Line source measurement system for nuclear material thermal properties

Advanced Sensors and Instrumentation Annual Webinar

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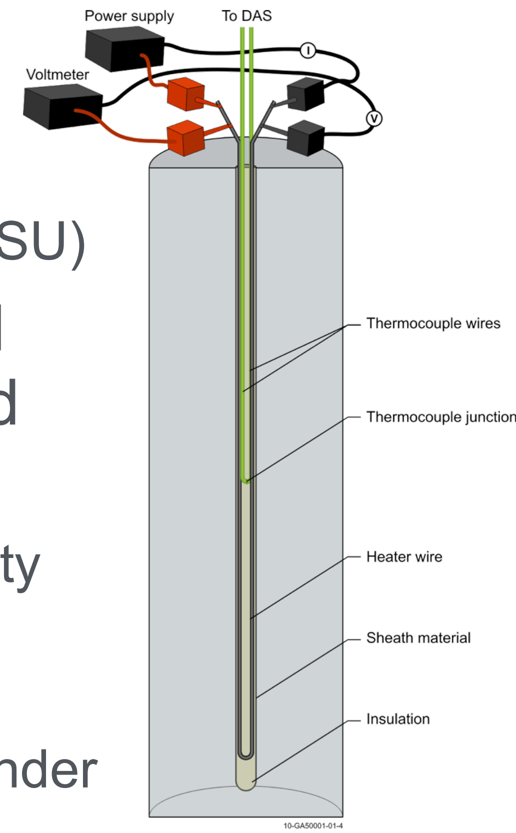
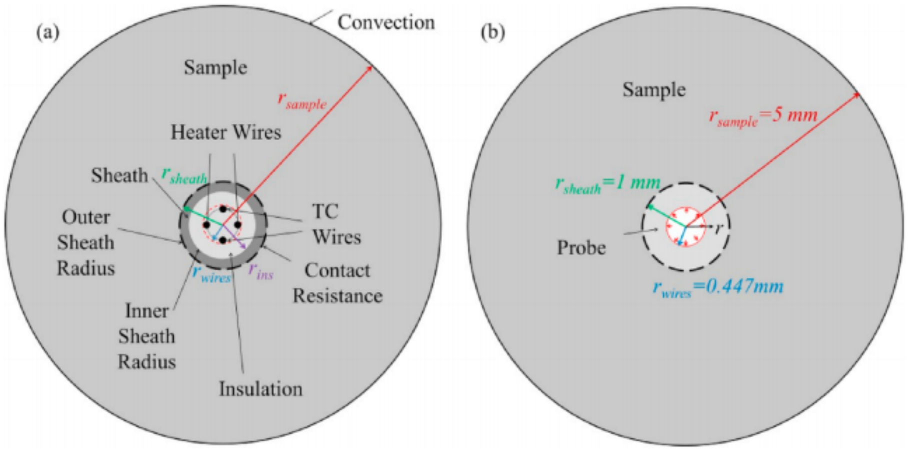
Project Overview

- **Goal:** Establish a capability to perform in-pile thermal property measurements under prototypic conditions for materials of interest
- Participants (2019)
  - Austin Fleming, Colby Jensen, Kurt Davis (INL)
  - Courtney Hollar, Dave Estrada, Ralph Budwig (BSU)
- Background: Previous work has established the thermal conductivity needle probe based on the transient line source method.
  - Technique determines sample thermal conductivity through a simplified data reduction algorithm, but requires a specific set of assumptions
  - These assumptions cannot always be satisfied under prototypic conditions



Accomplishments

- Multi-layered analytic thermal model developed



$$q_{1,i} = r_i\sqrt{p/\alpha_i} \quad q_{2,i+1} = r_{i+1}\sqrt{p/\alpha_i}$$

$$A_i = q_{2,i}[I_0(q_{1,i})K_1(q_{2,i}) + I_1(q_{2,i})K_0(q_{1,i})]$$

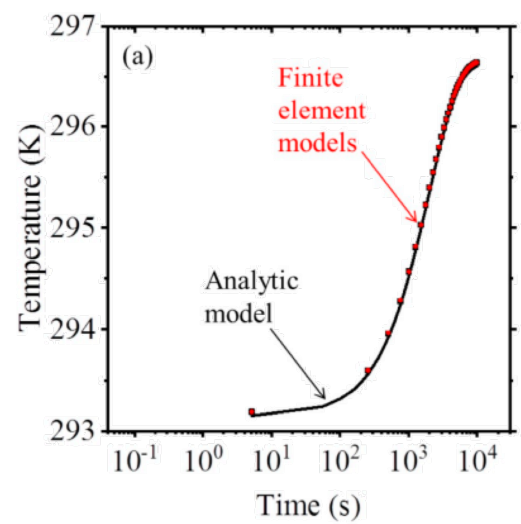
$$B_i = \frac{1}{2\pi kL}[I_0(q_{2,i})K_0(q_{1,i}) - I_0(q_{1,i})K_0(q_{2,i})]$$

$$C_i = 2\pi kLq_{1,i}q_{2,i}[I_1(q_{2,1})K_1(q_{1,i}) - I_1(q_{1,i})K_1(q_{2,i})]$$

$$D_i = q_{1,i}[I_0(q_{2,i})K_1(q_{1,i}) + I_1(q_{1,i})K_0(q_{2,i})]$$

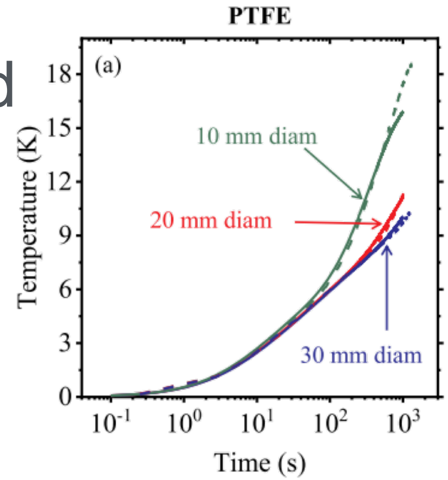
$$\begin{bmatrix}\theta_1\\ \varphi_1\end{bmatrix} = \begin{bmatrix}A_1 & B_1\\ C_1 & D_1\end{bmatrix}\begin{bmatrix}1 & R_{th}\\ 0 & 1\end{bmatrix}\begin{bmatrix}A_2 & B_2\\ C_2 & D_2\end{bmatrix}\begin{bmatrix}1 & 0\\ h & 1\end{bmatrix}\begin{bmatrix}\theta_3\\ \varphi_3\end{bmatrix}$$

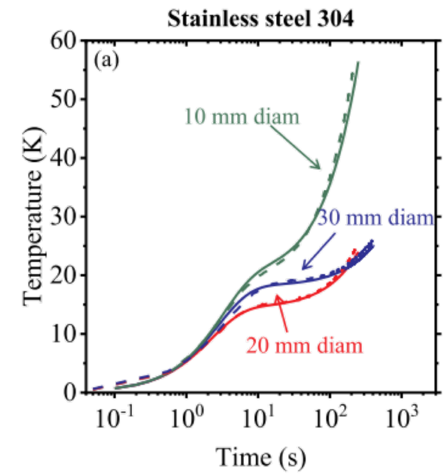
- Model enables:
  - Finite sample sizes
  - Contact resistance
  - Accounts for probe geometry
- Finite element model results were compared to the analytic model



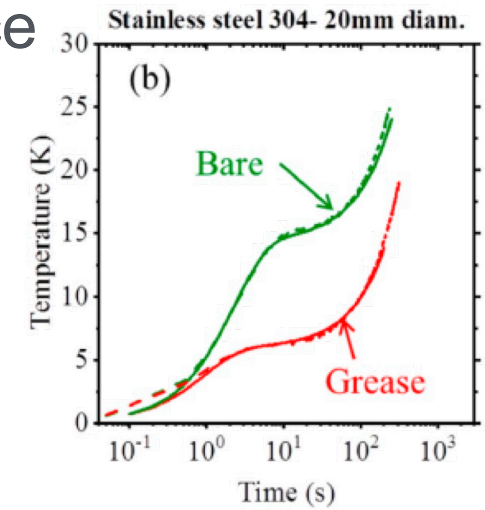
Accomplishments

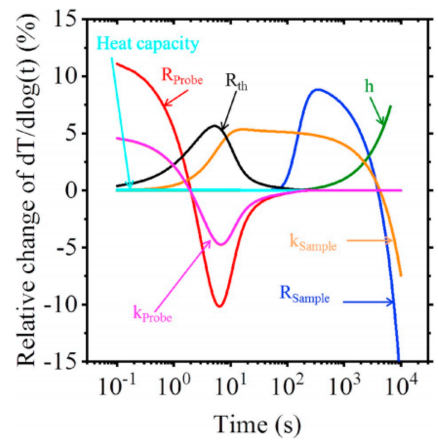
- A variety of sample material and sizes were experimentally tested and analyzed





- Thermal contact resistance variations were tested using thermal grease at probe interface

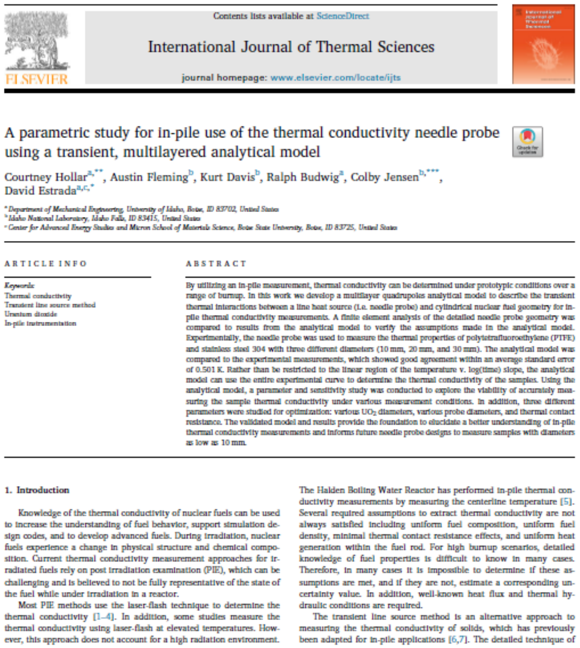




- Sensitivity Analysis was conducted for each thermal parameter

Accomplishments

- Developed and experimentally tested a frequency-domain configuration for the needle probe
- Published a journal article documenting time domain results.
- Drafted a journal article documenting frequency domain results.



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A parametric study for in-pile use of the thermal conductivity needle probe using a transient, multilayered analytical model

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ABSTRACT

By utilizing an in-pile measurement, thermal conductivity can be determined under prototypic conditions over a range of burnup. In this work we develop a multilayer quadrupoles analytical model to describe the transient thermal interactions between a line heat source (i.e. needle probe) and cylindrical nuclear fuel geometry for in-pile thermal conductivity measurements. A finite element analysis of the detailed needle probe geometry was compared to results from the analytical model to verify the assumptions made in the analytical model. Experimentally, the needle probe was used to measure the thermal properties of polytetrafluoroethylene (PTFE) and stainless steel 304 with three different diameters (10 mm, 20 mm, and 30 mm). The analytical model was compared to the experimental measurements, which showed good agreement within an average standard error of 0.501 K. Rather than be restricted to the linear region of the temperature v. log(time) slope, the analytical model can use the entire experimental curve to determine the thermal conductivity of the samples. Using the analytical model, a parameter and sensitivity study was conducted to explore the viability of accurately measuring the sample thermal conductivity under various measurement conditions. In addition, three different parameters were studied for optimization: various UO_2 diameters, various probe diameters, and thermal contact resistance. The validated model and results provide the foundation to elucidate a better understanding of in-pile thermal conductivity measurements and informs future needle probe designs to measure samples with diameters as low as 10 mm.

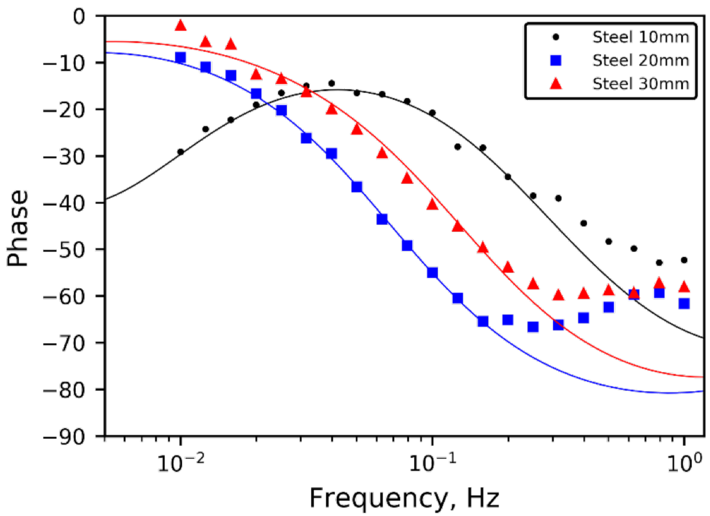
1. Introduction

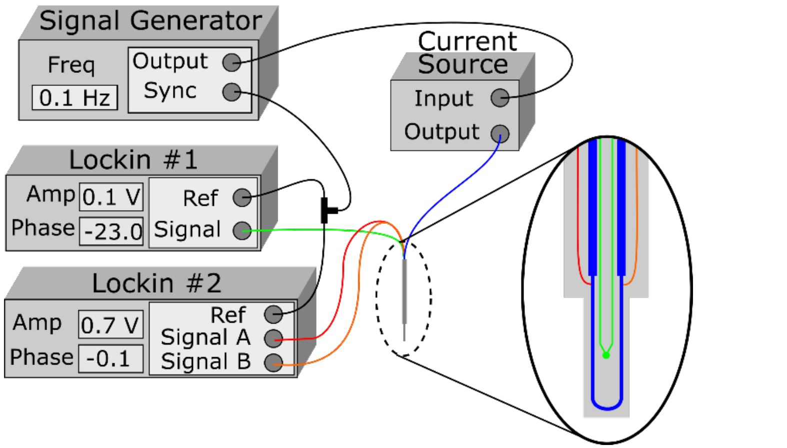
Knowledge of the thermal conductivity of nuclear fuels can be used to increase the understanding of fuel behavior, support simulation design codes, and to develop advanced fuels. During irradiation, nuclear fuels experience a change in physical structure and chemical composition. Current thermal conductivity measurement approaches for irradiated fuels rely on post irradiation examination (PIE), which can be challenging and is believed to not be fully representative of the state of the fuel while under irradiation in a reactor.

Most PIE methods use the laser-flash technique to determine the thermal conductivity [1–4]. In addition, some studies measure the thermal conductivity using laser-flash at elevated temperatures. However, this approach does not account for a high radiation environment.

The Halden Boiling Water Reactor has performed in-pile thermal conductivity measurements by measuring the centerline temperature [5]. Several required assumptions to extract thermal conductivity are not always satisfied including uniform fuel composition, uniform fuel density, minimal thermal contact resistance effects, and uniform heat generation within the fuel rod. For high burnup scenarios, detailed knowledge of fuel properties is difficult to know in many cases. Therefore, in many cases it is impossible to determine if these assumptions are met, and if they are not, estimate a corresponding uncertainty value. In addition, well-known heat flux and thermal hydraulic conditions are required.

The transient line source method is an alternative approach to measuring the thermal conductivity of solids, which has previously been adapted for in-pile applications [6,7]. The detailed technique of





Technology Impact

- *Provides information about the thermal properties or conditions of in-pile nuclear materials.*
- *Existing in-pile thermal property measurements are very limited (centerline TC,)*
- *This technology has the potential to provide information on several phenomena of interest:*
  - *Fuel Thermal Conductivity (burn-up dependent)*
  - *Gap Conductance/Pellet Cladding Mechanical Interaction (PCMI)*
  - *Other thermal performance parameters*

Conclusions

- Techniques were established to use with the thermal conductivity needle probe to account for finite sample sizes and a thermal contact resistance between the probe and sample
- Experimentally validated these models/techniques using both time-domain and frequency domain approaches
- The probe shows high potential for providing accurate in-pile thermal property measurements

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