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, P.Ugorowski, KSU; T.Blue, OSU; M.Anderson, UW; D.Knudson, INL, J.F.Villard, CEA

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

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.** – *Phil Ugorowski*
- **Ohio State Univ:** – *Tom Blue*
- **UW-Madison** – *Mark Anderson*

IRP Laboratory Partners

- **Idaho National Lab** – *Darrell Knudson*
- **CEA-Cadarache** – *Jean-Francois Villard*

External Advisory Board

- **DOE/INL:** B.Williams, R.Versluis, D.Wachs
- **Industry Experts**: Areva, GE, NuScale, 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), P.Ugorowski (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: *P.Ugorowski (KSU)***, M.Anderson (UW)***, B. Aagasie (UW), J.Roberts (KSU), D.Knudson (INL)*

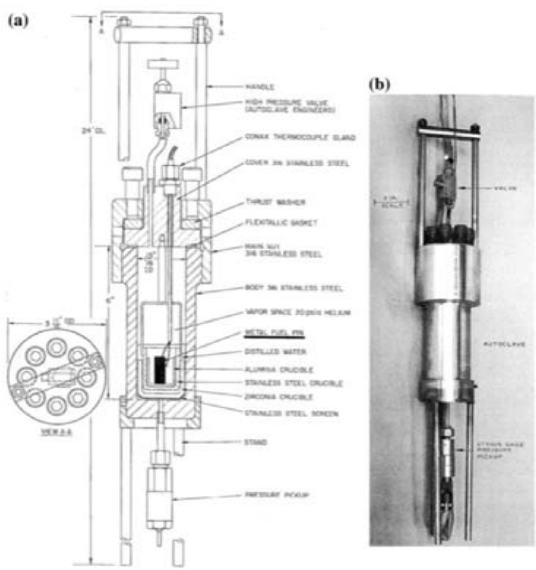
Task V: Transient Test Design: *M.Corradini (UW)***, G.Imel (ISU), and Advisory Board Members*

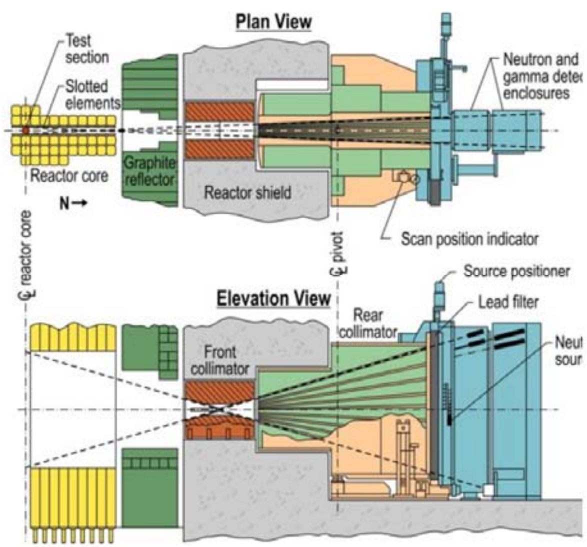
***** Indicates Team Leads or Co-Leads**

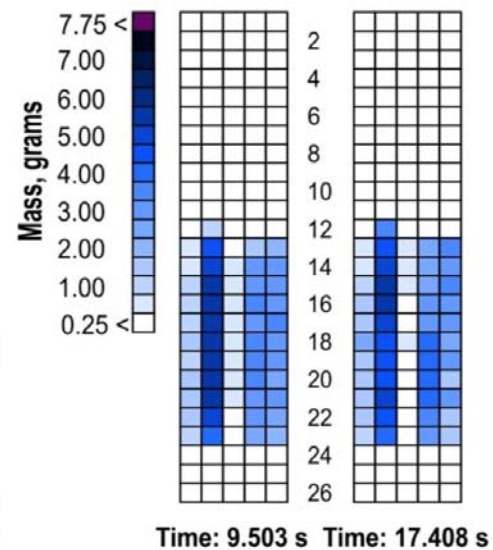
Project Scope and Objectives

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

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







Project Scope and Objectives

Objectives:

- Develop new concepts that lead to the design of the next generation fuel motion monitoring system to support transient testing, taking advantage of ‘line-of-sight’ core layouts; i.e., advancements in spatial and temporal resolution for hodoscope imaging.
- Develop novel instrumentation to support in-pile transient testing that includes local fast and thermal neutron flux measurements, fast response temperature and thermal conductivity measurements.
- Demonstrate the behavior of novel instrumentation measurement methods in a reactor environment using university TRIGA reactors as well as design for their use in a transient test reactor situation.

Project Tasks

The IRP combines the expertise of four universities and the INL (and its unique HTTL laboratory and staff) with an international partner that provides advice on instrumentation and test rigs. The IRP research team will focus on:

Task I: Development of innovations for real-time, ‘line-of-sight’ imaging for a transient test using the current hodoscope concept with advancements in detection and image resolution;

Task II: Development of novel sensors to measure local neutron fast/thermal flux, temperatures, thermal conductivity in rod geometry under transients;

Task III: Out-of-pile testing of these sensors under a common test protocol;

Task IV: In-pile testing of these instruments in a TRIGA reactor to demonstrate the capability to measure these key parameters in a radiation environment under transient conditions;

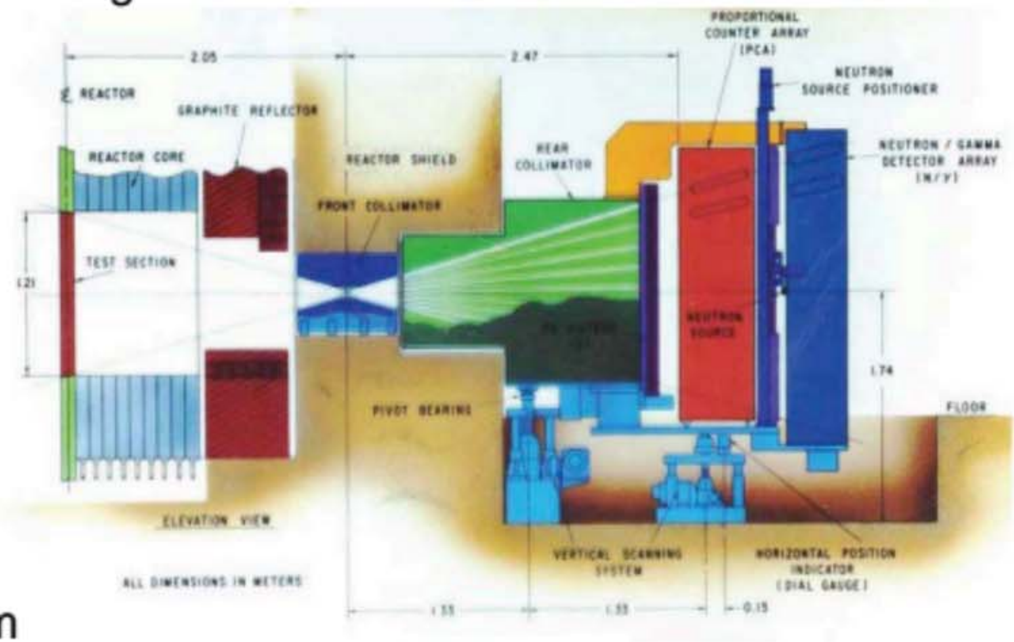
Task V: Conceptual design of a standard transient reactor experiment test capsule with this advanced instrumentation in collaboration with 2015-IRP.

https://sites.google.com/a/wisc.edu/treat-restart-project/home

Hodoscope

Hodos (Greek for "path") & Skopus (Greek for "observer")

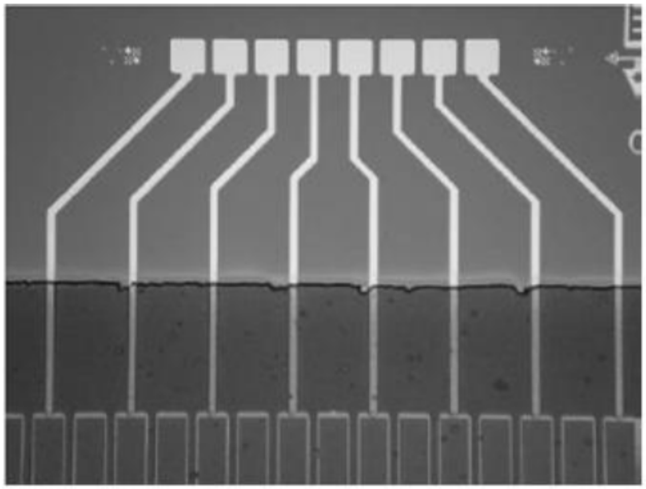
- The TREAT hodoscope is a radiation detector designed to measure the fast neutrons emitted from fission taking place within test items
- An array of 360 collimated tubes all pointed at the test item
  - 10 columns, 36 rows, 1810 mm long
  - Field of view
    - Height: 1200 mm
    - Width: 66 mm
  - Channel spacing (center to center) at reactor center
    - Horizontal: 6.6 mm with overlap
    - Vertical: 34.5 mm without overlap
  - Fuel-to-detector spacing ~ 3 m
  - Detectable motion
    - Horizontal: 0.5 mm; vertical: 5 mm
    - Mass: 0.1 - 1 g

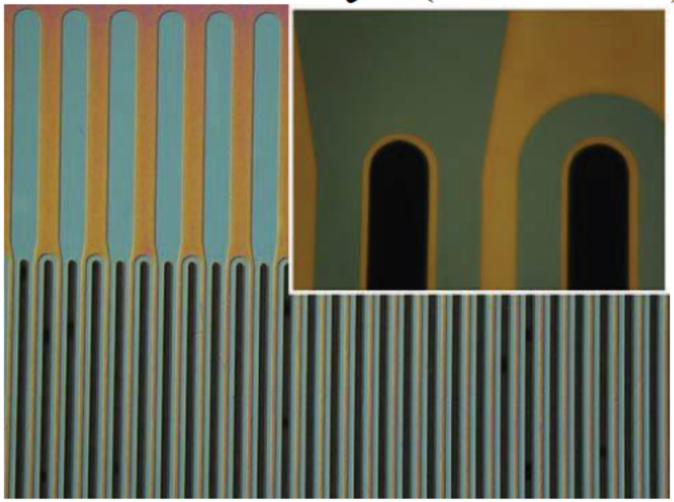


ANL/RAS 76-34 (1976) "Performance Review – Neutron Hodoscope at TREAT"

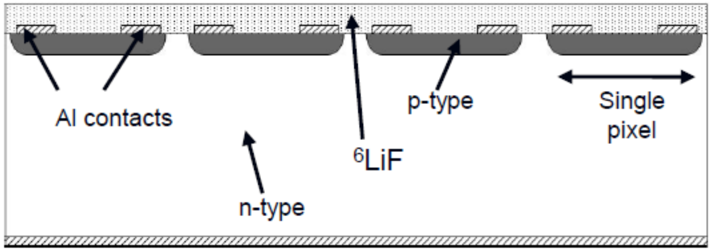
Improvements to Hodoscope (HENDA, Cloud Chamber - KSU)

High-Efficiency Neutron Detector Array (HENDA)

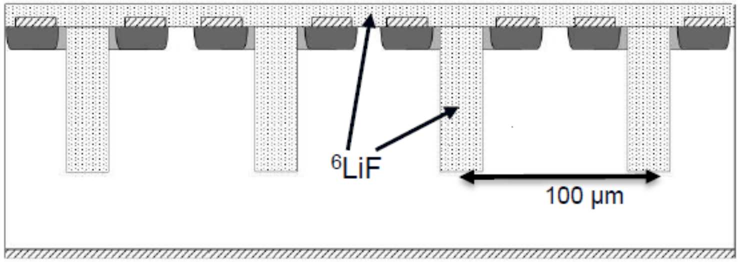




Planar -- Fastest Response



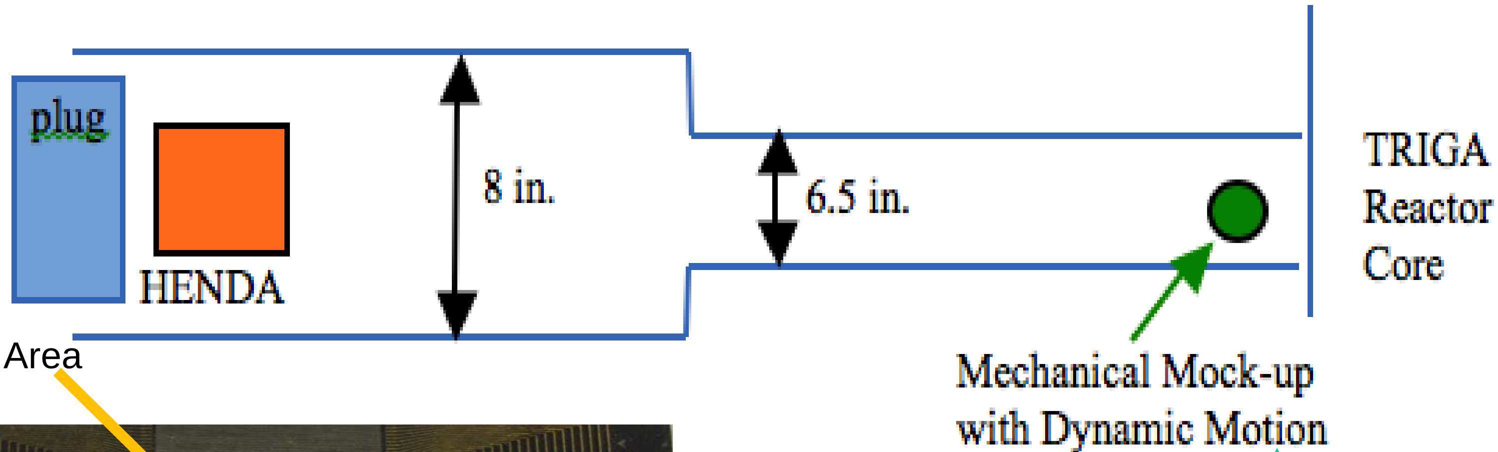
Trenched – Highest Efficiency



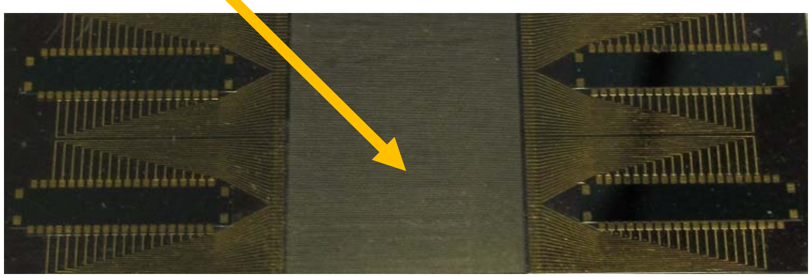
100 micron pixel pitch (center to center), each 1-D pixel read out separately

Fast-Neutron Position-sensitive HENDA (High-efficiency Neutron Detector Array)

Proposed fuel rod motion test at KSU



Active Area



Motion is detected in the ↕ direction

By detection of the fast-neutron ‘shadow’

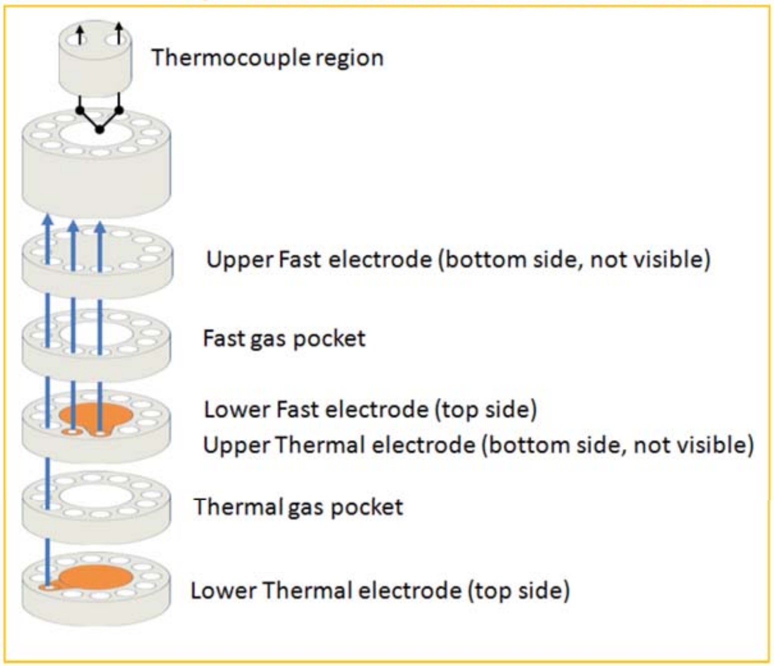
Active area has no electronics behind it -- flexible connectors allow electronics to be shielded from neutrons

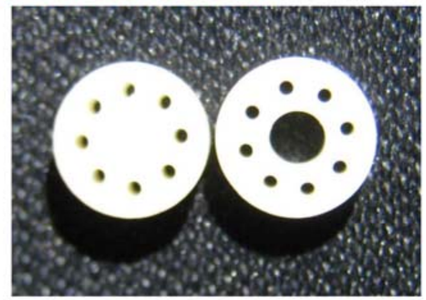
GOAL: Test the response of the Fast-Henda to fuel rod motion in a fast-neutron beam port of the KSU TRIGA reactor

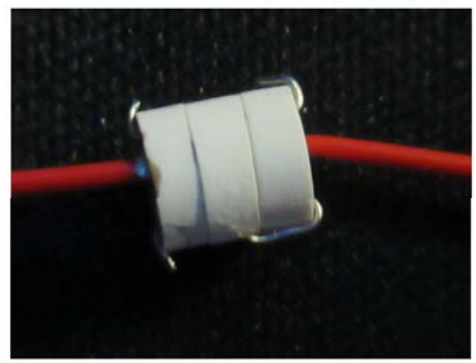
Micro Pocket fission detectors

Developed at KSU under several DOE awards
Currently being worked on at KSU and INL for deployment

Separate chambers measure fast and thermal neutron flux.



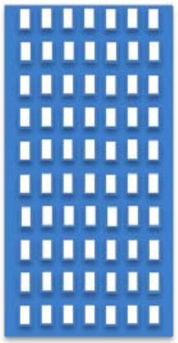




Micro Pocket Fission detector from INL

Can be used as stand-alone probes or part of an instrumented fuel bundle.

Could be used with the Hodoscope



2-D Array of Fast-sensitive MPFDs

- As with the HENDA, use ^{232}Th instead of Uranium, and cover with cadmium
- To minimize electronics needed, MPFDs can be linked in rows on one side and columns on the opposite side, and use readout system similar to wire chambers (row, column)
- A stacked design of multiple layers can increase efficiency
- If desired, gamma-sensitive detectors can be located behind active areas, as gamma absorption by the MPFD is minimal.

TREAT Hodoscope
Neutron Collimator
with >300 holes

Test the response of Fast-Neutron 2x2 MPFD array in a fast-neutron beam port of the KSU TRIGA reactor

Can time and 2D location of neutron events be adequately measured?

Advanced Thermal Sensors for TREAT

1. Determine feasibility and procedure for **distributed optical fiber** temperature measurements
   - **GOAL:** High spatial resolution temperature measurements with a single fiber (replace 1000's of TCs measurement and possibly improve the time response to 250Hz
   - **ISSUES:** Operation at high temperature, Radiation resistance, Stability and Accuracy.

2. Develop a high temperature radiation resistance **diamond diode temperature sensor**
   - **GOAL:** Compliment TC measurements with a more stable miniature diode, less resistant to nuclear heating and noise, more stable.
   - **ISSUES:** Determine radiation resistance, connection of leads, stability

3. Develop and test INL high **temperature radiation resistant TC's**
   - **GOAL:** Determine performance in transient test
   - **ISSUES:** Instrumenting a test can with TC in reactor core

4. Develop and test INL fuel **thermal conductivity sensor**
   - **GOAL:** Determine performance and applicability for TREAT tests
   - **ISSUES:** Transients probably are not possible, radiation affects, instrumenting in pile test can

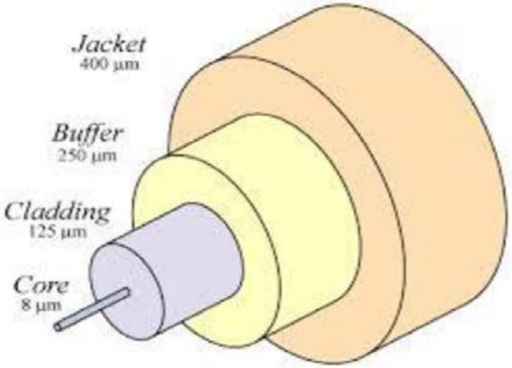
5. Develop and test INL **ultrasonic distributed temperature sensor**
   - **GOAL:** Determine performance and applicability for TREAT tests
   - **ISSUES:** Transient testing and instrumentation in reactor

Distributed optical fibers temperature sensors

Measure temperatures every 5mm over 10m lengths at 250Hz

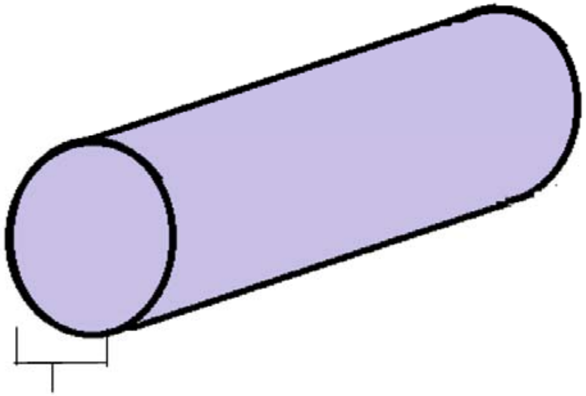
Silica (SiO_2)

- Amorphous glass structure
- Core pure SiO_2
- Cladding is SiO_2 doped with specific defect (germanium etc.)
- Coating can be acrylate/polymide
- Single mode/multimode
- Crystallizes (fails) at 1100 C
- Sensing failure around 750 C



Sapphire (Al_2O_3)

- Crystalline Structure
- One long single crystal
- Melts at 2050 C
- No cladding/coating
- Highly Multimode
- Sapphire sensing can theoretically withstand temperatures of 1600 C, still requires testing



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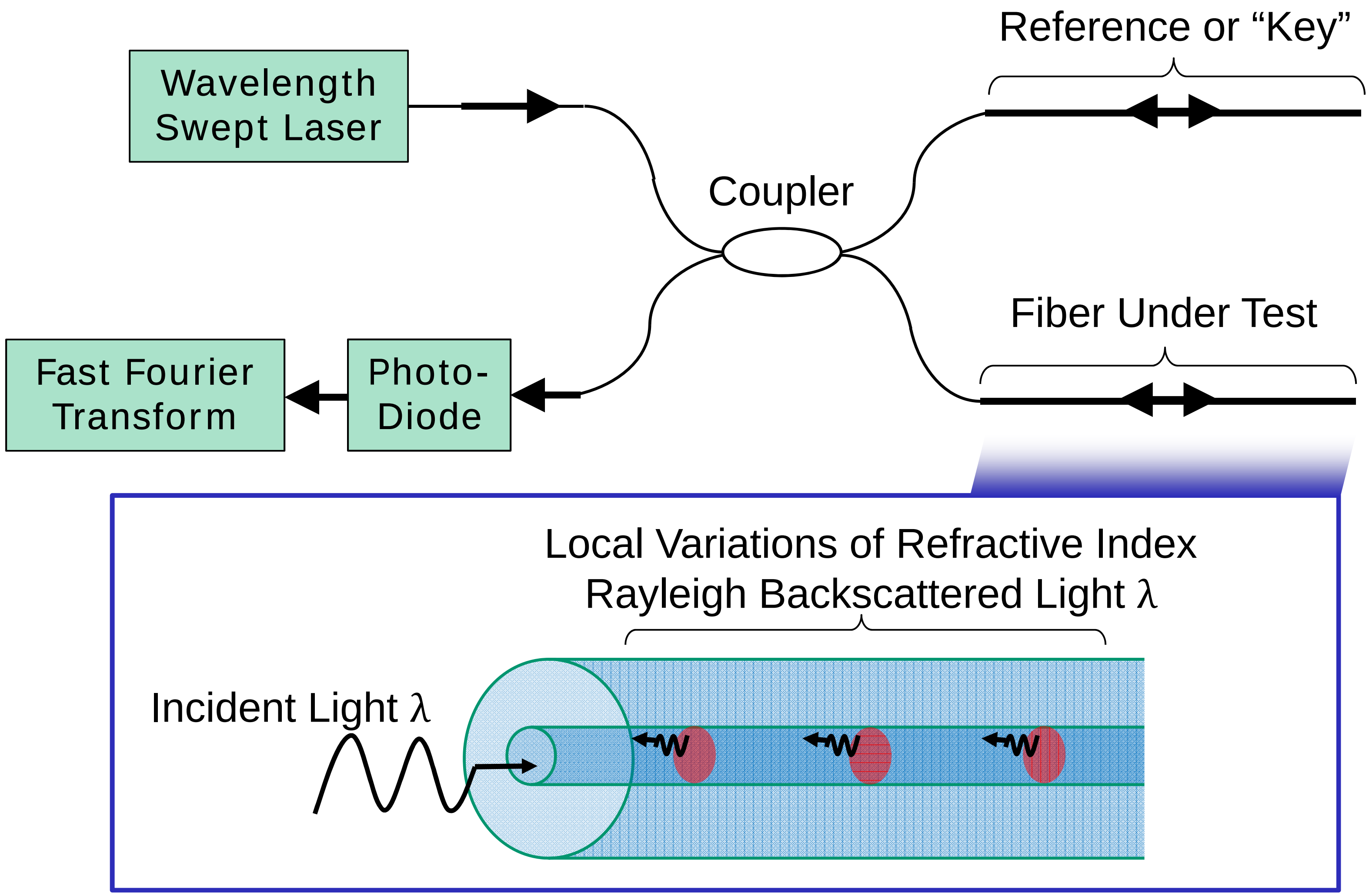
Distributed Optical Sensor



Possible limitation on Sensor

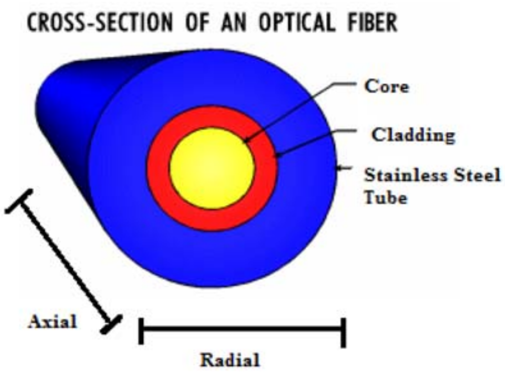
- Discrimination between thermal and mechanical stress
  - (temperature and strain)

- Radiation damage
  - Gamma Radiation and Neutron Radiation – messing with optics

- High Temperatures (>800 ^{o}C)
  - Chemical composition of fiber
    - Hydrogen diffusion from coating and ambient atmosphere
  - Amorphous structure of the silica
    - Atomic mobility can lead to a large change in molecular layout
  - Physical cracking and crystal formation
    - Surface cracks propagate leading to structural failure
    - "Devitrification" is the growth of crystalline structures

Protection of fiber

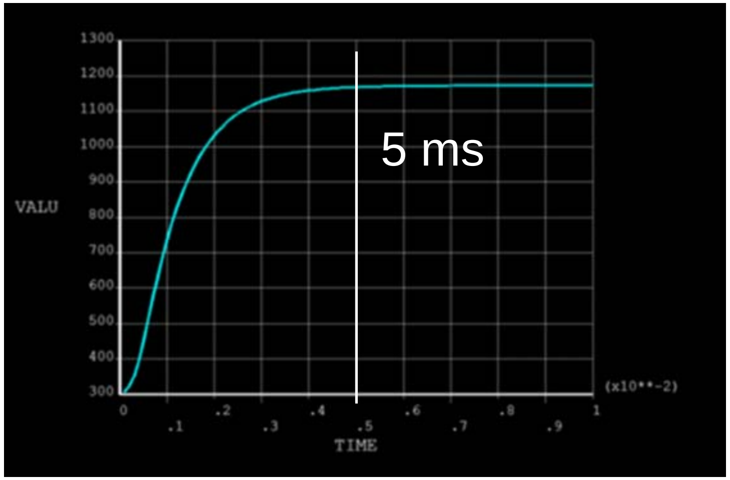
To protect fiber and reduce effects of mechanical stress we insert into a metal capillary tube (with helium back file)



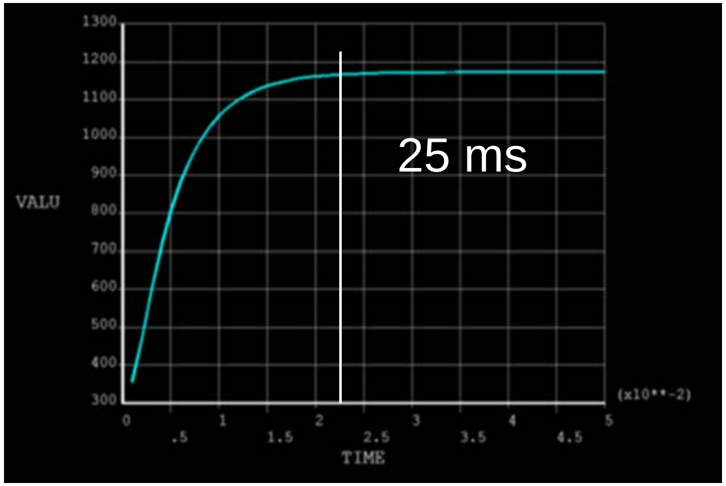
- Fiber is 125 microns in diameter
- SS tube is 152 microns (13 micron helium gap)
- Determine time constant
- Uniformly heated tube reaches steady state temperature in about 25 milliseconds

Bare fiber

900C

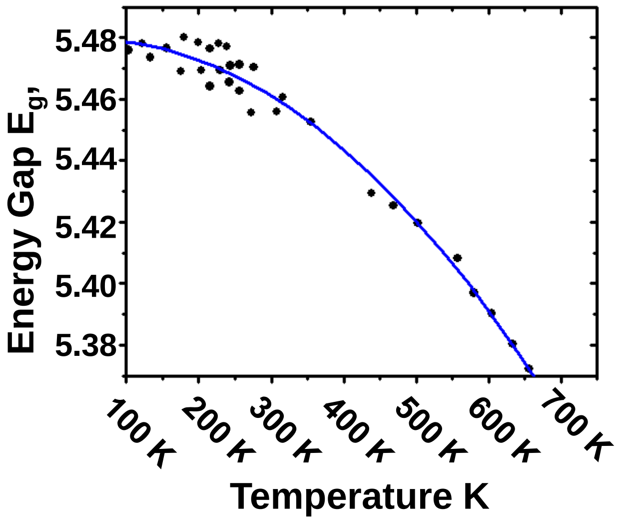


Clad fiber



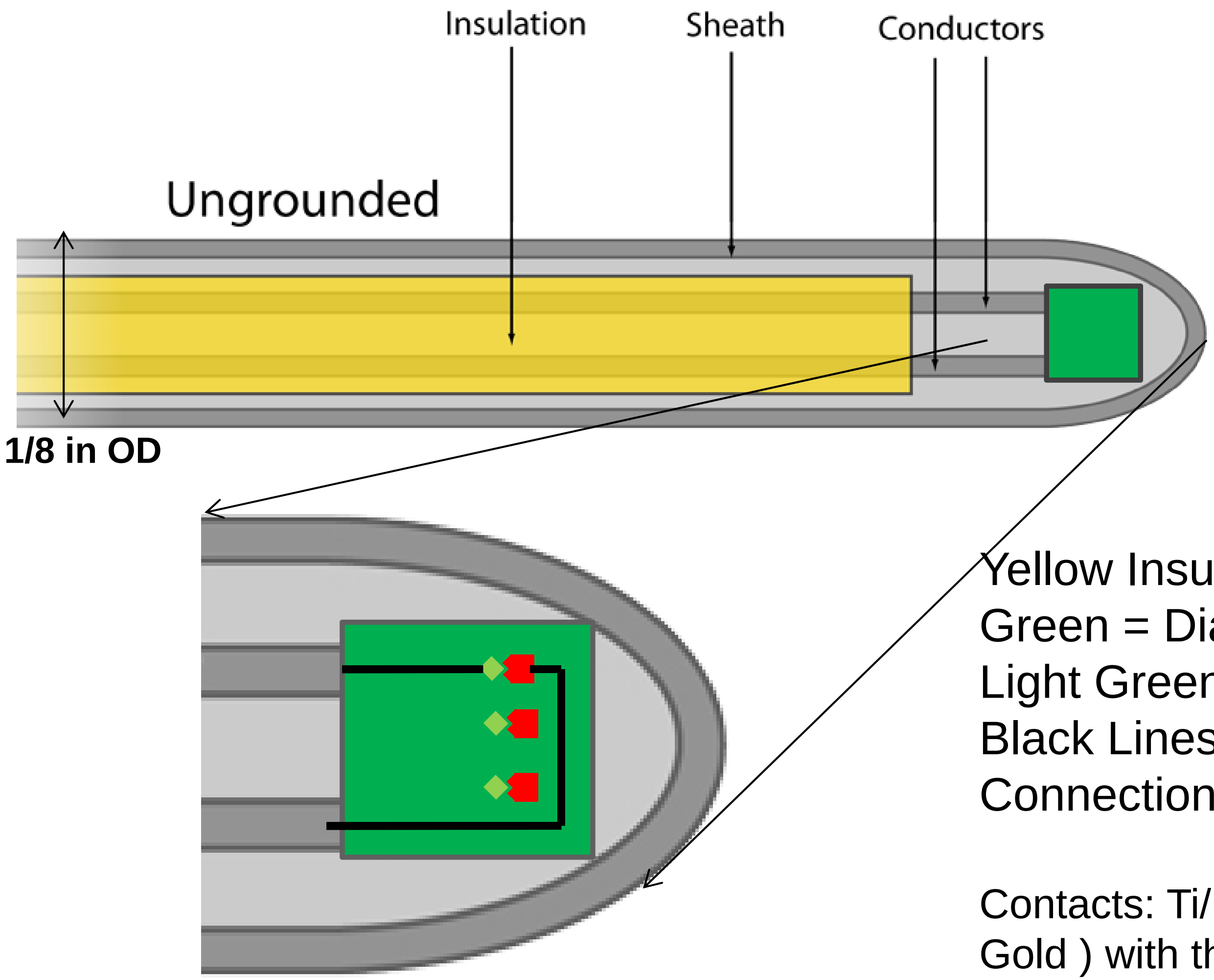
Plasma Enhanced Chemical Vapor Deposition Diamond Diode

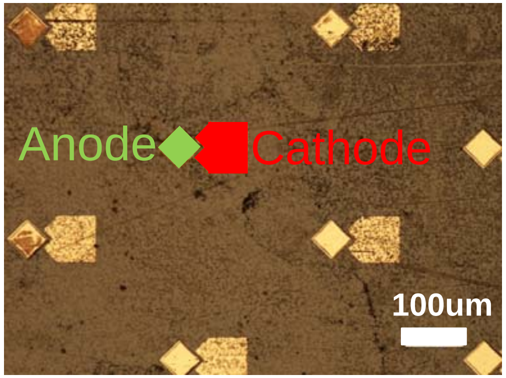
- Develop a diamond high sensitivity temperature sensor that's radiation hard, immune to electrical noise and stable.
- Temperature sensor should be able to detect a large temperature range & have a compact design.
- Diamond diode is an ideal device for this application.
- Near term finding suitable connectors (diode can withstand high temps)



Diamond PI junction will have the highest sensitivity compared to other materials because of it's large bandgap. Even at high temperatures the bandgap remains very large meaning the diamond will remain very stable at higher temperatures.

High temperature Diamond diode



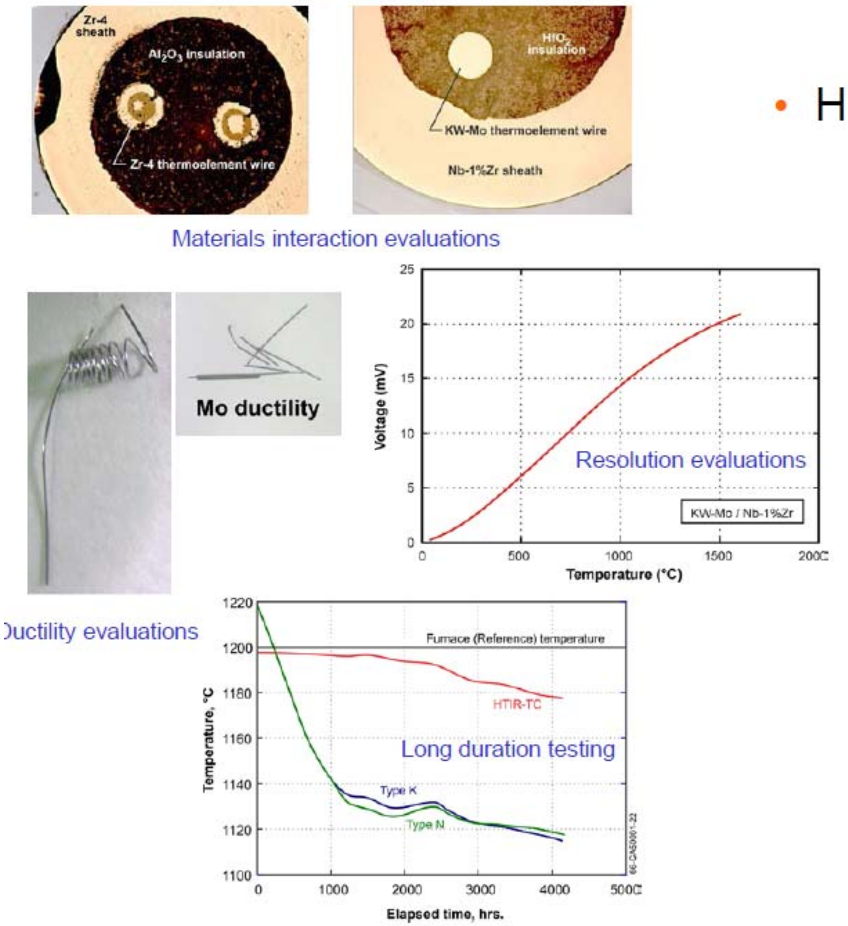


Yellow Insulator = MgO or Hafnia
Green = Diamond Sample
Light Green & Red = Contacts
Black Lines = Wired Bonded Connections

Contacts: Ti/Pt/Au (Titanium / Platinum / Gold) with thicknesses (10nm / 50nm / 200nm).

HTIR-TC

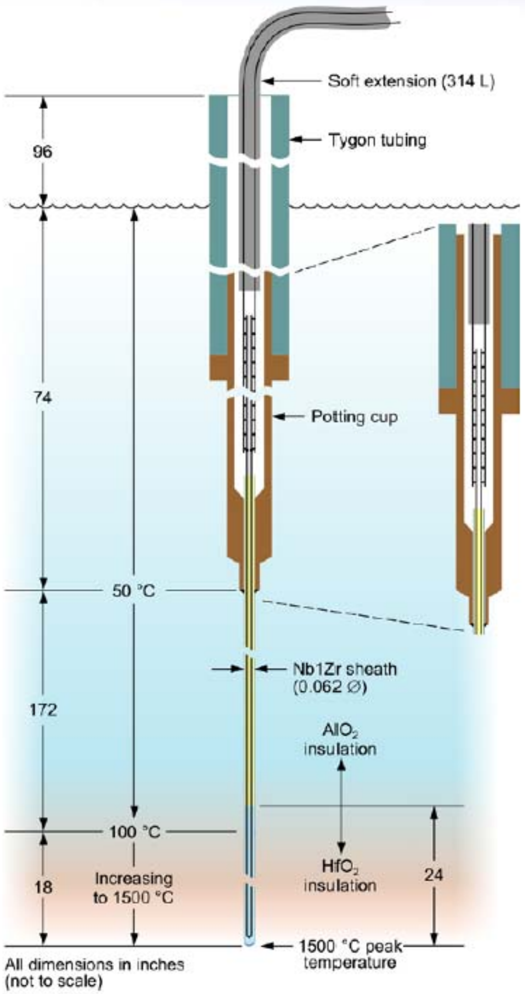
HTIR-TC Sets Standard for High Temperature, Nuclear Applications



- HTIR-TC development considered
  - Materials interactions
  - Ductility evaluations
  - Sensor resolution
  - Long duration behavior
- Resulting HTIR-TC
  - Mo/Nb thermoelements
  - Hafnia insulation
  - Nb sheath
  - Resists transmutation
  - High temperature capable

High Temperature thermal couples

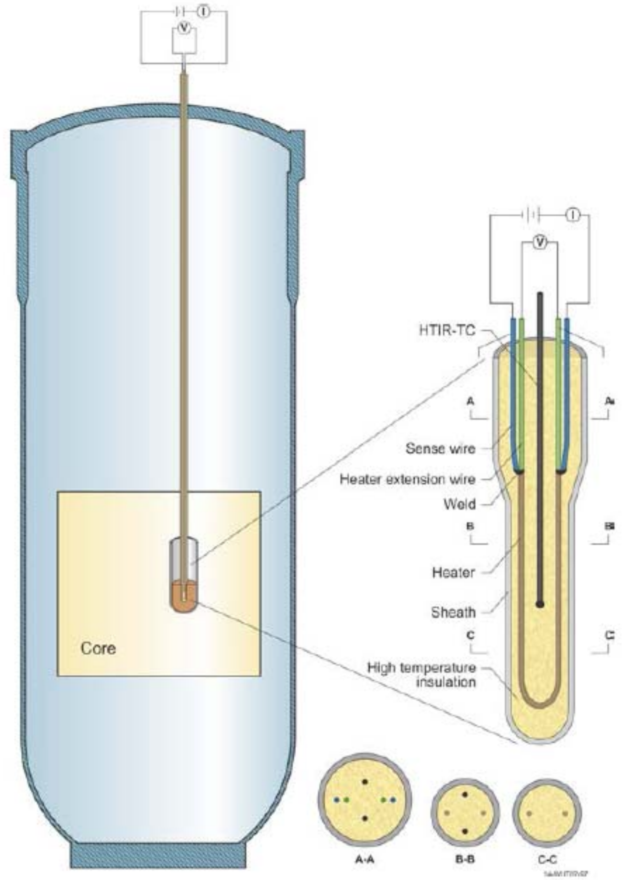
HTIR-TCs Designed for Experiments at UW-Madison



- HfO_2 insulation required in high temperature region – Al_2O_3 elsewhere
- Transition to soft extension in pool via custom potting cup
- Transition to soft extension protected by Tygon tubing

Thermal Conductivity Sensor

TCNP Overcomes Obstacles Associated with In-pile Thermal Conductivity Measurement



Dual diameter heater

- Smaller diameter heater wire in specimen
- Heater wire / lead materials and diameters selected to minimize heating in leads
- Transition to 4 wires for power detection located in cool location

Dual diameter probe

- Smaller diameter minimizes probe influence on specimen being measured
- Larger diameter accommodates larger diameter heater leads

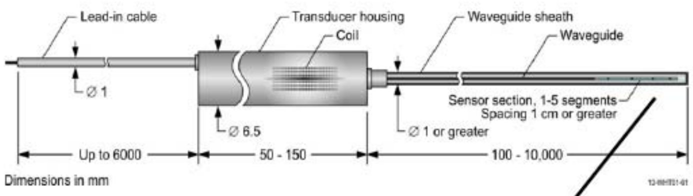
Irradiation resistant high temperature fabrication

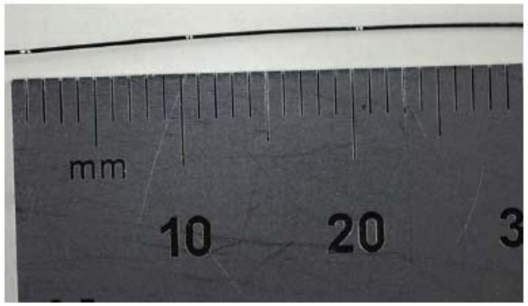
- TC-like construction with high temperature materials that resist interactions and transmutation
- Specialized welding techniques join small diameter heater to larger diameter leads
- Can include INL-developed HTIR-TCs for detection in high temperature irradiation conditions
- Specialized swaging techniques provide a dual diameter leak-tight sheath

Ultrasonic Temperature sensor

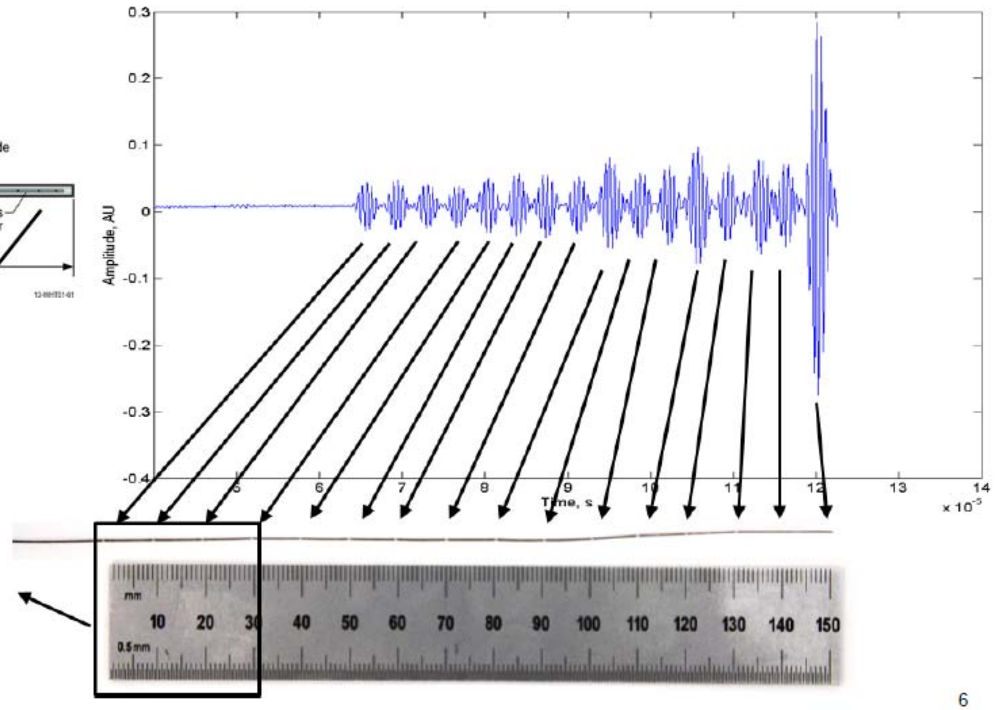
UT Allows Gradient Measurement

- Multiple sensor segments allow temperature profiling along probe length
- Sensor material selected for optimum performance in various environments
- Temperature resolution dependent on reflector spacing and sensor material
- Current design uses KW-molybdenum (MP~2600 °C)
- Reflector spacing of 1 cm or greater





150 mm sensor with 15 segments



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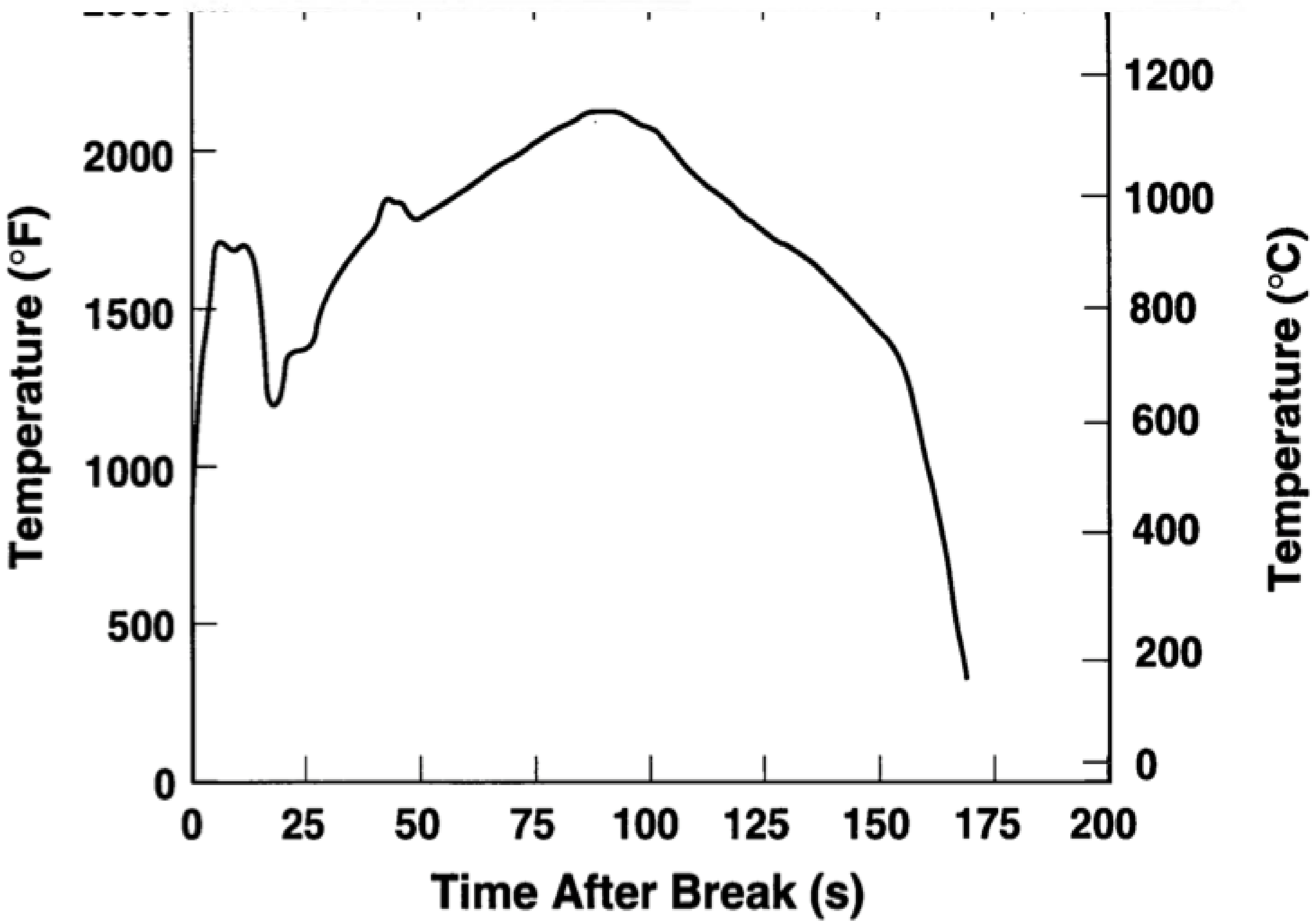
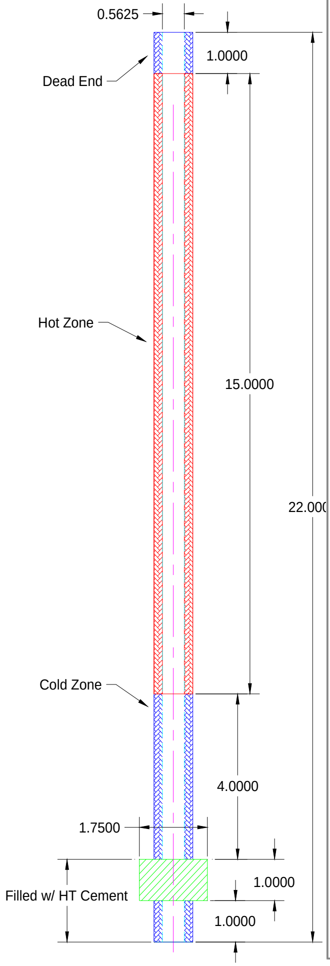
PROTOTYPIC LWR TEMPERATURE TRANSIENT

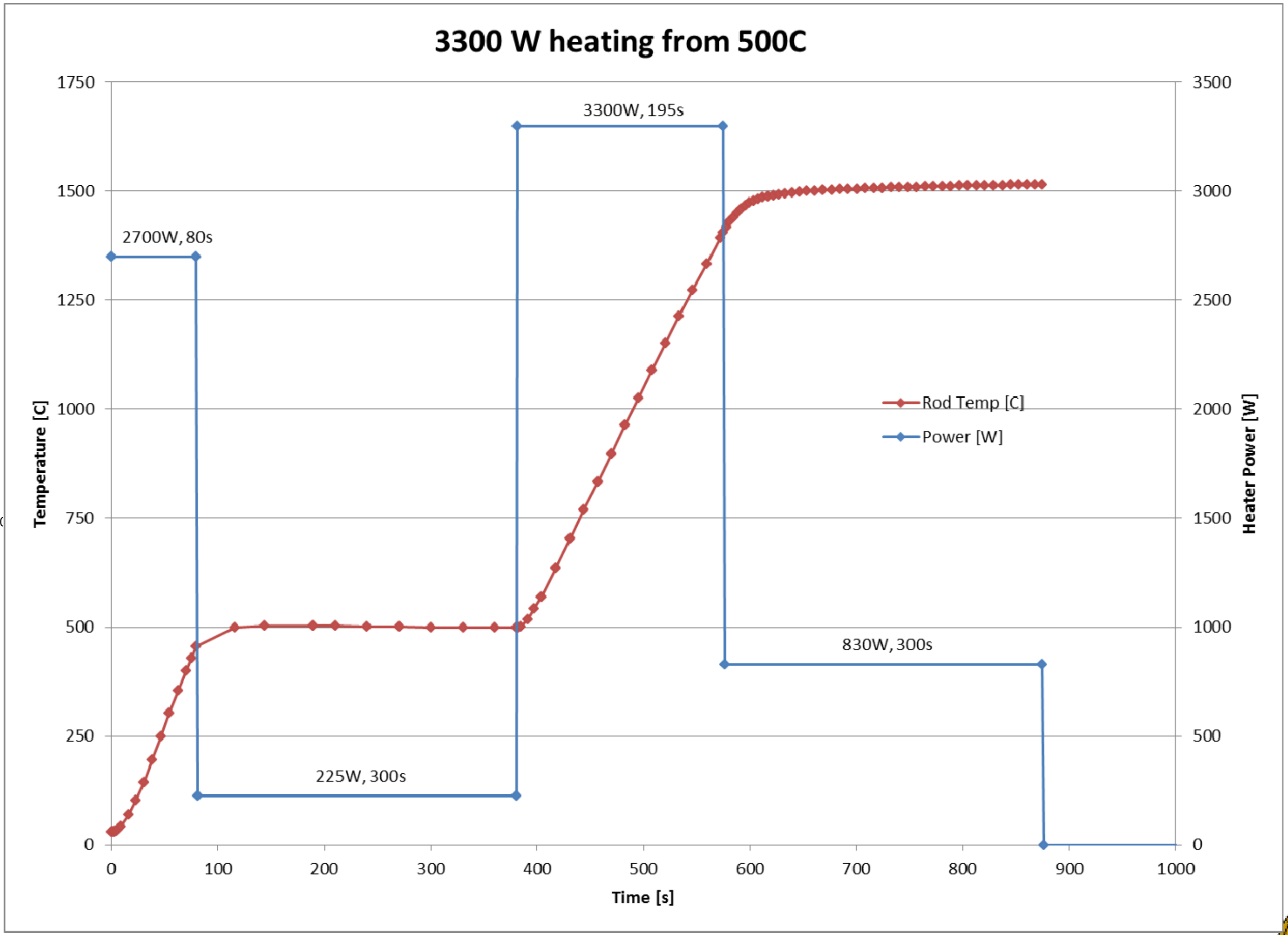
Test sensors in reactor environment with temperature transient



This requires a test article that can do rapid temperature transients and can also be put in reactor

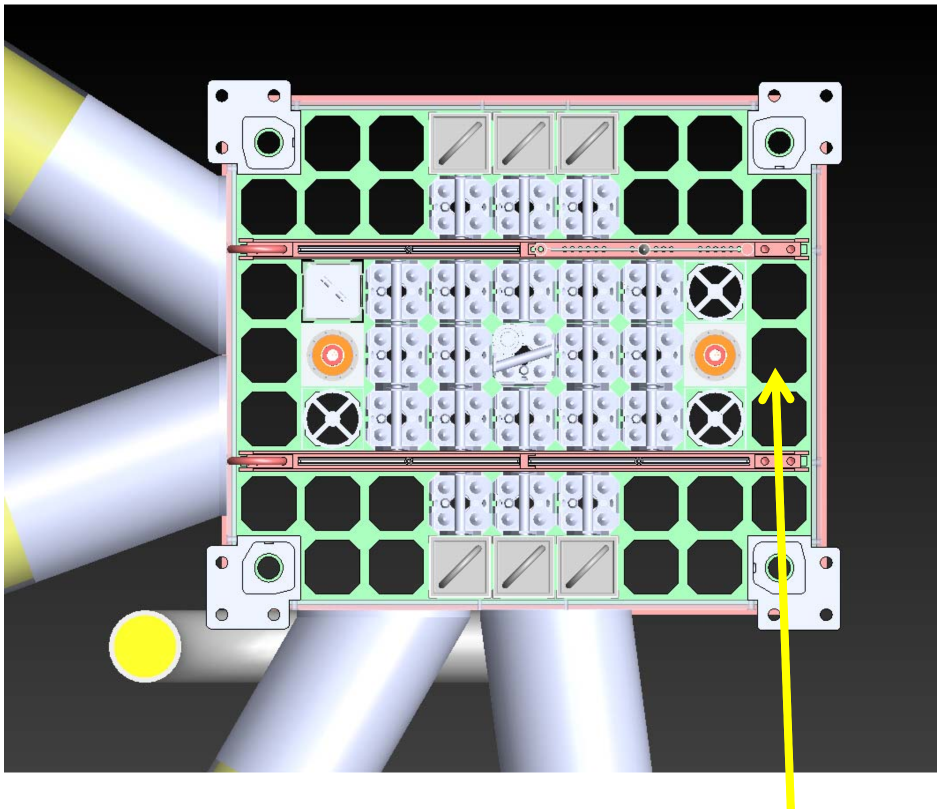
SER-22-16-1/Custom

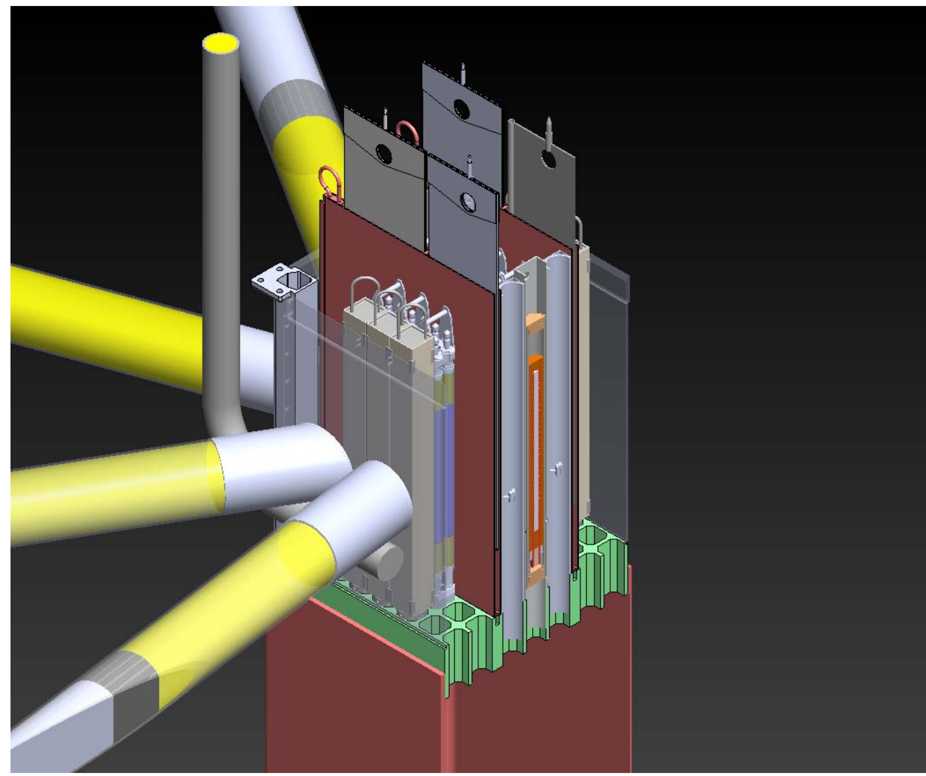




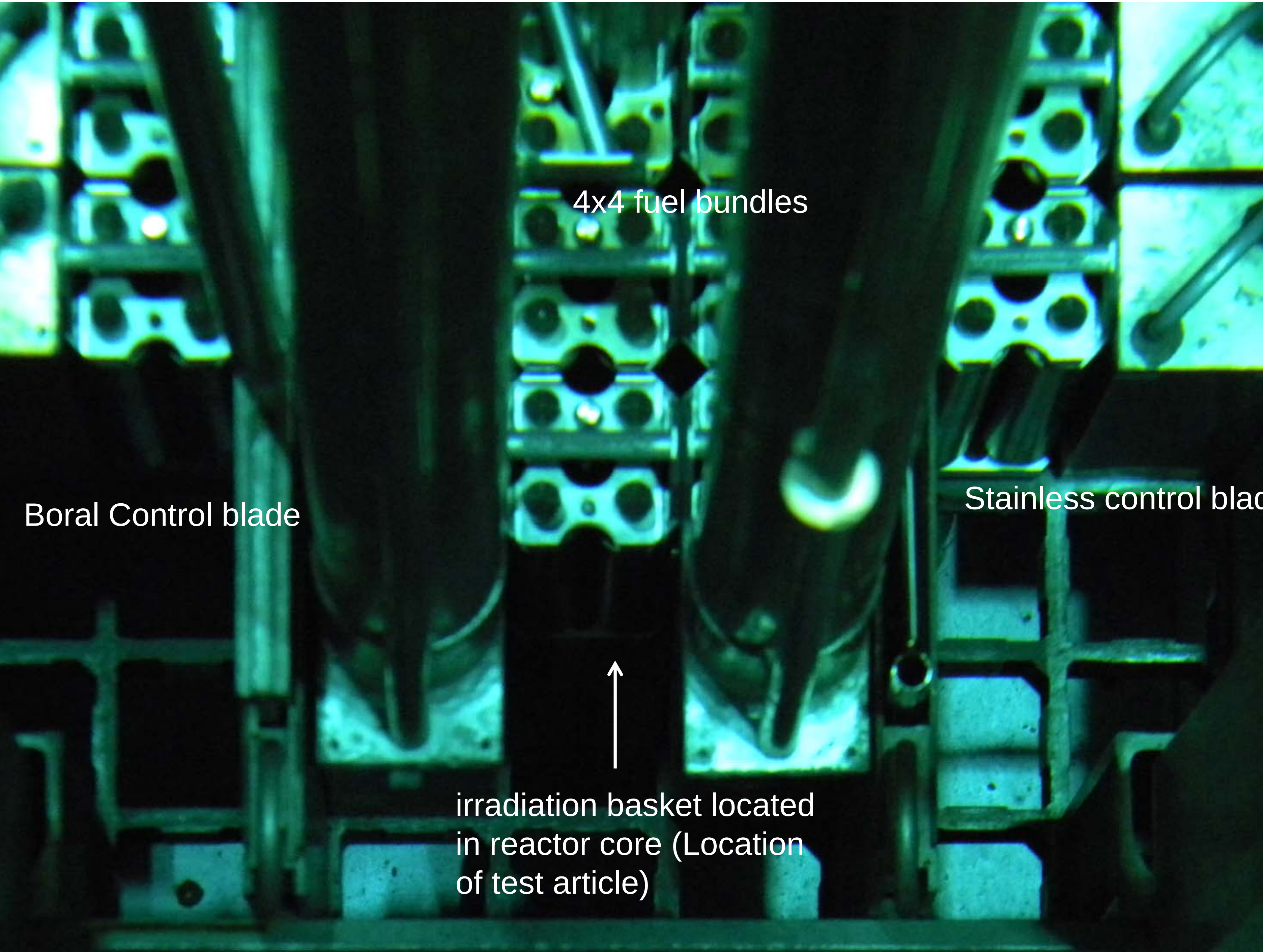
Reactor pulse or steady state runs

Power normalization: 8.347E+16 n/s → 0.9984 MW (±0.01%)

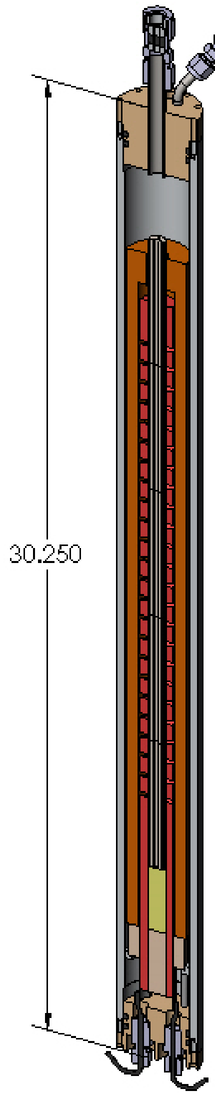




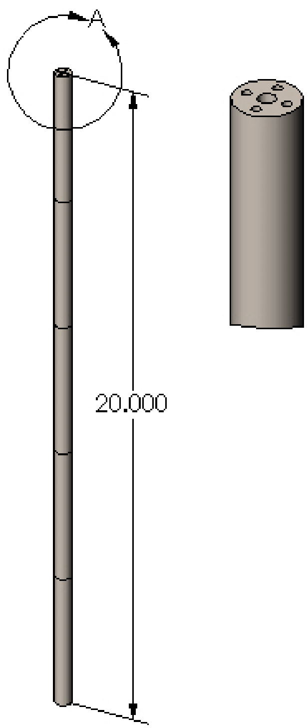
Location of test section


4x4 fuel bundles
Boral Control blade
Stainless control blad
irradiation basket located in reactor core (Location of test article)

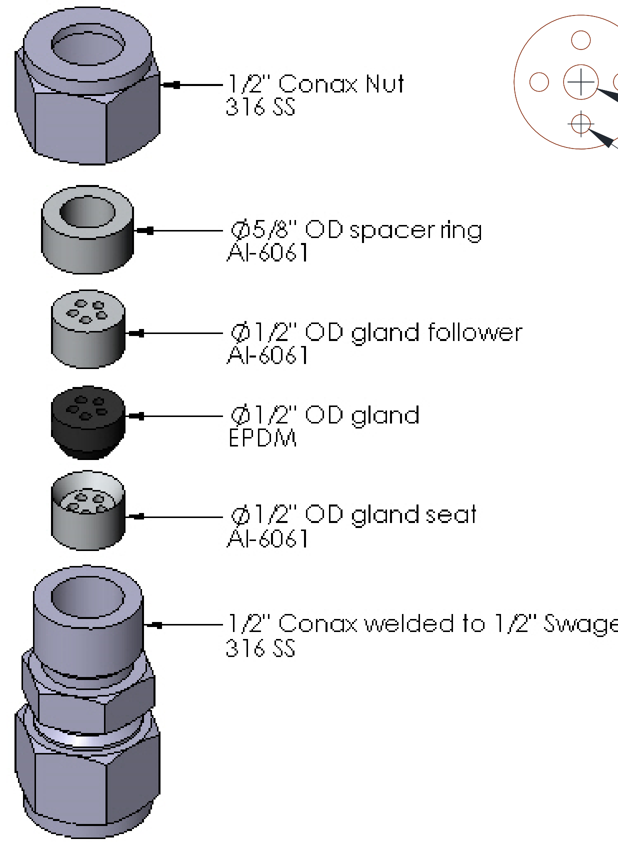
Underwater housing and Transient Rod Experiment Assembly



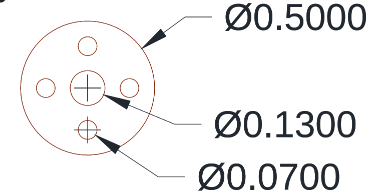
Alumina 5-bore rod
5x 4" segments



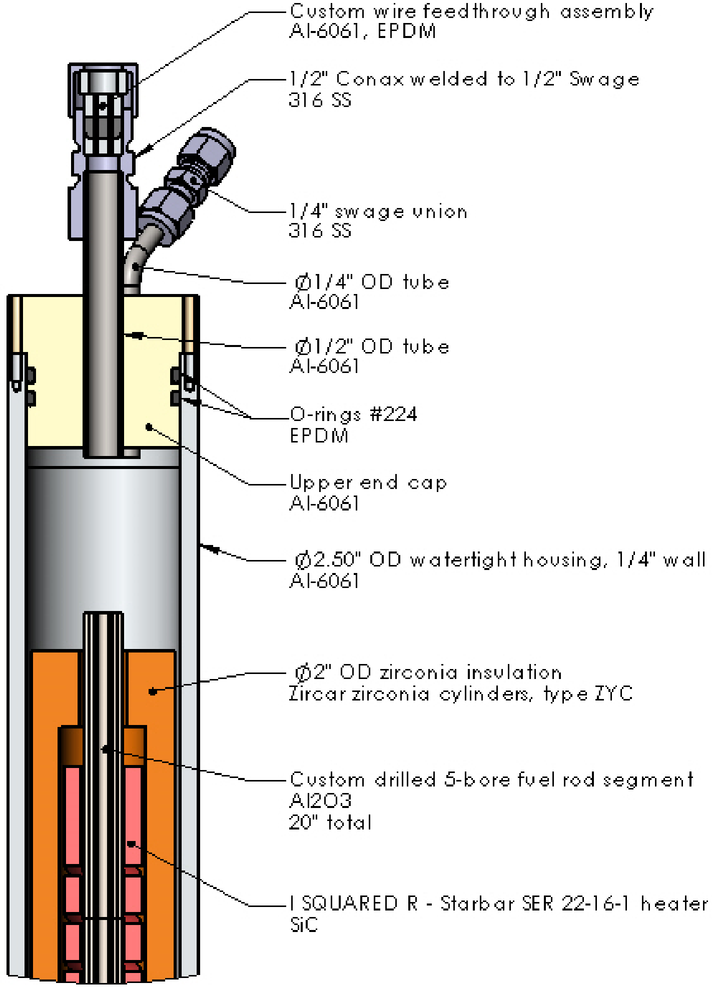
Wire feedthrough assembly

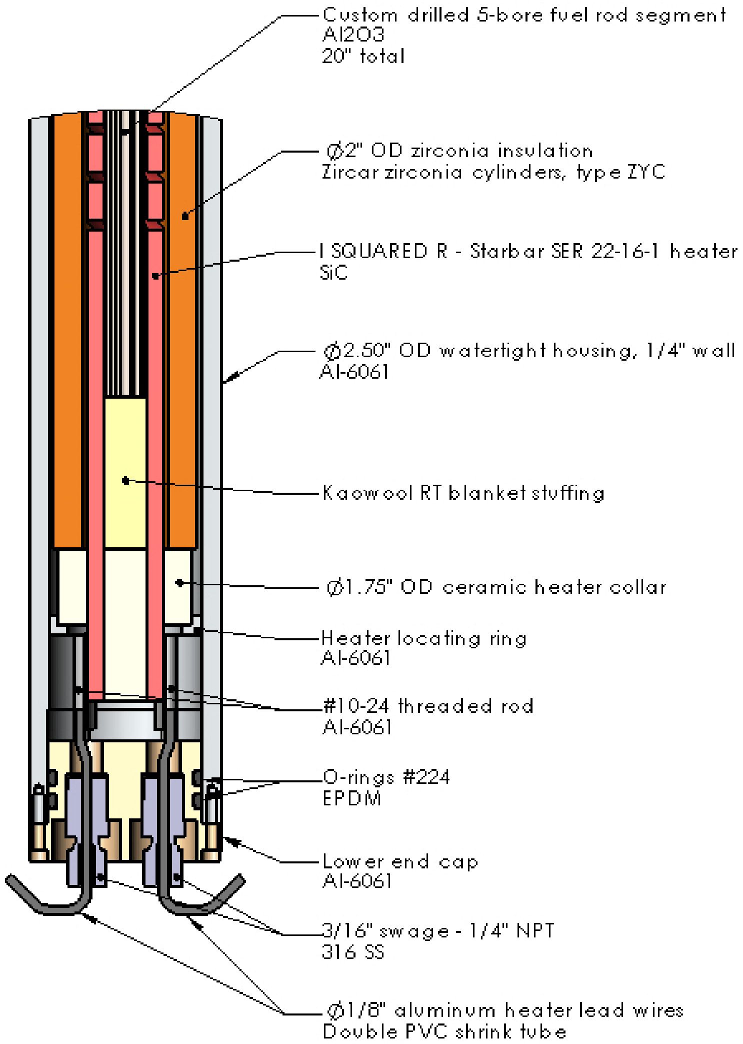


Custom Zirconia Cylindrical Core



Transient Rod Experiment Assembly





Radiation test of underwater housing completed

Tested underwater housing up to 6 hours full power irradiation