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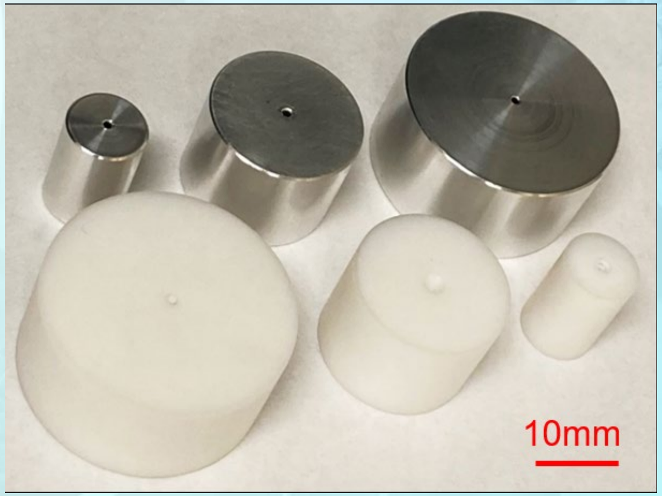
Advanced Sensors and Instrumentation

Line Heat Source Probe for In-Pile Thermal Conductivity Measurements



Advanced Sensors and Instrumentation (ASI)

April 13, 2023

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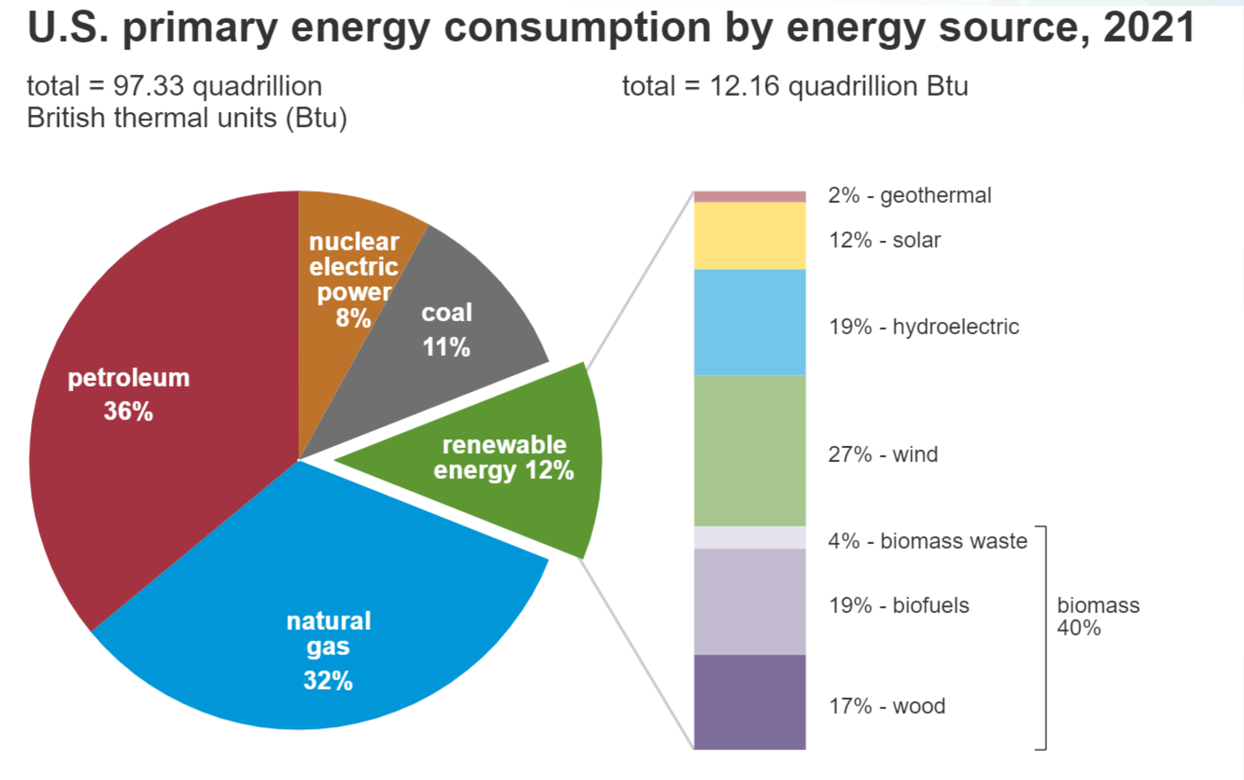
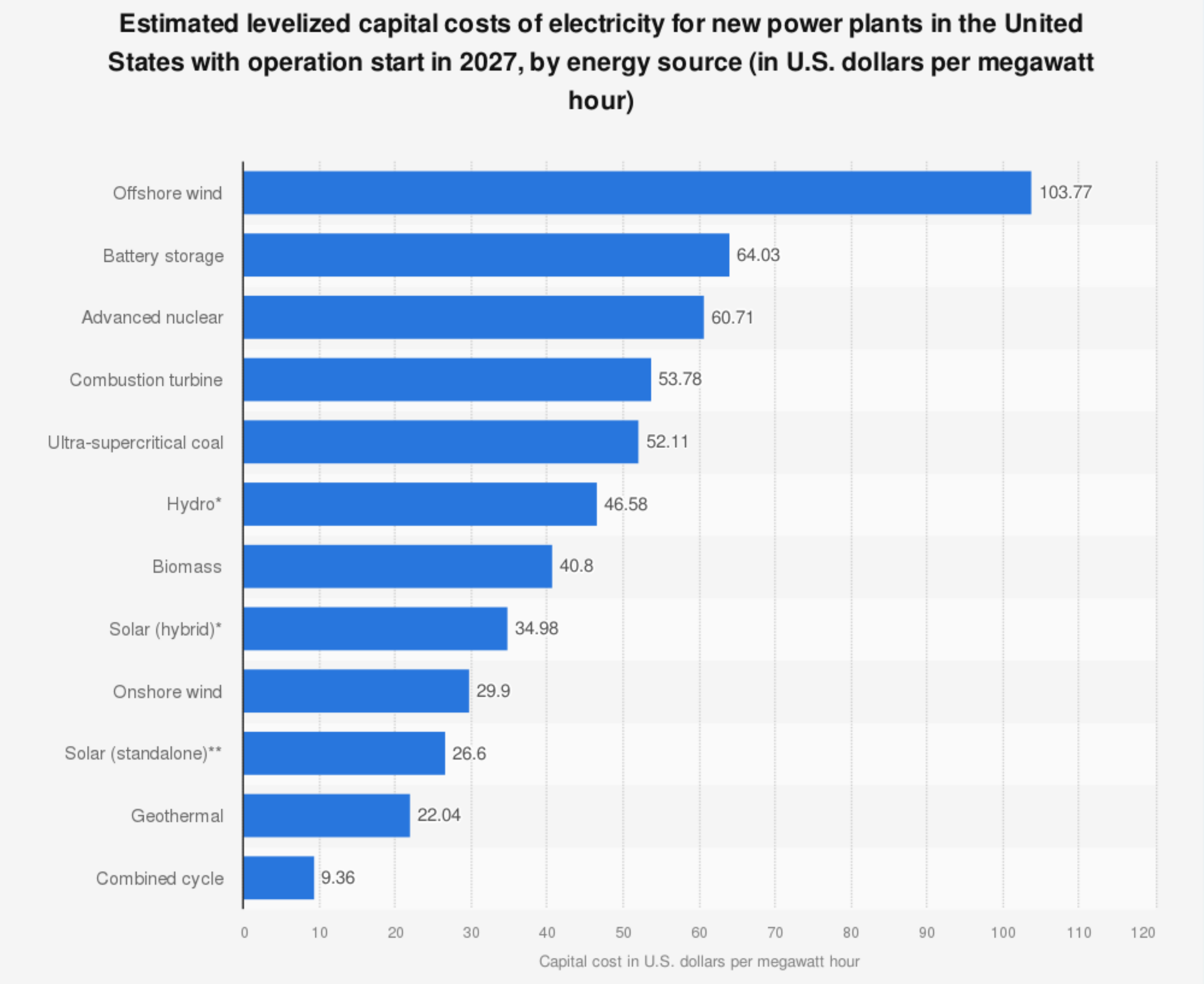
Boise State University /Idaho National Laboratory

Project Overview





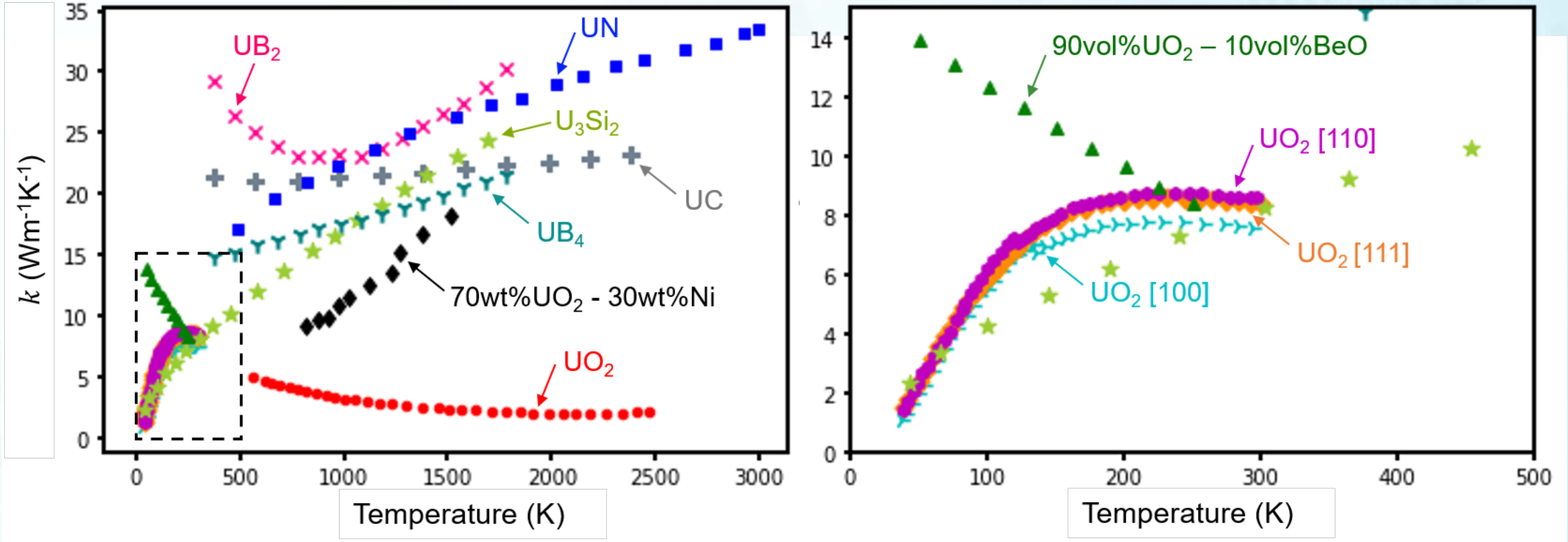
Nuclear benefits:

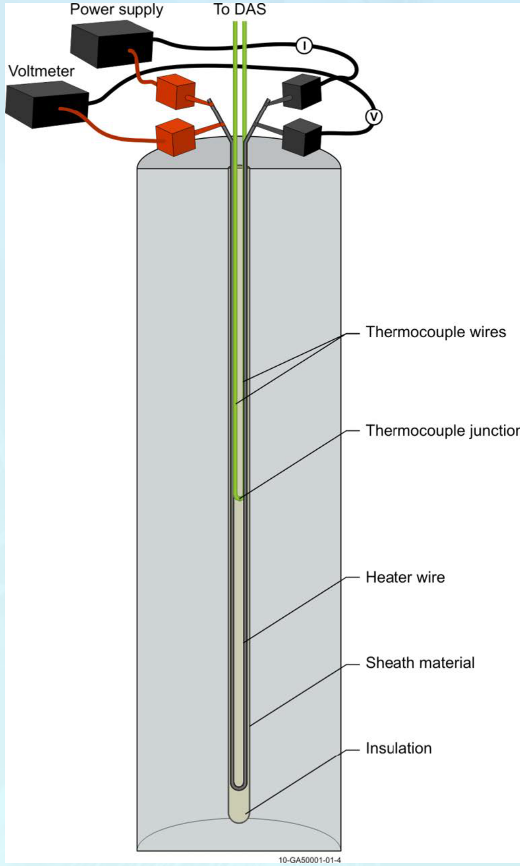
- Low operating costs, very strong concentrated form of energy, clean, and efficient

EIA, U.S. Energy Information Administration, Monthly Energy Review, Table 1.3 and 10.1, April 2022, preliminary data
EIA, U.S. 2021 Unweighted average levelized costs in 2021 U.S. dollars

Motivation

- Thermal conductivity degradation limits fuel performance and lifetime
- Sensors are needed for in-pile measurements of fuel performance





Katelyn Wada, Austin Fleming, Joshua Eixenberger, Brian J. Jaques, David Estrada, “Transient Multilayer Analytical Model of a Line Heat Source Probe for In-Pile Thermal Conductivity Measurements”, IJTS ***(Accepted with revisions)***

J. Daw, 6th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies, 2009

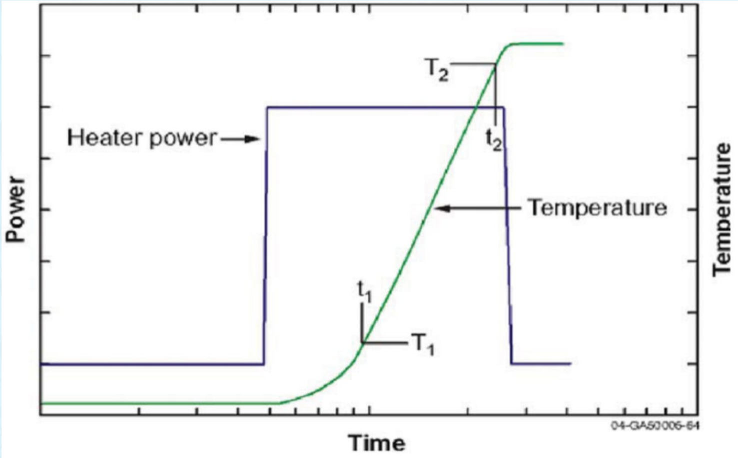
Background

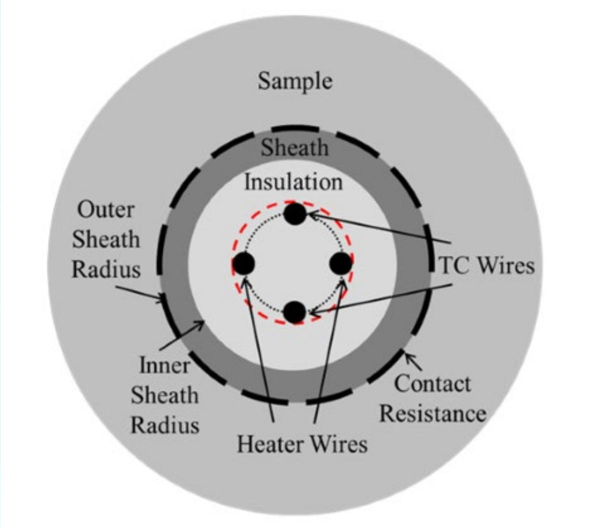
Standard out-of-pile thermal conductivity measurements
- Loss of information
- Cannot mimic reactor conditions

Traditional transient needle probe method
- Heater and thermocouple

$$k = \frac{Q_0}{4\pi LS}$$

•Previous work at INL: Solution without linear response
- Heater and thermocouple
- Larger package (40mm suggested sample diameter min.)
- Crosstalk issue





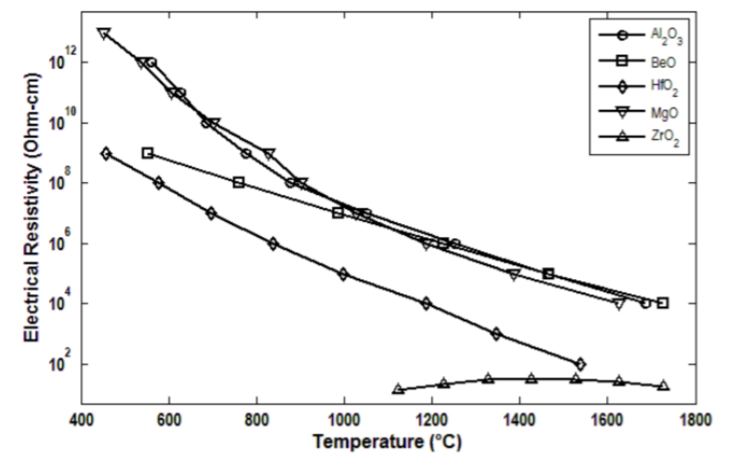
k = thermal conductivity, Q_0 = power dissipated by heater, L = heater length, S = slope of linear portion of transient response

C. Hollar, “A parametric study for in-pile use of the thermal conductivity needle probe using a transient, multilayered analytical model,” International Journal of Thermal Sciences, 2019,
J. E. Daw, “Hot wire needle probe for in-reactor thermal conductivity measurement,” IEEE Sensors Journal, 2012

Challenges

High temperature environment

- Probe must be adapted
- Heater/thermocouple method
- - High temperatures: electrical impedance decreases



How strongly ceramic insulators oppose the flow of electric current

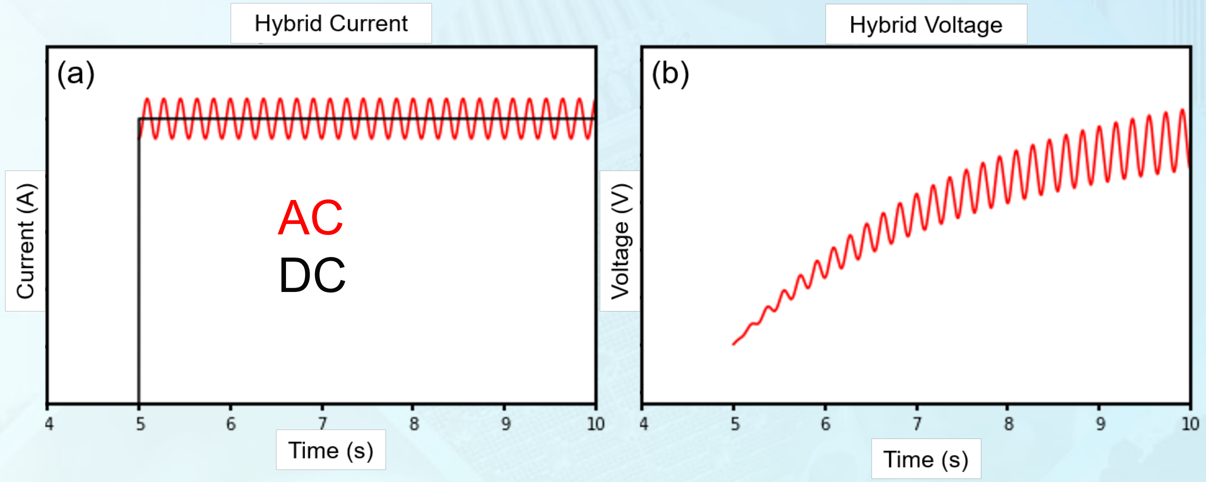
Minimizing probe diameter : better results for smaller samples and provides minimal intrusion

B. Fox, *'In-pile thermal conductivity measurement methods for nuclear fuels'*

Hybrid Technique

Single heater wire with no thermocouple

- Ohms law and the temperature dependent resistance of the wire
- Minimizes probe size
- Eliminates cross-talk issue



$$R(T) = R_0 + R'T$$

$$V = IR(T) = A\cos(\omega t)[R_0 + R'T]$$

Known I → V → $R(T)$ → T

R = resistance, R_0 = reference resistance, R' = temperature coefficient of resistance, T = temperature, V = voltage, I = current, A = amplitude, ω = frequency, t = time

1-wire probe design

Effective Probe Properties

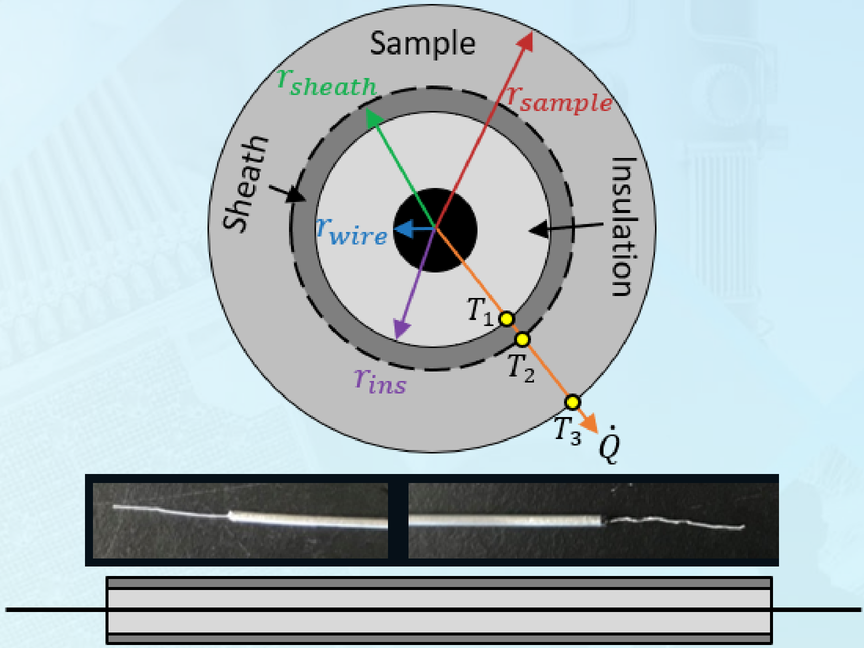
- Heat flow resistance network

$$k_{eff} = \frac{ln\left(\frac{r_{sheath}}{r_{wire}}\right)}{\frac{\ln\left(\frac{r_{ins}}{r_{wire}}\right)}{k_{ins}} + \frac{\ln\left(\frac{r_{sheath}}{r_{ins}}\right)}{k_{sheath}}}$$

- Averaged thermal mass

$$\frac{k}{\alpha} = C \rightarrow \alpha = \frac{k}{C}$$

$$C_{eff} = \frac{(A_{wire}C_{wire} + A_{ins}C_{ins} + A_{sheath}C_{sheath})}{A_{probe}}$$



Limitations: Expensive custom made probe, fragile 0.1mm platinum wire, difficult setup

k = thermal conductivity, r = radius, α = thermal diffusivity, C = heat capacity, A = area, eff = effective, ins = insulation, $\dot{Q}$ = heat flux

2-wire probe design

Probe Properties

- Thermal conductivity:

$$k = \alpha C$$

- Conservation of heat capacity:

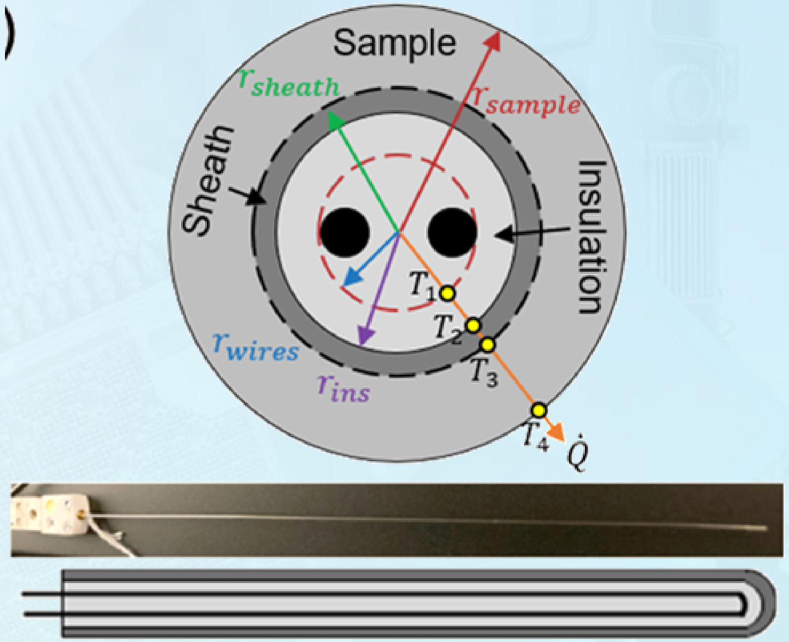
$$2C_w V_w = C_{weff} V_{weff}\ , C_I V_I = C_{Ieff} V_{Ieff}$$

- Conservation of time:

$$F = \frac{\alpha t}{L^2}\ , \alpha_{weff} = \frac{\alpha_w r_{weff}^2}{r_w^2}$$

- Insulator layer:

$$\alpha_{Ieff} = \frac{k_I}{C_{Ieff}}$$



Cheap, robust easy connection, dual temperature and thermal conductivity probe

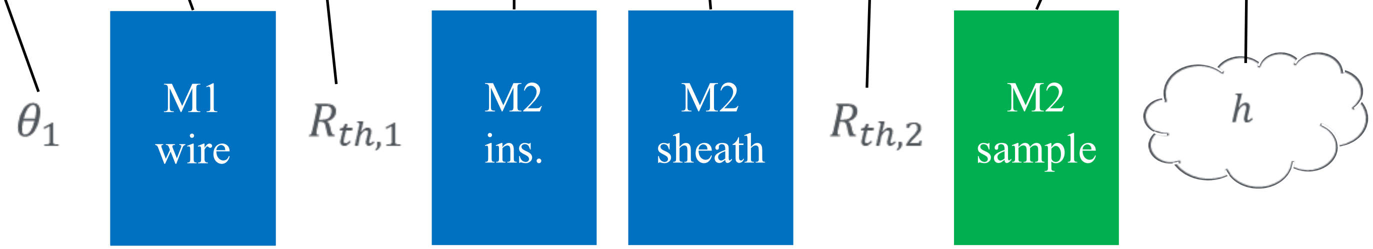
k = thermal conductivity, r = radius, α = thermal diffusivity, C = heat capacity, V = volume, eff = effective, I = insulation, w = wire, L = length, t = time, F = Fourier number, T = temperature, $\dot{Q}$ = heat flux

Thermal Quadrupoles

Analytical Model

*Traditional needle probe neglects

$$\begin{bmatrix}\theta_1\\ \varphi_1\end{bmatrix} = \begin{bmatrix}A_1 & B_1\\ C_1 & D_1\end{bmatrix}\begin{bmatrix}1 & R_{th,1}\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_2 & B_2\\ C_2 & D_2\end{bmatrix}\begin{bmatrix}A_3 & B_3\\ C_3 & D_3\end{bmatrix}\begin{bmatrix}1 & R_{th,2}\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_4 & B_4\\ C_4 & D_4\end{bmatrix}\begin{bmatrix}1 & 0\\ h & 1\end{bmatrix}\begin{bmatrix}\theta_3\\ \varphi_3\end{bmatrix}$$



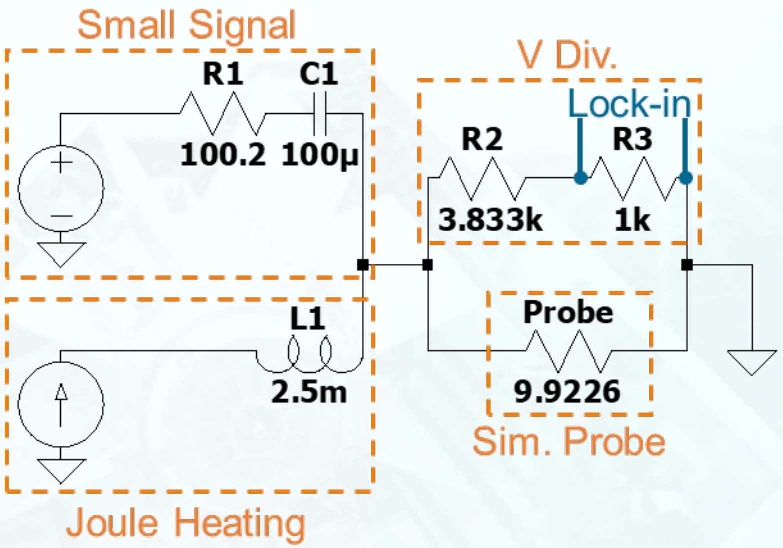
1-wire: sample layer **2-wire: insulation, sheath, and sample layers**	**Average temperature solution** **1-wire: wire, insulation, and sheath layer** **2-wire: effective wire layer**
$q_{1,i} = r_i\sqrt{p/\alpha_i}\,, q_{2,i+1} = r_{i+1}\sqrt{p/\alpha_i}$ $A_i = q_{2,i}\left[I_0(q_{1,i})K_1(q_{2,i}) + I_1(q_{2,i})K_0(q_{1,i})\right]$ $B_i = \frac{1}{2\pi kL}\left[I_0(q_{2,i})K_0(q_{1,i}) - I_0(q_{1,i})K_0(q_{2,i})\right]$ $C_i = 2\pi kLq_{1,i}q_{2,i}\left[I_1(q_{2,i})K_1(q_{1,i}) - I_1(q_{1,i})K_1(q_{2,i})\right]$ $D_i = q_{1,i}\left[I_0(q_{2,i})K_1(q_{1,i}) + I_1(q_{1,i})K_0(q_{2,i})\right]$	$q_i = r_i\sqrt{p/\alpha_i}$ $A_i = 1$ $B_i = \frac{1}{2\pi kL}\frac{I_0(q_i)}{q_iI_1(q_i)} - \frac{1}{\rho c\pi r_i^2 Lp}$ $C_i = \rho c\pi r_i^2 Lp$ $D_i = \frac{q_i}{2}\frac{I_0(q_i)}{I_1(q_i)}$

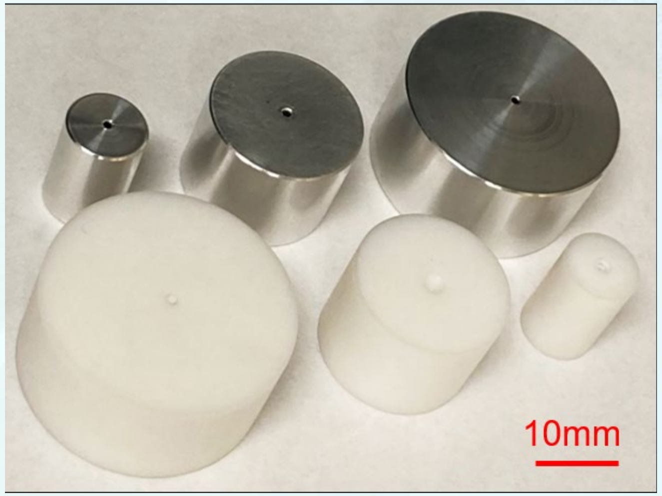
θ = Laplace temperature, φ = Laplace heat flux, R_{th} = thermal contact resistance, h = convection coefficient, index 1 = probe layer, index 2 = sample layer, α = thermal diffusivity, p = Laplace parameter, r = radius, k = thermal conductivity, L = length, I and K = modified Bessel functions, ρ = density, c = specific heat capacity

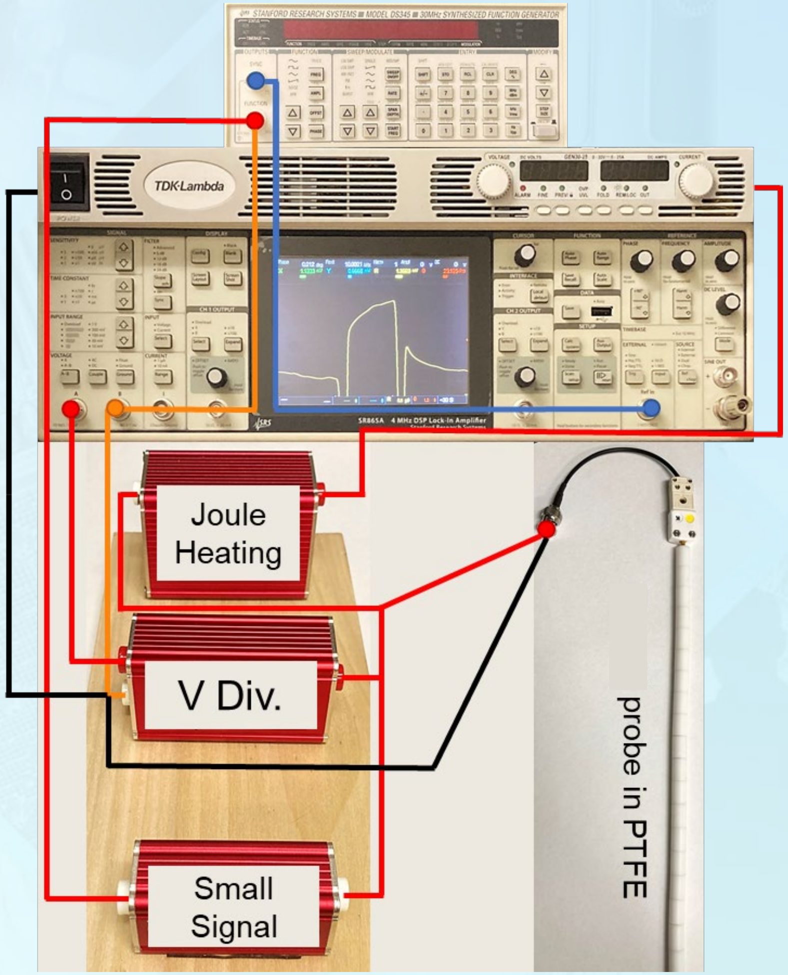
D. Maillet, Thermal Quadrupoles, 2000.

Experimental Setup

- **Electronics setup (at BSU and INL)**
- Complex circuit to increase signal to noise ratio
- Hybrid AC/DC measurement technique
- PTFE and Al samples of varying diameters used for measurements

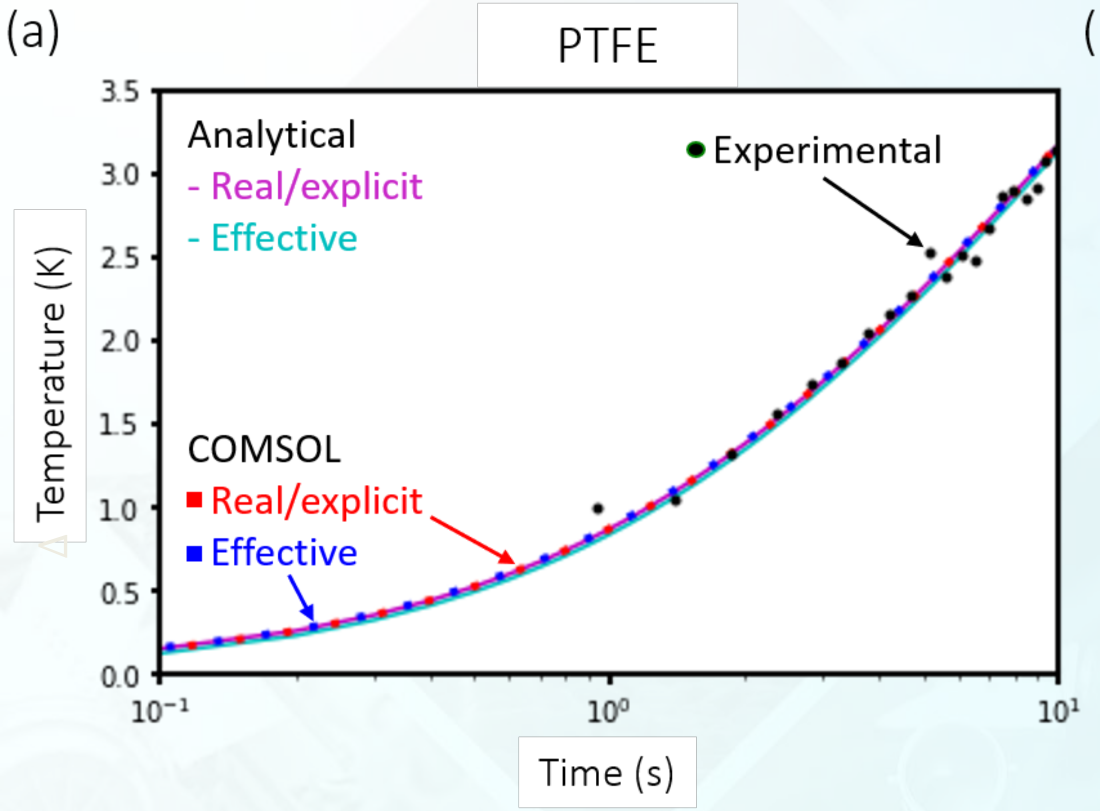


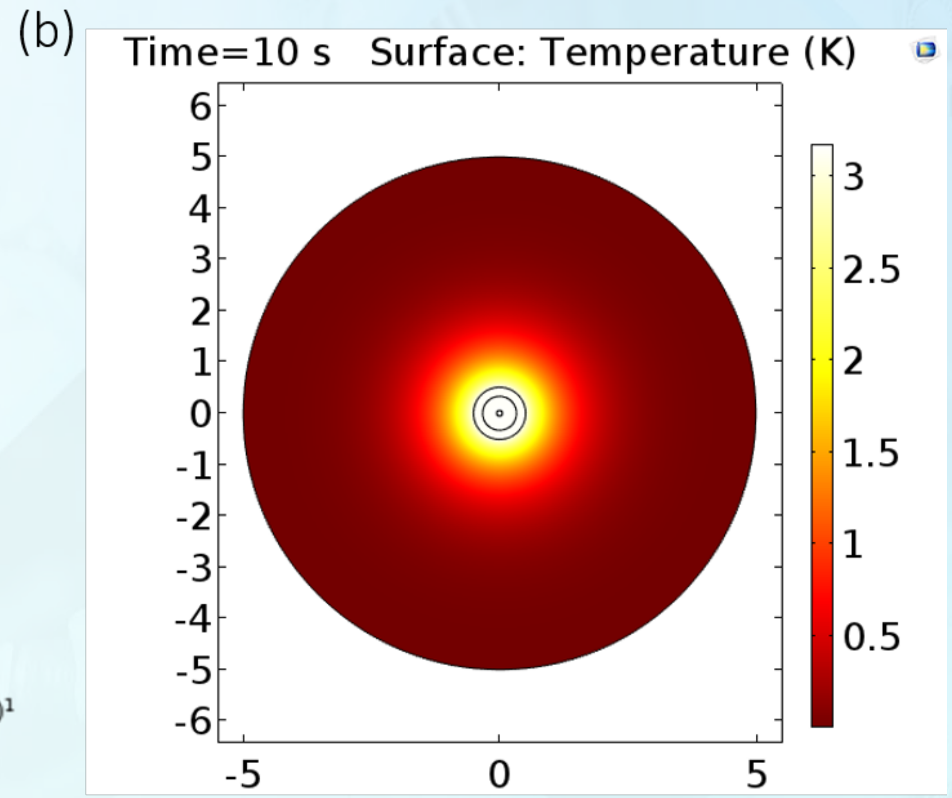




1-wire Results

- 2 analytical models for 1 wire geometry: effective and explicit/real

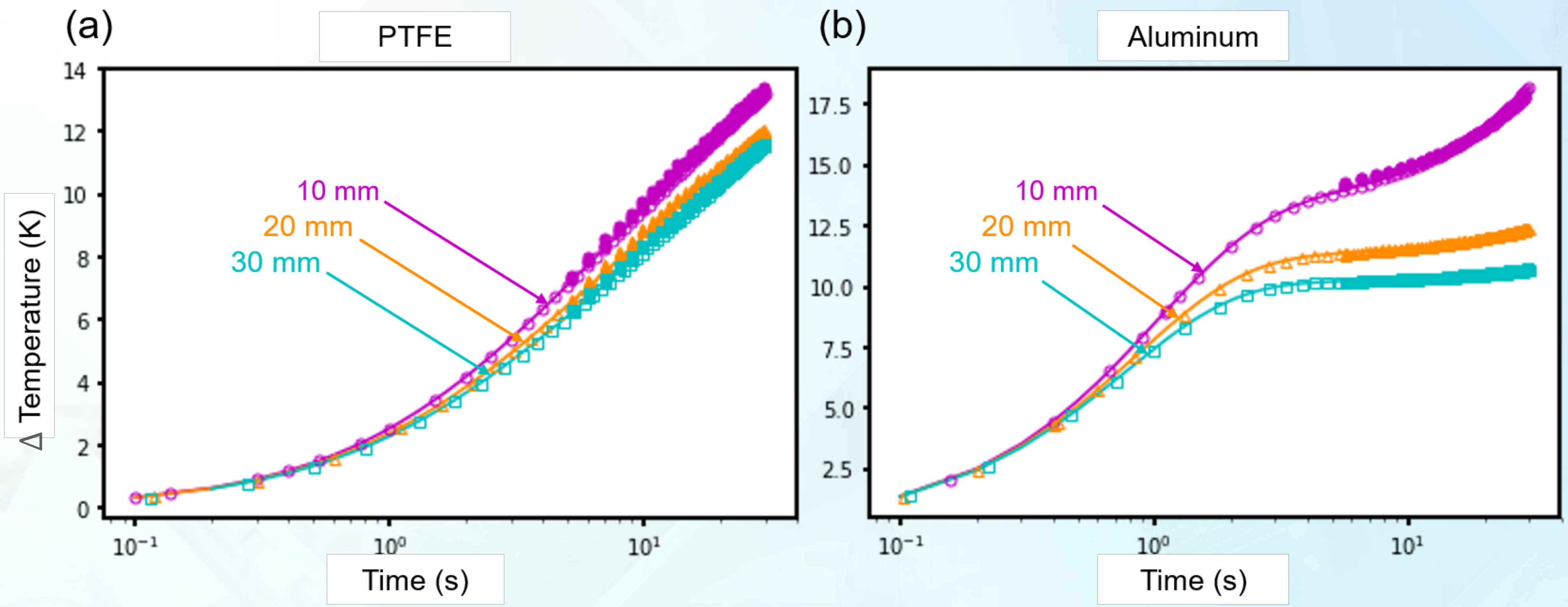




Wada, K., Fleming, A., & Estrada, D. (2023). Novel Thermal Conductivity Measurement Technique Utilizing a Transient Multilayer Analytical Model of a Line Heat Source Probe for Extreme Environments. In Energy Technology 2023. Springer. ***(Accepted)***

2-wire Results

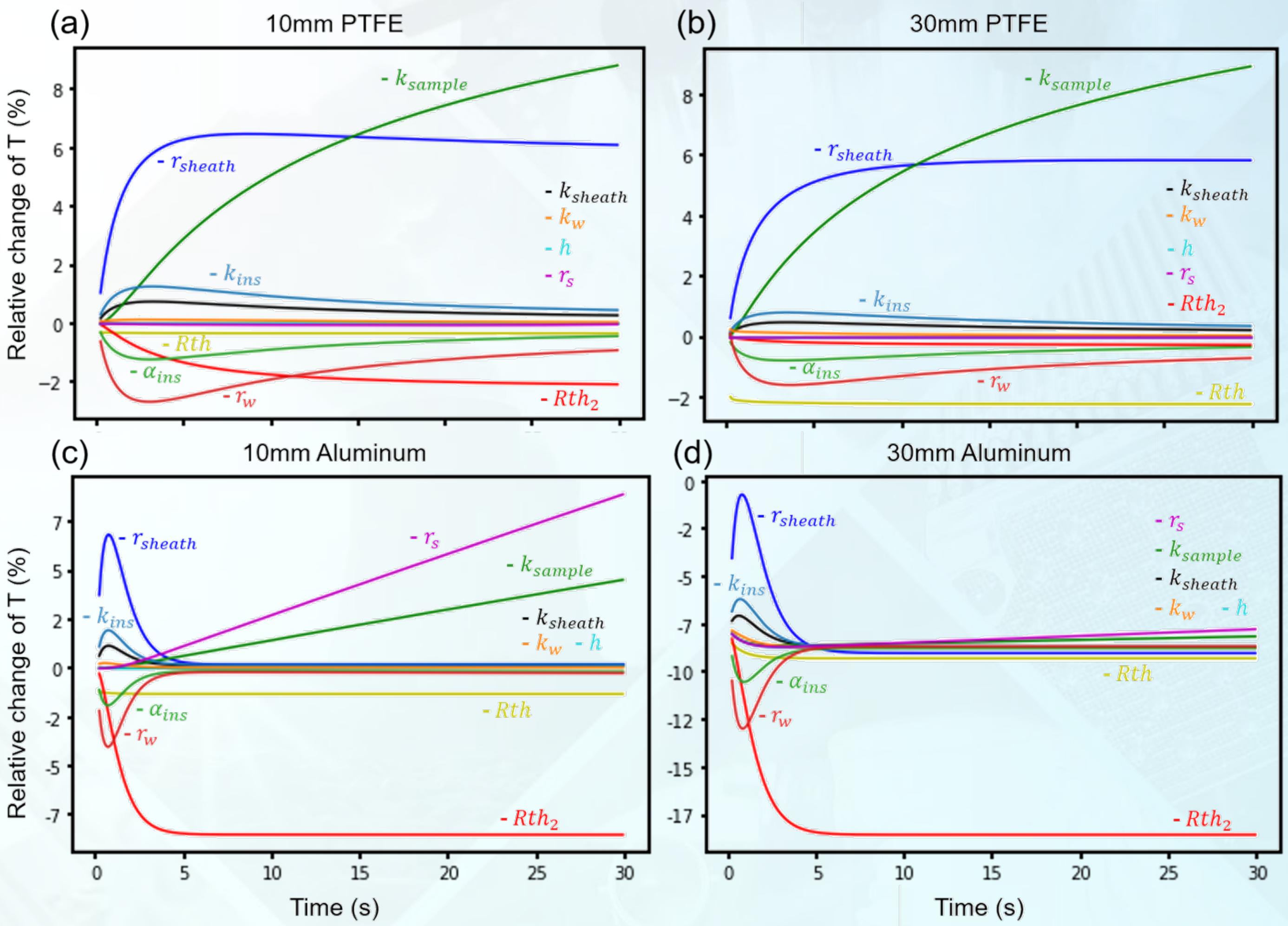
Combination model for 2 wire geometry



Analytical: solid lines, COMSOL: open symbols, Experimental: closed symbols

K. Wada, A. Fleming, J. Eixenberger, B. J. Jaques, and D. Estrada, “Transient multilayer analytical model of a line heat source probe for in-pile thermal conductivity measurements,” International Journal of Thermal Sciences, vol. 188, no. January, p. 108241, 2023, doi: 10.1016/j.ijthermalsci.2023.108241.

Sensitivity Parameter Study



k = thermal conductivity, r = radius, α = thermal diffusivity, C = heat capacity, A = area, eff = effective, ins = insulation, w = wire, h = convection coefficient, Rth = thermal contact resistance between wire and insulation, $Rth2$ = thermal contact resistance between sheath and sample

Katelyn Wada, Austin Fleming, Joshua Eixenberger, Brian J. Jaques, David Estrada, "Transient Multilayer Analytical Model of a Line Heat Source Probe for In-Pile Thermal Conductivity Measurements", IJTS ***(Accepted with revisions)***
Katelyn Wada, Austin Fleming, Joshua Eixenberger, Brian Jaques, David Estrada, "Analytical Models for In-Pile Thermal Conductivity Determination Utilizing Line Heat Source Probes", NPIC HMIT ***(Abstract accepted)***

Conclusions

- Solutions identified for: cross talk and probe size
- New measurement technique: Hybrid technique
- Analytical models for two different geometries developed and verified with FEM and experimental results
- Extreme applications not limited to nuclear

K. Wada, A. Fleming, and D. Estrada, "Novel Thermal Conductivity Measurement Technique Utilizing a Transient Multilayer Analytical Model of a Line Heat Source Probe for Extreme Environments," in Energy Technology 2023, Springer, 2023. doi: 10.1007/978-3-031-22638-0_13.

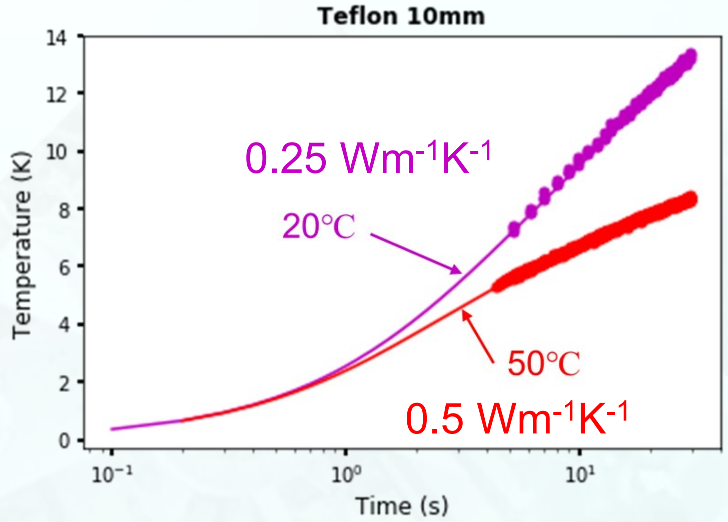
K. Wada, A. Fleming, J. Eixenberger, B. J. Jaques, and D. Estrada, "Transient multilayer analytical model of a line heat source probe for in-pile thermal conductivity measurements," International Journal of Thermal Sciences, vol. 188, no. January, p. 108241, 2023, doi: 10.1016/j.ijthermalsci.2023.108241.

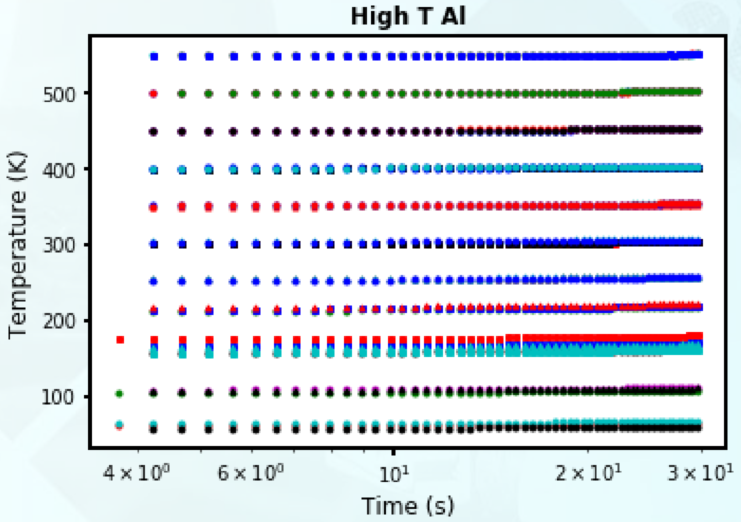
Future Plans

•High temperature testing

- Using high temperature tube furnace: MTI 4 zone furnace
- Measure thermal conductivity at 50℃ steps up to 550℃
- Discern thermal conductivity profile for entire range
- \- Requires multiple fit parameters

Preliminary data



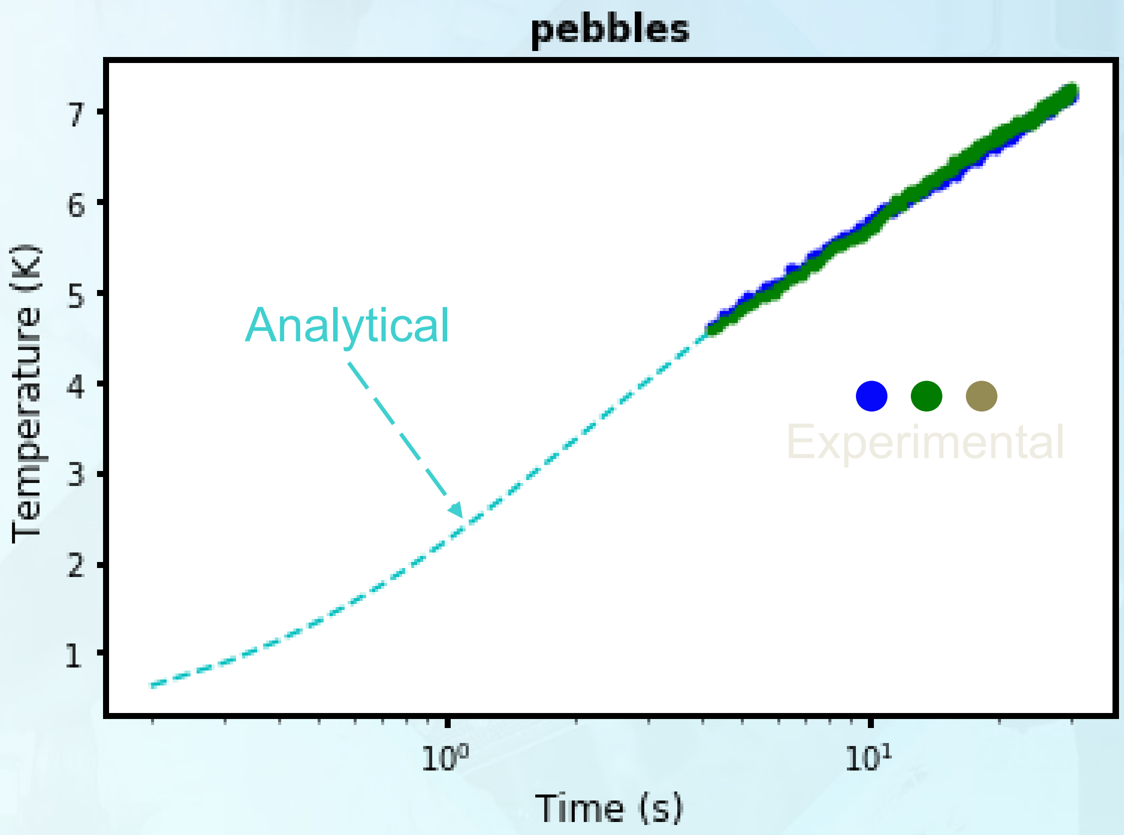


Pebble Bed Testing

Regression score function for a 2 parameter fit

$$Rth = 1\,\frac{Km^2}{W}$$
$$R^2 = 0.99375$$
$$k = 0.5918367\ \text{W/mK}$$
$$\alpha = 1.27142857\text{E}{-7}\ m^2/s$$

$$Rth = 0.01\,\frac{Km^2}{W}$$
$$R^2 = 0.990785$$
$$k = 0.555306\ \text{W/mK}$$
$$\alpha = 2.0142857\text{E}{-7}\ m^2/s$$



Thanks to Dr. Todd Otanicar for providing the samples

Thank you

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Supplementary

R' measurement:

- 0.013352 ΩK^{-1}