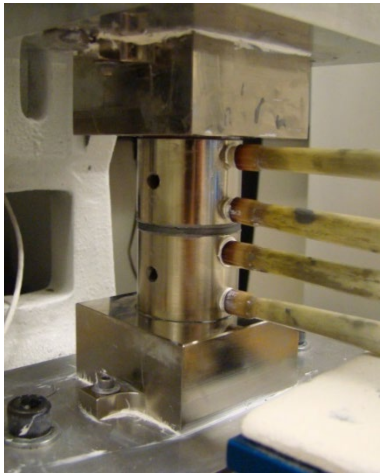
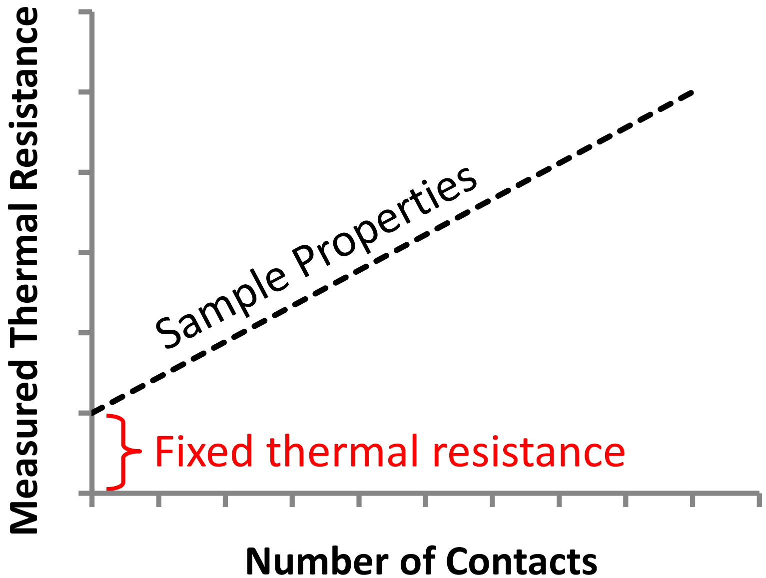
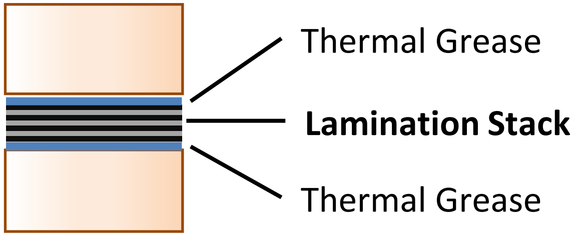


Photo Credit: Emily Cousineau

Approach

- Experiments performed on multiple stack heights
- Slope gives stack resistance as a function of number of laminations and contacts
- Eliminates fixed thermal resistance such as grease





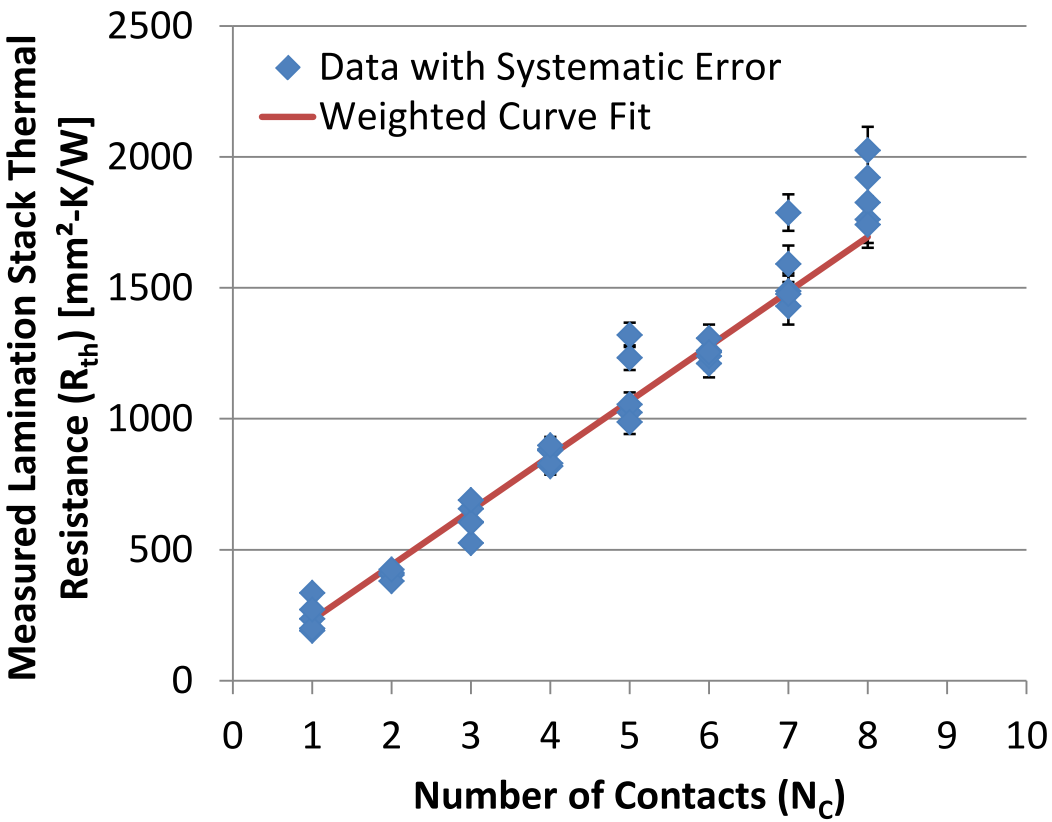
$$R_{th} = \underbrace{(R_C + R_L)}_{\text{slope}} N_C + \underbrace{R_L + 2R_G}_{\text{Intercept (fixed values)}}$$

R_{th} = thermal resistance
R_C = thermal contact resistance
R_L = thermal resistance of one lamination
R_G = thermal resistance of grease layer
N_C = number of contacts

Results

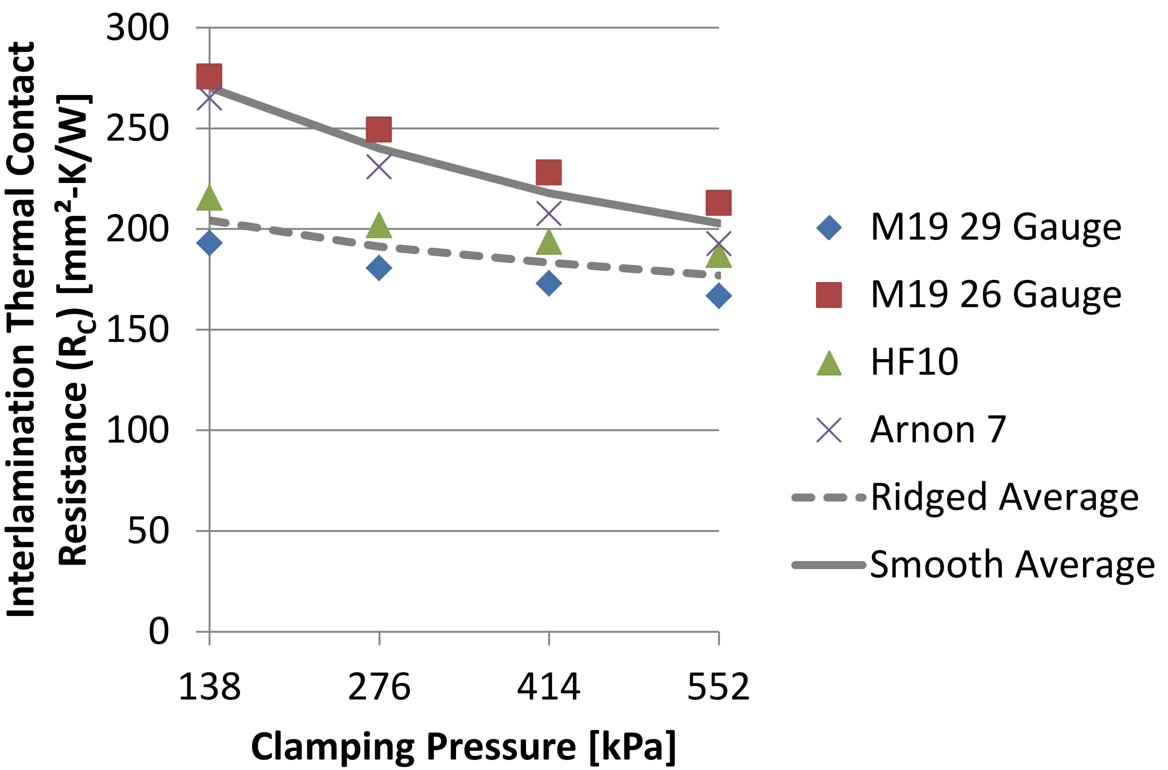
- Lamination bulk thermal conductivity measured to be 20-23 W/m-K for tested materials

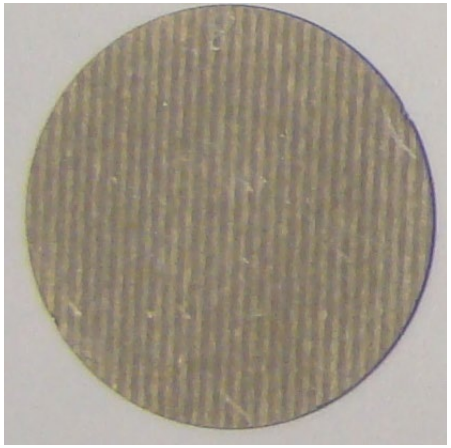
- 5 repetitions at each stack height
- Curve fit weighted on systematic error (error bars)



Full technical report available at: www.nrel.gov/publications/

Thermal Contact Resistance





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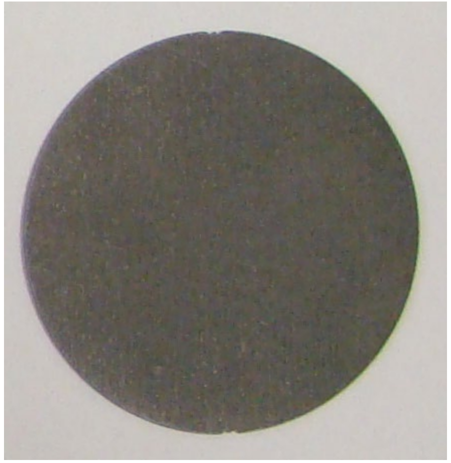


Smooth

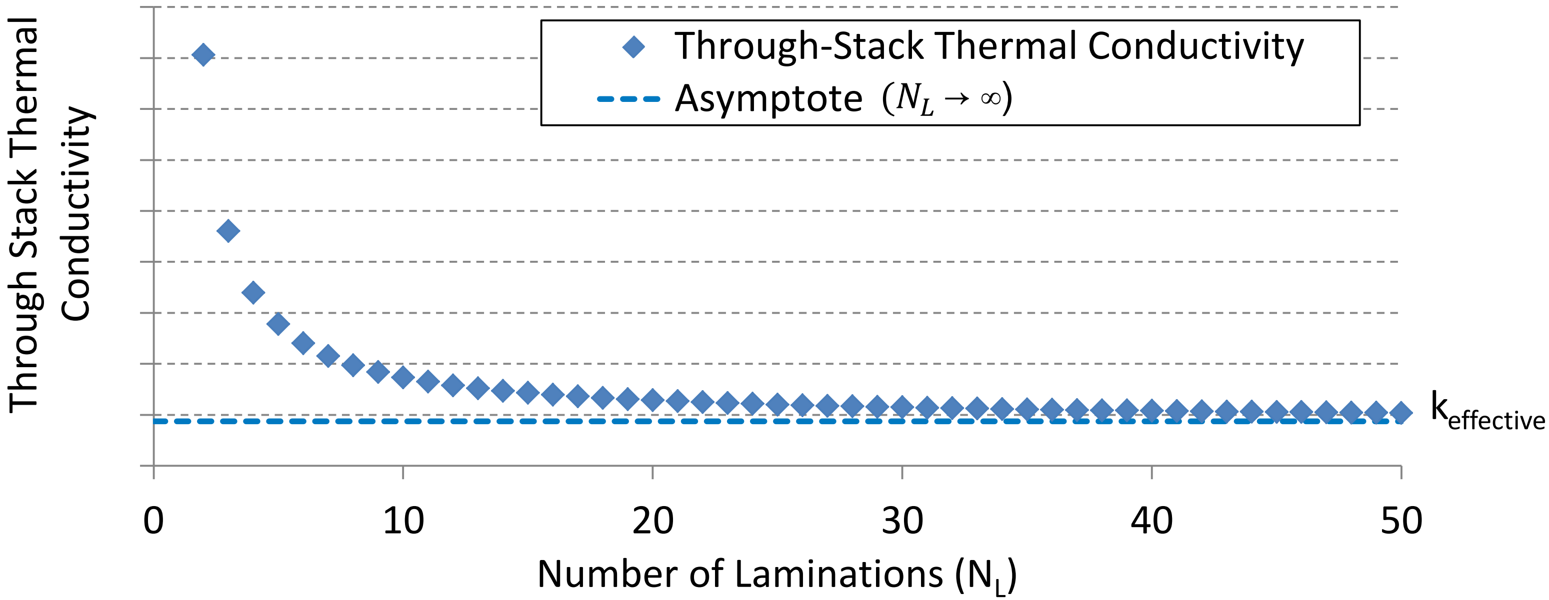
Photo Credit: Emily Cousineau

$$R_C = m - \frac{t}{k_L}$$

R_C = Interlamination thermal contact resistance
m = slope of curve fit
t = thickness of one lamination
k_L = bulk thermal conductivity

Effective Through-Stack Thermal Conductivity

- Short length inhomogeneity
- Effective through stack thermal conductivity approaches an asymptote between 30 and 50 laminations
- Typical motors have several hundred laminations



$$k = \frac{Total\ Thickness}{Total\ Resistance} = \frac{t \cdot N_L}{R_C N_C + R_L N_L} \qquad \lim_{N_C \to N_L} k = \frac{t}{R_C + R_L} = k_{effective}$$

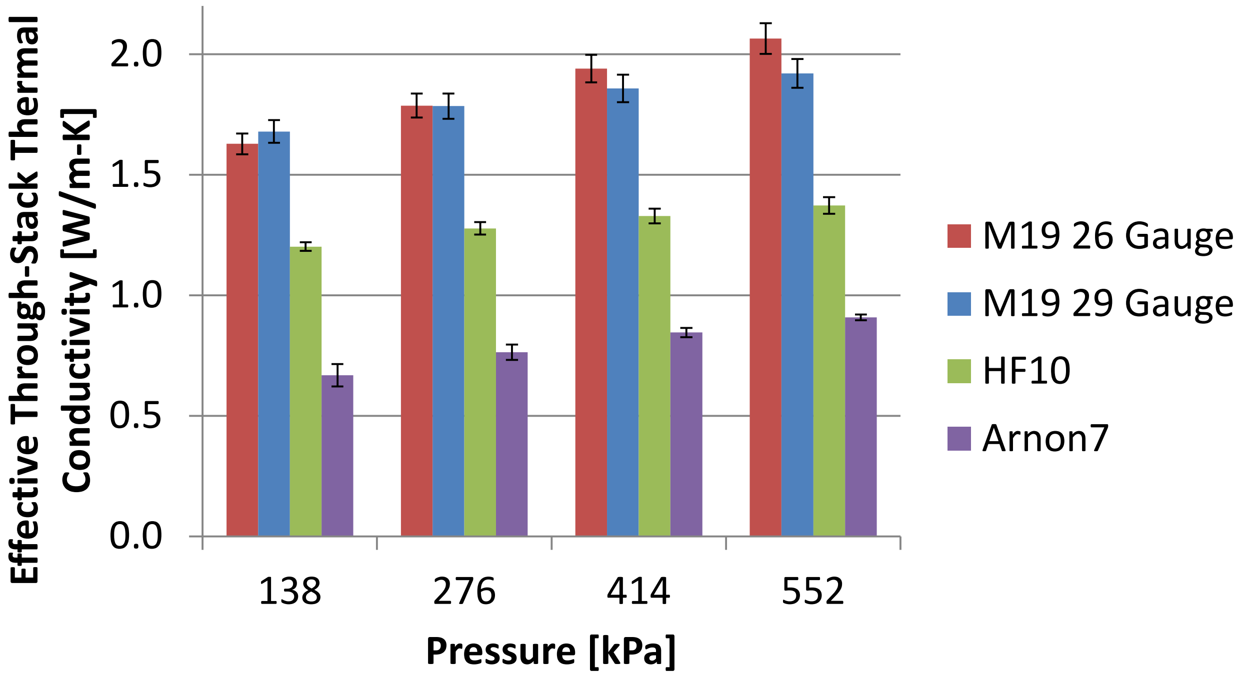
k = thermal conductivity
t = thickness of one lamination

N_C = number of contacts
N_L = number of laminations

R_C = thermal contact resistance
R_L = thermal resistance of one lamination

Effective Through-Stack Thermal Conductivity

- Thinner laminations have more contacts per unit length
- Higher pressure lowers contact resistance
- Error bars represent 95% confidence interval



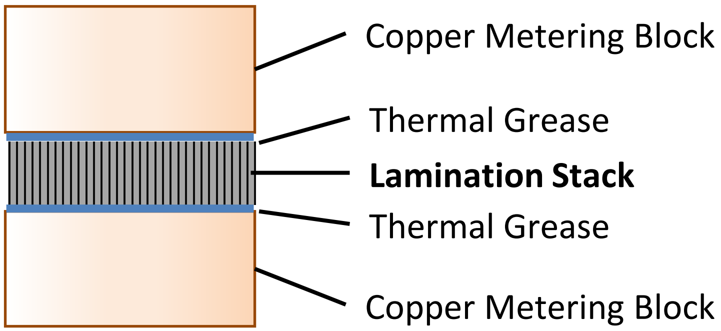
$$k_{effective} = \frac{t}{R_C + R_L}$$

$k_{effective}$ = effective thermal conductivity
t = thickness of one lamination

R_C = thermal contact resistance
R_L = thermal resistance of one lamination

In-Plane Thermal Conductivity

- In-plane thermal conductivity measured on test apparatus used to measure through-stack
- In-plane thermal conductivity measured to be the same as bulk
  - Effect of splitting into laminations negligible
- Confirms a basic area weighted average formula for thermal conductivity



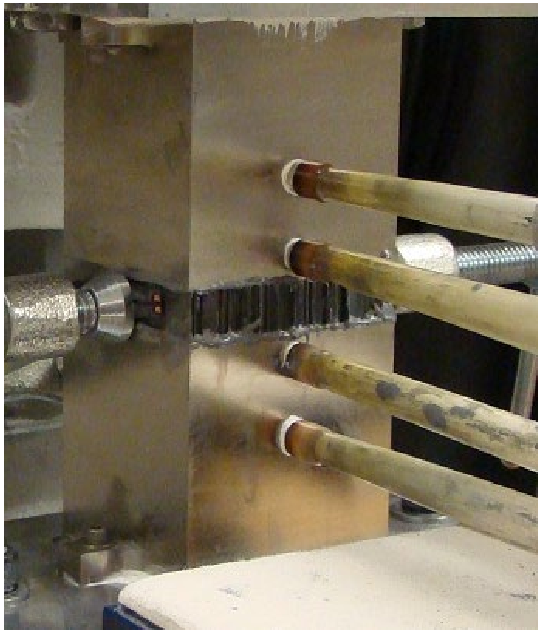


Photo Credit: Emily Cousineau

Samples provided by Oak Ridge National Laboratory

Conclusions

- For this class of materials and pressures tested:
  - Lamination-to-lamination thermal contact resistance measured to be 170 to 280 mm^2-K/W
    - Reduces with pressure
    - Affected by surface topography
  - Effective through stack thermal conductivity measured to be between 0.7 to 2.1 W/m-K
    - Strongly impacted by lamination thickness and contact resistance
  - Lamination bulk thermal conductivity measured to be 20-23 W/m-K for tested materials
    - In-plane thermal conductivity is the same as the bulk material properties

Acknowledgments:

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

Andy Wereszczak
Tim Burress
Oak Ridge National Laboratory

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