Advanced Instrumentation for Transient Reactor Testing

2014 Integrated Research Project
Idaho State, Kansas State, Ohio State, UW-Madison
Idaho National Laboratory, CEA-Cadarache

Michael Corradini, Project Lead; G.Imel, ISU, J.Roberts, KSU; T.Blue, OSU; M.Anderson, UW; K.Davis, INL, J.F.Villard, CEA

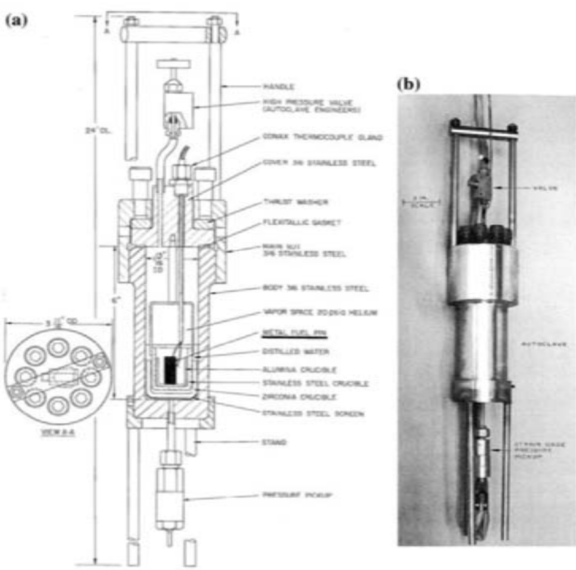
May 20th, 2017

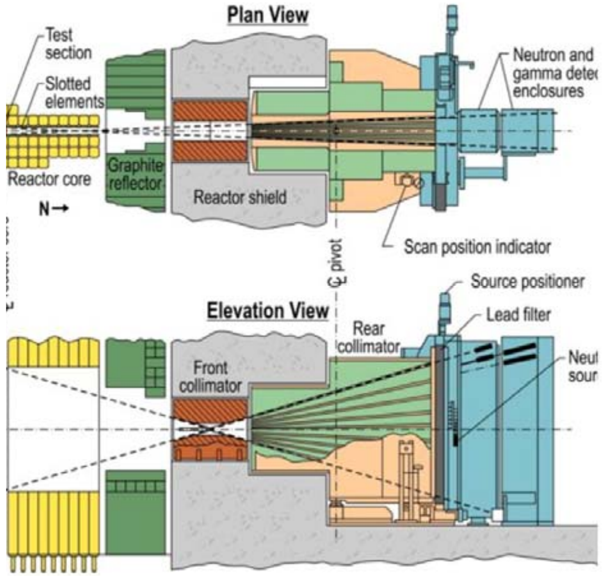
Idaho State UNIVERSITY K·STATE INL WISCONSIN ENERGY INSTITUTE UNIVERSITY OF WISCONSIN–MADISON

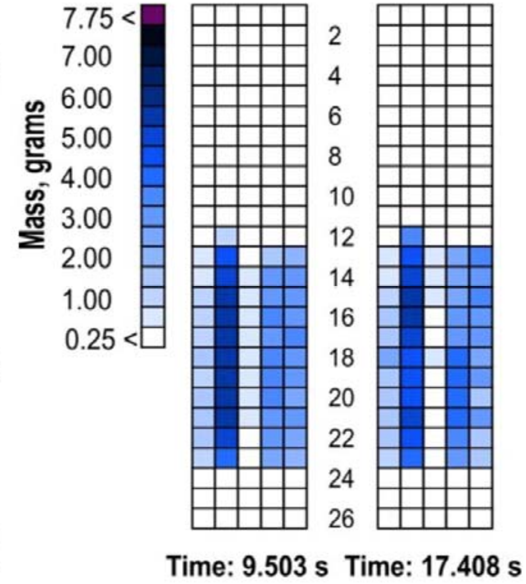
IRP Project Scope

Motivation: Ability to monitor fuel behavior in real-time will provide more information on the fuel rod state, help provide a better understanding of the physics of fuel behavior under transients

Scope: Develop and demonstrate innovative measurement diagnostics for real-time in-situ monitoring to support transient reactor testing.







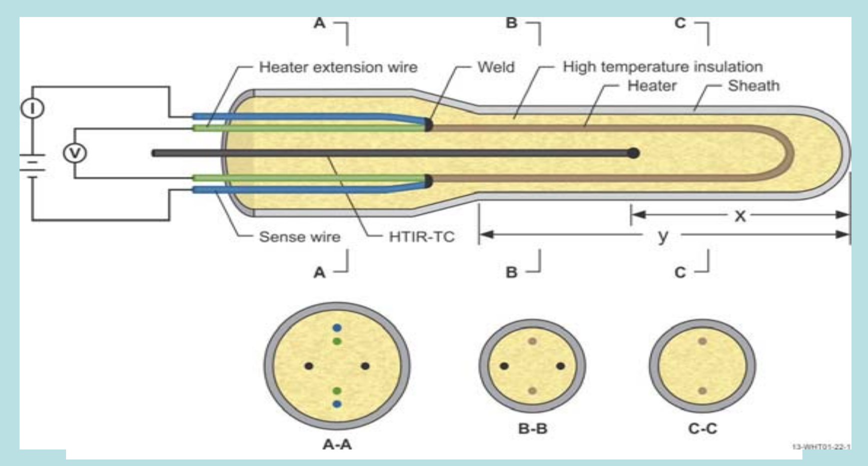
Advanced Instrumentation for Transient Reactor Testing

M.L.Corradini, University of Wisconsin

Technology Summary

Our team is developing specific innovative measurement diagnostics for real-time in-situ monitoring in support of transient reactor testing in three key program elements:

- Develop concepts that lead to next generation fuel motion monitoring system; i.e., advancements in spatial and temporal resolution for hodoscope imaging.
- Develop instrumentation to support in-pile transient testing that includes temperature measurements, local fast and thermal neutron flux measurements.
- Demonstrate these novel instrumentation measurement methods in a reactor environment using university TRIGA reactors.



Key Personnel

G.Imel, ISU, J.Roberts, KSU; T.Blue, OSU; M.Corradini, M.Anderson, UW; K.Davis, INL, J.F.Villard, CEA

Program: Integrated Research Project IRP-NE Budget: $3m

Key Milestones & Deliverables	
Task 1	• Modeling of TREAT for hodoscope optimization • Improve HB design w MSND design development
Task 2	• Design, fabricate, test MPFD for use in TREAT • Design, fabricate, test Diamond TC sensor • Design, fabricate, test Distributed TC sensor • Fabricate and test HTIR, Ultrasonic TCs, TC probe
Task 3 and 4	• Out-of-pile testing of these instruments in transient • In-reactor (TRIGA) testing of these instruments

Technology Impact

Currently transient reactor testing involves hodoscope measurements with post-test fuel examination. This diagnostic development seeks to provide in-situ real-time monitoring of local fluxes and temperatures

Provide TREAT In-situ Real-time Measurements for Transient Fuel Testing

Project Organization

Advanced Instrumentation for Transient Reactor Testing
IRP Organization

IRP Project Lead
Michael Corradini (UW)

IRP University Partners

- **Idaho State Univ.** *George Imel*
- **Kansas State Univ.** *Jeremy Roberts*
- **Ohio State Univ:** *Tom Blue/Ray Cao*
- **UW-Madison** *Mark Anderson*

IRP Laboratory Partners

- **Idaho National Lab** *Kurt Davis*
- **CEA-Cadarache** *Jean-Francois Villard*

External Advisory Board

- **DOE/INL:** S.Schuppner, D.Wachs, C.Jensen
- **Industry Experts**: Areva, GE, NRC, NuScale, Terrapowr,Westinghouse

Task Areas & Investigator Distributions:

Task I: Real-Time Imaging: *G.Imel (ISU)***, P.Ugorowski (KSU)***, J.Roberts (KSU), T.Unruh (INL), M.Anderson (UW)*

Task II: Sensors: *M.Anderson***, J. Blanchard, J.Ma (UW), T.Blue (OSU), D. McGregor (KSU), J.Daw (INL)*

Task III: Out-of-Pile Tests: *T.Blue (OSU)***, M. Anderson (UW)***, D.Knudson (INL), B.Chase (INL)*

Task IV: In-Pile Tests: *D. McGregor (KSU)***, M.Anderson (UW)***, B. Agasie (UW), J.Roberts (KSU), K.Davis (INL)*

Task V: Transient Test Design: *M.Corradini (UW)***, G.Imel (ISU),*

***** Indicates Team Leads or Co-Leads**

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G.Imel, K. Tsai, H. Aryal, ISU

Task I:

- Improve modeling (MCNP) of the flux at the hodoscope plane with million particles to ensure better quality flux predictions.
- Figure below shows the X-Y flux plot with the flux measured in # of neutrons/cm^2.
- Use Filtered Back Projection technique to ascertain source distribution from the flux obtained analytically.

Alternate option being investigated is to use the MAMMOTH code from INL for transient simulation (ongoing)

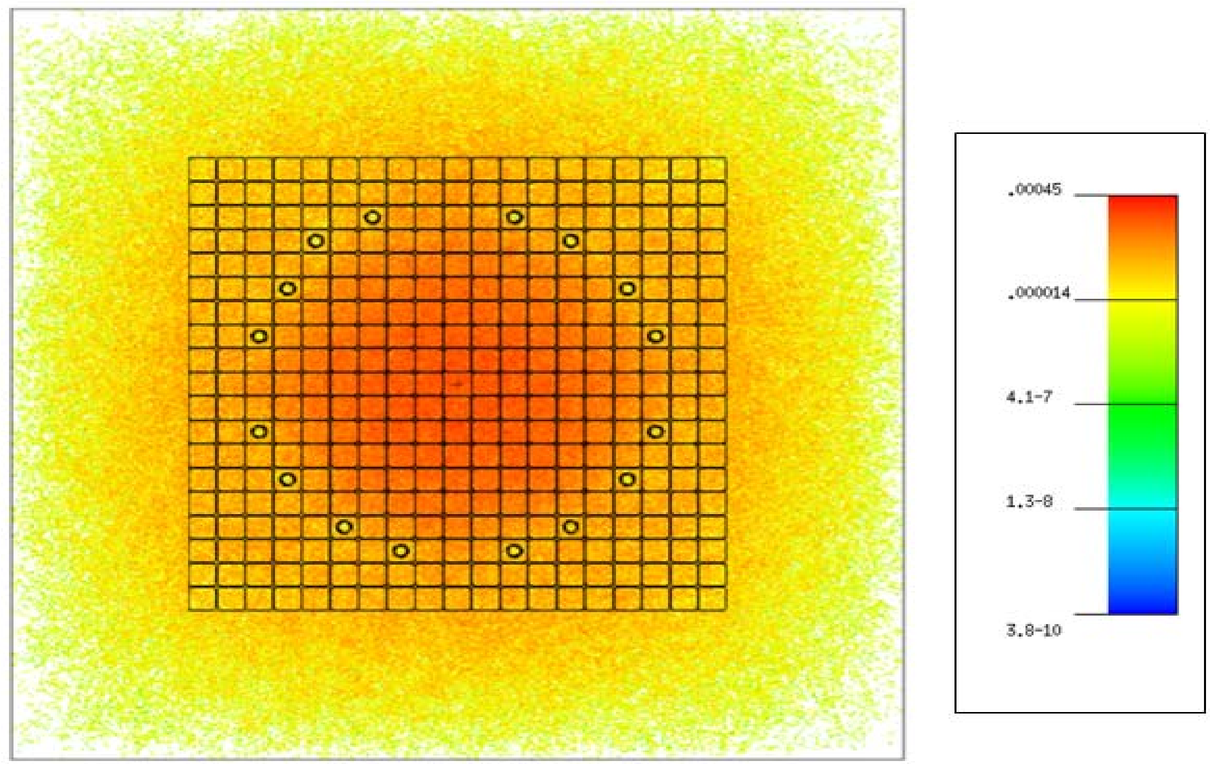

Figure 1. Radial Flux Plot (X-Y) with Flux (#/cm^2) and distances in cm

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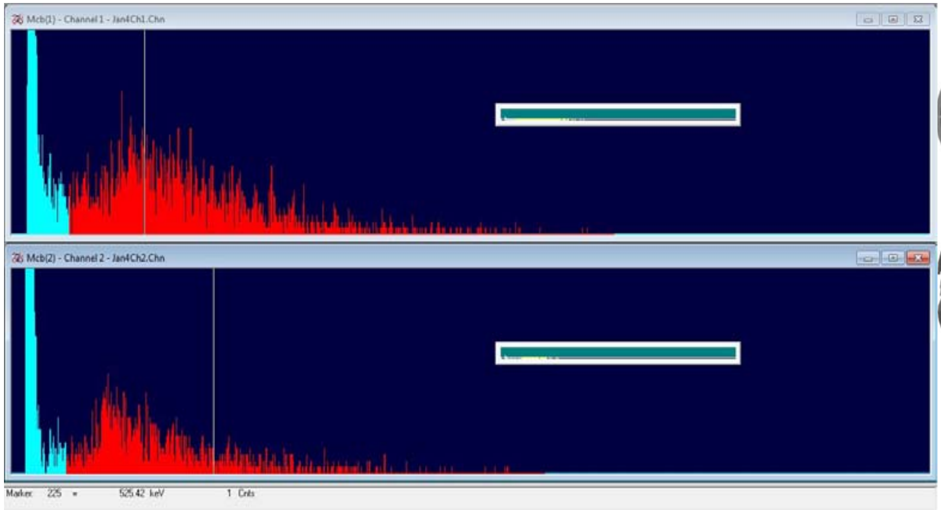
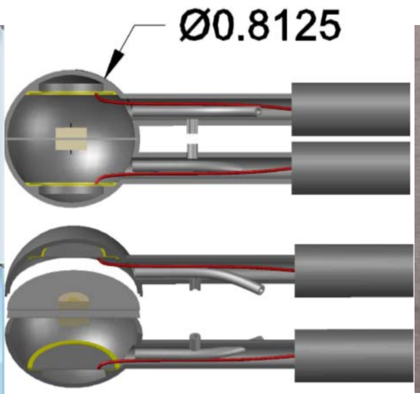
G.Imel, K. Tsai, H. Aryal, ISU

Task II:

- Support fission chamber development through measurement verification of the fissile material deposits produced at partner, KSU.
- Cross-calibration measurements of KSU samples has been made with the back-to-back (BTB) fission chamber.
  - Efforts are made towards reducing noise of the system for increased accuracy of calibration measurements.
- Progress made towards fabricating a smaller BTB fission chamber (OD 0.8125 in.) to access the center of the AGN-201 reactor, which has the higher neutron flux.





(Left) BTB cross-calibration spectrums between two KSU fissile samples. (Above) New BTB fission chamber design and current fabrication progress.

Advanced Instrumentation for Transient Reactor Testing

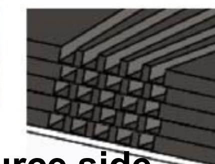
Senior Personnel: J. Roberts, J. Geuther, M. Harrison, D. McGregor, Students: J. Boyington, W. Fu, P. Ghosh; U.G. Students: M. Alshenqiti, G. Collison, E. Schlaikjer, R. Seymour

KSU highlights over project period:

- **Development of three, unique approaches for fast-neutron detection**
  - **Hornyak evolutions with better geometry**
  - **Microstructured semiconductor neutron detectors**
  - **Proton-recoil gas scintillator**
- **Design of a hodoscope mock-up for testing technologies and simulating measurements**
- **Preliminary study of micro-pocket fission detector (MPFD) integrity with reactor pulses**

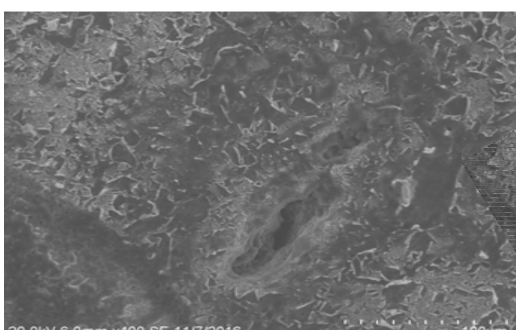
HODOSCOPE “MOCKUP” COLLIMATOR

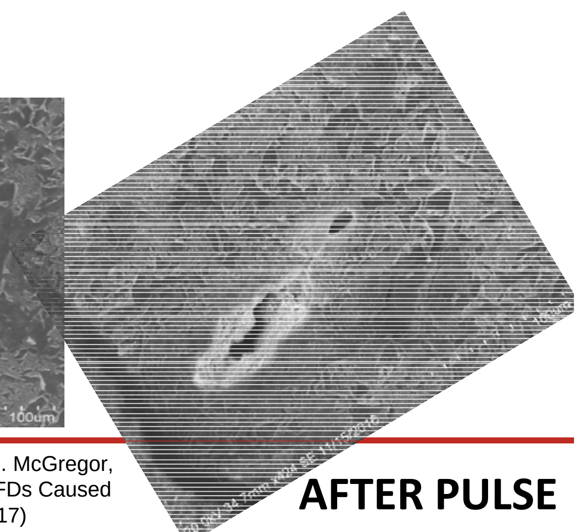
detector side



source side

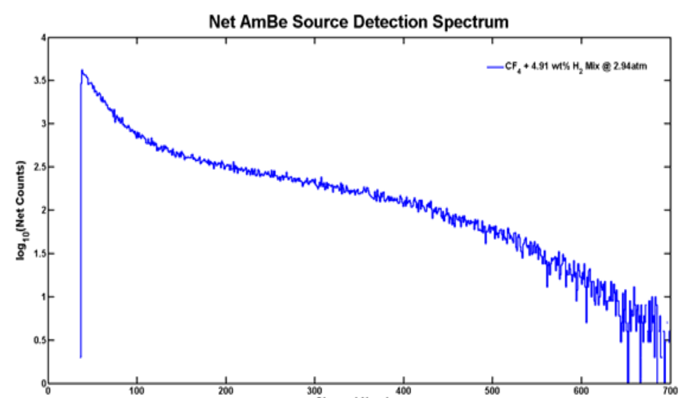
BEFORE PULSE





AFTER PULSE

M.J. Harrison, M.A. Reichenberger, D.M. Nichols, D.S. McGregor, J.A. Roberts. “Preliminary Analysis of Damage to MPFDs Caused by Reactor Pulses.” Trans. Amer. Nucl. Soc. **116**. (2017)



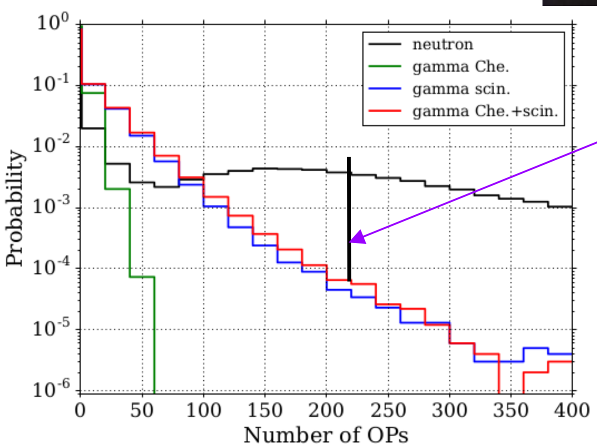
$CF_4 + H_2$ DETECTOR

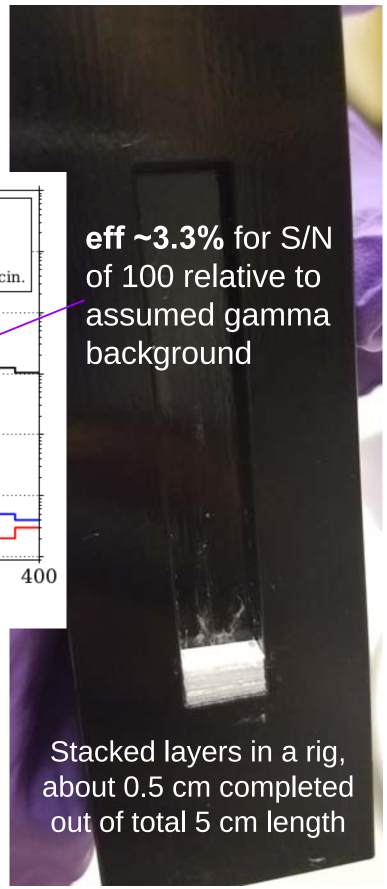
Advanced Instrumentation for Transient Reactor Testing

Senior Personnel: J. Geuther, M. Harrison, D. McGregor, J. Roberts G.Students: J. Boyington, W. Fu, P. Ghosh; U.G. Students: M. Alshenqiti, G. Collison, E. Schlaikjer, R. Seymour

HORNYAK EVOLUTIONS

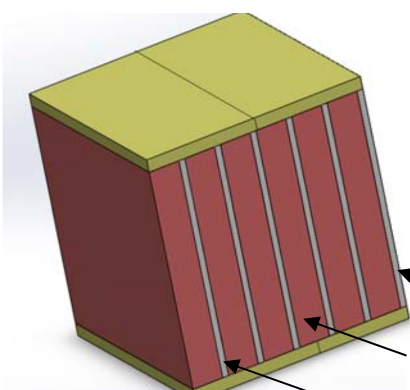
Goals: better light collection and reduced Cherenkov noise.





eff ~3.3% for S/N of 100 relative to assumed gamma background

Stacked layers in a rig, about 0.5 cm completed out of total 5 cm length



SiPM

PMMA ~ .2 mm

ZnS(Ag) ~ 12 μm

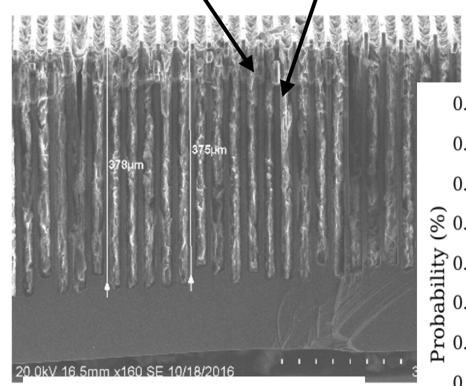
FAST-SENSITIVE MSNDs

Original plan: actinide (e.g., ^{237}Np) reactant, with predicted ~3% intrinsic efficiency.

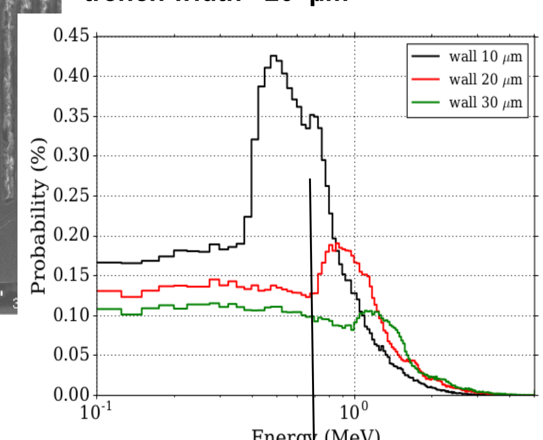
P. Ghosh, W. Fu , R. Fronk, D.S. McGregor, J.A. Roberts. "Evaluation of MSNDs for Fast-Neutron Detection and the TREAT Hodoscope." *Trans. Am. Nucl. Soc.* **115** (2016); expanded treatment submit to *Ann. Nucl. Energy* (2017)

Improved plan: hydrogenous reactant (paraffin), with predicted nearly double the efficiency (for mono-directional, fission-spectrum neutrons, assuming sufficient LLD)

paraffin **silicon**



walls ~7 μm
trench depth ~370 μm
trench width ~20 μm

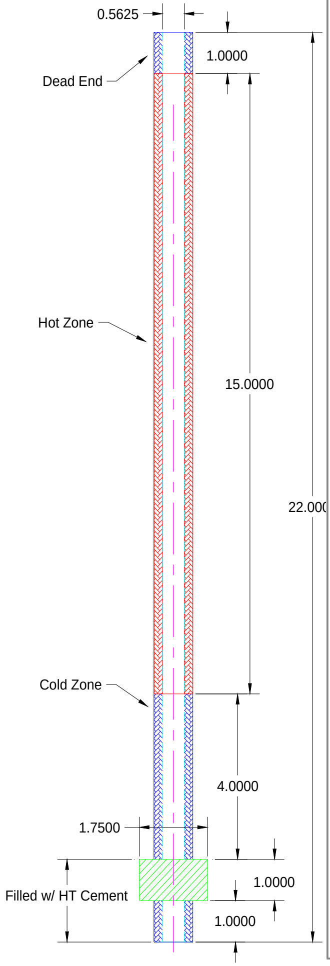


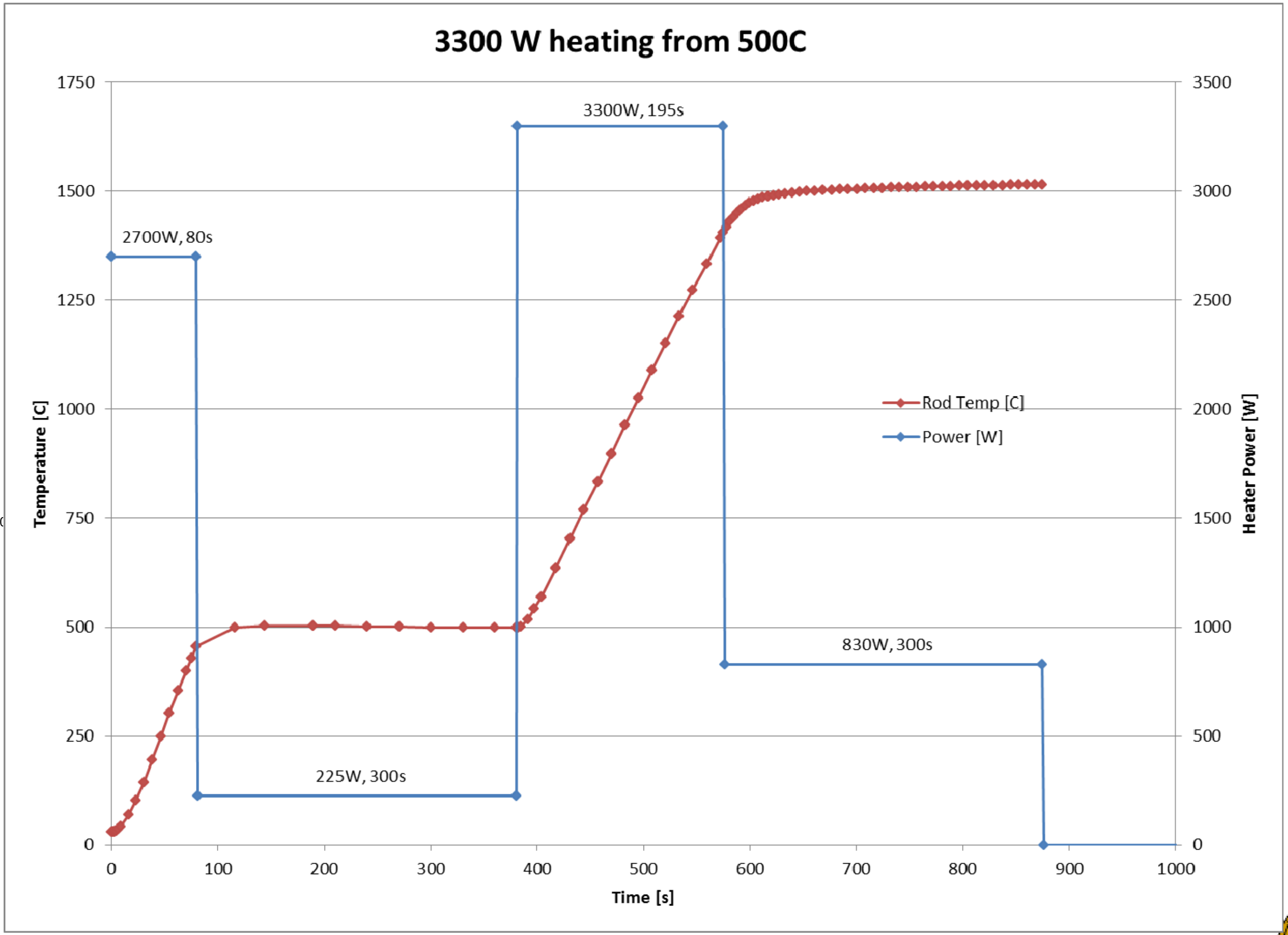
Need further information on expected source and background!

eff = 5.4% for LLD of 700 keV

Fuel Rod Transient Experiment

SER-22-16-1/Custom





Advanced Instrumentation for Transient Reactor

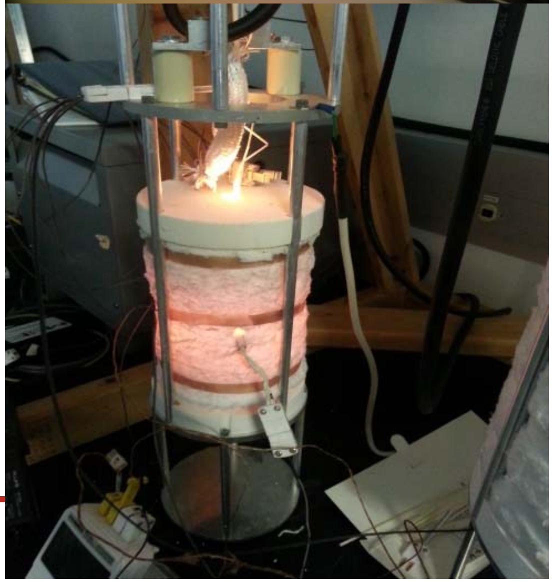
T.Blue, R.Cao, B.Wilson; OSU

OSU Objectives

- Task IIC: Fiber Optic Temperature Sensors
- OSU is tasked with testing innovative fiber optic temperature sensors for measuring temperature profiles in the TREAT testing vehicle

Key Accomplishments

- Determined the radiation limits of distributed temperature sensing in commercial silica fiber
- Innovated silica fiber sensors to produce distributed temperature measurements up to 1000 C
- Mechanically ruggedized silica fiber for TREAT
- Invented a new type of sapphire optical fiber that can read out distributed temperature measurements
- Modeled the time response of optical fiber sensors

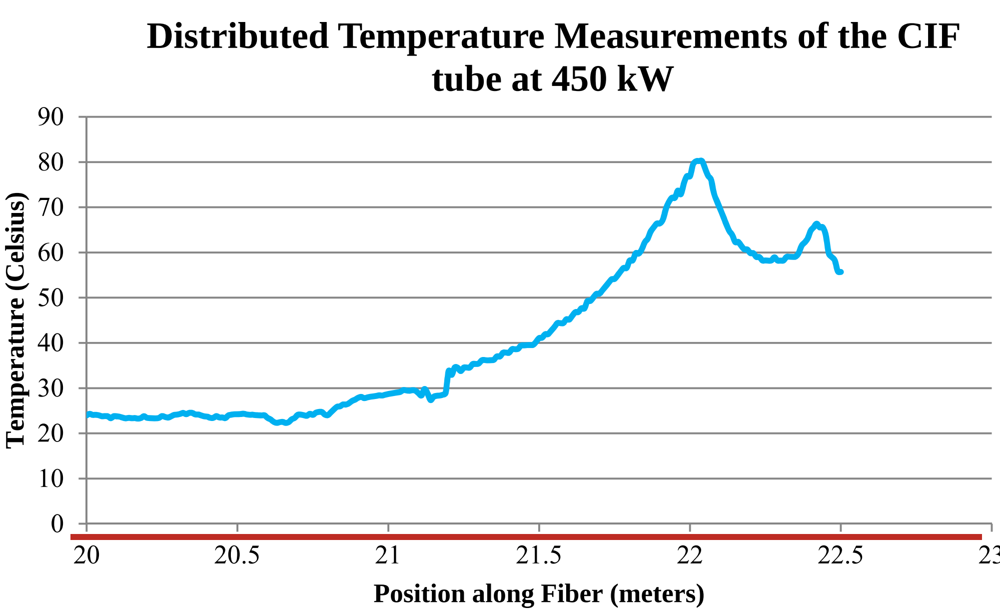


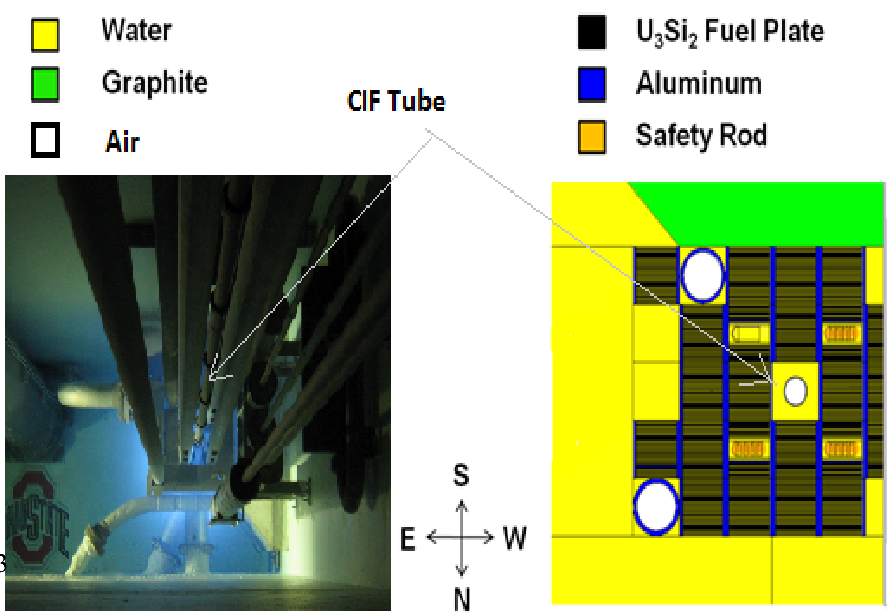
Advanced Instrumentation for Transient Reactor

T.Blue, R.Cao, B.Wilson; OSU

Current OSU Research / Experiments

- Investigating the accuracy of optical fiber sensors in a nuclear environment (i.e. effects of gamma heating)
- Developing radiation hard optical fibers and fiber sensors for long term use in nuclear reactors
- Developing a sapphire optical fiber and sensor capable of producing distributed temperature measurements to temperatures up to 1600 C





Advanced Instrumentation for Transient Reactor

J.Bredemann, T.Kim, M.Anderson, P.Brooks; UW

Distributed Fiber Sensor Testing

Improvement in fabrication and design has increased short term sensing to ~1000ºC & long term sensing to ~800ºC

Color Code Key	Green Claim made before IRP began work	Red Work completed by IRP	Black Work currently ongoing in IRP	
General Fiber Test Matrix				
Area of Inquiry	**Updated Matrix showing current status of Fiber testing**			
Spatial Limit	Fiber Length [2-20 m]	Bend Radius (signal) [> 5 cm]	Strain Sensitivity	-
Temporal Limit	Acquisition Rate [0.2 - 250 Hz]	Labview Limiting [Currently ~5 Hz displayed]	Sheathing Impact [25ms time delay]	-
Resolution Limit	Software Limit [0.64 - 2.56 mm]	-	-	-
Accuracy & Precision	Luna Quoted Specs [± 0.4-1.6 °C]	Check Luna Specs	-	-
Mechanical Failure	Handling/Ben Limit	Tension Limit	Coating Removal	-
Thermal Failure	Temp Gradient [30°C/cm - 500°C/cm]	Molecular Mobility [Temp > 700-800°C Initial Anneal]	Melting Point [1713°C]	Broadband H sites [Initial T > 900°C, Con't T > 850°C]
Chemical Failure	Coating Influence	Gaseous Influence	Carbon Coating	-
Radiation Failure	Gamma Site Creation [Minimal to null]	Gamma Excitement [300-500 nm absoption band]	Neutronic Damage [Damage increases 300-500 nm bands]	Fluence Limit [No observed impact on sensor signal strength]

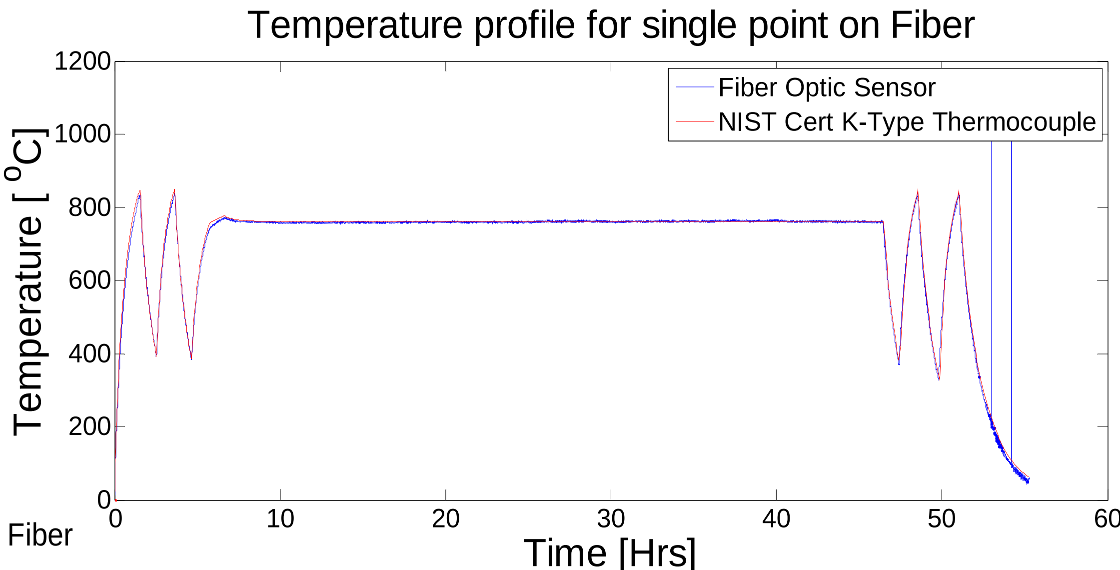
Advanced Instrumentation for Transient Reactor

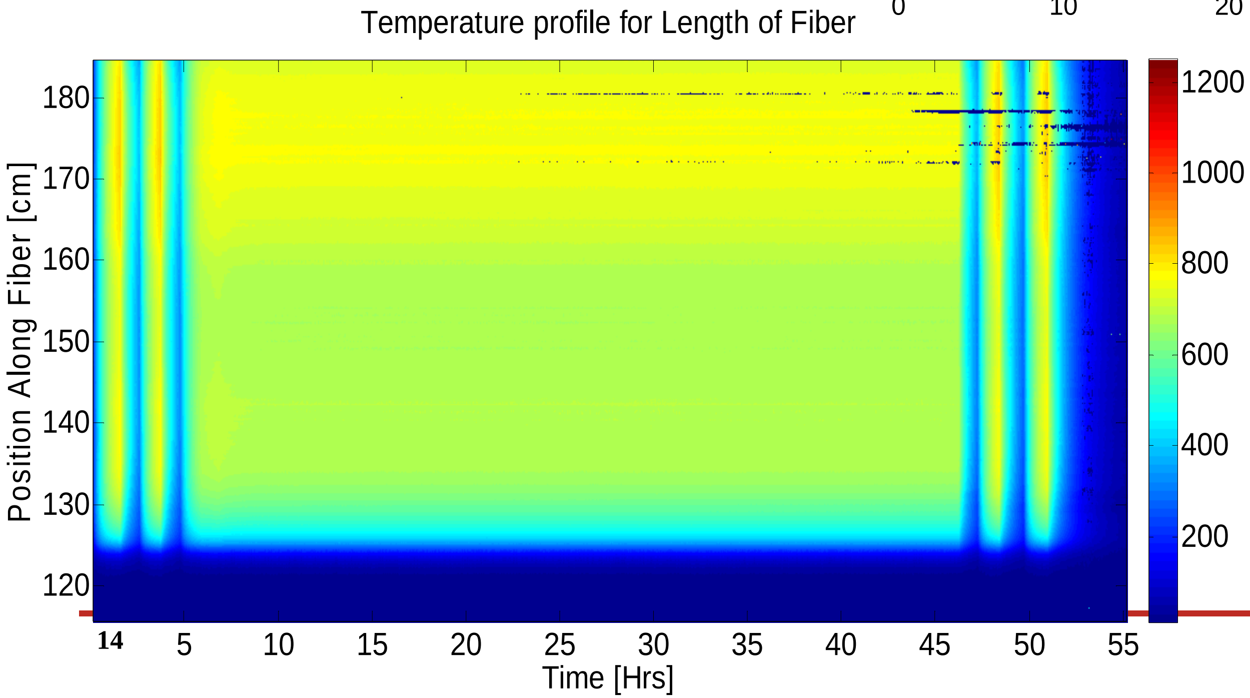
J.Bredemann, M.Anderson, P.Brooks; UW

- **Objectives**
  - Understand failure mechanisms at high temperatures and look to solutions to allow for increase in maximum sensing temperature and sensor lifetime
  - Quantitatively investigate the limitations of fiber sensing (acquisition rate, time response, accuracy and precision of temperature data, sheath impact, etc.)
  - Experimentally examine the impact of radiation dose on the fiber sensing ability
- **Achievements**
  - Developed an initial heat treatment procedure to increase short term maximum temperature sensing from 800^oC to ~1000^oC and stable, long term maximum temperature sensing from 700^oC to 800^oC
  - Experimentally measured time response of sheathed fiber to be ~25ms
  - Experimentally demonstrated successfully temperature sensing inside of a nuclear reactor core at low temperatures (<100^oC) and have shown that minimal if any degradation of sensing signal occurs for long reactor radiation exposures
- **Current research**
  - Performing attenuation testing of irradiated fibers to investigate quantitative impact of radiation damage and potential temperature effects unique to the fibers (up to 1000^oC)
  - Compare several techniques for possible further increase of fiber sensor maximum temperature sensing (high temperature calibration, potential software upgrades, etc.)

Distributed Optical Fiber Sensing Ability

Improvement in fabrication and design has increased maximum short term sensing by ~150ºC and long term sensing by ~100ºC





Standard Deviation:

$\pm$5ºC

$\pm$0.66%

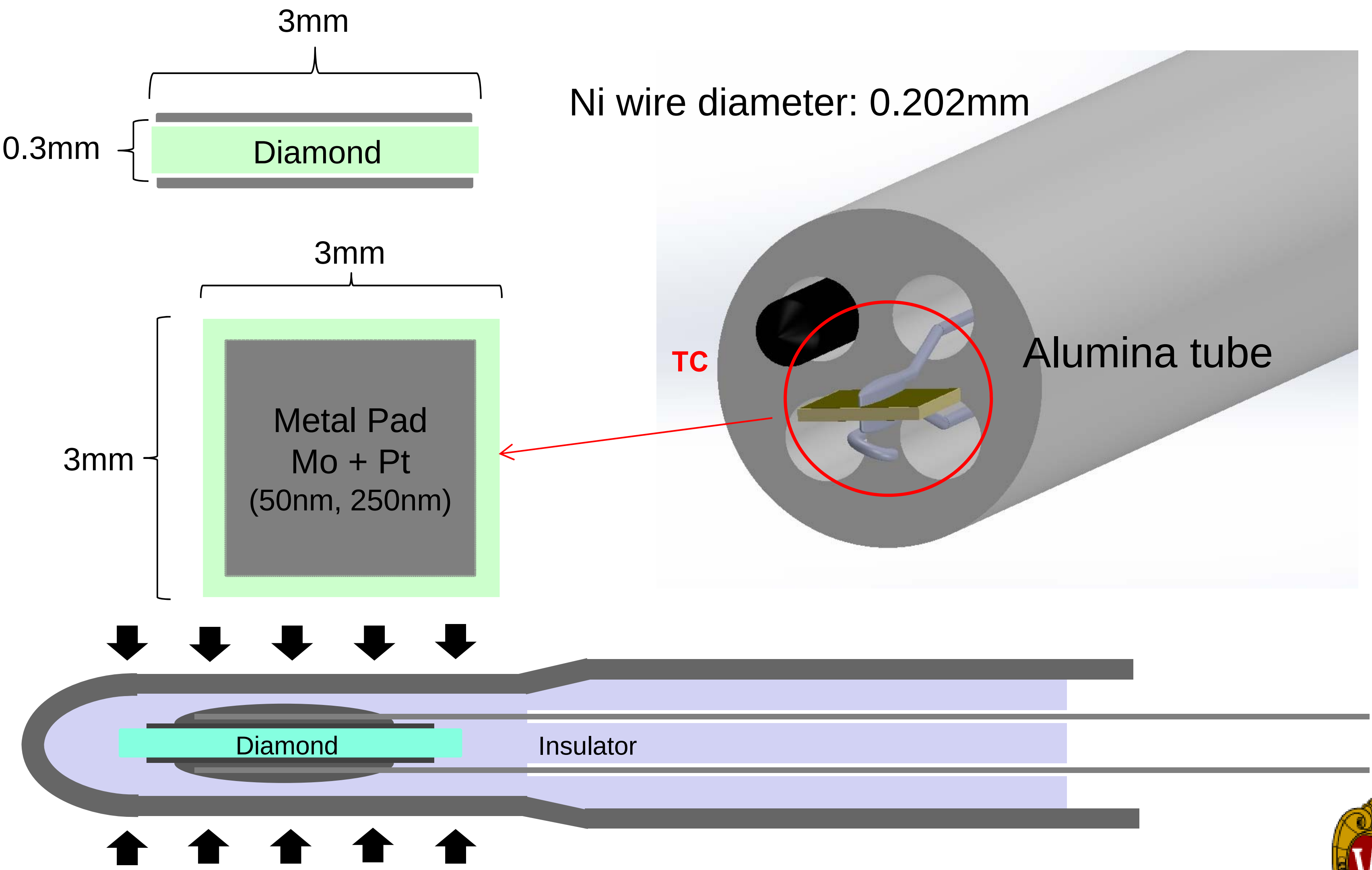
Advanced Instrumentation – Diamond Thermistor

T.Kim, J.Bredemann, M.Anderson, P.Brooks; UW

	TC (K-type)	HTIR-TC	RTD (Pt)	Diamond Thermistor
Temperature Range	-200~1350 ℃	800 ℃ ~ 1800 ° C	0~1000℃	**200℃~700 ℃** **Further Test to 1500 ℃**
Sensitivity	0~54mV (0~1350℃), 41 µV/° C	0.117~13.01mV (25~1242℃), 12.56 µV/° C	N/A	N/A
Sensitivity Coefficient	N/A	N/A	500℃ : 0.00119 700℃ : 0.0090 962℃ : 0.00066	**500℃ : 0.025** **700℃ : 0.015**
Accuracy	Max error (℃): 4.0 at 1000℃ 9.0 at 1200℃	At 1240 ℃ 1234.15 ~1248.72 ℃	500℃: ± 2.8℃ 700℃: ± 3.8℃	**Need to be measured**
Stability	Drift: at 1000° C, 5° C	0.0002 ° C/sec at 1240 ℃	**Drift Rate** typically < 0.001 ° C < 0.003 ° C 100 hours at 1070 ° C	**Need to be measured**
Response Time	Smaller diameter, faster. 1/16 size, Time constant (63.2%) $\tau = 0.4$ sec Steady state reading: 5τ	Similar to TC (K-type) 1/16 size.	-Longer than TC, depends on the physical size and design.	**Diamond only** **1×1×0.3 mm : 100 µs.** **Depends on physical size**
Radiation Resistance	15° F change 2.21×10^{17} n/cm^2 0~1000° C : 5: x10^{20} nvt	4.5×10^{25} n/cm^2 , E>0.10 MeV, 1200° C	Fast neutrons (E> 1.0Mev) cause the transducer output sensitivity shift.	**Detector performance good to 1.3×10^{15} n/cm^2. Leakage current decrease after irradiation.** **-Need to be measured.**

Advanced Instrumentation – Diamond Thermistor

T.Kim, J.Bredemann, M.Anderson, P.Brooks; UW



INL Sensors – TC Probe

Thermal Conductivity Probe: Received probe and are using several ceramics to test accuracy over a range of thermal conductivities and temperatures

Material	Conductivity [W/m K]
Uranium Oxide	5
Boron Nitride [UHP]	100
Boron Nitride [SiO matrix]	15
Al-B hybrid	28
Alumina	28
Zirconia	2
Aluminum Nitride	180-130 (20C - 300C)
Silicon Nitride	28-16 (20C-1000C)
Macor Machinable Glass	1.46

INL Sensors

- HTIR sensor is under test at UW out-of-pile
- INL Ultrasonic TC fabricated (three probes)
  - Inconel with 1 sensing region
  - Inconel with 5 sensing regions
  - Moly with 1 sensing region
- All were shipped to UW and testing underway
- Cross-comparison with other sensors

Task III and Task IV: Integral Testing

Task III: Out-of-pile testing has begun with selected sensors (ongoing spring and summer)

- MSND and MPFD results at KSU
- HTIR and Fiber optic results at OSU and UW
- Diamond-diode at UW
- Combined TC sensors in test canister

Task IV: Safety case is developed to present to Reactor Safety committee for review and approval (summer)

In-pile testing with HTIR, Fiber-Sensor, Ultrasonic Thermometry, and Diamond Thermistor (summer - fall)