U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Thermal Conductivity Measurement of Irradiated Metallic Fuels Using TREAT

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Project Objective

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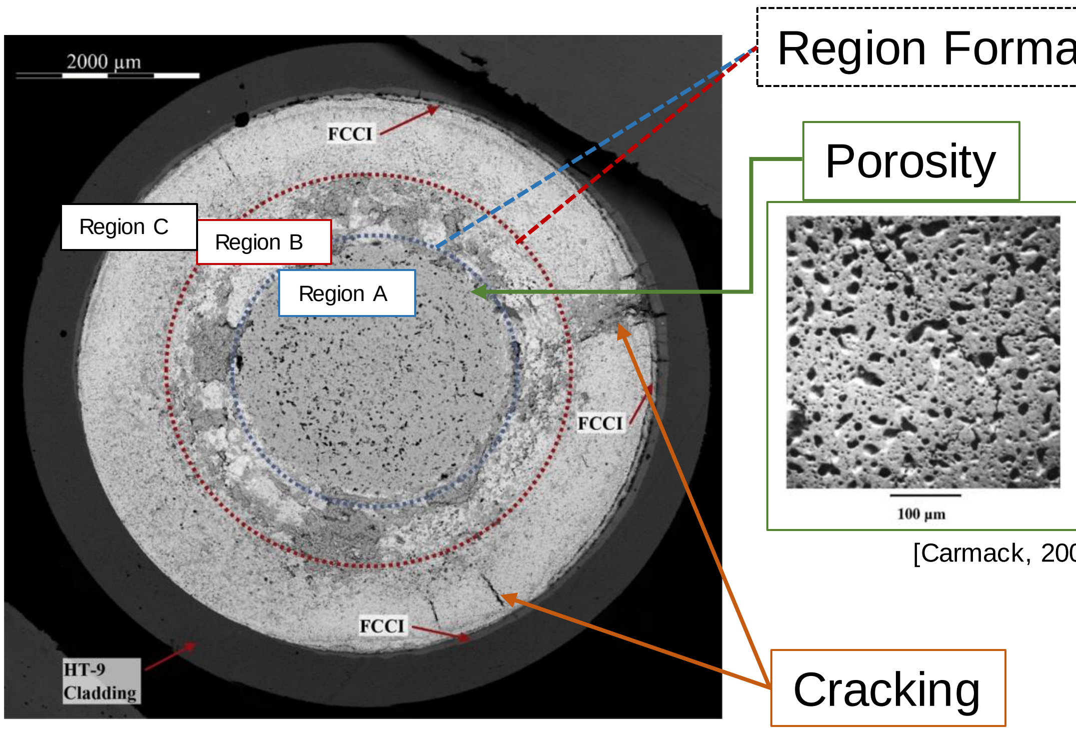
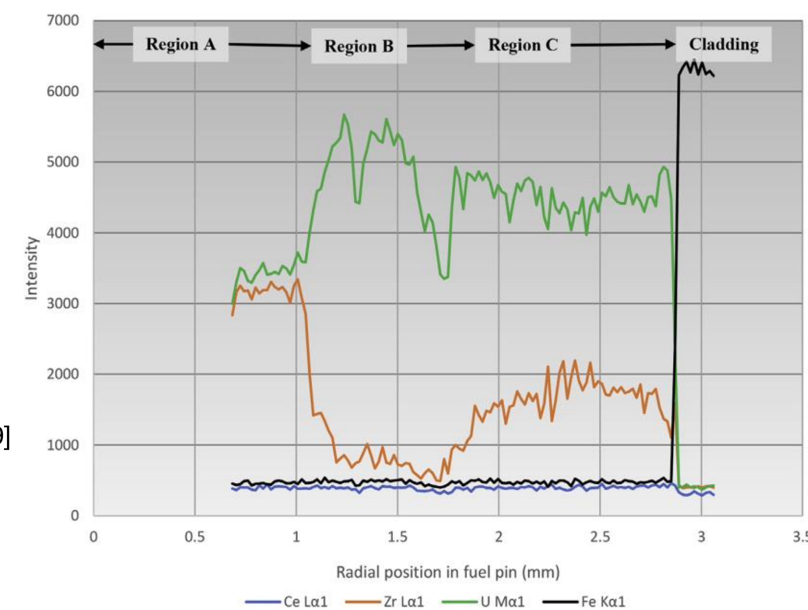
- Determine thermal conductivity & diffusivity of U-Pu-Zr fuels irradiated to various burnup levels using TREAT pulse shaping
- Develop fuel thermal property models based on pre- and post-irradiation microstructure analysis



[Carmack, 2009]

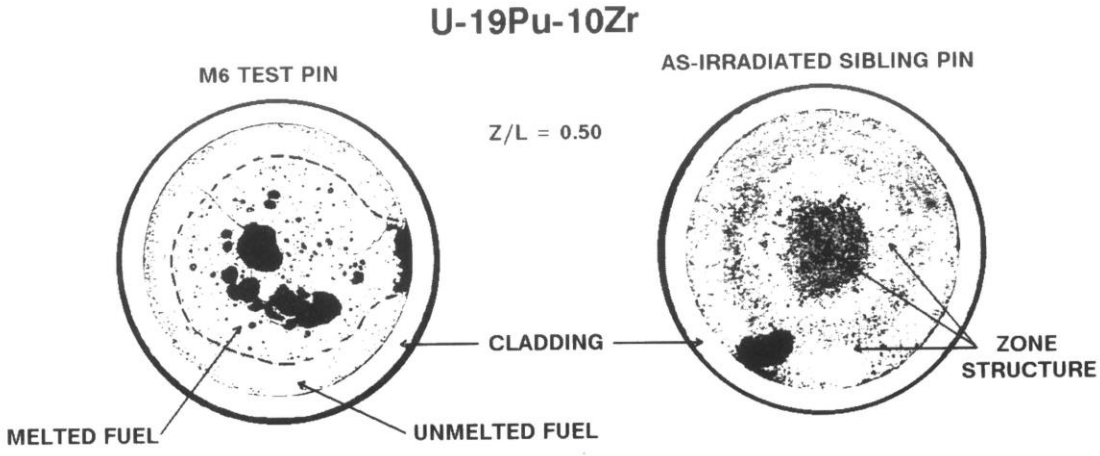
[Harp, 2017]

$$\alpha = \frac{k}{\rho c_p}$$



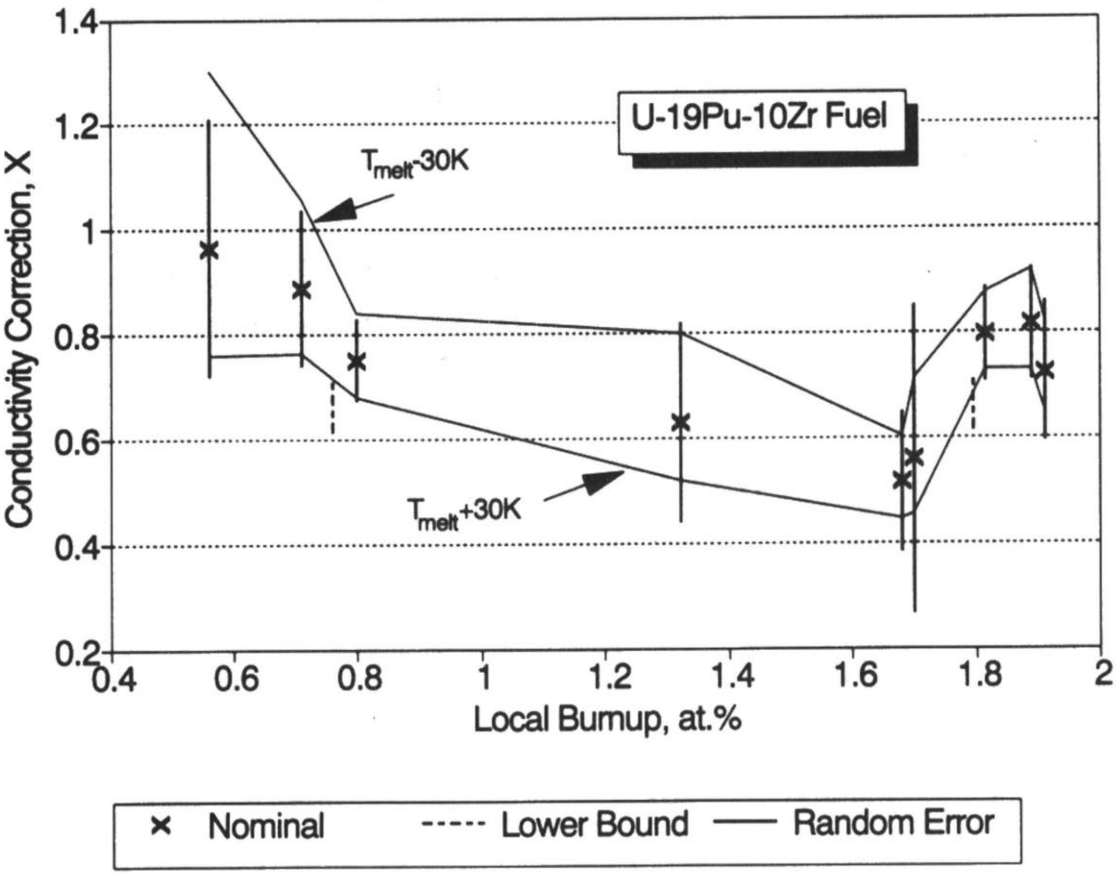
Metal Fuel Thermal Conductivity Data

- Metal alloy fuels are historically used and studied in fast reactors, and U–20Pu–10Zr is being studied by DOE programs
- Thermal conductivity data for irradiated fuels at different burnups are essential for fuel performance and safety design
- Thermal conductivity estimation by Bauer and Holland in 1980s
  - Thermal conductivity were estimated between melted region at fuel center and sodium coolant outside cladding based on cross-section images
  - Significant conductivity reduction is probably due to increased fuel porosity



Bauer, T.H. and J.W. Holland, Nuclear Technology, 1995. **110**(3): p. 407-421

Available Thermal Conductivity Data for U-Pu-Zr Fuels at Low Burnups



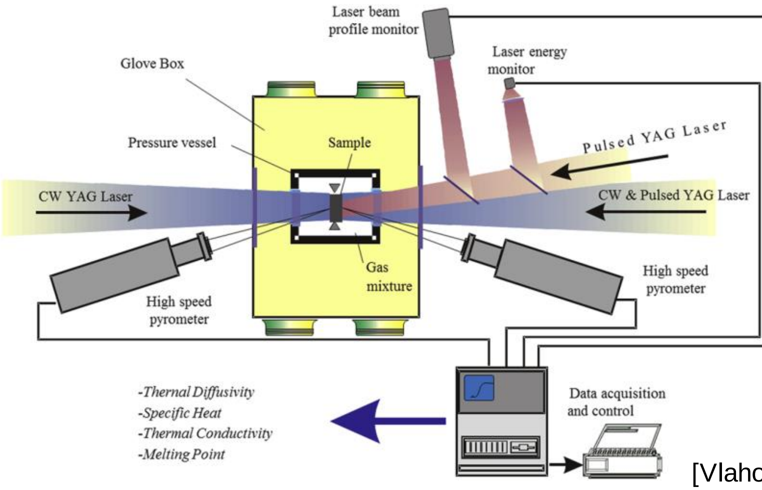
Bauer, T.H. and J.W. Holland, Nuclear Technology, 1995. **110**(3): p. 407-421

State of the Art Measurement Methods

Out-of-Pile, Irradiated Fuels

■Hot-Cell basted LFA testing

- Radioactivity poses added complexity
- Testing is destructive (one burn-up level) and only measures in axial direction

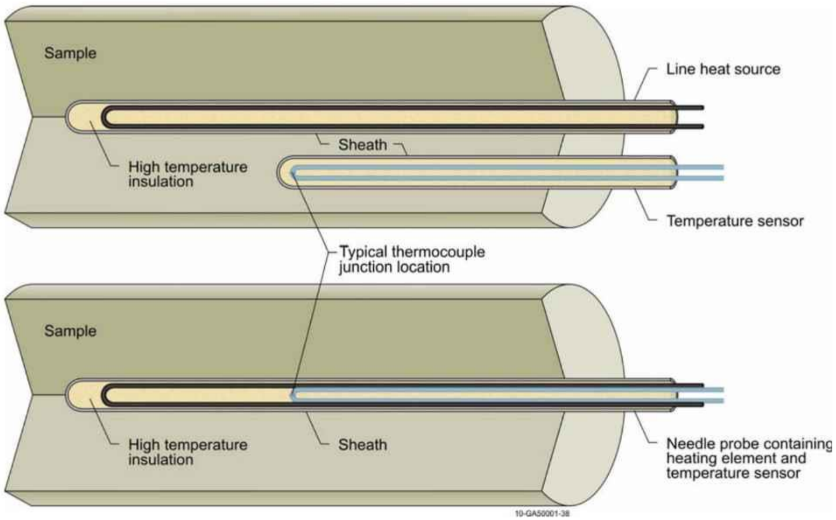


[Vlahovic 2017]

In-Pile

■Needle Probe & Transient Hotwire

- Instrumentation is difficult to achieve and disturbs fuel structure



[Fox 2010]

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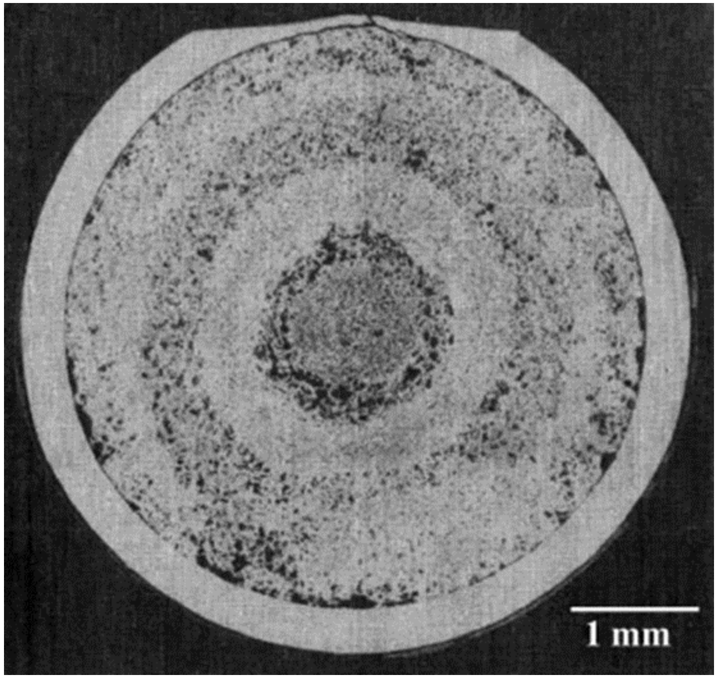
Research Goal

Develop a thermal property measurement method with two attributes:

1. **Non-Destructive**
   - Preserve structure of interest
   - Subsequent testing
2. **In-pile Nuclear Heating**
   - Eliminate the need for hot cell
   - Utilize reactor condition
   - Radial heat transport

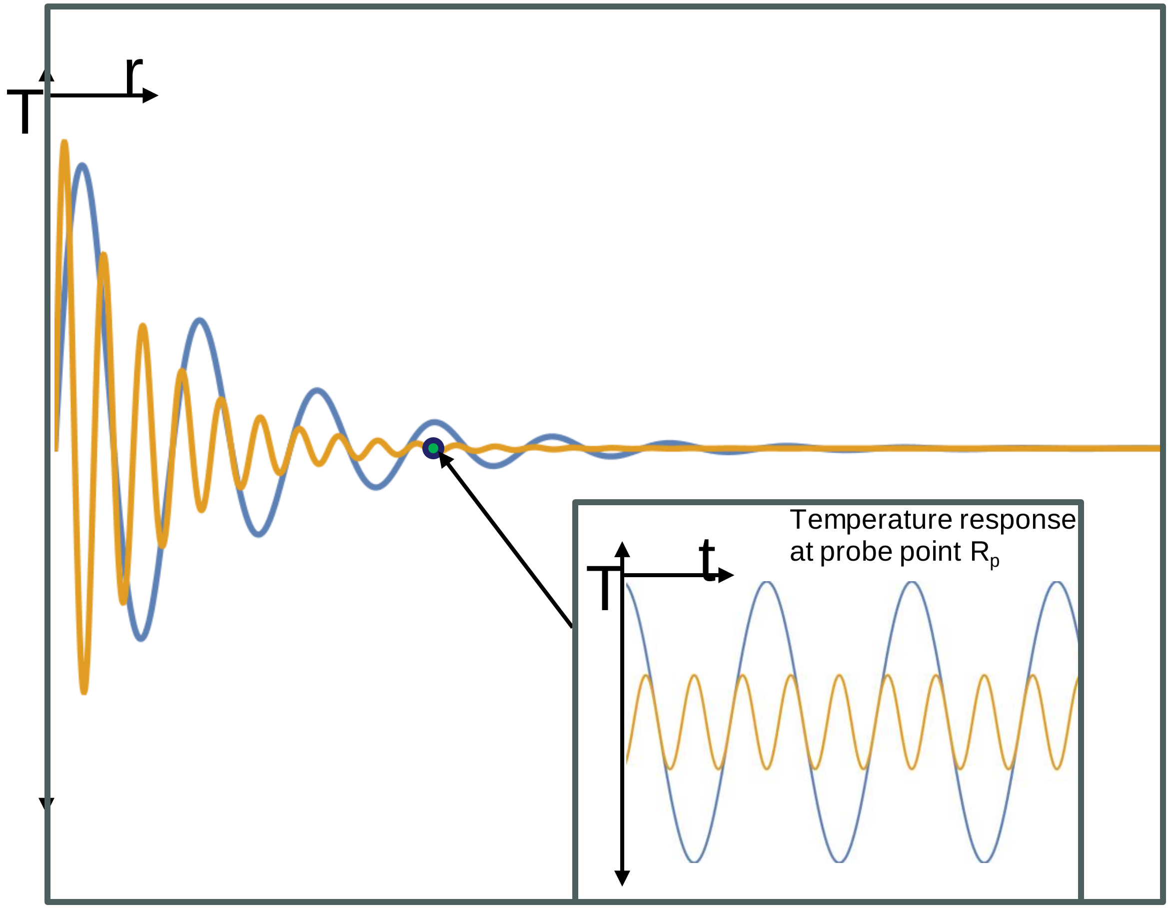


[Carmack, 2009]

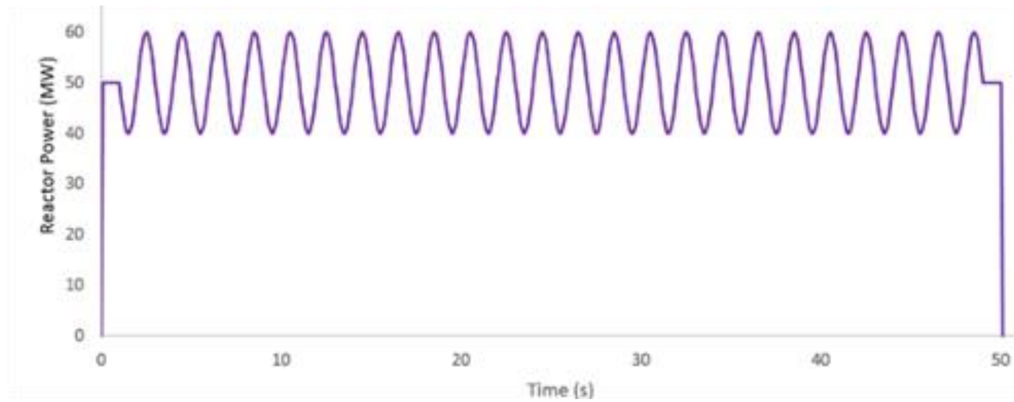
Thermal Wave Overview

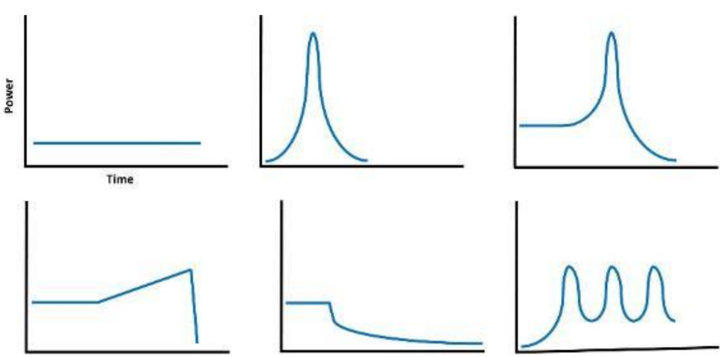
2 temperature waves propagating in response to sinusoidal temperature variation along the left boundary

	Wave 1	Wave 2
Source Amplitude	A	A
Frequency	f_1	$f_2 = 3*f_1$
$R_{th}=\sqrt{\frac{\alpha}{\pi f}}$ (thermal diffusion length)	R_{th1}	$\sqrt{\frac{1}{3}}R_{th1}$
$\sigma = \frac{1}{R_{th}}$ (wave number)	σ_1	$\sqrt{3}\sigma_1$

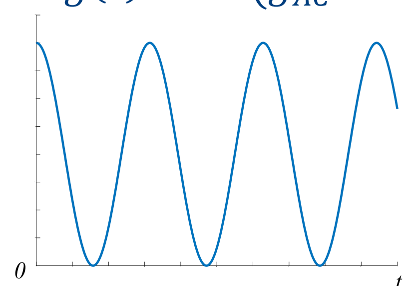


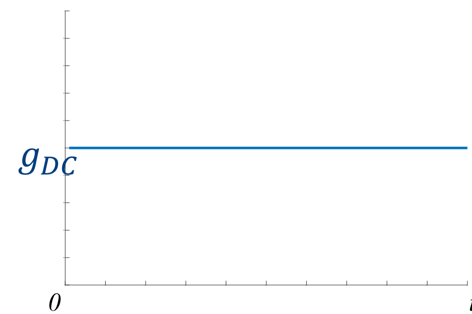
Controlled Heat Generation in TREAT

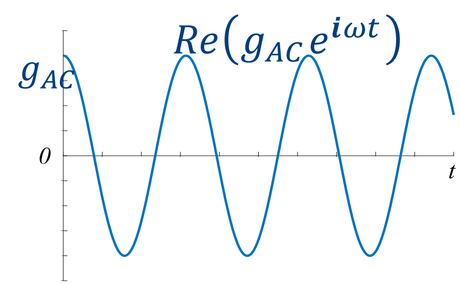




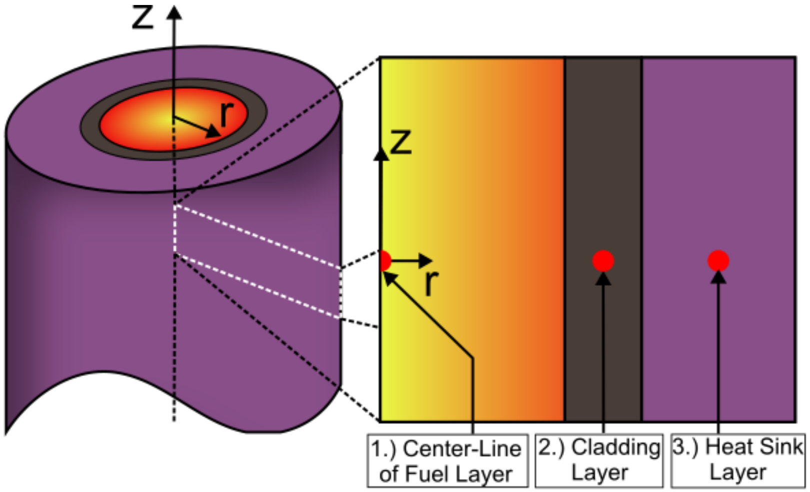
$$g(t) = Re\left(g_{AC}\, e^{i\omega t}\right) + g_{DC}$$

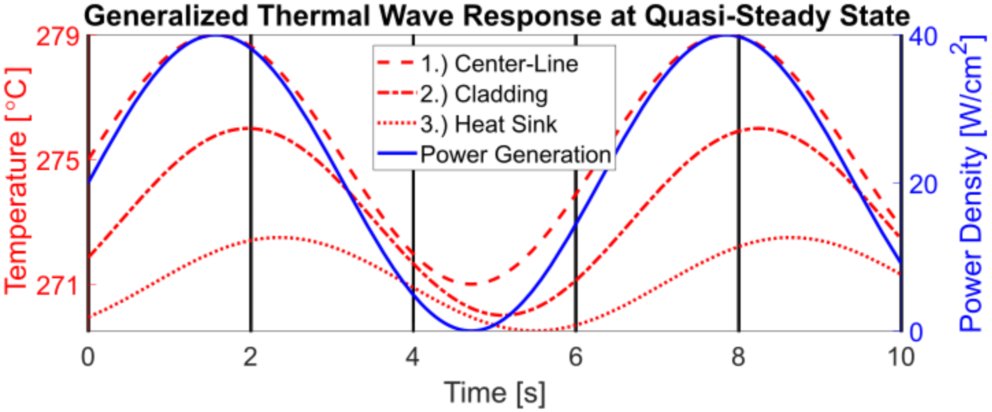




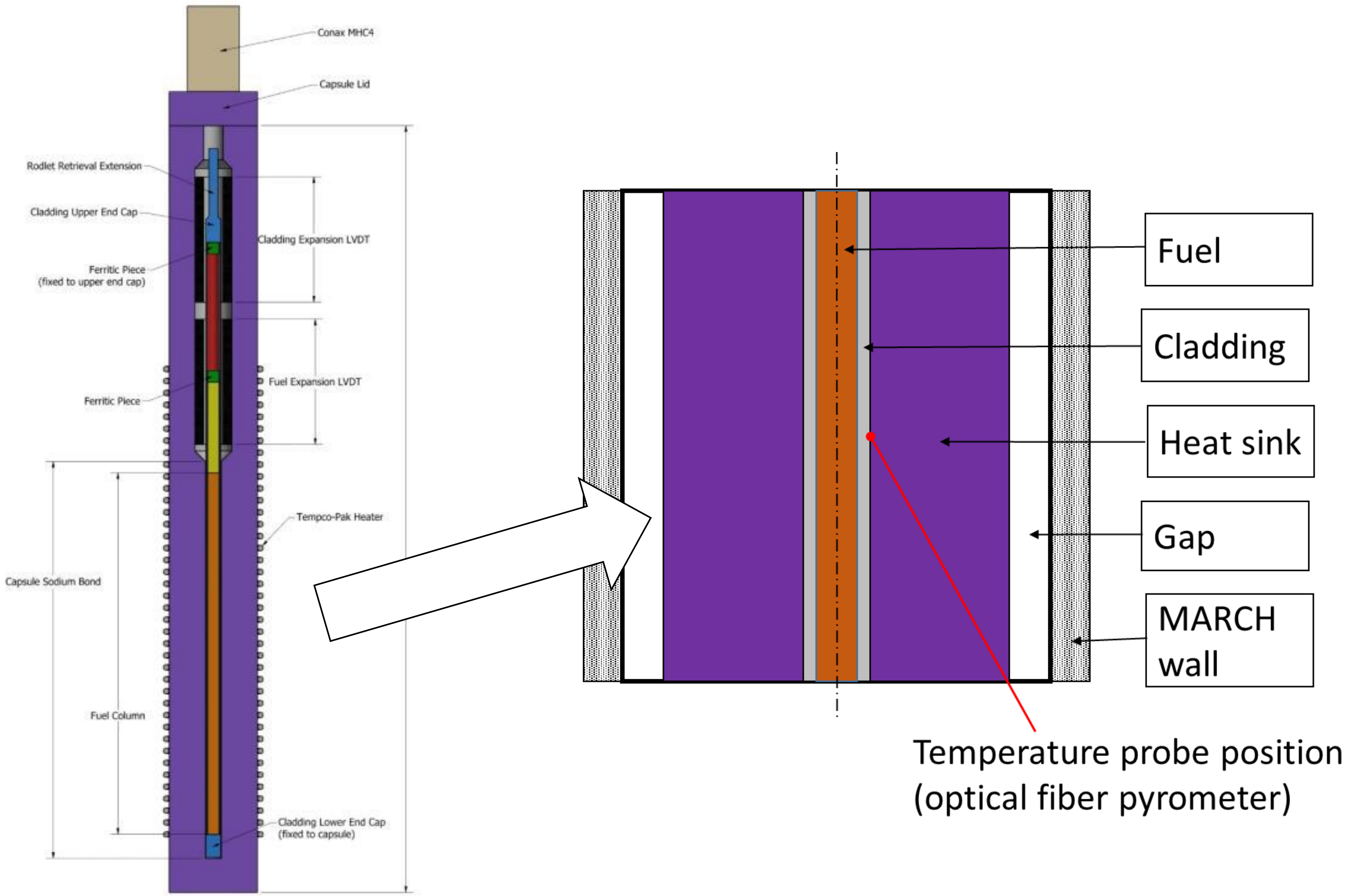


Idealized Thermal Wave Response for a Simplified Fuel-Cladding-Heatsink System





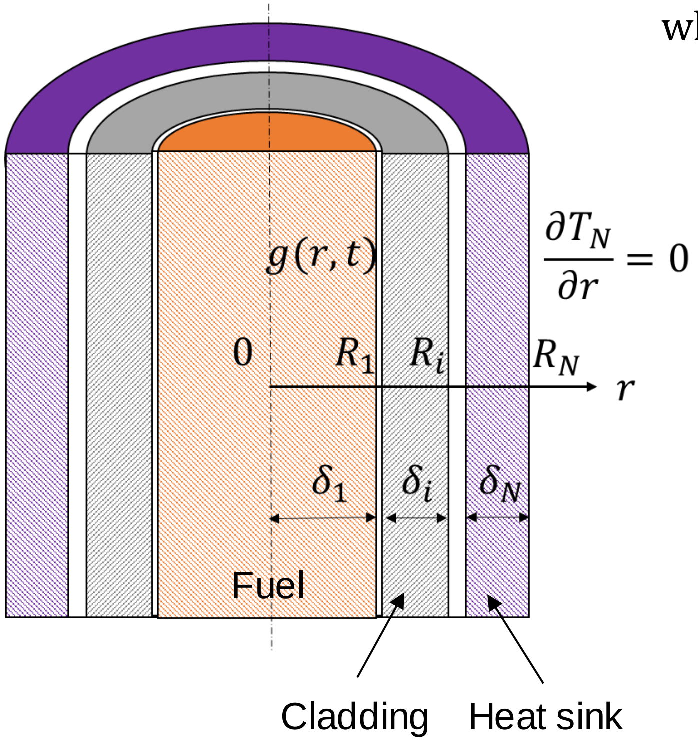
Temperature Heat-sink Overpower Response Module (THOR)

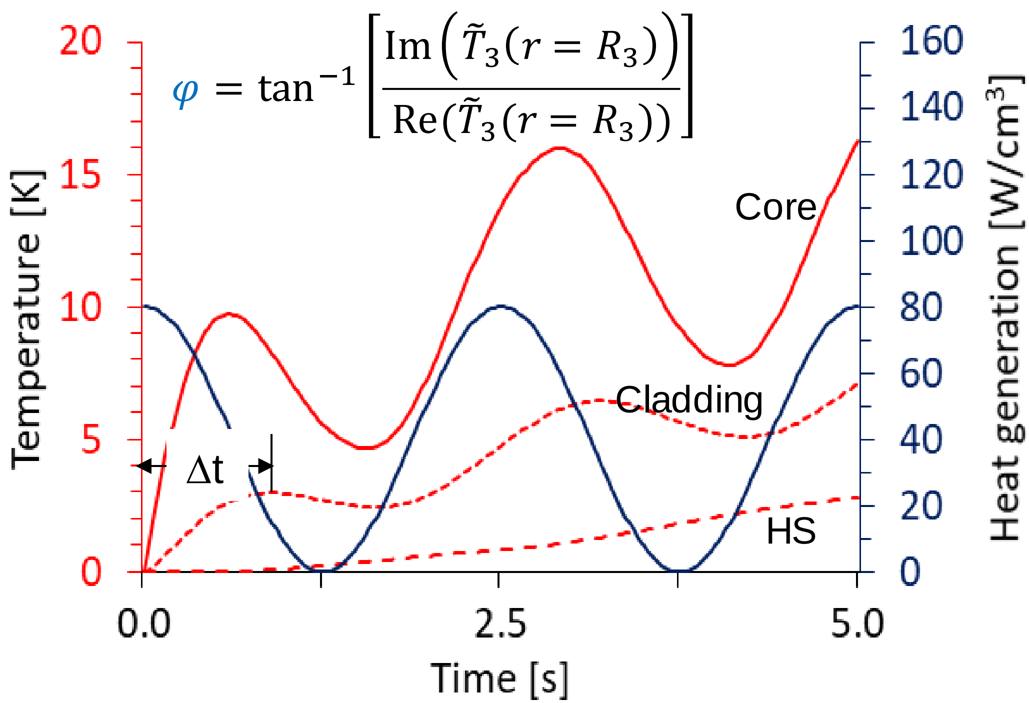


Measurement of Thermal Diffusivity - Conductivity Using Thermal Wave

$$g(t) = Re\left(g_{AC}e^{i\omega t}\right) + g_{DC} \implies T(r,t) = Re\left(\tilde{T}_i(r,\omega)\right) + T_{DC}(r,t)$$

$$\text{where } \tilde{T}_i(r,\omega) = \frac{2\pi\alpha_1 g_{AC}(\omega)}{k_1}\int_0^{R_1} G_i\left(r\middle|r';\omega,\alpha_j,k_j\right)r'dr'$$





Uncertainty for Measurements Based on a Single Test

Measurement performed only at the optimal frequency. As a result, only one parameter among *k* and α of fuel is unknown, and the other is precisely known.

$$u(\alpha_1|x_i) = \frac{S(x_i)}{S(\alpha_1)}u(x_i);\ u(k_1|x_i) = \frac{S(x_i)}{S(k_1)}u(x_i)$$

Parameter	Un	0.2Hz 5mm Ti		0.2Hz 10mm Ni200		0.34Hz 10mm Na		0.2Hz 6mm HT9	
		k_1	α_1	k_1	α_1	k_1	α_1	k_1	α_1
k of cladding	5%	1.8%	-0.8%	0.4%	-0.2%	1.3%	-0.5%	1.2%	-0.6%
k of heat sink	5%	-6.9%	3.3%	-5.6%	2.5%	-6.4%	2.7%	-6.4%	3.0%
α of cladding	5%	-4.5%	2.2%	-3.6%	1.7%	-5.2%	2.2%	-4.1%	1.9%
α of heat sink	5%	5.0%	-2.4%	-1.1%	0.5%	5.2%	-2.2%	-0.1%	0.0%
δ of fuel	1%	1.0%	-0.5%	-3.3%	1.5%	1.0%	-0.4%	-0.6%	0.3%
δ of cladding	1%	0.4%	-0.2%	-0.5%	0.2%	0.3%	-0.1%	0.0%	0.0%
δ of heat sink	1%	-1.4%	0.7%	0.5%	-0.2%	-1.9%	0.8%	0.5%	-0.3%
Probe Position	1%	3.3%	-1.6%	5.9%	-2.7%	4.8%	-2.0%	4.1%	-2.0%
Phase	0.5°	-6.8%	3.3%	-6.7%	3.1%	-6.7%	2.7%	-6.7%	3.2%
Total Uncertainty		12.5%	6.0%	11.7%	5.3%	13.1%	5.5%	11.0%	5.2%

Sample Selection and Preparation

- **Over 13,000 Mark-III/IIIA/IV fuel rods (U-10Zr) and 600 U-Pu-Zr fuel rods were cast and irradiated to burnups ranging from 10% (U-Zr) to 20% (U-Pu-Zr)**
- **Only a tiny portion of fuels has been subjected to post-irradiation examination. Even smaller fraction has been subjected to detailed characterization with state-of-the-art tools available now**
- **Four TREAT experiments using U-19Pu-10Zr sample of burnups at 1.9, 4.9, 11.2 and 19.3 at% are proposed considering the limitation of NSUF TREAT scheduling and project scope.**

Composition	Burnup (at %)
U-19Pu-10Zr	1.9
U-19Pu-10Zr	4.9
U-19Pu-10Zr	11.2
U-19Pu-10Zr	19.3

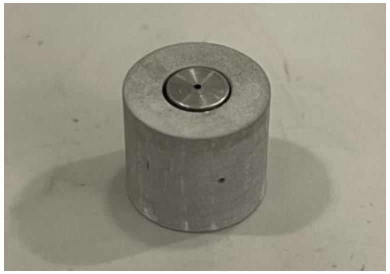
Ongoing Work at the University of Pittsburgh:

1. **<u>Develop and demonstrate</u> the proposed measurement method via laboratory experimentation**

2. **<u>Quantify the capabilities</u>, limits, and errors associated with the developed measurement method**

3. **<u>Investigate the applicability</u> of the method on degraded samples to prove the relevance for nuclear fuel property tracking**

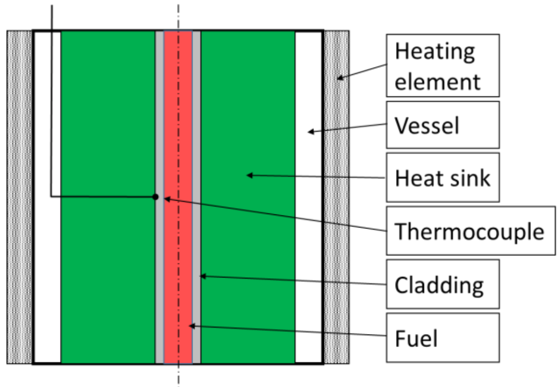
<u>Stage 1:</u> Investigatory rectangular coordinate system experiment

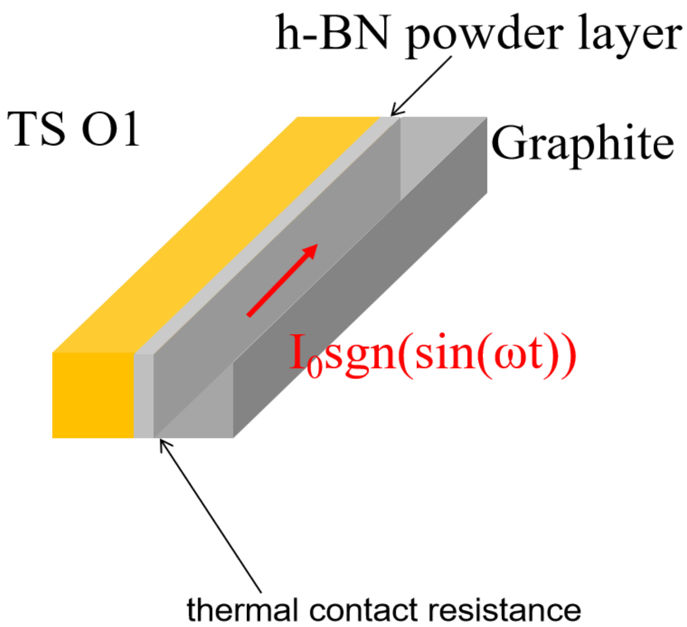


<u>Present:</u> Refined proof of concept and expanded study

<u>Stage 2:</u> Proof of concept cylindrical coordinate system experiment

Stage 1 (Rectangular): Plane Layered System

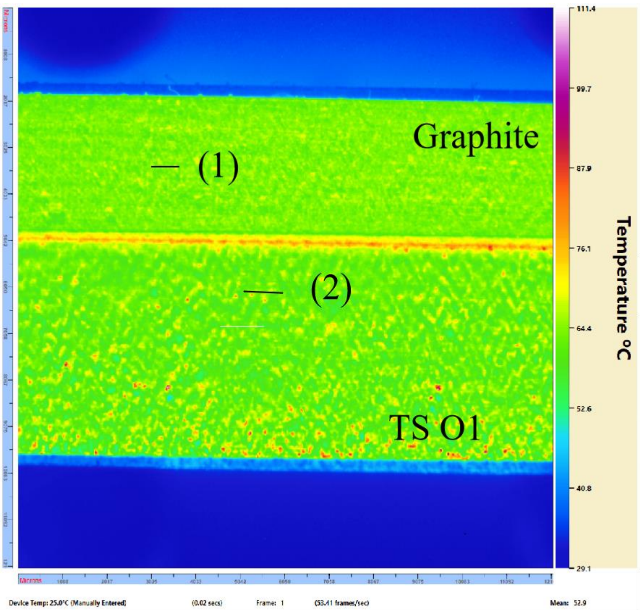


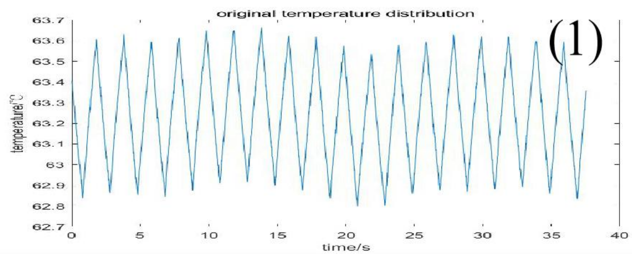


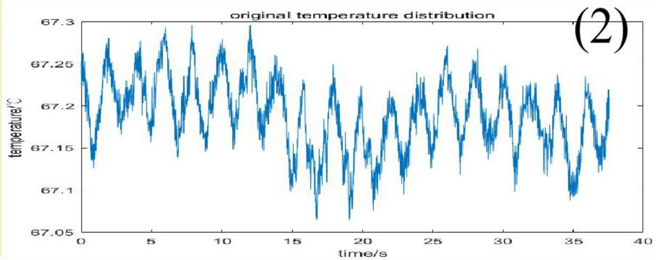
- A plane, layered system was used to in lab testing
- Electrical heating used to simulate reactor power shaping
- Temperature is measured by an IR video camera

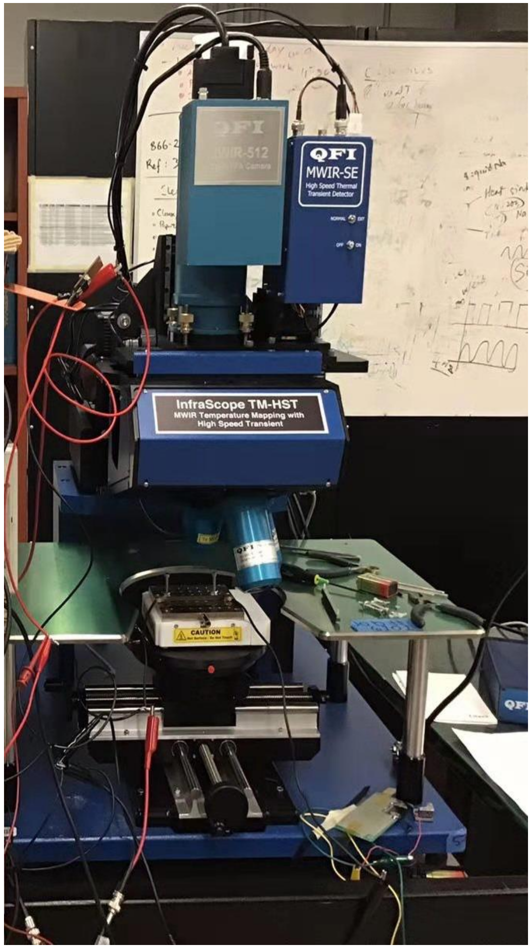
Material type	Conductivity W/m*K	Diffusivity m^2/s	Density kg/m^3	Heat capacity J/kg*K
Graphite	83	64.2e-6	1820	710
h-BN	22.643	12.445e-6	2280	798
Tool Steel O1	64	17.78	7810	461

Stage 1(Rectangular): Experimental System



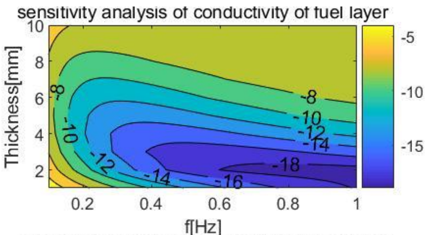


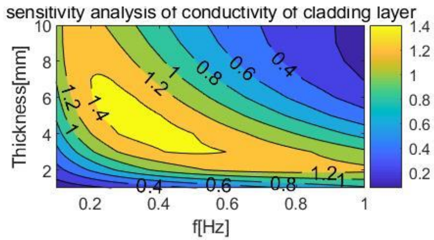


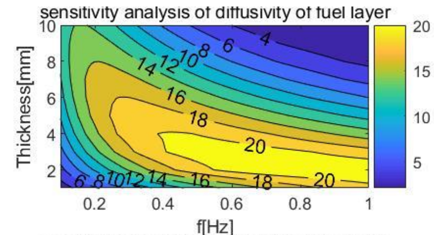


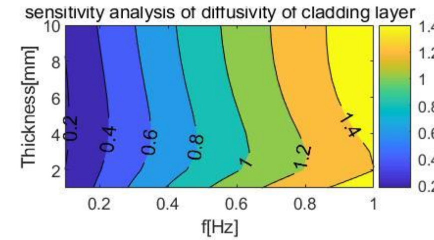
QFI InfraScope™ MWIR Temperature Mapping Microscope

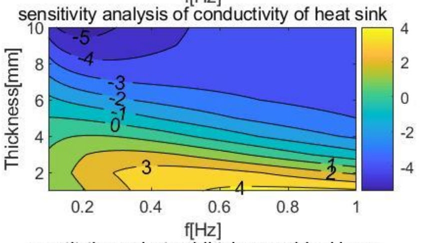
Experimental Design: Thickness of Fuel Layer

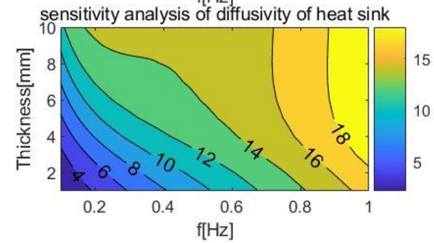


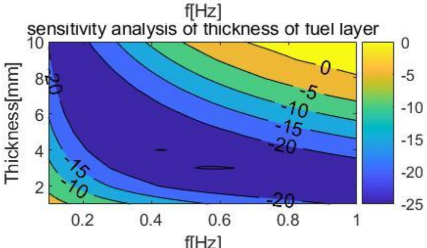


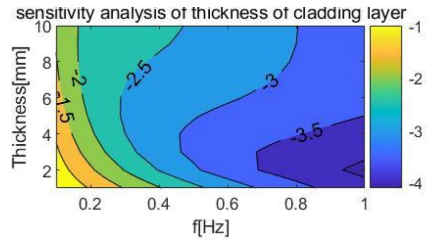


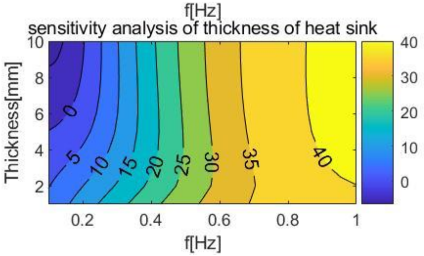






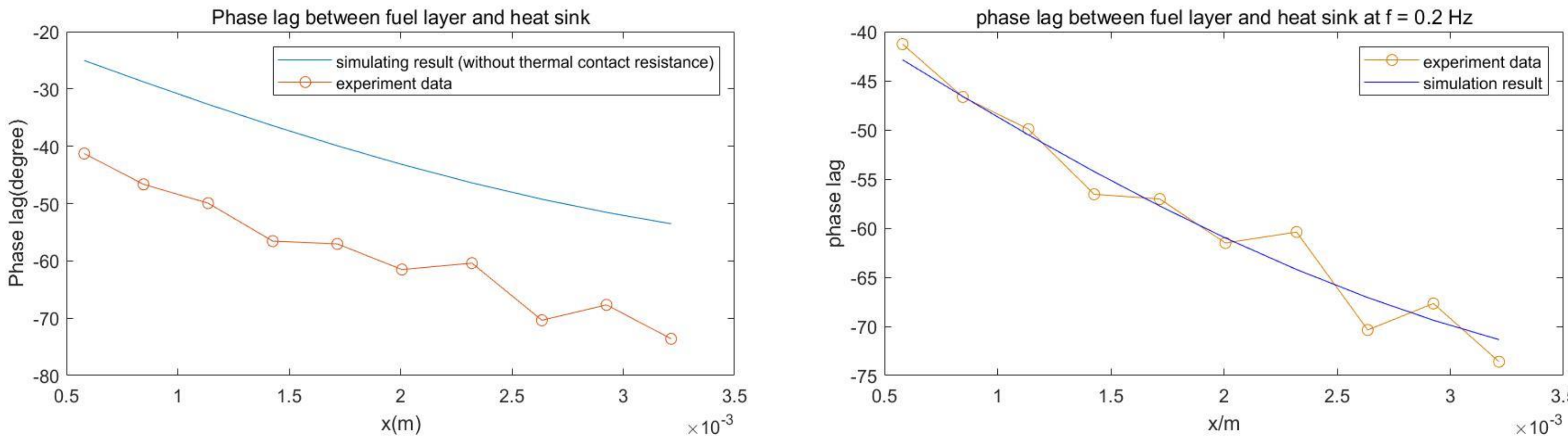






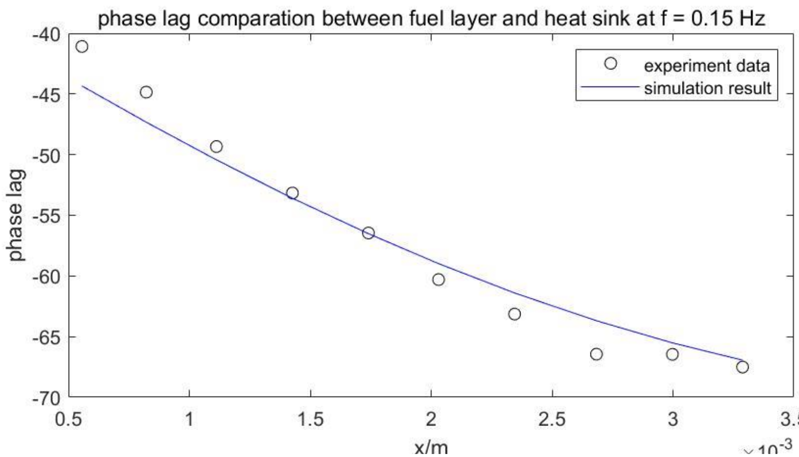
- **The ideal frequency is [0.4, 1.0] Hz**
- **The ideal thickness of fuel layer is [2, 4] mm.**

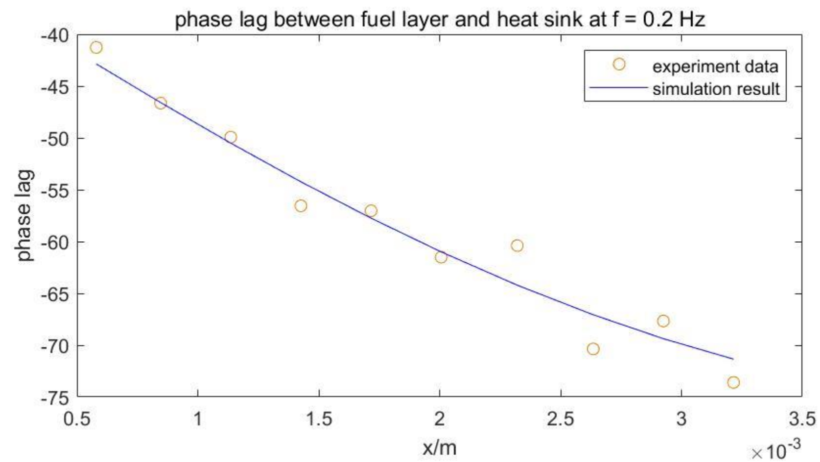
Stage 1 (Rectangular): Thermal Contact Resistance

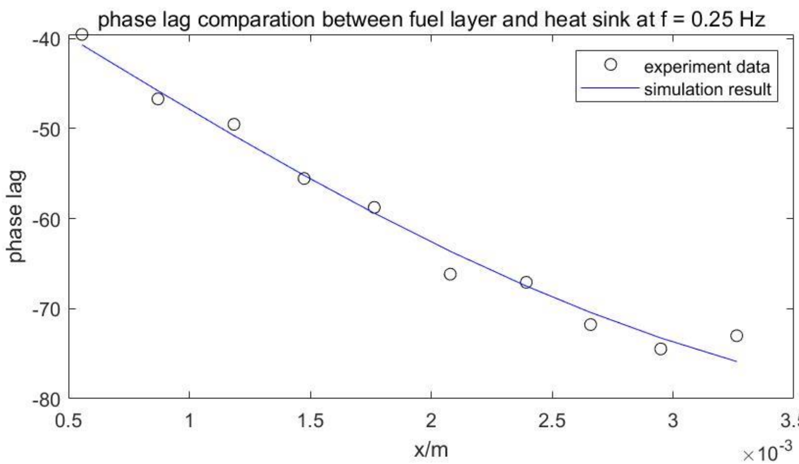


- Thermal contact resistance poses a technical challenge in lab experiments. It became another unknown to be determined
- It will not be an issue for reactor experiments because of sodium bonding between fuel and cladding

Stage 1 (Rectangular): Computational Fitting for Thermal Contact Resistance





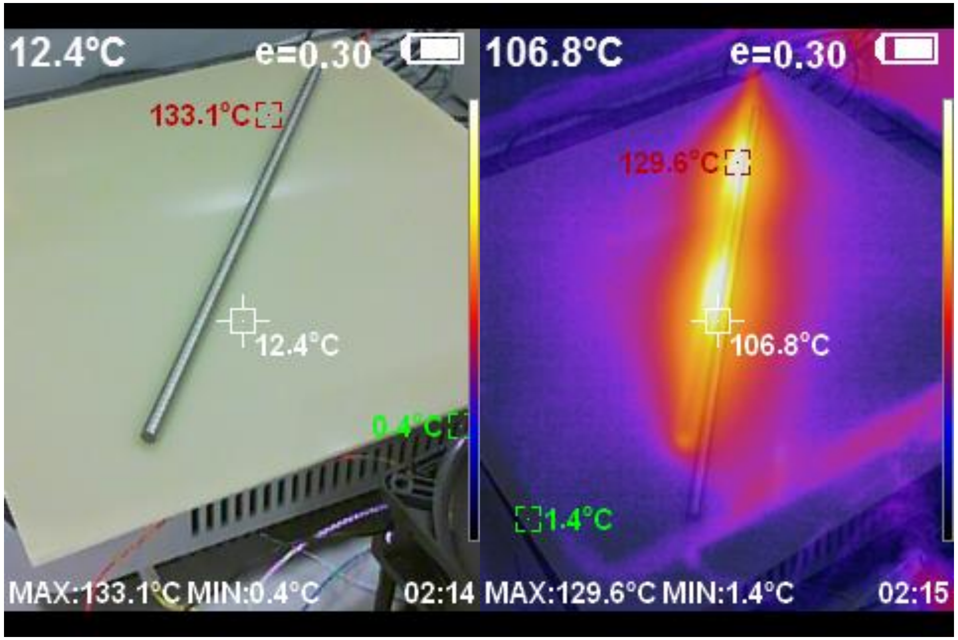


Frequency/Hz	0.15	0.2	0.25
Thermal contact resistance (K/W)	6.4188e-05	4.8166e-05	3.8659e-05

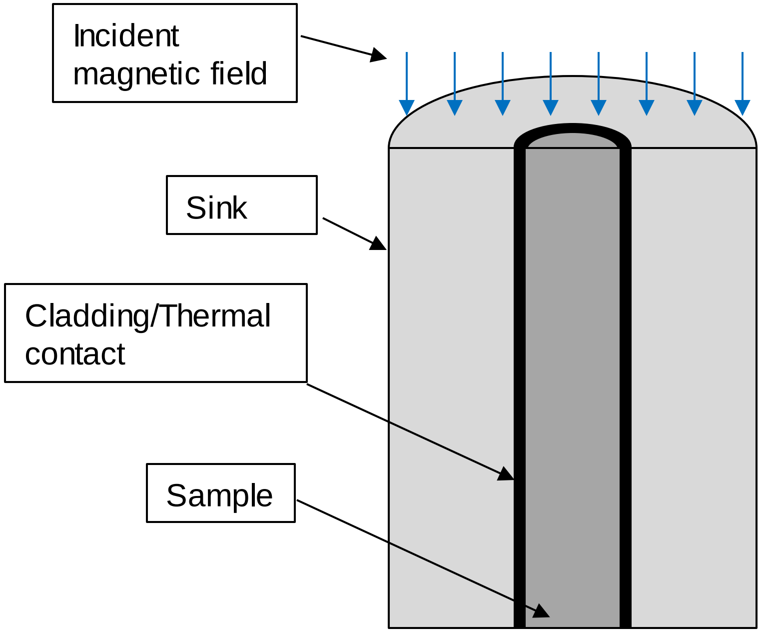
Stage 2 (Cylindrical): Heating Mechanism

- **Near volumetric heating mechanism**
- **Strong heating response in ferritic stainless steels**
  - Negligible to no response in other materials

SS430 response vs surroundings:

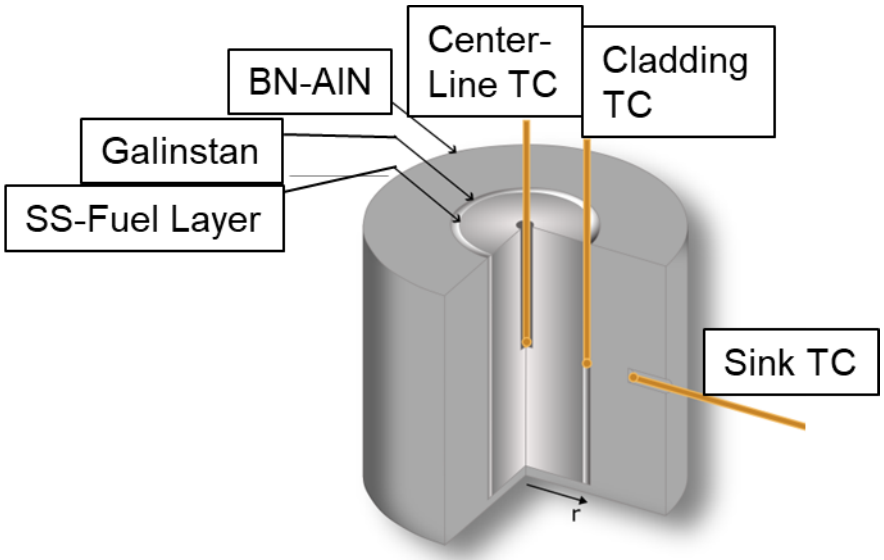


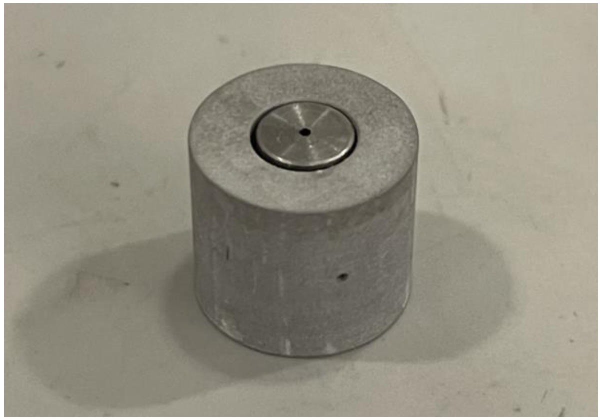
Idealized Specimen:



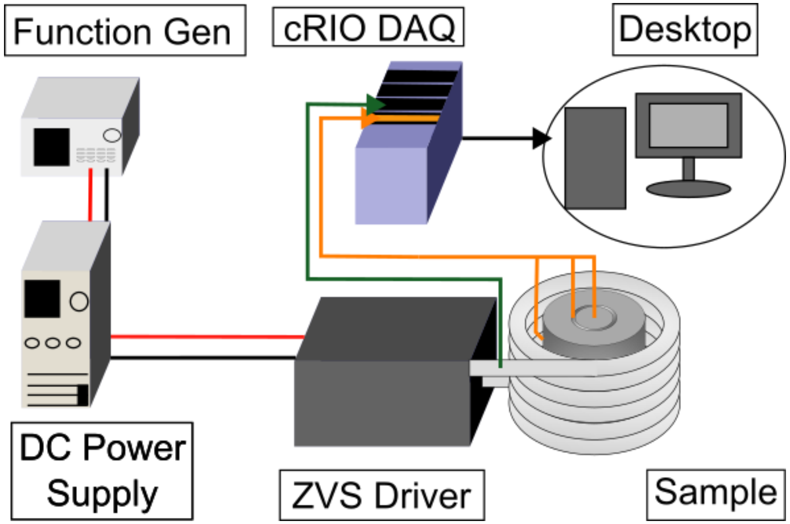
Stage 2 (Cylindrical): Experimental Setup

Specimen Assembly:





Experimental Setup:



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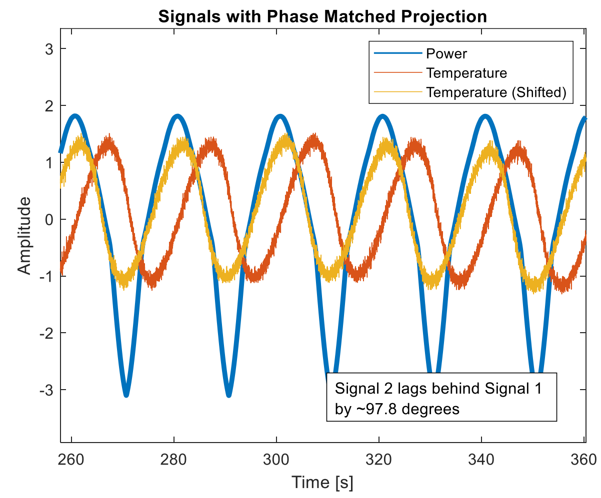
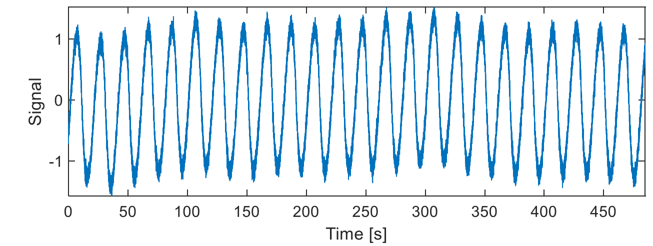
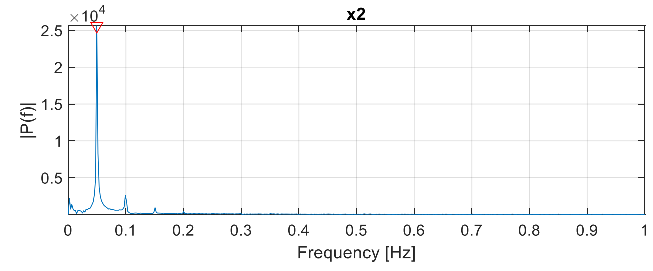
Stage 2 (Cylindrical): Testing Procedure

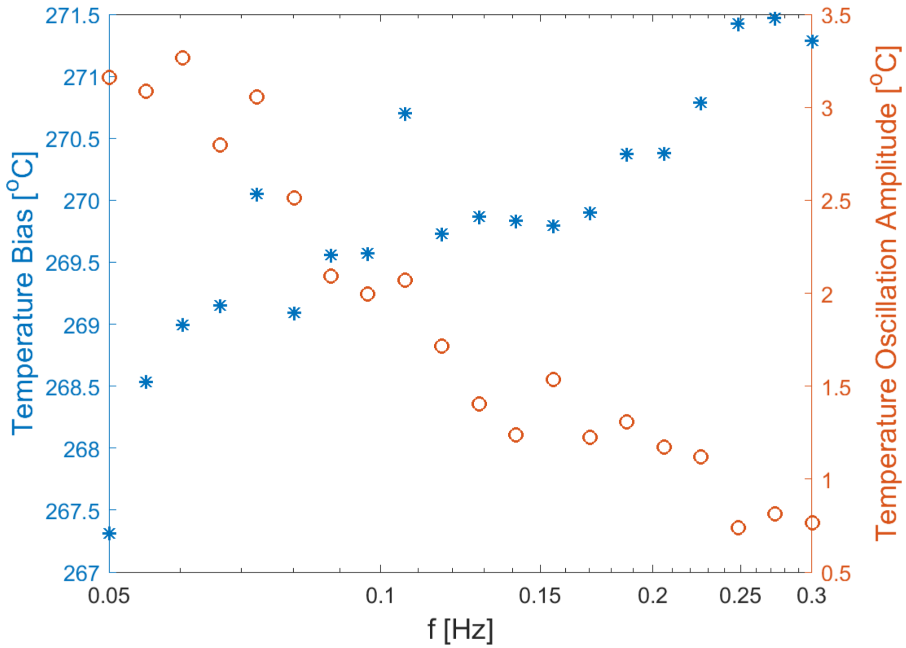
- **Heat specimen to <u>quasi steady state</u>**
- **Test:**
  - N = 24 Cycles
  - Frequency sweep: <u>20 logarithmically spaced frequencies</u> across [0.05 -0.3 Hz]
- **Post-process consists of FFT analysis to calculate phase <u>delay between the sink temperature wave and the power</u>**
- **Use nonlinear least-squares regression to <u>back-out the predicted thermal properties</u> of the fuel layer**







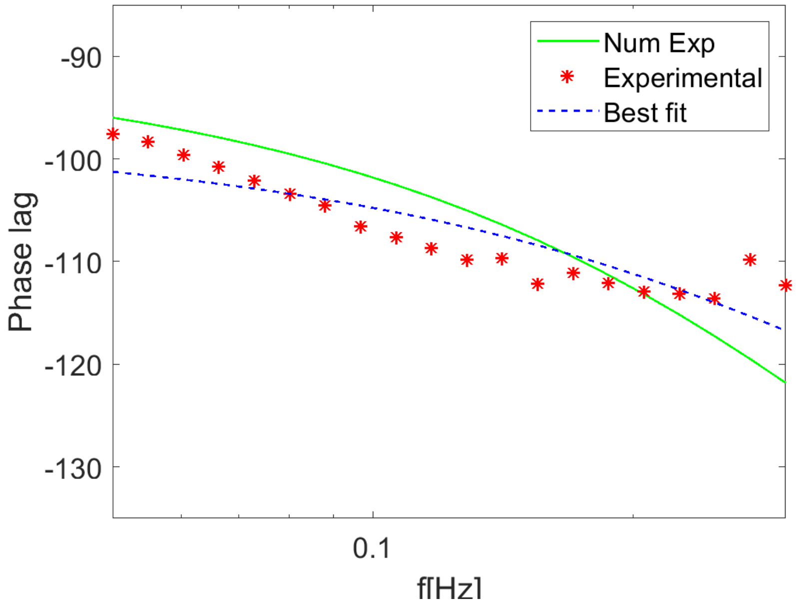
Stage 2 (Cylindrical): Wave Components at the Probe Point



- **Amplitude falls as frequency rises, limiting the frequency upper bound**
  - $R_{th} = \sqrt{\frac{\alpha}{\pi f}}$
- **Bias trend due to system settling (slower f tested first)**
- **Low amplitude to bias ratio**

Stage 2 (Cylindrical): Results & Takeaways (Phase curve & Predictions)

1. **Thermal diffusivity sensitivity of the fuel layer is high**
2. **Frequency sweeps are preferred to spatial sweeps**
3. **Temp bias is high for fine gauge TC. Optical preferred.**
4. **Heating method likely needs altered due to non-uniformity (skin depth)**



	Actual	Predicted	$\frac{Actual}{Predicted}$
$\alpha_{fuel}\ [\frac{m^2}{s}]$	6.88e-6	7.15e-6	1.0391
$k_{fuel}[\frac{W}{mK}]$	24.2	2.40	0.099
$\alpha_{cladding}[\frac{m^2}{s}]$	8.66e-6	–	–
$k_{cladding}[\frac{W}{mK}]$	16.5	–	–
$\alpha_{heatsink}[\frac{m^2}{s}]$	2.87e-5	–	–
$k_{heatsink}[\frac{W}{mK}]$	75.8	–	–
$r_{probe}[mm]$	5.60	5.57	0.947

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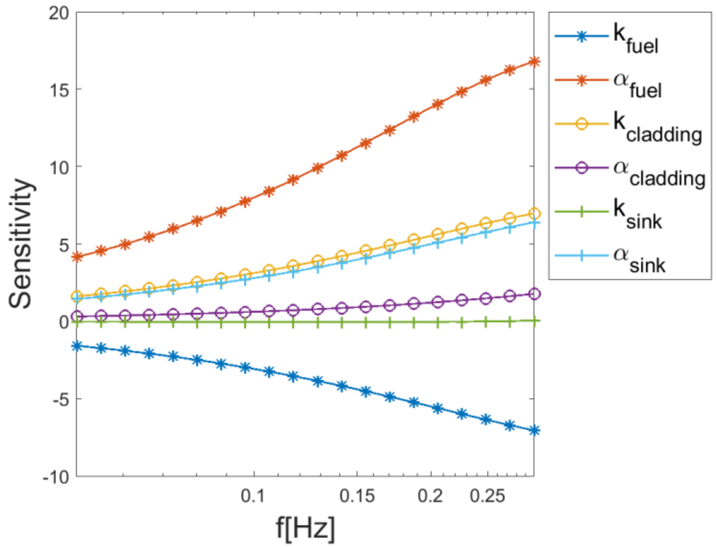
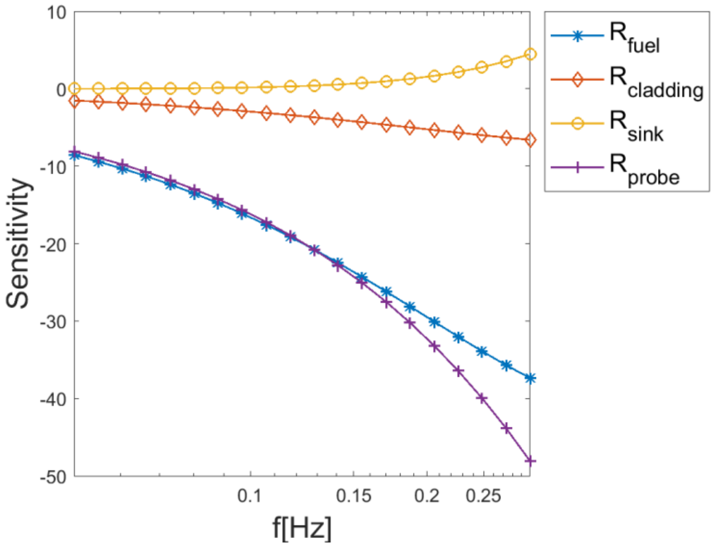
Preliminary System: Results & Takeaways (Sensitivity error source)

Thermal Sensitivities:



Length Sensitivities:



$$S(x) = \frac{\phi(x+\Delta x) - \phi(x)}{\Delta x / x}$$

$$\tilde{T}_i(r,\omega) = \frac{2\pi\alpha_1\tilde{g}(\omega)}{k_1}\int_0^{R_1} G_i(r|r';\omega,\alpha_1,k_1)r'\,dr'.$$

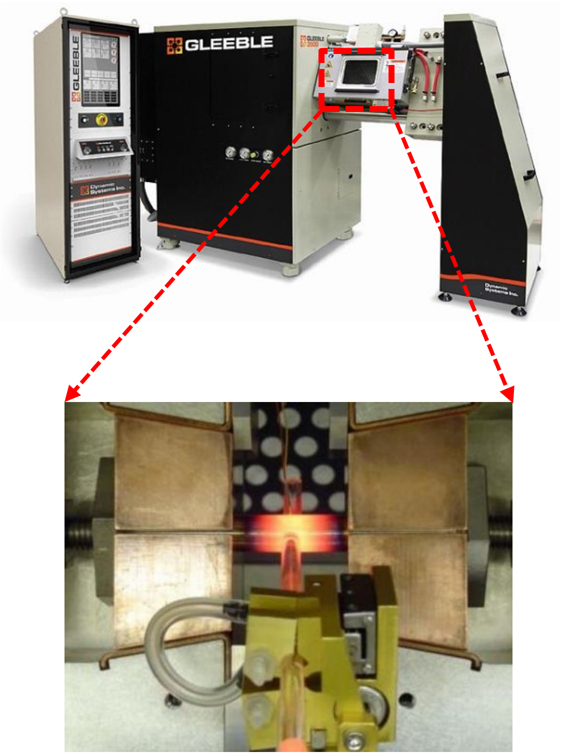
$$\phi = \arctan\frac{Im(\tilde{T}_i)}{Re(\tilde{T}_i)}. \qquad \alpha = \frac{k}{\rho c_p}$$

- **Roughly 2x as sensitive to α than to k**
  - k cancels in leading coefficient, direct dependence in Green's function
- **Strong Sensitivity to layer and probe radial lengths**

On-Going & Future Experimentation

Future Experimentation will be twofold:

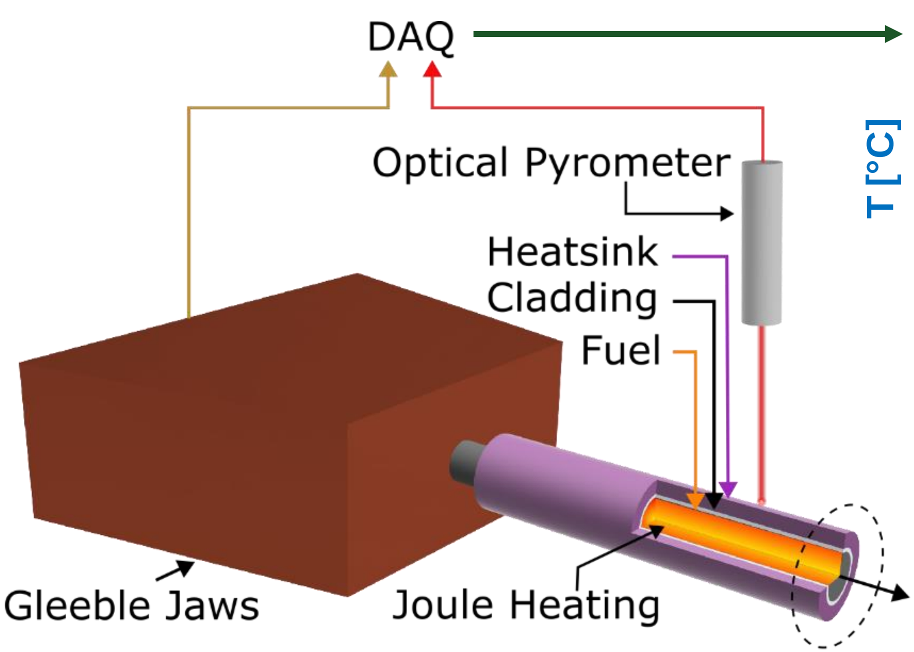
1. **Enhancement of experimental heating**
   - Transition to <u>Gleeble 3500</u> thermal-mechanical physical simulation system
     - Improved environmental and heating control
2. **Exploratory external heating adaptation**
   - Can we measure properties of samples using an <u>outer conductive layer</u> to drive heating
     - Open the door for supplementary degradation-based experimentation



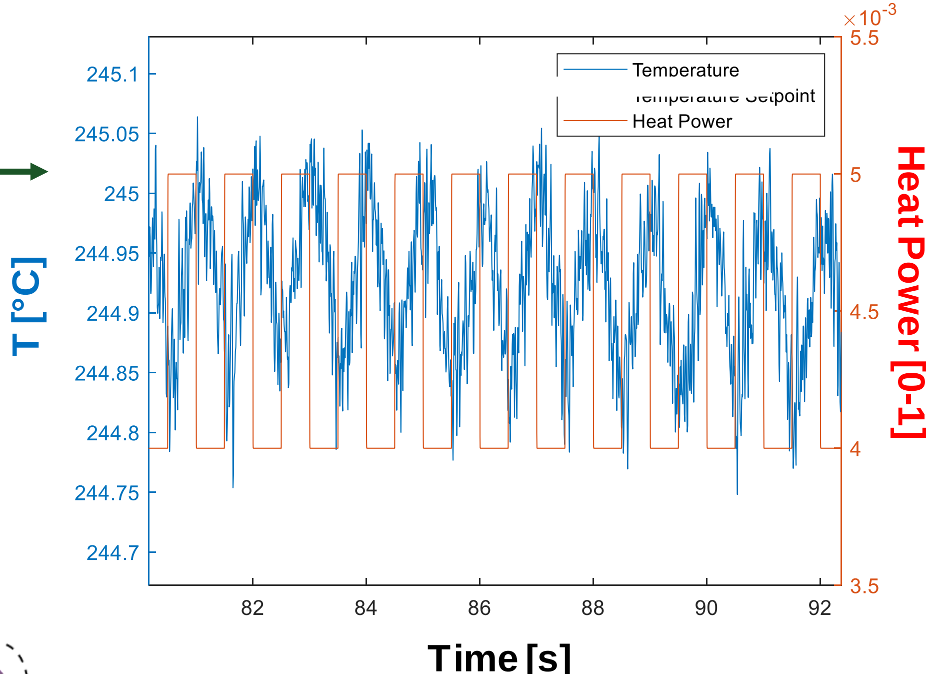
[Dynamic systems, Inc]

On-Going Experimentation: Gleeble based Thermal Wave testing

- **Test 2 orders of α**
  - 10^{-6} [m^2/s]
- **Heating:**
  - Utilize high speed joule heating
- **Temperature Measurement:**
  - Optical Pyrometer



Initial fuel wall temperature & power probing of an un-sheathed specimen at 1Hz using welded TC:



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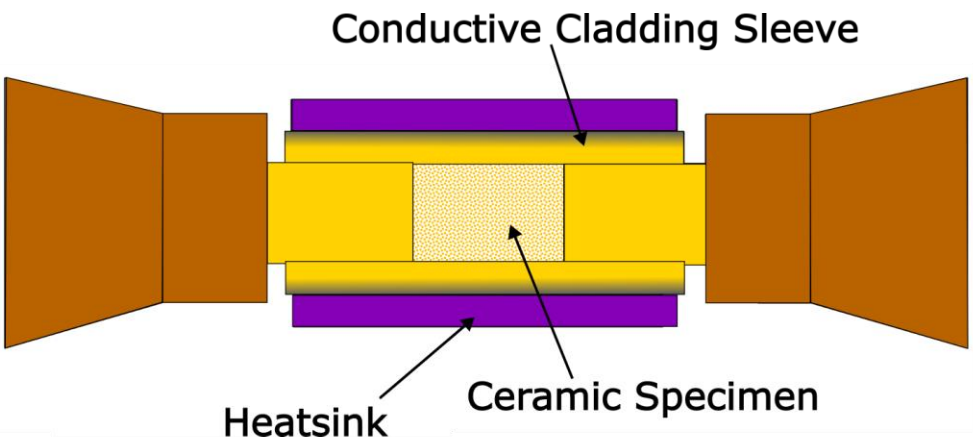
Future Work: Degradation Study

- We can apply this method to a system with the source in external layer.
- Conductive sleeve to drive heating in a ceramic specimen
- Initial sensitivity studies show a sufficient degree of sensitivity



Highlights – Overall

- **Recent Accomplishments:**
  - Completed study of the magnetic heating-based cylindrical system
  - The refined Gleeble 3500-based cylindrical experiment has been designed and preliminary tests are underway
- **Issues (schedule/cost/technical):**
  - Delays in Pitt Gleeble installation has resulted in needing to use neighboring university's system (Carnegie Mellon)
- **Look Ahead (30/60/90 days):**
  - Complete modelling work (Monte-Carlo & Nondimensionalization studies) for publication
  - Begin experimental investigation of external heat source measurements & degradation studies

MARCH-SETH-THOR

- TREAT separate Effect Test Holder (SETH)
- SETH holder with a heat sink (THOR)
- Sample preheating to desired temperature
- Power shaping to simulate harmonic heating for no more than 30 seconds