



# In-core measurement systems for nuclear materials characterization and codes V&V

**Advanced Sensors and Instrumentation  
Annual Webinar**

**October 29, November 5,  
November 12, 2020**

Zilong Hua  
Idaho National Laboratory

# Project Overview

| Activity   | Objective  | Participants in FY20   | Schedule                                    |
|--|--|--|---|
| RUSL<br>(Resonant Ultrasonic Spectroscopy – Laser) | Real time monitoring of microstructure evolution, i.e., grain restructuring and phase transformation, of nuclear fuels | Rob Schley<br>David Hurley<br>Zilong Hua<br>Larry Aagesen (INL)                                      | Zero-Group-Velocity plate wave measurements |
| Needle Probe                                       | Develop and qualify a thermal conductivity measurement technique for prototypic in-pile conditions                     | Austin Fleming<br>Kurt Davis (INL)<br>Katelyn Wada<br>David Estrada (BSU)                            |   |
| EIS<br>(Electrochemistry Impedance Spectroscopy)   | Develop EIS-based sensor for in-situ measurement of cladding corrosion   | Hongqiang Hu<br>Ling Ding (INL)<br>Mike Hurley<br>Claire Xiong<br>Min Long<br>Michael Reynolds (BSU) |   |
| PTR<br>(Photothermal Radiometry)                   | Contactless, remote thermal conductivity measurement   | Zilong Hua<br>Rob Schley<br>David Hurley (INL)   | In-situ/in-core experiments                 |

# Summary of accomplishments

- Milestones:
  - RUSL
    - Complete design of RUSL irradiation experiment with free standing sample
    - Define specifications for RUSL Validation and Verification test for fuel microstructure characterization in coordination with NEAMS
    - Scoping studies to ascertain the change in the phase transition temperature of metallic fuels
  - EIS
    - Test the Electrochemical Impedance Sensor (EIS) sensor at PWR relevant conditions in static autoclave and perform finite element (FE) models
    - Study of corrosion of cladding material in simulated PWR environment using impedance measurement
  - Needle Probe
    - Development and out-of-pile testing of a novel line source method for measuring nuclear fuels and materials
  - PTR
    - Demonstration of bench-top fiber-based Photo Thermal Radiometry (PTR) system to measure nuclear fuels and materials thermal conductivity
    - Complete feasibility assessment for the applicability of PTR to irradiation experiments

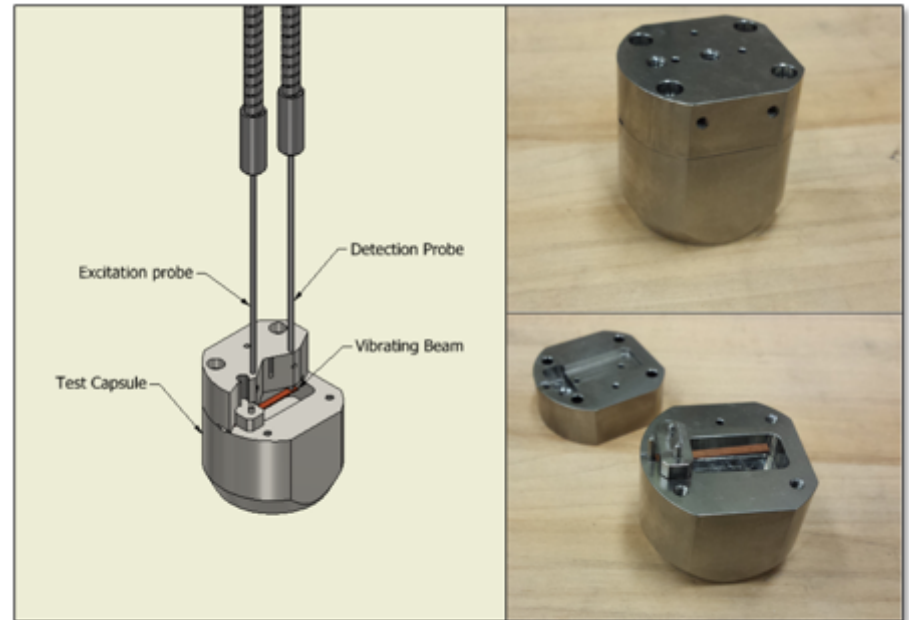
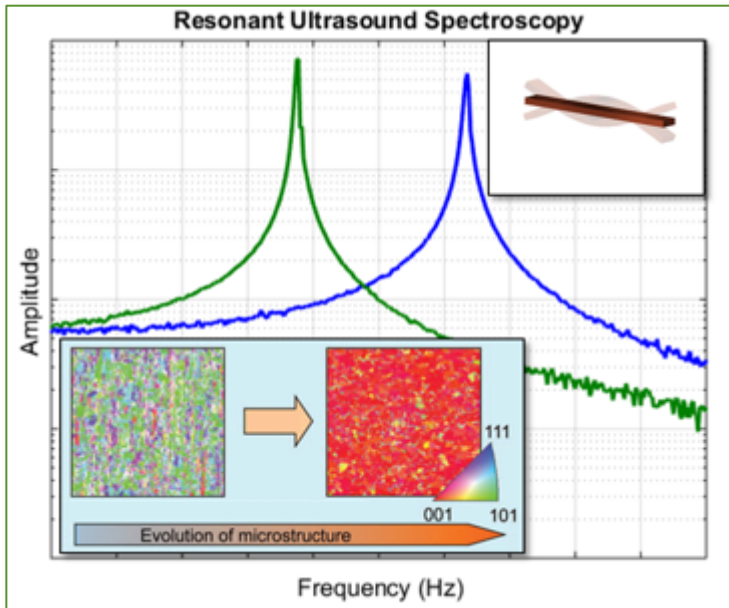
# Technology Impact

## In-core measurement systems

- Monitor the critical physical property or important phenomena relating to nuclear reactor safety and efficiency
  - Thermal conductivity
  - Microstructure evolution
  - Cracking
  - Corrosion
- Provide real-time information in coupled extreme environments, which is lacking from PIE
- High TRL for commercialization

# Accomplishments (1/4 - RUSL)

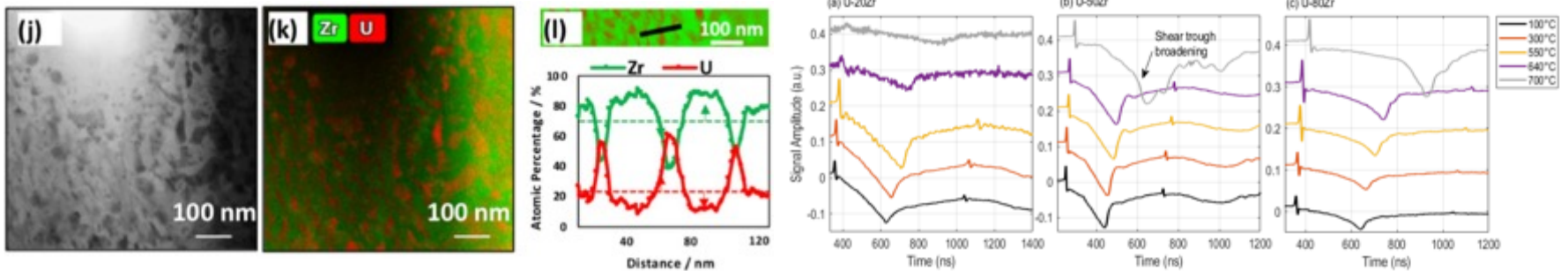
- Elasticity properties – microstructure evolution
- Previous cantilever beam capsule
  - In-core test performed at TREAT, with good results obtained



MIMIC-RUSL Test Capsule

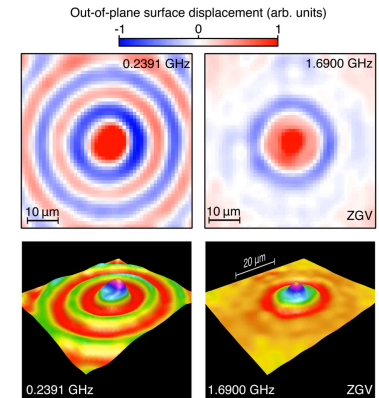
# Accomplishments (1/4 - RUSL)

- External Funding resulting from FY19 work
  - NNSA funding for the aLEU-RUSL which will implement this measurement technique for the study of phase transition temperatures of Low Enriched Uranium (LEU) U-Mo
  - A sister experimental-computational study on U-Zr: irradiation induced phase transformation



# Accomplishments (1/4 - RUSL)

- Novel zero group velocity (ZGV) plate wave measurements
  - Remove ultrasonic attenuation from coupling with environments
  - Have low losses and high Q-factor
  - Measure intrinsic attenuation related to dislocation density

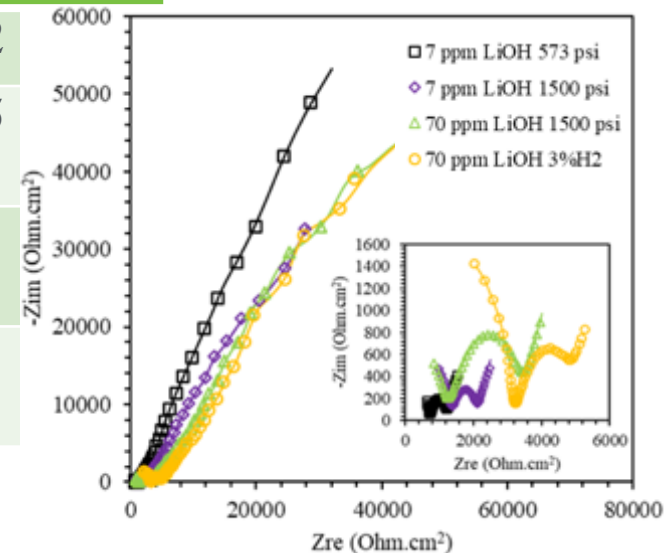


*Q. Xie et al., "Imaging gigahertz zero-group-velocity lamb waves," Nature Communication, 10, 2228 (2019)*

# Accomplishments (2/4 - EIS)

- In-situ EIS experiment
- Results compared favorably with industry standard method

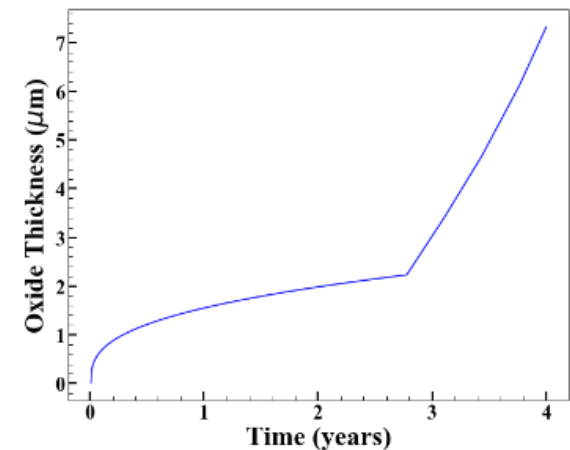
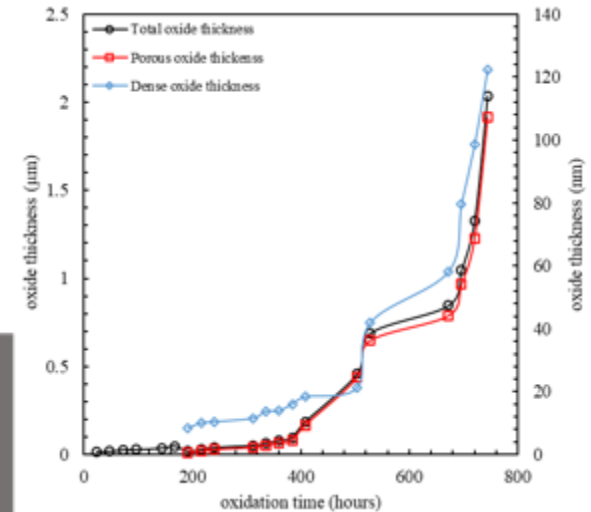
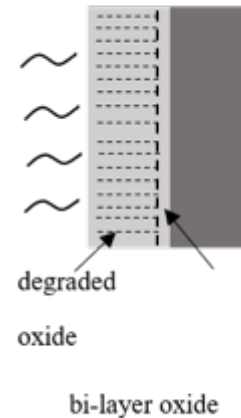
| Testing conditions   | Oxide thickness calculated from weight gain ( $\mu\text{m}$ ) | Oxide thickness calculated from cole-cole diagram ( $\mu\text{m}$ ) |
|----------------------|---|---|
| Water                | 0.44  | 0.312   |
| 7 ppm LiOH/573 psi   | 1.06  | 0.315   |
| 7 ppm LiOH/1500 psi  | 1.51  | 1.30  |
| 70 ppm LiOH/1500 psi | 2.66  | 1.89  |





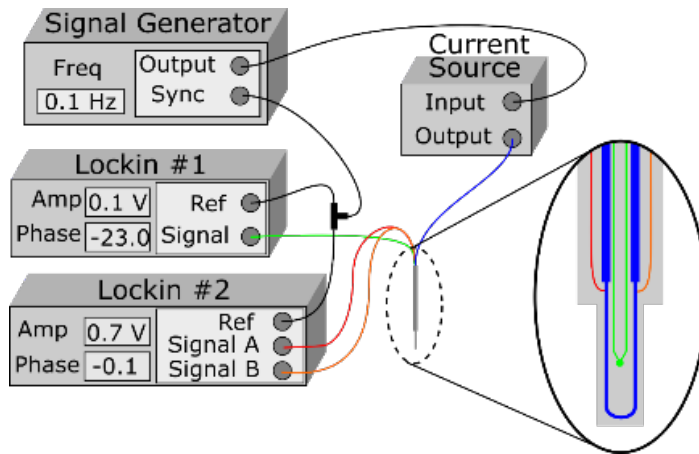
# Accomplishments (2/4 - EIS)

- Real-time oxide development recorded
- Threshold safety parameter proposed (represented by impedance)
  - Oxide thickness
  - Corrosion rate
- FEA Modeling
  - 7.2  $\mu\text{m}$  of oxide after 4 years
  - Maximum depth of hydride penetration will not happen at surface



# Accomplishments (3/4 – Needle probe)

- Building on previous work with in-pile line source methods to improve high temperature performance and smaller sample size.
- FY20 work focused on establishing a new measurement technique which would eliminate the need for a thermocouple, thereby minimizing the probe size and cross talk problems at high temperatures.



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

Courtesy Hella<sup>1</sup>, Austin Fleming<sup>2</sup>, Karl Davis<sup>3</sup>, Ralph Busby<sup>4</sup>, Colby Jones<sup>5</sup>, David Estrada<sup>6</sup>

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### ARTICLE INFO

#### Keywords:

Thermal conductivity

Transient heat conduction

In-pile methods

### ABSTRACT

By utilizing an in-pile measurement, thermal conductivity can be determined under prototype conditions over a range of burnup. In this study we develop a multilayered analytical model to describe the transient thermal interaction between a line heat source (a needle probe) and cylindrical reactor fuel geometry for single thermal conductivity measurements. A parametric analysis of the analytical model geometry was compared to results from the analytical model to verify the accuracy of the analytical model. Experimentally, the needle probe was used to measure the thermal properties of prototypic fuel (PWR) and stainless steel (SS) with three different diameters (10 mm, 15 mm, and 20 mm). The analytical model was compared to the experimental measurements, which showed good agreement within an average standard error of 4.5%. Further study is necessary to the lower region of the temperature. In addition, the analytical model can use the same experimental setup to determine the thermal conductivity of the sample. Using the analytical model, a parametric and sensitivity study was conducted to explore the viability of accurately measuring the sample thermal conductivity under various measurement conditions. In addition, these different parameters were studied for optimization: various (1% diameter, 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 various future needle probe design to increase sample width diameter 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 do not substitute fuels only in post-irradiation measurements (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.

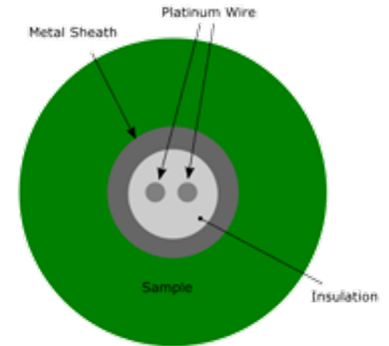
Most PIE methods use the laser flash technique to determine the thermal conductivity [1–5]. In addition, some studies measure the thermal conductivity using laser flash at elevated temperatures. However, this approach does not account for a high radiation environment.

The Idaho Boiling Water Reactor has performed in-pile thermal conductivity measurements by measuring the convection temperature [1]. Several proposed approaches to assess thermal conductivity are not always suitable including various fuel compositions, uniform fuel density, minimal thermal contact resistance effects, and uniform heat generation within the fuel rod. For high burning 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 flow and thermal conductivity conditions are required.

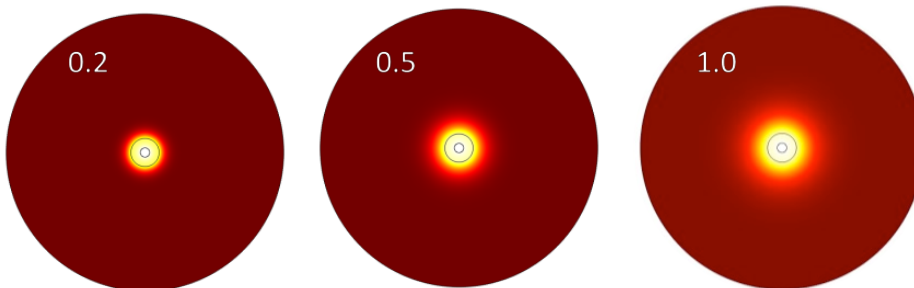
The transient line source method is an alternative approach to measuring the thermal conductivity of solids, which has previously been adapted for in-pile application [1,7]. The detailed technique of

# Accomplishments (3/4 – Needle probe)

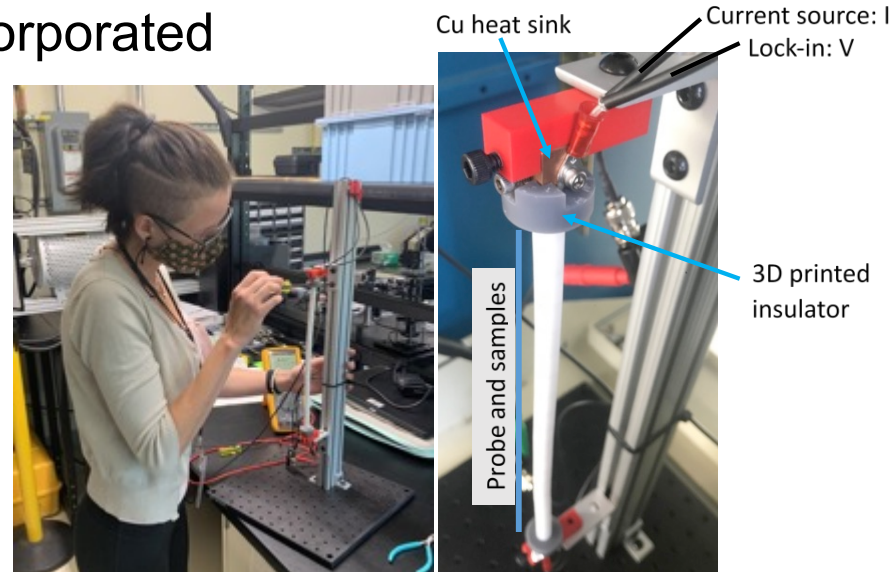
- Theoretical foundations were established for a “hybrid” technique between the 3-omega and transient line source techniques
- A probe compatible with this technique was designed and procured
- Analytic and FEA (COMSOL) models were developed for this new probe geometry
- Test samples were procured and incorporated into a test stand at INL



Cross-section of new probe geometry being tested



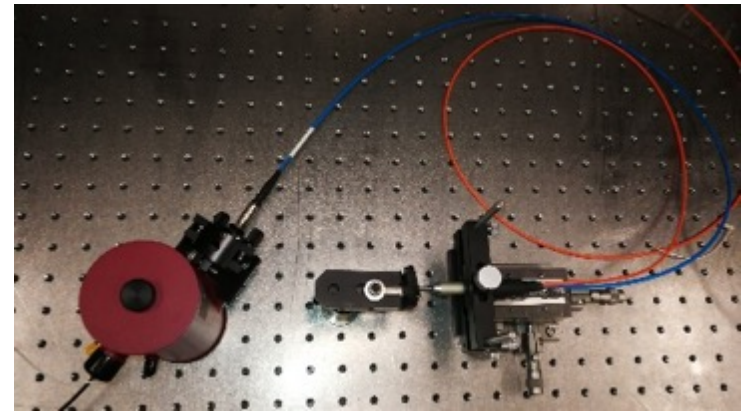
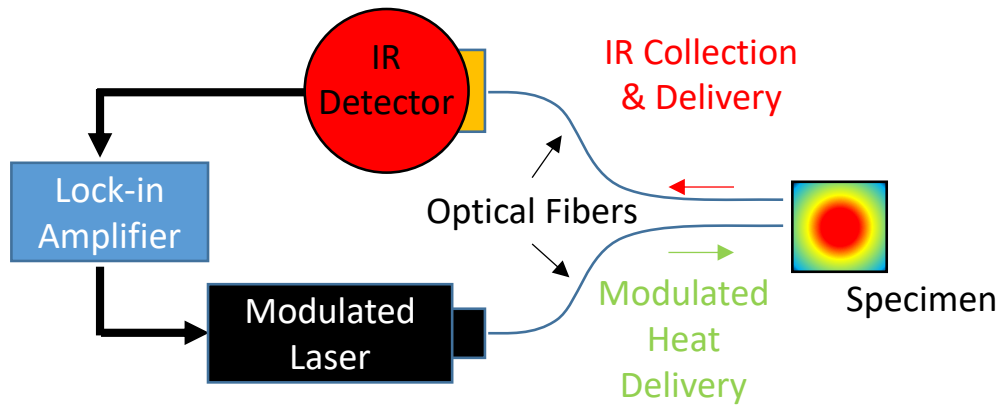
COMSOL modeling results of the new probe geometry at three different time



Katelyn Wada (Intern from Boise State University) experimentally tests the novel needle probe

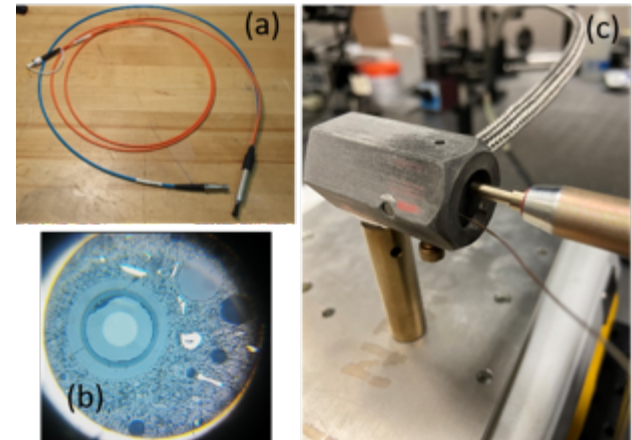
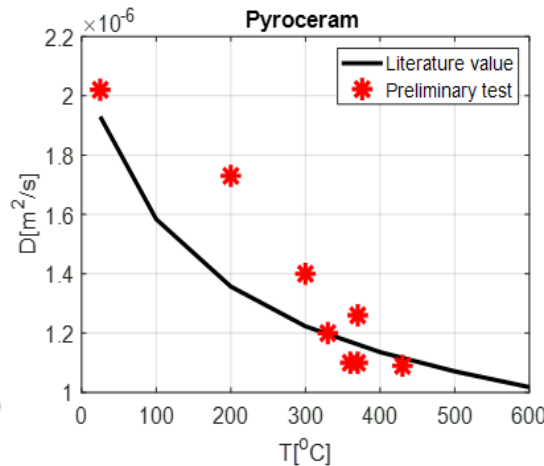
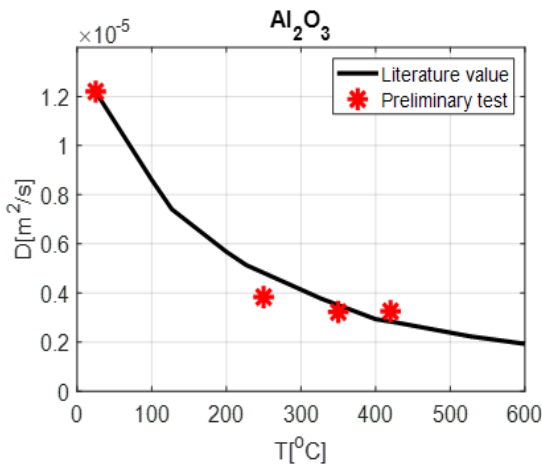
# Accomplishments (4/4 - PTR)

- Thermal wave – thermal conductivity
- Blackbody radiation – unique advantages
- Free-space system validated on a set of reference samples; new measurement methodology developed



# Accomplishments (4/4 - PTR)

- In-core instrument designed, fabricated, and tested
  - First generation (room temperature)
  - Second generation (200-700C; test up to 500C)



# Conclusions/Look ahead

- In-situ PTR tests performed with promising results obtained
- In-core tests performed or scheduled
- Journal papers (PTR) prepared

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