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Development of Thermal Barrier Materials

PRESENTED BY

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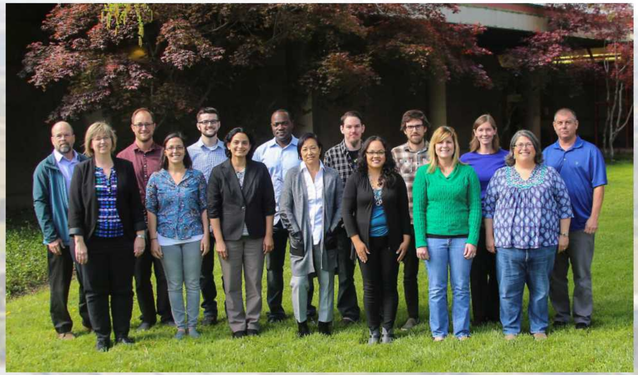
Sandia, CA

Chemistry, Combustion & Materials Science

Materials Research

Materials Chemistry Department

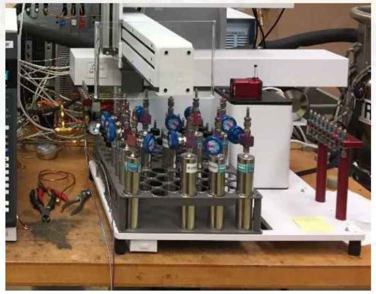


The Materials Chemistry Department provides creative solutions to materials problems impacting national security.

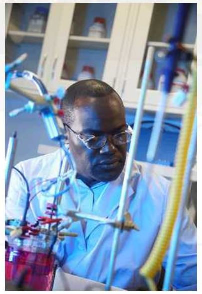
Polymer Lab

Synthesis Lab

MAC Lab



Plating Lab



Thermal-Elec Lab

Thermal-Physical & Electrical Lab

- Materials characterization of a wide range of materials (from foams to metals),in different states and morphologies (liquid, thin coatings, composites…) and under different accelerated environments (temperature, humidity).

Materials:	**Properties:**	**Applications:**
polymers, metals, ceramics, composites, dielectric, thermoelectric, anisotropic materials…	Thermal conductivity, diffusivity, heat capacity, latent heat, dielectric constant, capacitance, resistivity…	R&D of new materials Qualification under different environments Lifetime and Aging studies

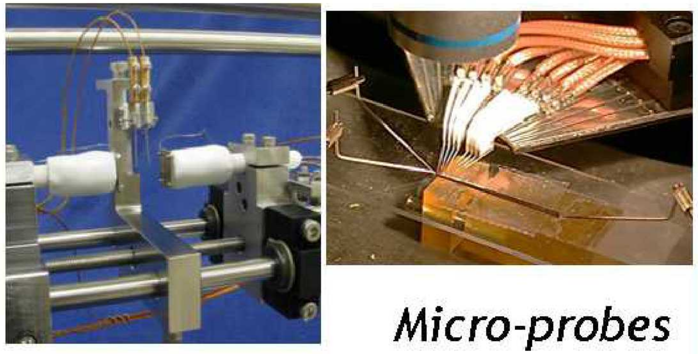
- Thermal, physical and electrical testing using state of the art and custom methods for accurate and realistic materials characterization.

Thermophysical System

TGA-DSC

High and ultra low resistivity setup

Custom designs



Micro-probes

Building foundational Capabilities and Understanding for a Sustained Thermal Barrier Coating Research Program

Dr. Stephen Busch (Combustion Research Facility)

Dr. Karla Reyes (Materials Chemistry)

Building foundational Capabilities and Understanding for a Sustained Thermal Barrier Coating Research Program

- Collaboration with Dr. Stephen Busch from Combustion Research Facility (CRF) at Sandia
- Reducing heat loss is key to reducing fuel consumed by medium- and heavy-duty trucks
- Thermal barrier coatings (TBCs) are a potential means to improve diesel engine efficiency, both directly and through enhanced waste heat recovery
- TBCs are expected to improve diesel combustion engine efficiency by several percentage points, but the effects of coating properties on critical factors such as turbulent mixing rates and combustion completeness must be better understood and controlled for these benefits to be realized
- Current approaches to TBCs in engines
  - Plasma-sprayed ceramic coatings
    - Common R&D approach: stabilized ZrO_2 sprayed onto a bond coat
    - Durability issues; efficacy varies widely
  - Metal-based coating
    - Toyota's SiRPA: porous aluminum surface layer coated with silica
    - Durability issues, application in production engines not verified
  - Polymer-based coating
    - Adiabatics Inc.: particles of insulating material (ceramics, silica microspheres, etc.) mixed with a resin and a solvent, then sprayed onto the surface
    - Some expectation of durability; properties can be varied to suit experimental goals

Kawaguchi, A., Iguma, H., Yamashita, H., Takada, N., Nishikawa, N., Yamashita, C., Wakisaka, Y. and Fukui, K., "Thermo-Swing Wall Insulation Technology; - A Novel Heat Loss Reduction Approach on Engine Combustion Chamber," SAE Technical Paper 2016-01-2333, 2016, DOI: https://doi.org/10.4271/2016-01-2333

Developing innovative TBC materials requires an innovative approach

Underlying hypothesis: the successful development of TBCs for diesel engines will be driven by material property requirements based on understanding of interactions between coating properties and factors critical to rapid, efficient diesel combustion

- Turbulent mixing rates
- Completeness of combustion
- Wall heat loss
- Thermodynamic properties of the working fluid

We developed a set of coatings with a well-defined and characterized set of properties

We use a simple coating material system.

- Silica microspheres in a phosphate-based resin
- Inexpensive application via solvent-based liquid spraying process

Iteration to develop coating formulations with variations in the desired properties:

- Thickness, roughness, density

Accurate quantification of thermophysical properties by analysis of coated coupons in the thermophysical properties lab using existing capabilities, including:

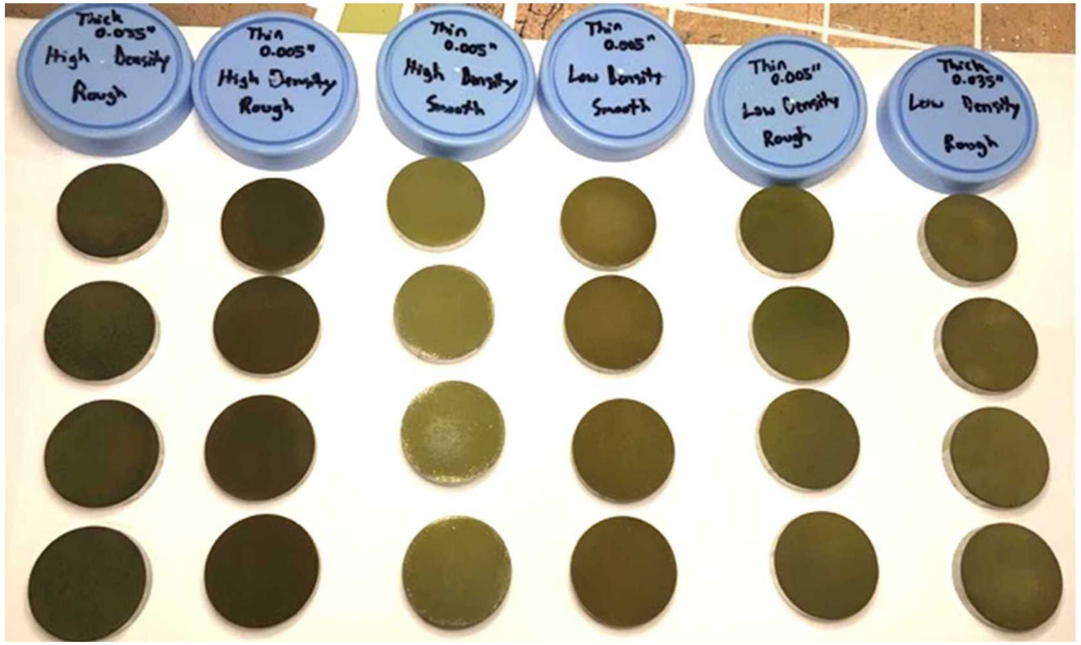
- Density measurement of bulk coating material via Archimedes' method
- Surface roughness measurement: 3D laser scanning microscope
- Independent measurement of thermal conductivity of the coating aggregate
- Direct measurement of specific heat capacity of the coating aggregate

Finalized coating formulations will be applied to piston crowns, witness samples, and spray chamber test apparatuses

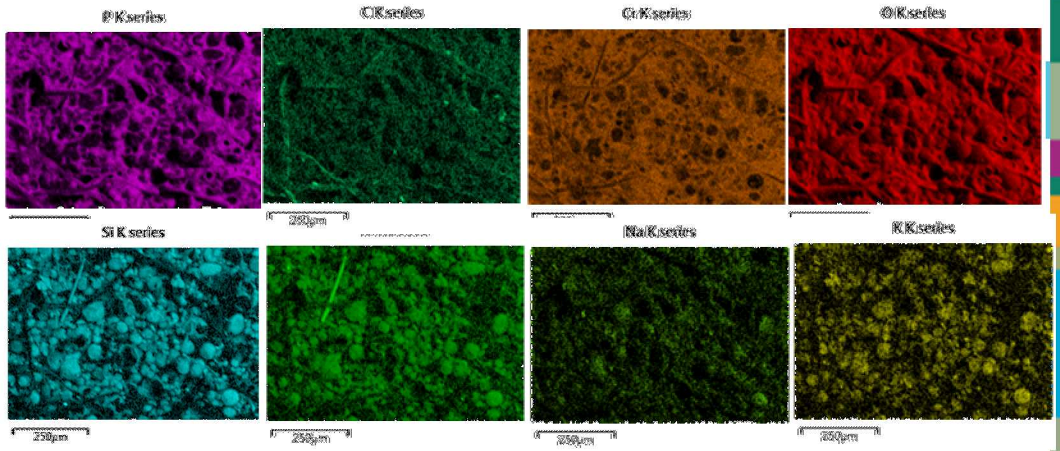
Development of the first generation of coatings

- Understanding of their coating materials and processes
- An initial set of eight coatings has been developed and four coated coupons have been obtained with each coating formulation
- Objectives for first set of coatings
  - Assess control and ability to vary thickness, density, and roughness
  - Develop plan for second iteration of improved coating formulations

Batch	Target Thickness	Density	Roughness	Label
Batch 1	Thick (0.035”= 889 um)	Low	Smooth	Tk-LD-Sm
Batch 2	Thick (0.035”= 889 um)	Low	Rough	Tk-LD-Ro
Batch 3	Thick (0.035”= 889 um)	High	Smooth	Tk-HD-Sm
Batch 4	Thick (0.035”= 889 um)	High	Rough	Tk-HD-Ro
Batch 5	Thin (0.005” = 127 um)	Low	Smooth	Tn-LD-Sm
Batch 6	Thin (0.005” = 127 um)	Low	Rough	Tn-LD-Ro
Batch 7	Thin (0.005” = 127 um)	High	Smooth	Tn-HD-Sm
Batch 8	Thin (0.005” = 127 um)	High	Rough	Tn-HD-Ro



Microscopy and elemental analysis

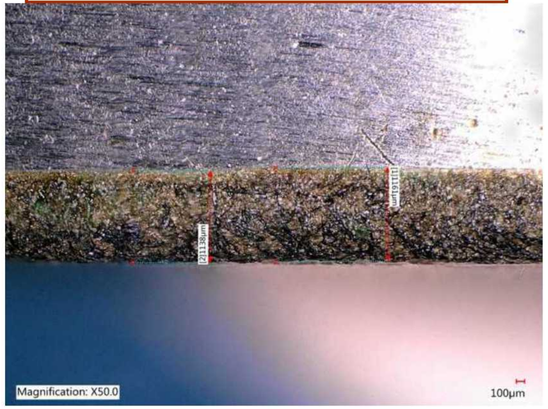


Coating adhesion to the aluminum substrate is very good

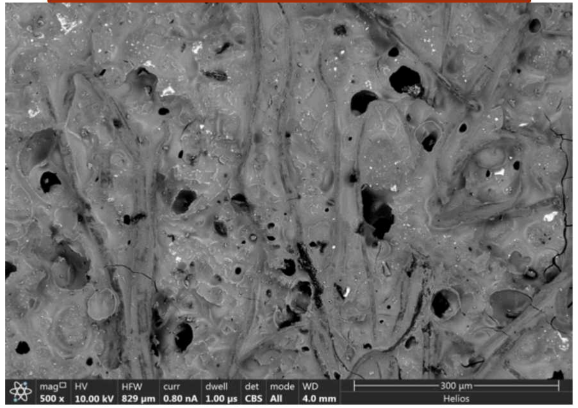
- Voids were not observed along the interface with the aluminum blanks
- **Conclusion:** we have some measure of confidence that the coatings will adhere well to aluminum pistons

- Energy-dispersive X-ray spectroscopy (EDS) was used for elemental analysis of the coatings.
- P, C, O and Cr elements were detected in the resin matrix.
- Si, K, Na, Al elements from the glass microspheres can be seen exposed in the surface (spherical shape and ~50 microns diameter).

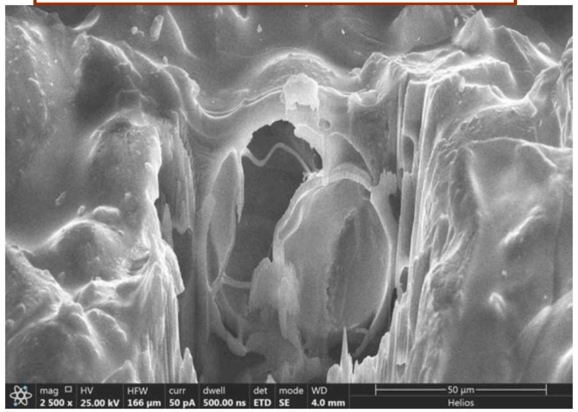
Interface



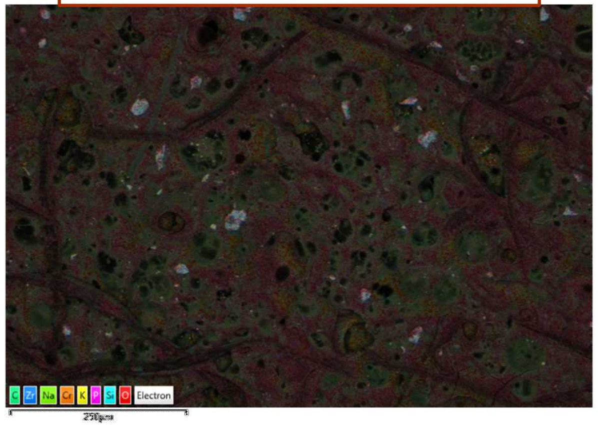
Surface



Cross-section



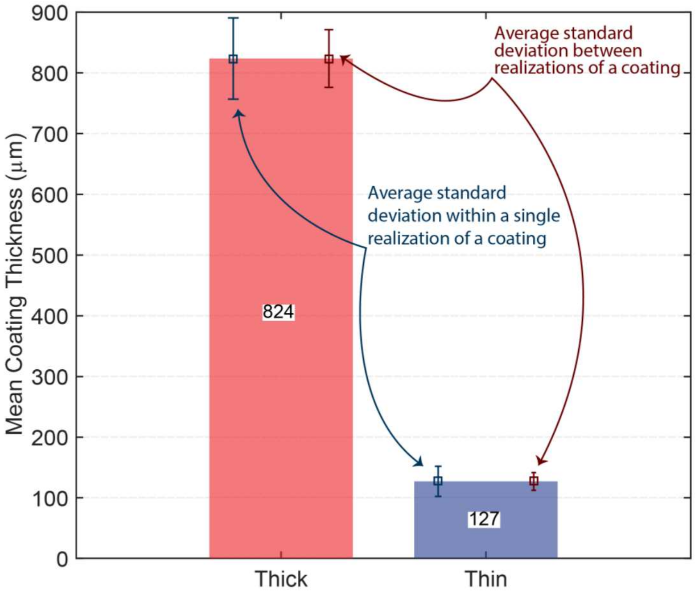
Elemental Mapping



Materials Characterization

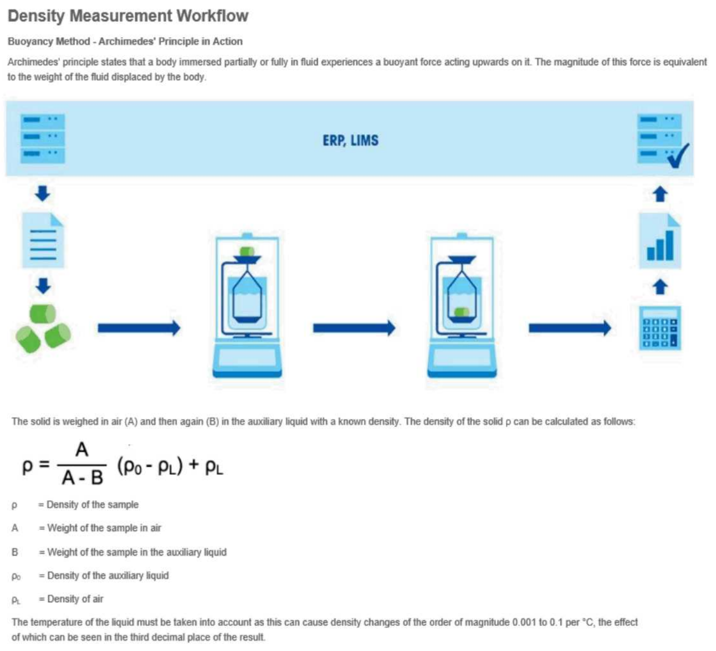
Thickness

Thickness is measured non-destructively with an Elcometer 456 digital coating thickness gauge



- Conclusion: Demonstrated repeatable control of coating thickness sufficient to provide directional information in engine experiments

Density



Density Measurement Workflow

Buoyancy Method - Archimedes' Principle in Action

Archimedes' principle states that a body immersed partially or fully in fluid experiences a buoyant force acting upwards on it. The magnitude of this force is equivalent to the weight of the fluid displaced by the body.

ERP, LIMS

The solid is weighed in air (A) and then again (B) in the auxiliary liquid with a known density. The density of the solid ρ can be calculated as follows:

$$\rho = \frac{A}{A - B} (\rho_0 - \rho_L) + \rho_L$$

ρ = Density of the sample

A = Weight of the sample in air

B = Weight of the sample in the auxiliary liquid

ρ_0 = Density of the auxiliary liquid

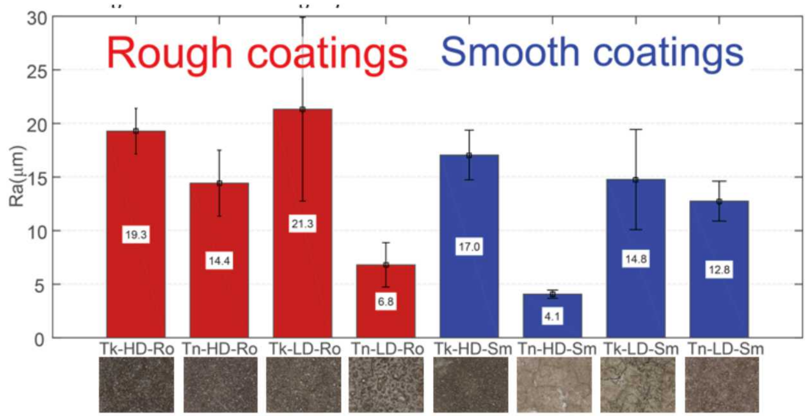
ρ_L = Density of air

The temperature of the liquid must be taken into account as this can cause density changes of the order of magnitude 0.001 to 0.1 per °C, the effect of which can be seen in the third decimal place of the result.

Stand-alone samples	Density (g/cm³)
Only Resin	1.44
High Density ("HD")	0.78
Low Density ("LD")	0.19

Significant difference between high and low density material

Roughness



Current coating processes produce inconsistent coating roughness values

Roughness values are often several times rougher than Toyota's coating[1]

Conclusion: the coating or the process has to be changed to achieve control of the surface roughness

- Microsphere size distribution has been identified as a key issue; the second iteration of coatings has e a more tightly controlled size distribution

Thermal conductivity measurement: equipment and methodology

- The thermal conductivity measurements were carried out using a thermal property system (model: TPS 3500)
- Hot Disk Sensor- A Hot Disk Sensor consists of an electrically conducting pattern on a thin sheet of Nickel. The sensor is fitted between two pieces of the sample, each one with a plane surface facing the sensor. The sensor applies an electrical current, high enough to increase the temperature of the samples up to several degrees. At the same time, the sensor records the resistance (temperature) increase as a function of time. The heat generated dissipates through the sample on either side at a rate dependent on the thermal transport characteristics of the material. By recording the temperature versus time response in the sensor, thermal conductivity can accurately be calculated.
- Thin Film Measurements-
  - **Measuring the background material-** Prior to measuring a film sample or coating, you must first determine the apparent thermal conductivity of the Kapton® insulation layer of the TPS Thin Film Sensor. Apparent thermal conductivity refers to the thermal conductivity of all sample material located between the Nickel foil of the Thin Film sensor and the background material used. This includes the Kapton® layer and any air present.
  - **Measuring the Unknown Thin Film Sample or Coating-** You will need to accurately measure or have been provided the thickness of the film sample or coating (± 0.5 μm).

Figure 1: Pictures of thermal property system and oven used in this work. (photos modified from Thermtest, Inc. website)

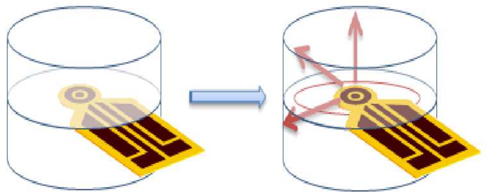


Figure 2: Scheme of how the Hot disk sensor is sandwiched in between two identical samples to perform the measurements.

$$\frac{\mathbf{P}}{\mathbf{2}} = \mathbf{A} \times \boldsymbol{\lambda} \times \frac{\mathbf{\Delta T}}{\mathbf{\Delta X}}$$

where **P** is the total output of power, **A** is the area of the conducting pattern, λ is the thermal conductivity of the film sample or coating, **ΔT** is the fully developed temperature difference across one of the insulating layers and **ΔX** is the thickness of the film sample or coating.

Specifications

TC: 0.005 - 10 W/(mK)
Temp: -40 to 300 °C
Repeatability: Typically better than 3%
Sample thickness: 0.01 - 2 mm

Thermal conductivity of the coatings has been successfully measured

Thermal conductivity has been successfully measured at temperatures up to 300C

- Observed peak surface temperatures for thermo-swing coatings are on the order of 280°
- Thermal conductivity is very low and approaches the detection limit for the thin coatings
- Toyota's SiRPA coating: ~0.6 W/mK [1]; partially stabilized zirconia: 0.4-1.2 W/mK [2]

Thick coatings: smooth conducts better than rough, possibly due to additional resin applied to smooth the surface

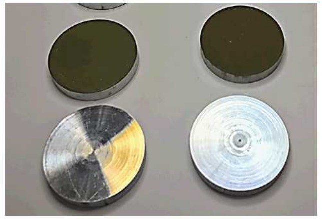
- Density determination in progress

Thin coatings: differences in thermal conductivity are small and may be within the range of sample-to-sample variability

Conclusion: measurements of thermal conductivity are possible for every type of coating, and values are relevant for application in a diesel engine

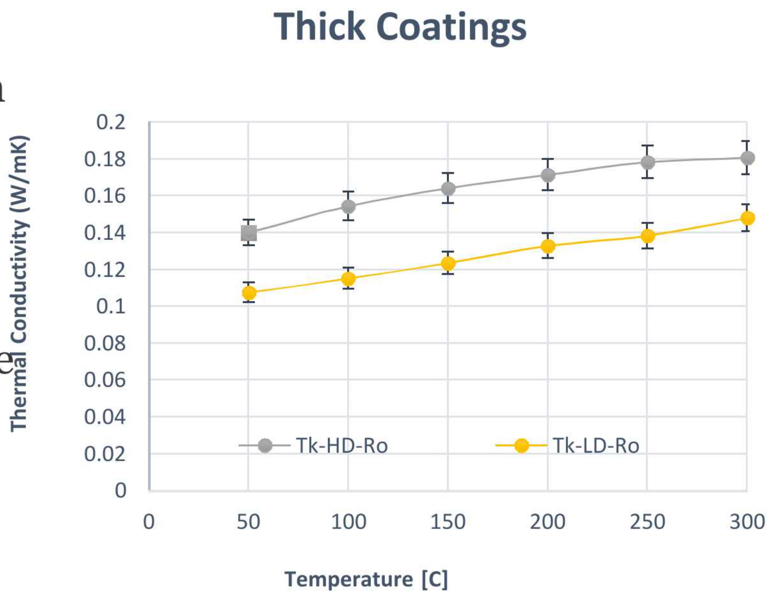
Al alloy 6061 substrate

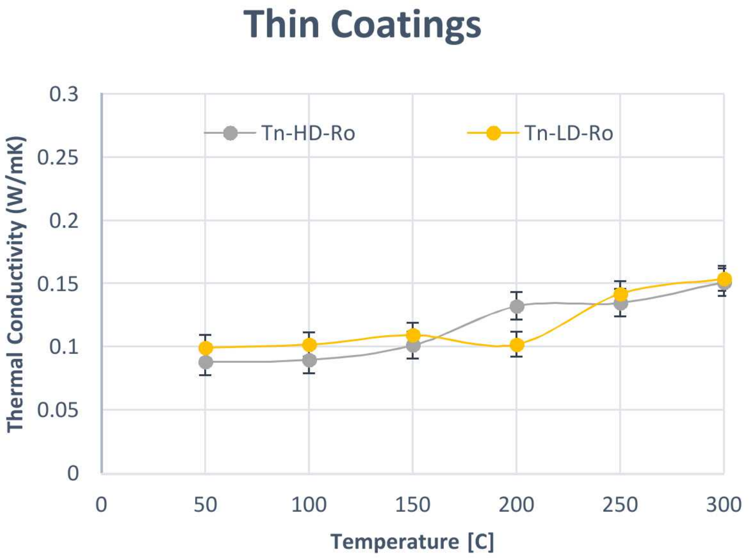
Th.Conductivity of the sensor	Th. Conductivity of the Substrate	Th. Diffusivity of the Substrate	Spec.Heat of the Susbtrate
0.02428 W/mK	186.6 W/mK	77.55 mm²/s	2.406 MJ/m³K



Thermal properties	
Melting temperature (T_m)	585 °C (1,085 °F)
Thermal conductivity (k)	151–202 W/(m·K)
Linear thermal expansion coefficient (α)	2.32 × 10⁻⁵ K⁻¹
Specific heat capacity (c)	897 J/(kg·K)

The apparent thermal conductivity was ~ 0.0244 W/m/K, which includes the thermal conductivity of all sample material located between the Nickel foil (inside the sensor) and the Al-6061 (such as Kapton® layer and any air present).





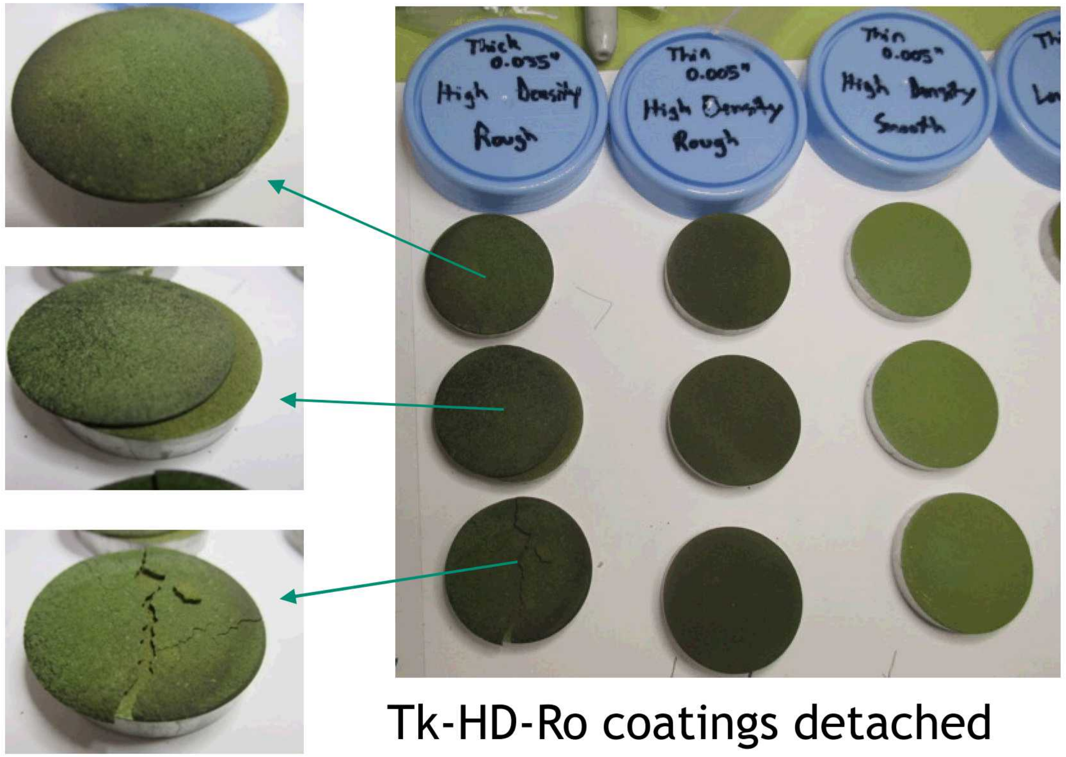
3% error bars represent the maximum possible instrument error

[1]Kawaguchi, A., Iguma, H., Yamashita, H., Takada, N., Nishikawa, N., Yamashita, C., Wakisaka, Y. and Fukui, K., "Thermo-Swing Wall Insulation Technology; - A Novel Heat Loss Reduction Approach on Engine Combustion Chamber." SAE Technical Paper 2016-01-2333, 2016, DOI: https://doi.org/10.4271/2016-01-2333.

[2]Tritt, T.M., ed. *Thermal Conductivity: Theory, Properties, and Applications*, Kluwer Academic/Plenum Publishers, New York: 2010

Thermal cycling damage to one coating type

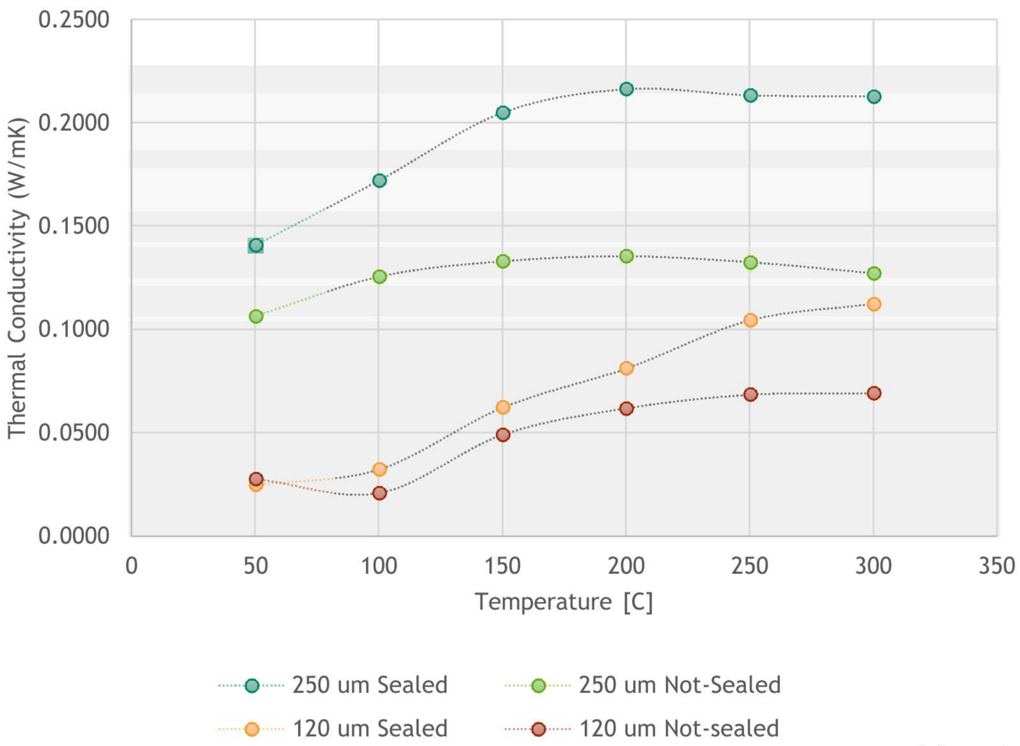
- All coating types survived thermal cycling with the thermal conductivity measurements except one:
  - Thick, high-density, rough
- Spalling occurred over the entirety of each coupon
- The cause is believed to be excessive thickness
- Based on discussions with the supplier, the next iteration of coatings will be thinner and more durable

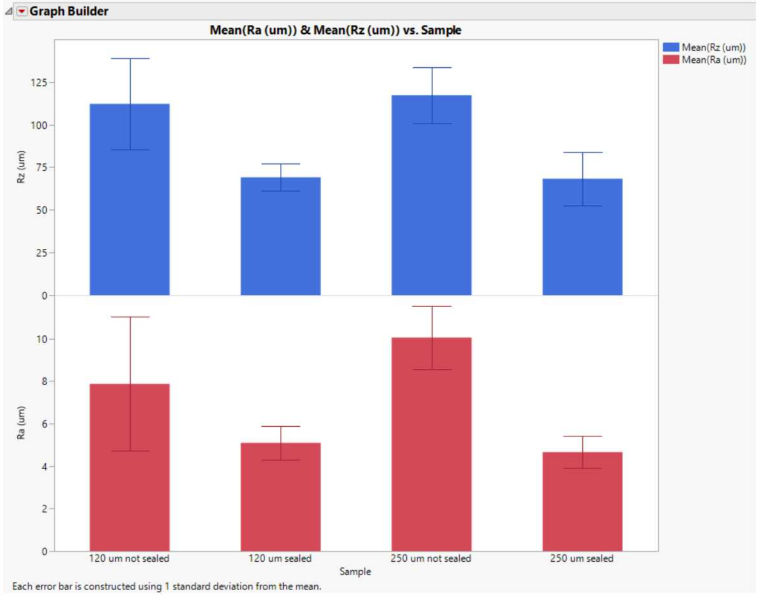


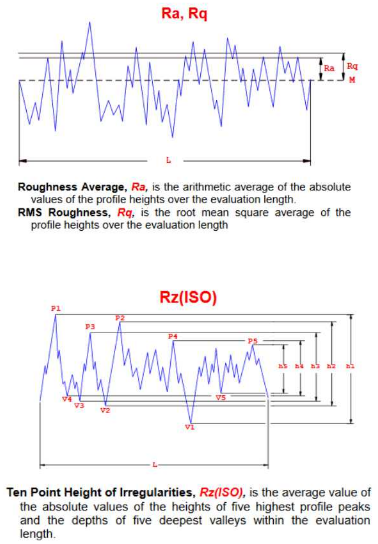
Tk-HD-Ro coatings detached after being exposed to 300 °C

Second generation of coatings

- Reduce thickness to avoid thermal stress
- Smaller diameter of glass microballoons
- Add sealing layer for smoother films







Next: density measurements

Path forward

Next steps (FY19)

- Finish the characterization of the second iteration of coating formulations
- Install engine, perform shakedown testing, develop operating points
- Develop efficiency modeling framework

FY20 plans

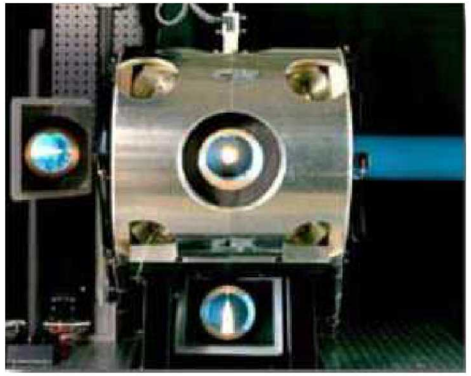
- Obtain coated pistons
- In-situ, in-use engine experiments: energy balance analyses and piston surface temperature measurements
- Optical experiments in spray chamber: infrared translucence, spray-wall interactions, and quenching distance

Augmentation of the medium-duty diesel combustion research lab for in-situ, in-use measurements with coated pistons

- Online fuel flow measurement
- Custom-made MEMS-based piston surface temperature RTDs (Org 8634)
- Wireless telemetry system to transmit surface temperature data (Org 8362, discussions with RF working group)

Energy balance analyses based on experimental measurements

- Evaluation at several engine loads with each coated piston and an uncoated piston
- Influence of coating thickness, density, and roughness on energy balance



Optical measurements

- Spray-wall interactions: high-resolution imaging and surface temperature measurements in the constant volume combustion chamber: effects of coating thickness and roughness on jet spreading, surface temperature, and quenching distance
- Time-resolved thermographic imaging in the optical medium-duty diesel engine: evaluation of surface temperature evolution and IR translucence

Materials Capability Development for Prediction and Optimization of Engineered Anisotropic Thermal Barriers

Dr. Karla Reyes

Austin Acosta (intern)

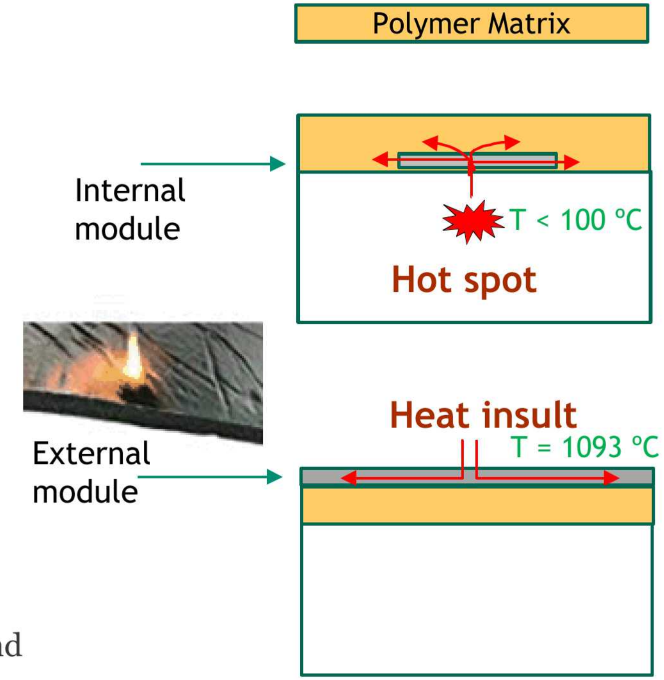
Engineered Anisotropic Thermal Insulation

Problem: Thermal insulation materials (such as foams) deal with problems arising from heat dissipation, thermal stresses, and warping due to high temperatures.

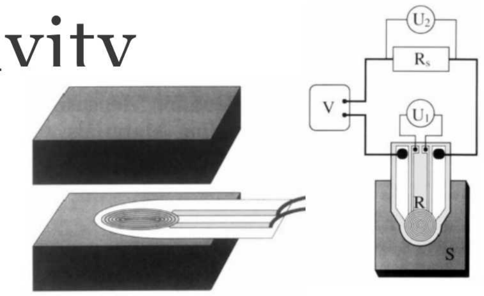
Hypothesis: Anisotropic thermal barriers can be engineered to optimize the heat transfer in-plane and through-plane directions.

Gap: Capabilities (experimental & modeling) are needed to determine the overall and individual thermal properties of the advanced barriers.

- ✓ *Scenario # 1*- Addition of internal layers to avoid overheating of internal components, such as batteries or electronics.
  - ✓ Needs: fast heat dissipation from electronics to heat sinks.
  - ✓ Materials: polymer matrices (such as foams and elastomers) and additives (such as ceramic fillers) to increase thermal conductivity pathways, while keeping good electrical insulation and low outgassing.
- ✓ *Scenario # 2*- Addition of external layers to protect thermal insulation from high temperature insults (such as fires).
  - ✓ Needs: high in-plane thermal conductivity for heat dissipation and low through-plane thermal conductivity for thermal insulation.
  - ✓ Materials: high thermal conductivity films such as graphite or metals used as outer shells. Other desired properties are fire retardant, high emissivity, high electrical conductivity (faraday cage) and corrosion resistant.



Current Methods to Measure Thermal Conductivity

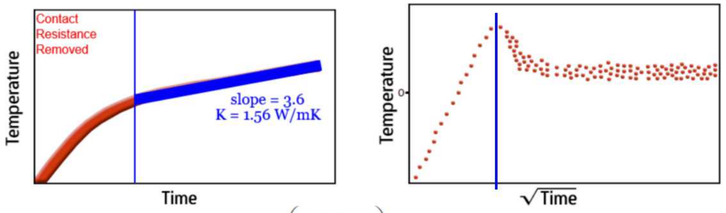


There are only three absolute methods of measuring thermal conductivity.

(1) Guarded Hot Plate – This method is only good for measuring low thermal conductivity materials.

(2) Laser Flash Apparatus – it is a well-known method for testing medium to high thermal diffusivity, but then the density and specific heat are used to calculate the thermal conductivity. However, the density and specific heat of composite or layered materials can be very challenging to measure, which makes this technique unreliable for anisotropic materials.

(3) Hot Disk Transient Plane Source (TPS) – This is a versatile method for testing low to high thermal conductivity materials, where the thermal conductivity is directly (or independently) measured.



$$\Delta T_{ave}(\tau)+\Delta T_i = \frac{1}{\alpha}\cdot\left(\frac{R(t)}{R_0}-1\right)$$

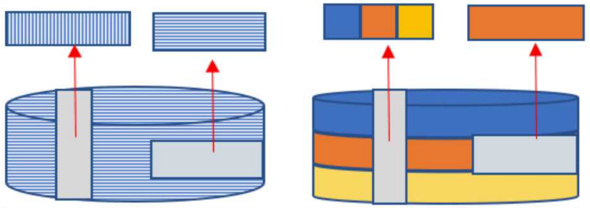
$$\Delta T(\mathrm{t}) = \frac{P}{\pi^{3/2}\cdot r\cdot k}D(t)$$

$$\tau = \sqrt{\frac{t}{\theta}}\ and\ \theta = \frac{r^2}{\alpha_r}$$

Where
P = power
r = sensor radius
k = thermal conductivity
α = thermal diffusivity
ρc_p = volumetric specific heat

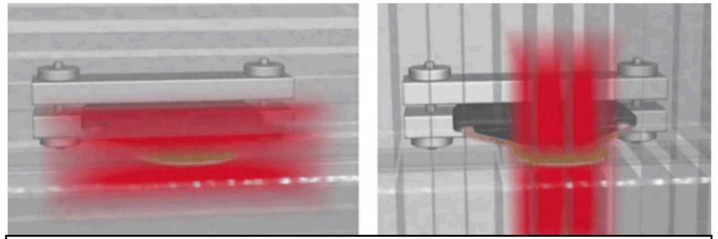
Anisotropic measurements

"Homogenous" vs. "Non-homogenous"
Anisotropic materials Layered systems



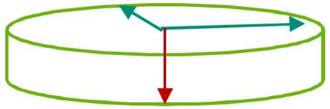
Traditional methodology cannot be used to measure layered materials.

r = Radial   a = Axial



TPS technique for anisotropic measurements.

Assuming that thermal properties in x and y directions are the same and different in z direction.



$k = (k_r.k_a)^{1/2}$

$$\rho c_p = \frac{k_r}{\alpha_r} = \frac{k_a}{\alpha_a}$$

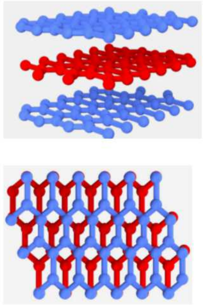
Volumetric specific heat is needed

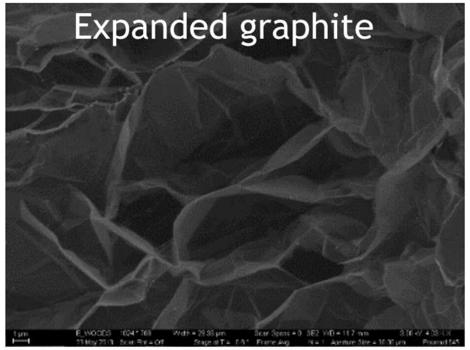
TPS- Anisotropic Module (previous work)

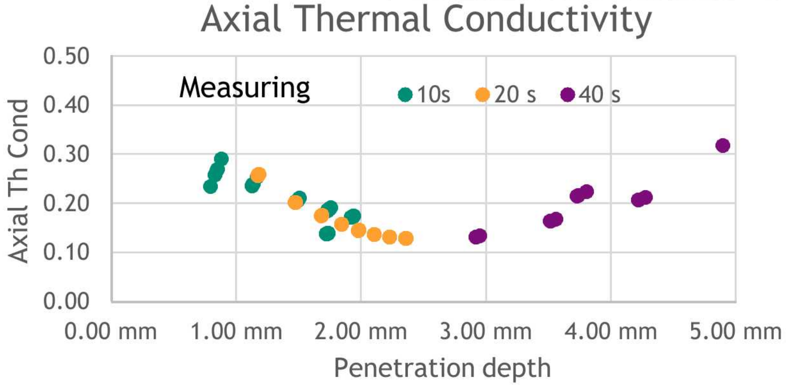
	Thermal Cond. (W/mK) at different penetration depths		
Materials	Isotropic	Radial	Axial
Graphite	9.08 ± 0.05 (0.5% error bars)	25.20 ± 1.1 (4% error bars)	6.5 ± 0.25 (4% error bars)

Non-homogenous

composite (layered) materials	**1.15 ± 0.10 (9% error bars)**	**5 - 12 (>50% error bars)**	**0.1- 0.3 (>50% error bars)**



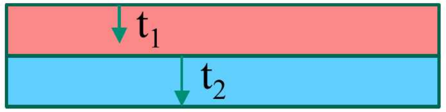




Problem: Non-homogeneous materials

- Radial: top and bottom has different thermal conductivities
- Axial: different measuring times → different "penetration depths" → different thermal conductivities
- Penetration depth ≠ thickness

Penetration depth will depend on measuring time (t) and thermal properties of each layer.



$t_1 \neq t_2$

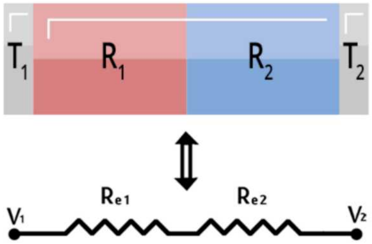
$$D = b\sqrt{at}$$

Where
D = penetration depth
b = temperature sensitivity constant
a = thermal diffusivity (mm2/s)
t = measuring time (s)

Material 1 (th diffusivity)	Thickness	Time for 100% penetration	Material 2 (th diffusivity)	Thickness	Time for 100% penetration
Al alloy ($69.6\ mm^2/s$)	10 mm	**0.35 s**	Polyurethane ($0.49\ mm^2/s$)	10 mm	**51 s**

Methodology to measure anisotropic thermal conductivity of layered systems

Principle:
Resistance in Series



Thermal Resistance:

$$R = x/(A * k)$$

Where:

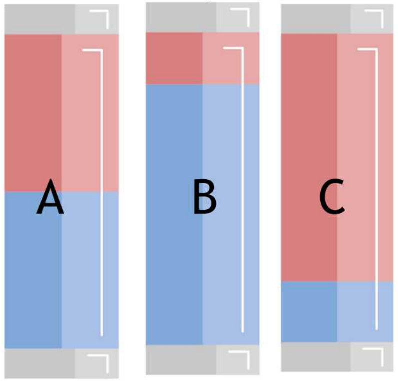
R = thermal resistance

x = penetration depth or width of material

A = area

k = thermal conductivity

High radial thermal conductivity



Low radial thermal conductivity

	Material 1 (thermal cond)	Thickness (% of total thickness)	Measuring time	Material 2 (thermal cond)	Thickness (% of total thickness)	Measuring time	Axial Thermal Resistance (conductivity)
A	Al alloy (163 W/mK)	5 mm (50%)	0.1 s	Polyurethane (0.032 W/mK)	5 mm (50%)	15 s	0.156 m2K/W (0.064 W/mK)
B	Al alloy (163 W/mK)	2 mm (20%)	<0.05 s *	Polyurethane (0.032 W/mK)	8 mm (80%)	30 s	0.250 m2K/W (0.04 W/mK)
C	Al alloy (163 W/mK)	8 mm (80%)	0.25 s	Polyurethane (0.032 W/mK)	2 mm (20%)	2 s	0.0625 m2K/W (0.16 W/mK)

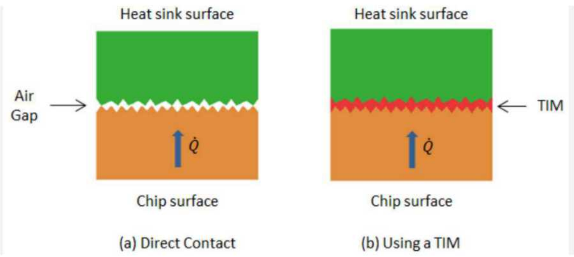
*Measuring time < 0.1 s cannot been performed with TPS 3550

This does not account for contact resistance between the different layers.

If contact resistance is a significant issue…

Plan B- we will use thermal interface materials (TIM). TIMs facilitate the movement of heat between the heat producing components and heat sinks by reducing the thermal resistance between them.

Plan C- we will use vapor deposition to create conductive thin layer (such as Al) on pyrex glass (which is a thermal conductivity reference material (1.14 W/mK)

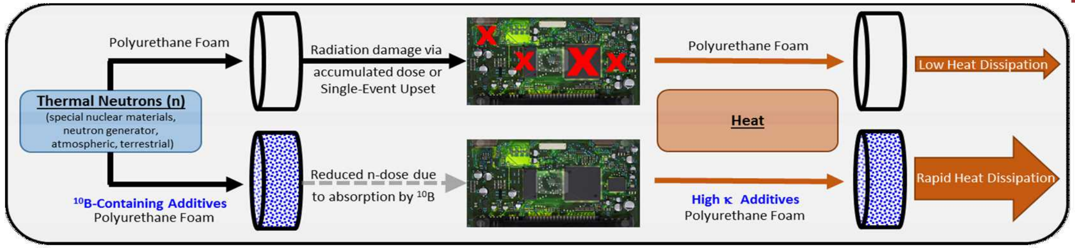


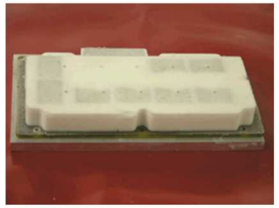
RESISTANCE IN SERIES
http://thermtest.com/ris
https://neutrium.net/heat_transfer/thermal-resistance/

Anisotropic Materials Fabrication
Inspiration from previous and current work

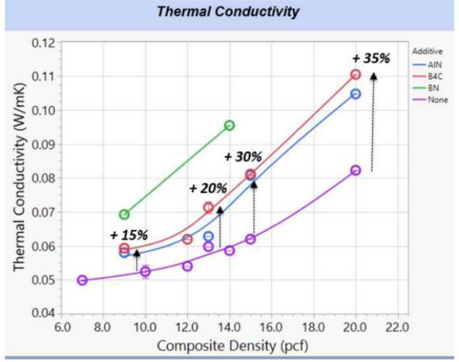
Enhanced Capability Composite Polyurethane Foam Materials
Matt Walker[1], A. Abelow[1], P. Feng[2], A. Nissen[1], K. Reyes[1], E. Withey[1]

Materials Chemistry [1]; Radiation/Nuclear Detection Materials & Analysis [2]
Sandia National Laboratories (Livermore, California)





Radiation + shielding



Inspiration: ^{10}B-additives can be used for radiation shielding and heat dissipation of electronics.

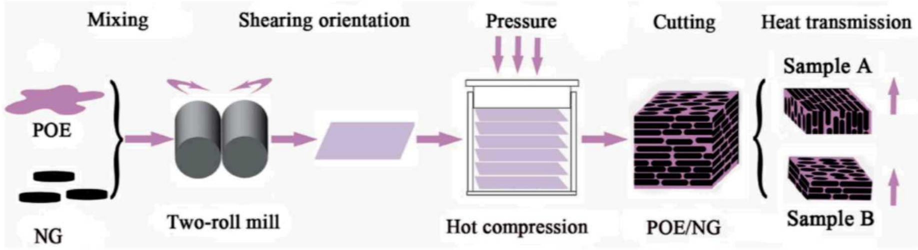
EMR gasket → Ag-coated Al filled fluorisilicone elastometer
[PI: Greg O'Bryan, Adriana Pavia-Sanders; Nick Myllenbeck; Tiffany Longfield; Karen Krafcik; Karla Reyes]

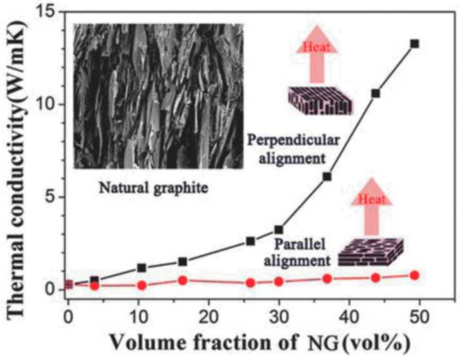
Development of a formulation capable of meeting requested specifications

* Durometer Hardness 70 ± 7 Shore A
* Tensile strength 180 psi (124 N/cm2, min)
* Elongation 60/260% (min/max)
* Compression Set 30% (max)
* Volume resistivity 0.012 Ω•cm (max)

Inspiration: Electromagnetic shielding leverage barriers made of conductive materials to protect against electromagnetic radiations (EMR). Metal additives normally increase both electrical and thermal conductivities.

A Facile Route to Fabricate Highly Anisotropic Thermally Conductive Elastomeric POE/NG Composites for Thermal Management
Advanced Materials Interfaces (IF 4.834) **Pub Date : 2017-11-23** , *DOI: 10.1002/admi.201700946*
Chang-Ping Feng, Lu Bai, Yan Shao, Rui-Ying Bao, Zheng-Ying Liu, Ming-Bo Yang, Jun Chen, Hai-Ying Ni, Wei Yang





Inspiration: Graphite was used to fabricate anisotropic thermally conductive elastomers. The high electrical conductivity of graphite also can serve as Faraday cage.

Anisotropic Materials Fabrication - *Engineered Anisotropic Barriers*

Polymer	Abbreviation	Properties
Low-density polyethylene	LDPE	Chemically inert, flexible, insulator
High-density polyethylene	HDPE	Inert, thermally stable, tough and high tensile strength
Polypropylene	PP	Resistant to acids and alkalies, High tensile strength
Polystyrene (thermocole)	PS	Thermal insulator. Properties depends on the form, expanded form is tough and rigid
Polytetrafluoroethylene	PTFE	Very low coefficient of friction, excellent dielectric properties, chemically inert
Polyvinyl chloride	PVC	Insulator, flame retardant, chemically inert
Polychlorotrifluoroethylene	PCTFE	Stable to heat and thermal attacks, high tensile strength and non wetting

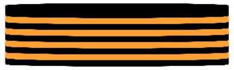
Light weight
Mechanical protection
Corrosion resistance
Mold ability and Economical

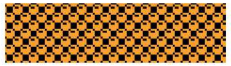
Low thermal conductivity
Low electrical conductivity
Poor temperature resistance

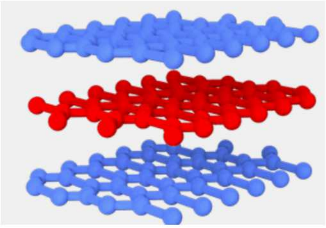
Polymer Matrix

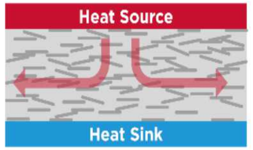
anisotropy

Layered system | Additives

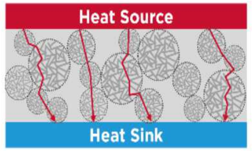

Layered


Mixed

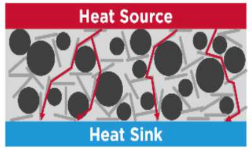




Platelets alone tend to align in the polymer flow direction, creating thermal pathways that are more effective for heat spreading.

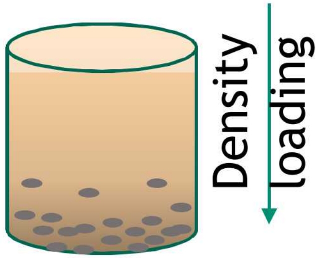


Using hBN agglomerates helps to randomly orient the platelets, creating more isotropic thermal conductivity.

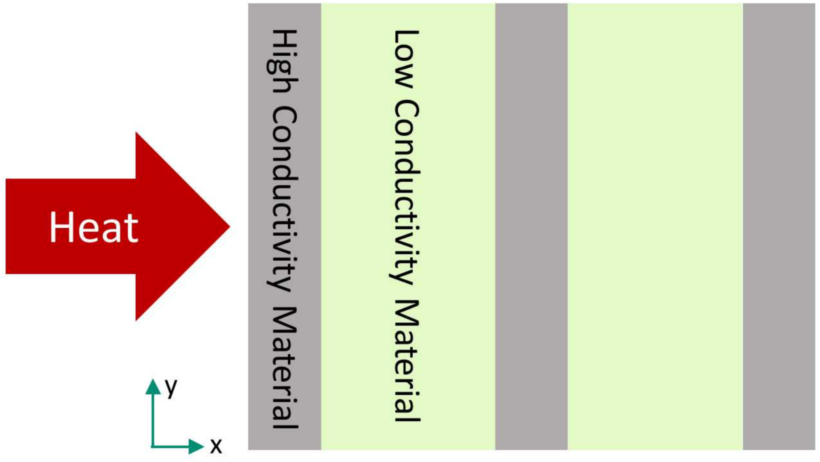


Combining BN platelets with non-acicular particles will disrupt alignment, improving through-plane thermal conductivity.

Materials	Properties	Shielding
Ceramic (such as BN)	High thermal conductivity Low electrical resistivity	***Thermal*** Electrical Insulator Radiation
Graphite	High thermal conductivity High electrical resistivity	***Thermal*** Electromagnetic
Metals (Al, Cu, Ag…)	High thermal conductivity High electrical resistivity magnetics	***Thermal*** Electromagnetic



Prediction tool to guide material design



A ‘quick tool’ was developed to give an estimate of what the relative thicknesses should be for each layer, assuming 1D heat transfer.

While the first iteration of this tool may be simple, we will work to refine it by adding in more physics (such as interface conditions) to improve the prediction.

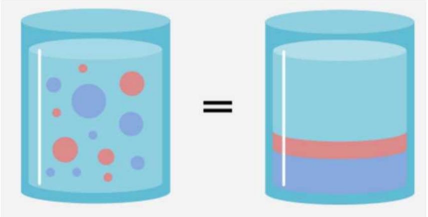
Besides thermal properties, compatibility, corrosion, mechanical properties, fabrication, sensitivity, among others will be considered to “down-select” the prospective materials.

	A	B	C	D
1		x direction	y direction	
2	Desired Conductivity (W/mK)	0.95	200	
3				
4		Conductivity (W/mK)	Thickness (m)	
5	Material 1	0.5	0.01	
6	Material 2	500	0.03	
7				
8				

Choose any two to get the third

	A	B	C	D
1		x direction	y direction	
2	Desired Conductivity (W/mK)	0.95	200	
3				
4		Conductivity (W/mK)	Thickness (m)	
5	Material 1	0.5	0.01	
6	Material 2	500	0.03	
7				
8				

Rule of mixtures will be used for the composite materials and to calculate other properties such as heat capacity



The mass of each individual component is equivalent to the total mass of the mixture, which can theoretically be broken down into separate parts.

$$C_{p\,mixture} = \left(\frac{m_1}{m_{mixture}}\right)C_{p1} + \left(\frac{m_2}{m_{mixture}}\right)C_{p2}$$

Where:

C_p = Heat Capacity

m = Mass

$m_{mixture}$ is $m_1 + m_2$

Preliminary Results

Polyurethane foams

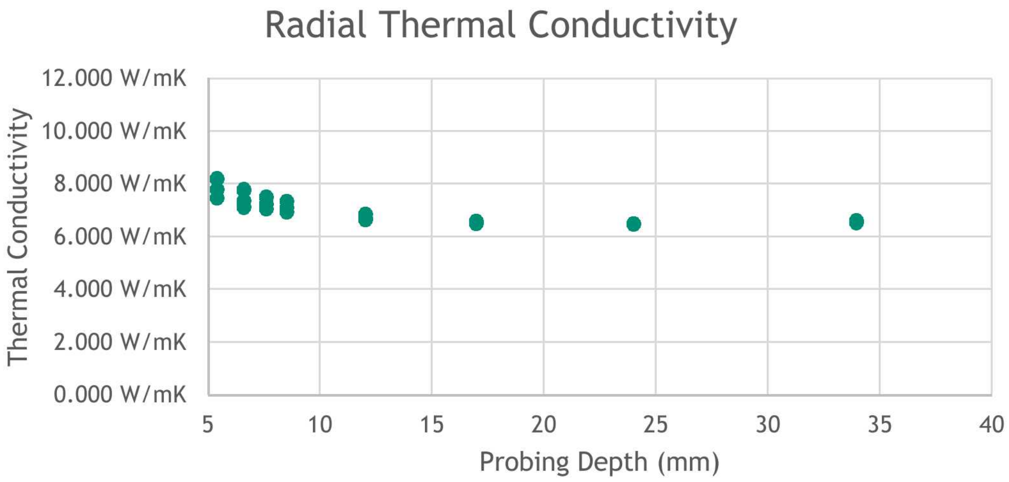
Sample Name	Density (kg/m^3)	Therm Cond. (W/mK)
Last-A-Foam-EF4003	48	0.04019
Last-A-Foam-5020-07	112	0.04452
Last-A-Foam-6070-8.5	136	0.04589

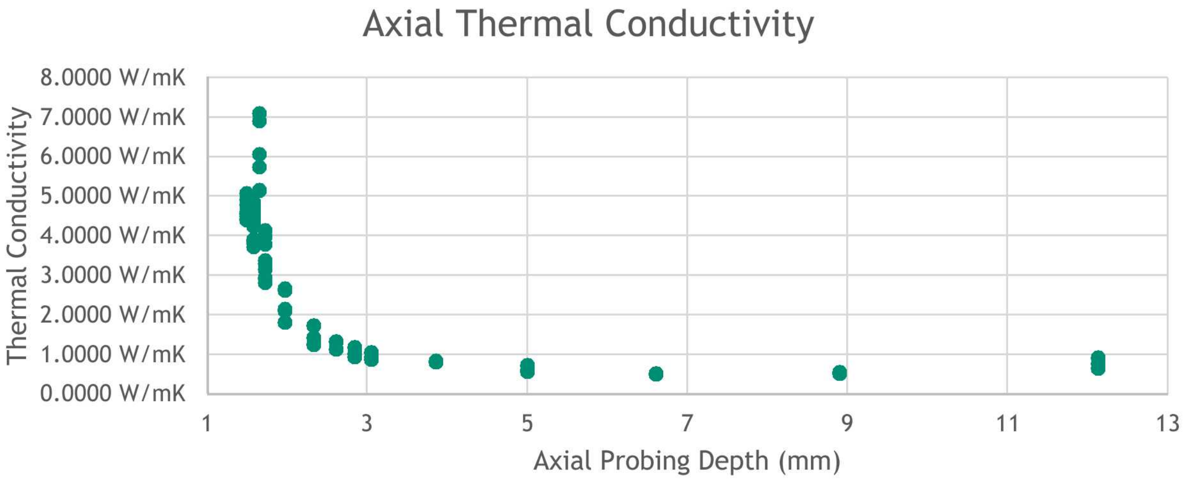
Tflex – 1.00 mm

Polyurethane foams – 23.63 mm

Tflex

- Tflex™ 700 is a soft gap filler thermal interface material with great thermal performance and high compliancy.
- Unique silicone and ceramic filler technology
- Tflex™ 700 is electrically insulating, it is stable from -45°C thru 200°C and meets UL 94V0 flame rating.
- Naturally tacky, it requires no additional adhesive coating to inhibit thermal performance.
- Thermal conductivity of Tflex is 7.1 mW/K

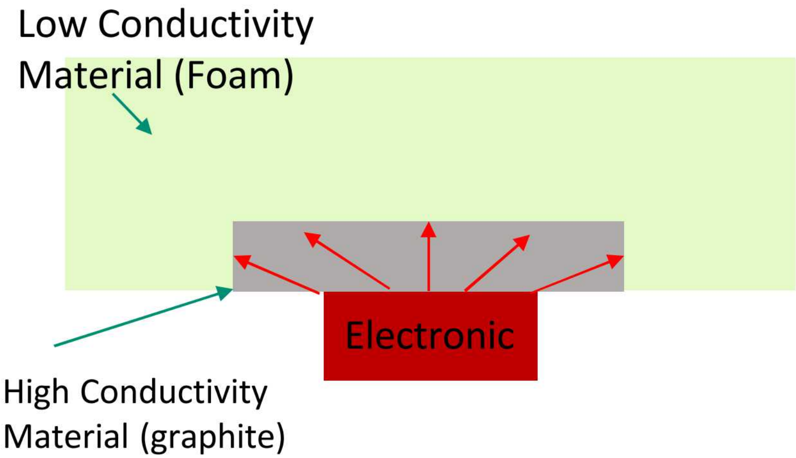




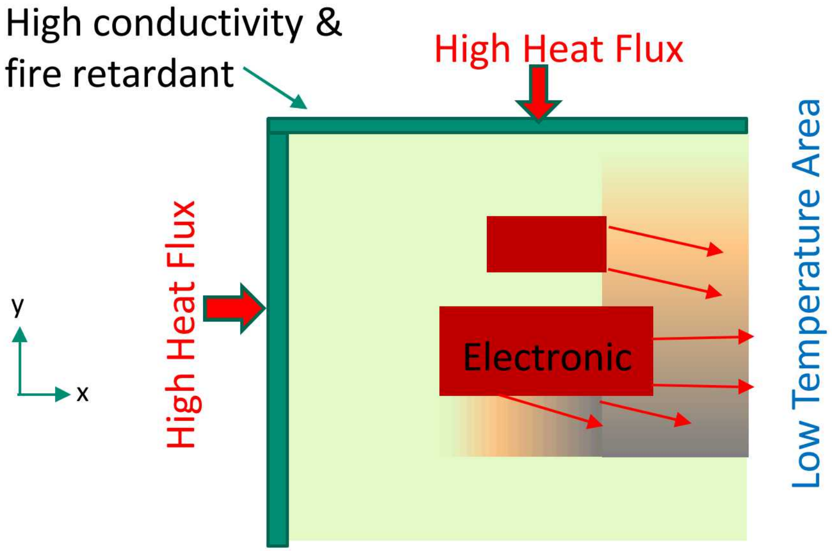
Probing depth was determined using the thermal diffusivity and specific heat using the rule of mixture.

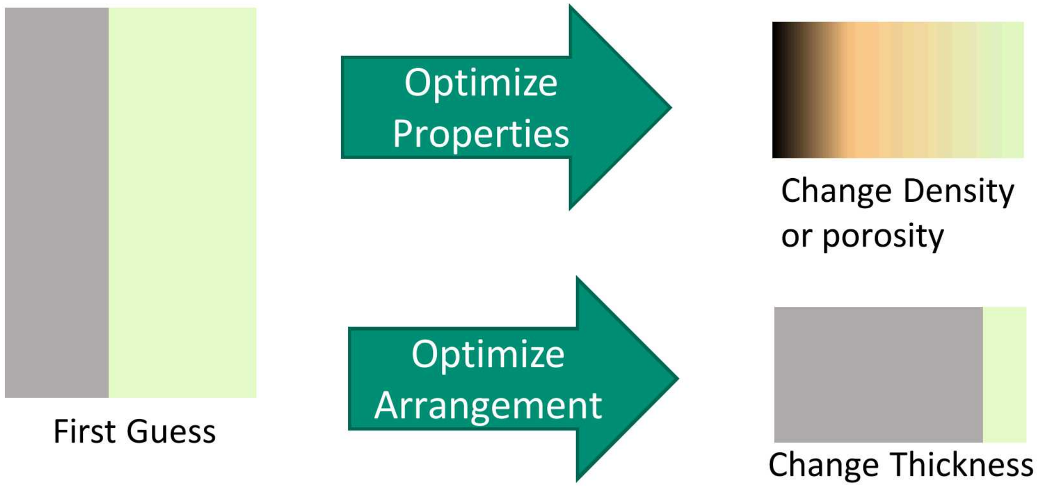
Next steps: Define thermal management needs using modeling

2 materials system



3 materials system





Use current capabilities in Sierra Thermal/Fluids Aria to understand complicated heat transfer and material configurations.

Couple Aria with Dakota to optimize the arrangement of layers and properties.

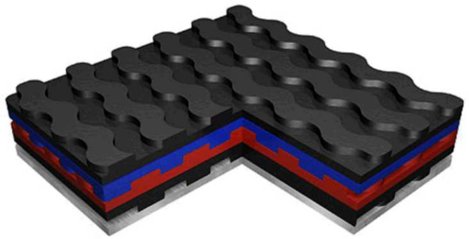
Expected outcomes: desired thermal conductivity in x and y directions.

Next steps: Optimization of thermal barriers

Based on the prediction tool outputs, thermal barrier system will be fabricated to satisfy the thermal management needs for different scenarios.

- To create strong interfaces, we are going to experimentally study surface roughness and morphologies to create interlocking connections between the graphite and foams during the molding process.

- If significant, the thermal contact resistance will be determined, and the experimental values can be inputted into the models to have more accurate predictions.



$$R_{\lambda_m} = R_{\lambda_b} + R_c \longrightarrow \frac{d}{\lambda_m} = \frac{d_b}{\lambda_b} + R_c$$

Where d = distance = thickness
m = measured
b = bulk
c = contact

- The best candidate thermal barrier materials fabricated will be evaluated for chemical compatibility (corrosivity) with external environments and with other materials present, their influence on bulk mechanical properties, electrical resistivity, and behavior in electromagnetic and radiation environments.

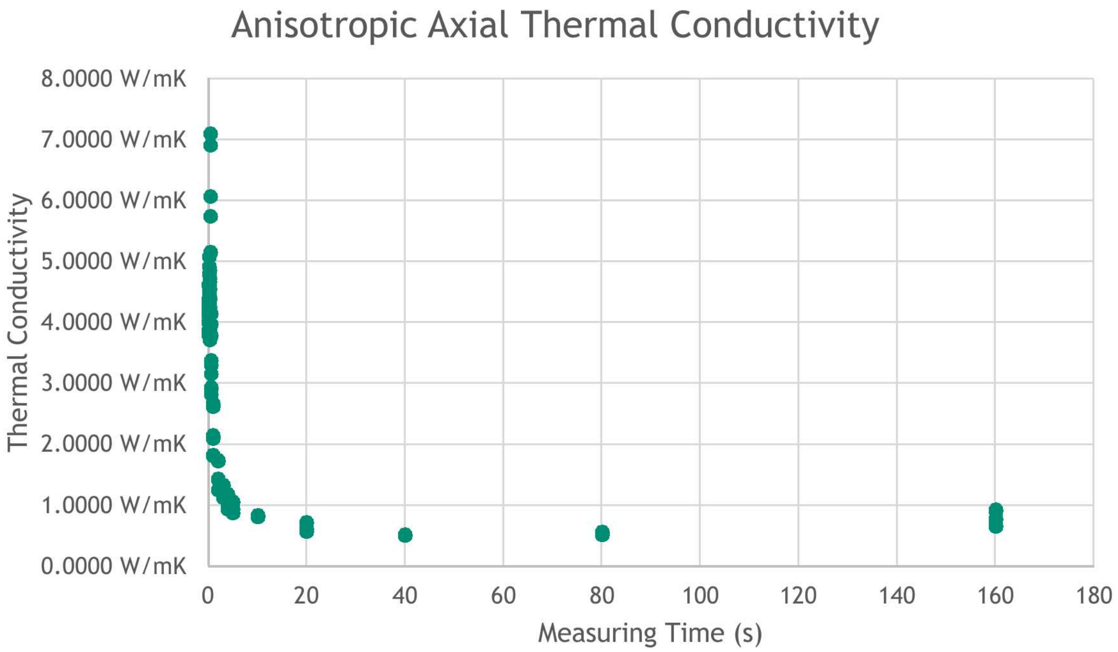
Conclusions

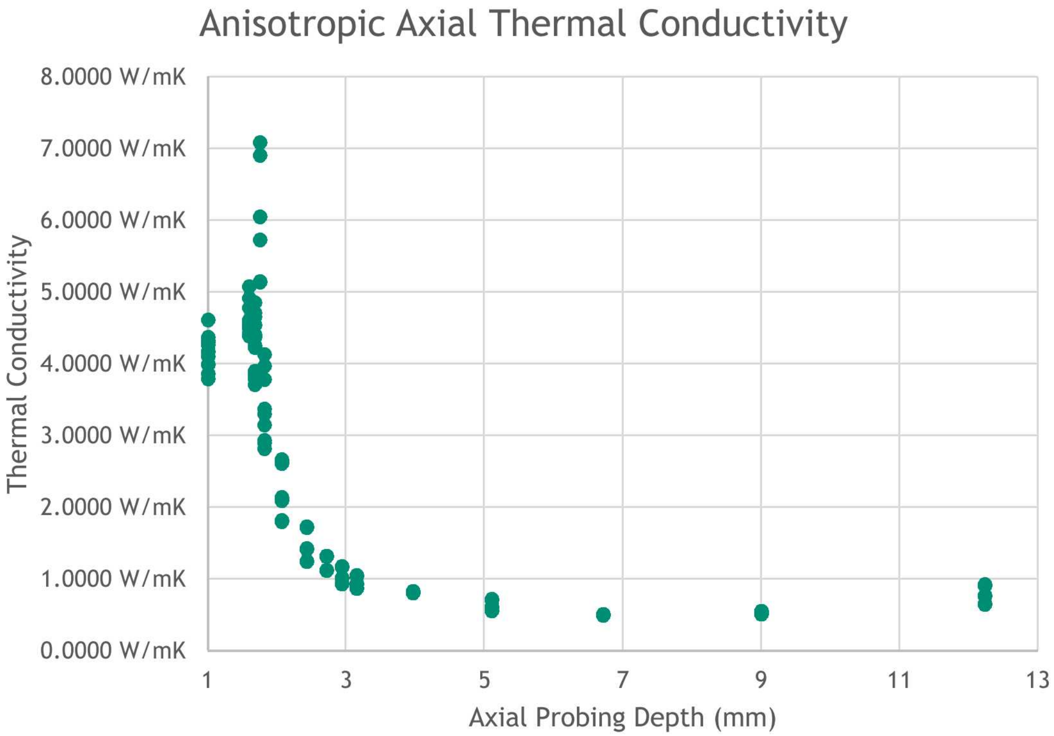
- Better understanding of how the materials properties affect the thermal transport properties is need in order to develop thermal barrier materials
- Advanced experimental methodologies are needed for measurements of realistic samples in order to capture the effects of features (interfaces, surface roughness and density) missed during bulk measurements.

Acknowledgment

- Dr. Stephen Busch
- Austin Acosta
- Sandia Microscopy Lab
- Sandia Materials Chemistry Department

Measuring time → probing depth





The axial or through plane thermal conductivity of the layered TFlex and polyethylene material was measured using the Anisotropic Module on the Hot Disk Thermal Constants Analyser. In the anisotropic module the axial and radial thermal properties are distinguished and calculated individually based on the materials specific heat. A bulk material specific heat was calculated by using the rule of mixtures specific heat equation below.

$$C_{p\ Mixture} = \left(\frac{v_1}{v_{mixture}}\right) C_{p\ 1} + \left(\frac{v_2}{v_{mixture}}\right) C_{p\ 2}$$

where v_1 is the volume of layer one

v_2 is the volume of layer two

$v_{mixture}$ is the volume of both layers

C_{p1} and C_{p2} are the specific heats of layers one and two respectively