Instrumentation to Enhance ATR NSUF Irradiation Testing

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ATR NSUF User's Week 2011

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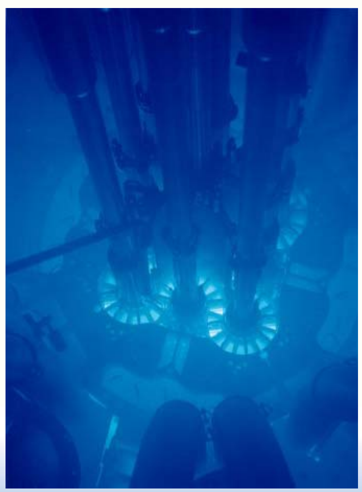
Advanced Instrumentation Needed to Grow ATR Missions



Goal – Provide ATR users real-time measurement of key parameters during irradiation

- **Advanced ATR instrumentation needed to grow nuclear program support.**
  - **Naval reactors**
  - **DOE (NGNP, FCRD, ATR NSUF)**
  - **LWR industry**
- ***Real-time* measurement of key parameters during irradiation:**
  - **Potential for more accurate data**
  - **Avoids disturbing phenomena of interest during post-test exams**
  - **Reduces costs**

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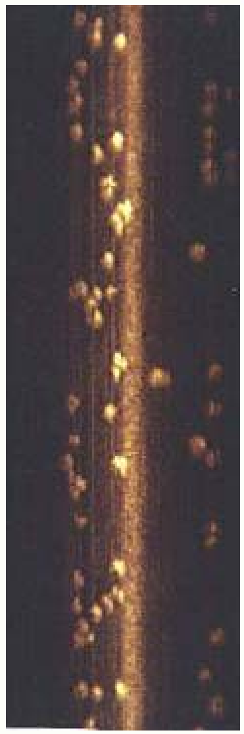
"..despite over 50 years of use, many life-limiting problems.." - Donald Olander

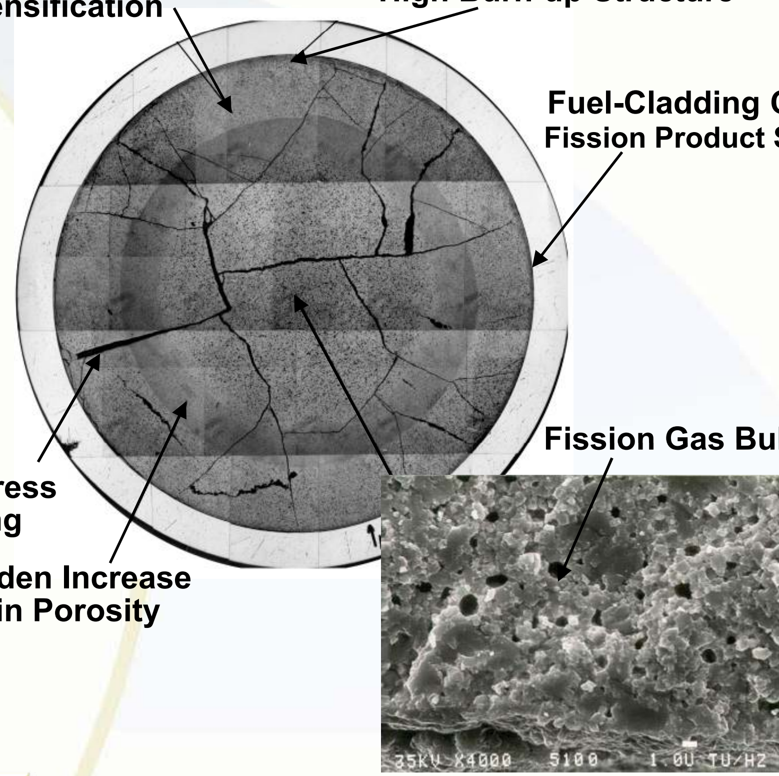
Irradiation Effects

PWR Uniform Corrosion

Coolant Effects



BWR Nodular Corrosion



Real-time, high resolution/accuracy data provide insights needed to resolve data

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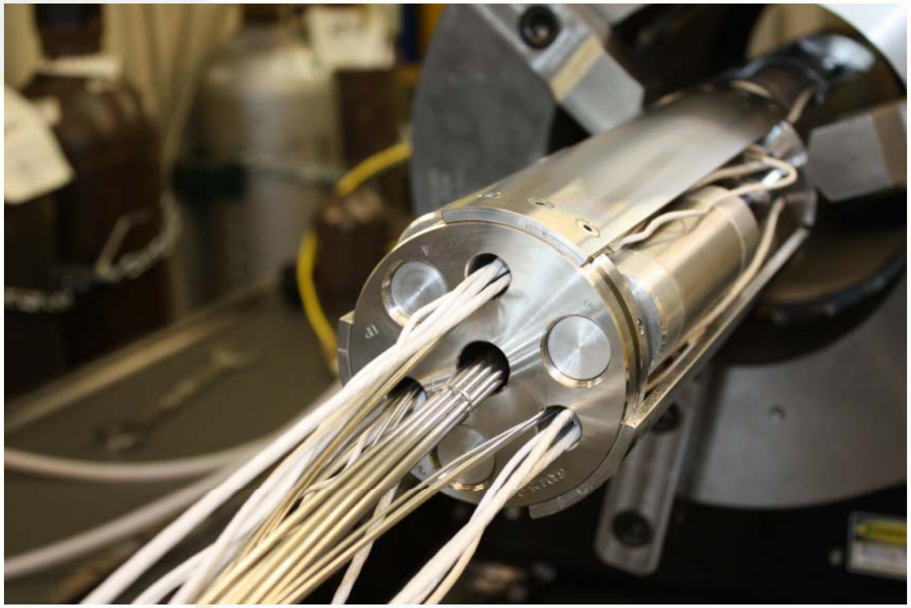
In-Pile Instrumentation Must Meet Several Design Requirements

- Reliable
- Accurate
- Miniature
- High temperature resistant
- Corrosion resistant
- Neutron / gamma 'resistant'
- Non-intrusive
- "Low" cost



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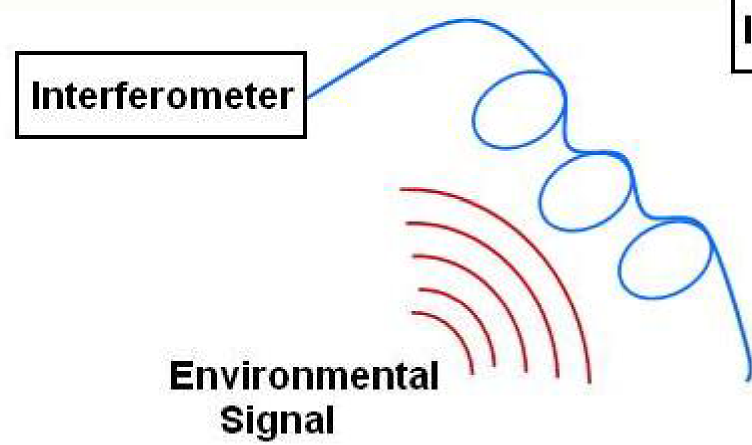
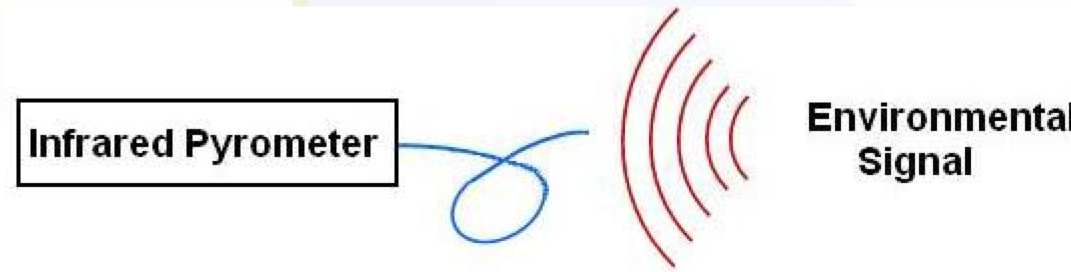
Remote Sensor Types

Intrinsic: effects of measured quantity on signal being transmitted take place in sensor

Extrinsic: fiber/waveguide/wire carries signal, but signal change occurs outside sensor



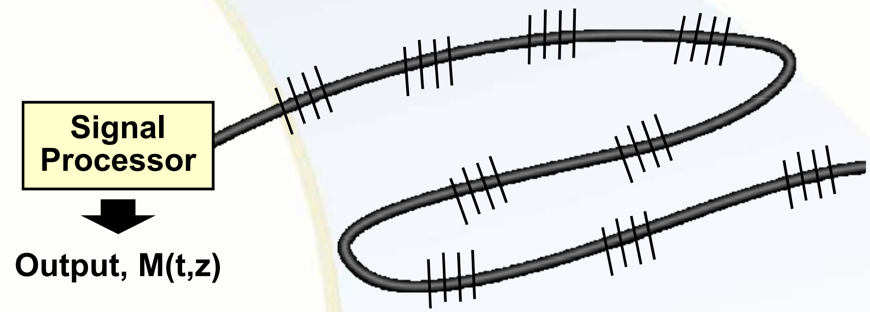


Examples: Fiber optic temperature sensors

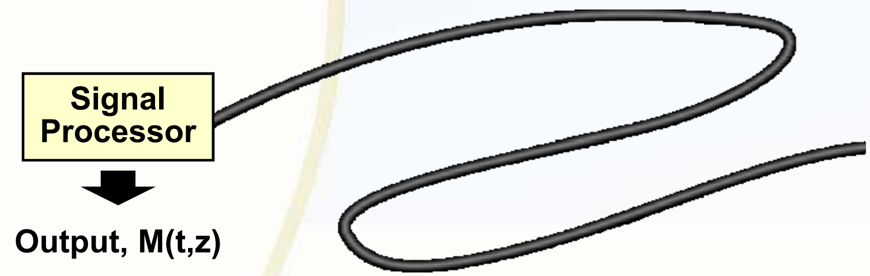
Remote Sensor Types (continued)

Point sensor:
Measurement occurs only at sensor location.

Multiplexed sensor:
Multiple localized sensors are placed at intervals along fiber length.



Distributed sensor:
Sensing distributed along length of fiber.



High Temperature Test Laboratory Capabilities Facilitate In-pile Instrumentation Development

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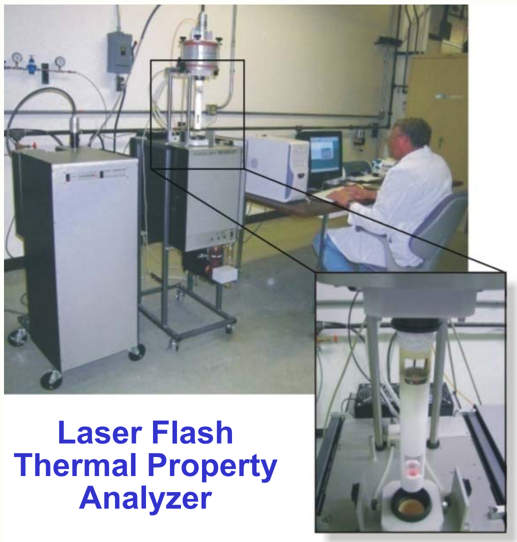
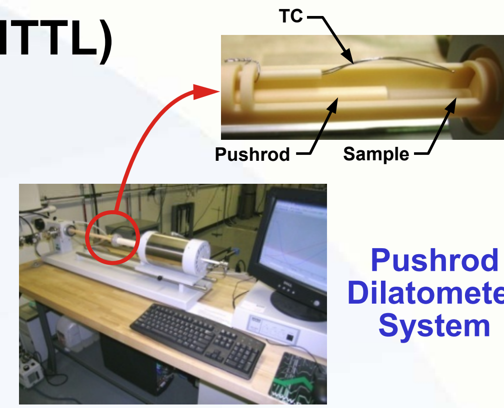
- **Specialized fabrication capabilities, evaluation equipment, and trained staff *available* at INL's High Temperature Test Laboratory (HTTL)**
- **HTTL-developed products and capabilities already attracting new customers**

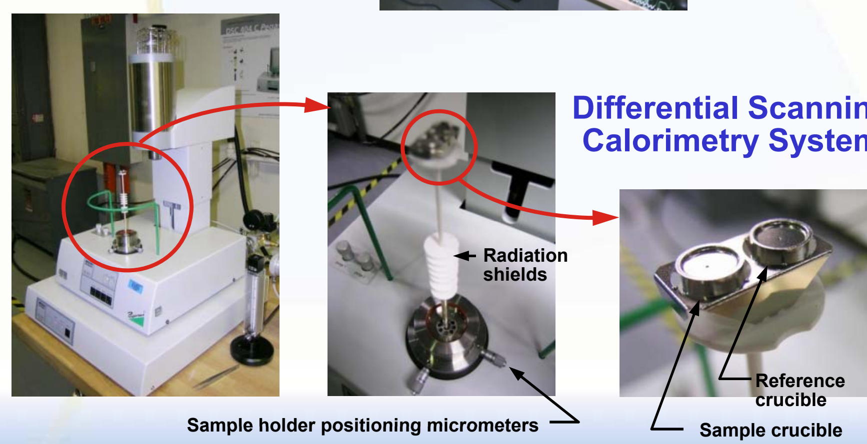


Laser Flash Thermal Property Analyzer



Pushrod Dilatometer System

Thermocouple Fabrication and Evaluation Equipment



Differential Scanning Calorimetry System

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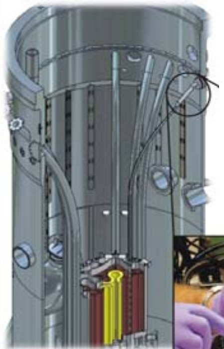
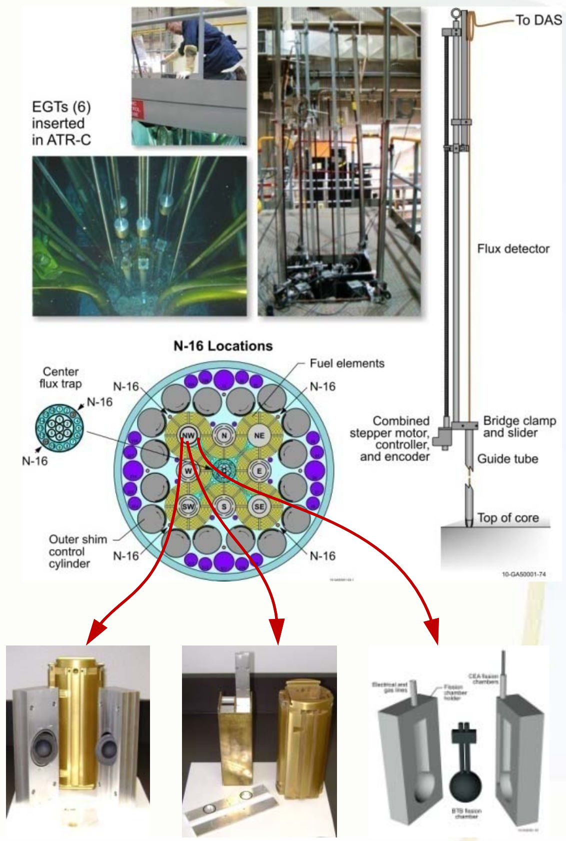
HTTL-Developed Products and Capabilities Provide New Resources for ATR Users

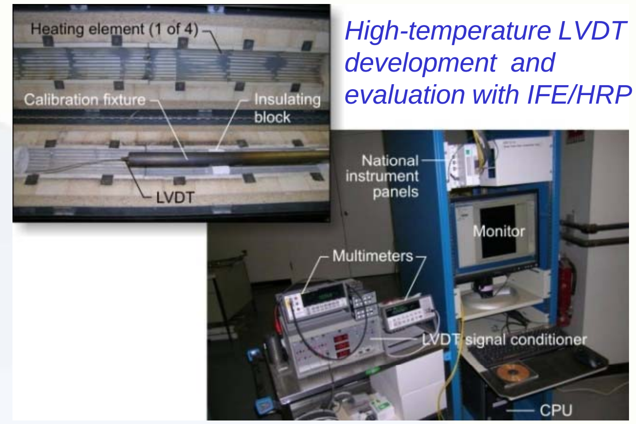


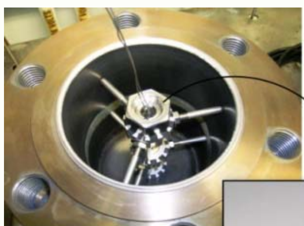

AGR-1 Test Capsule installed in ATR with INL HTIR-TCs

Flux sensor evaluations and micro-pocket fission chamber development with CEA and ISU

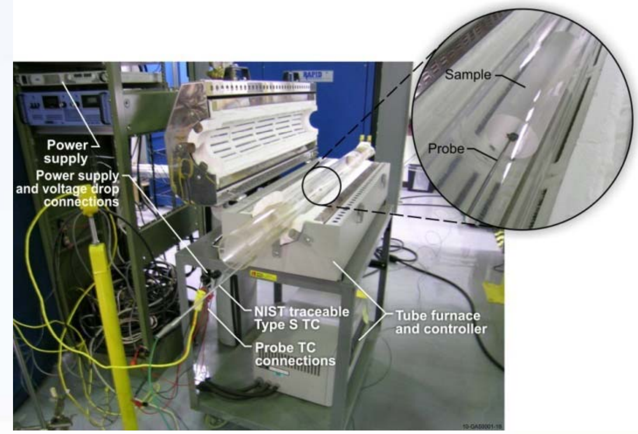


High-temperature LVDT development and evaluation with IFE/HRP

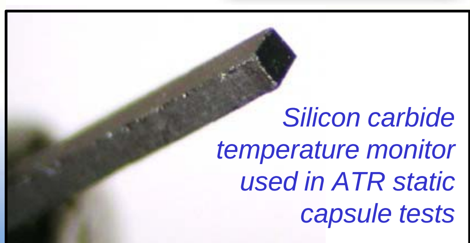





Creep test rig development and evaluation with IFE/HRP and KAERI



Thermal conductivity probe development with MIT, UC-Berkeley, and USU



Silicon carbide temperature monitor used in ATR static capsule tests

4-pack of melt wires encased in quartz tube, to be used in ATR static capsule tests

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Strategy

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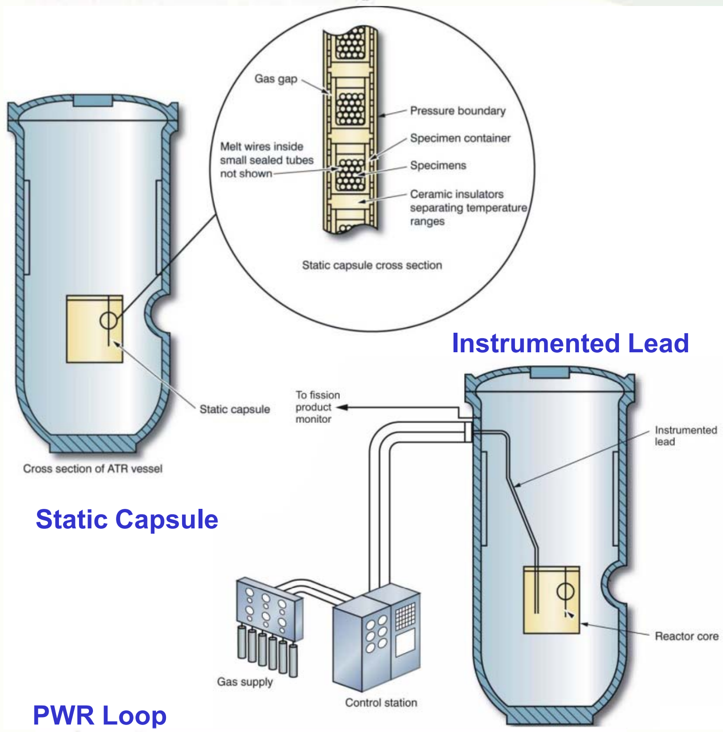
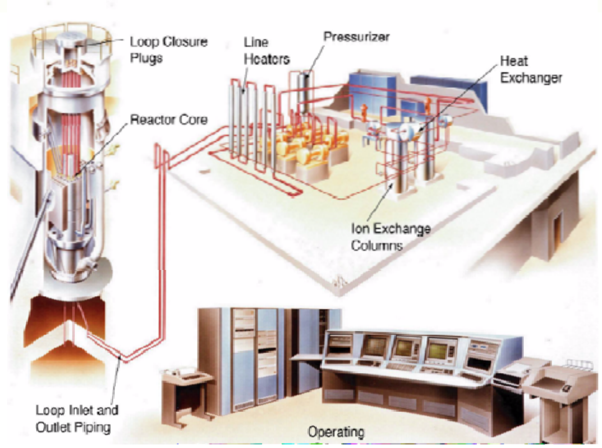
Several Instrumentation Enhancements Available for Various ATR Test Locations





Parameter	Parameter			ATR Technology	Proposed Advanced Technology	
	Static Capsule/ Rabbit	Instr. Lead	PWR Loop		Available at Other Reactors	Developmental
Temperature	√	√	√	• Melt wires (single) • Paint spots (single) • SiC Temperature Monitors (range)		• Wireless (range) • Ultrasonic thermometers
		√	√	• Thermocouples (Type N, K, C, and HTIR-TCs)[a]		• Fiber Optics
Thermal Conductivity		√	√	• Out-of-pile examinations	• Degradation using signal changes in thermocouples	• Hot wire techniques
Fluence (neutron)	√	√	√	• Flux wires (Fe, Ni, Nb)	• Activating foil dosimeters	
		√	√		• Self-Powered Neutron Detectors (SPNDs) • Miniature fission chambers	• Moveable SPNDs
Gamma Heating		√	√		• Gamma thermometers	
Dimensional	√	√	√	• Out-of-pile examinations		
		√	√		• LVDTs (stressed and unstressed) • Diameter gauge	• Ultrasonic Transducers • Fiber Optics
Fission Gas (Amount, Composition)		√	√	• Gas Chromatography • Pressure sensors • Gamma detectors • Sampling	• LVDT-based pressure gauge	• Acoustic measurements with high-frequency echography
Loop Pressure			√	• Differential pressure transmitters • Pressure gauges with impulse lines		
Loop Flowrate			√	• Flow venturis • Orifice plates		
Loop Water Chemistry			√	• Off-line sampling /analysis		
Crud Deposition			√	• Out-of-pile examinations	• Diameter gauge with neutron detectors and thermocouples	
Crack Growth Rate			√		• Direct Current Potential Drop Technique	

[a]Type C thermocouple use requires a “correction factor ” to correct for decalibration during irradiation.

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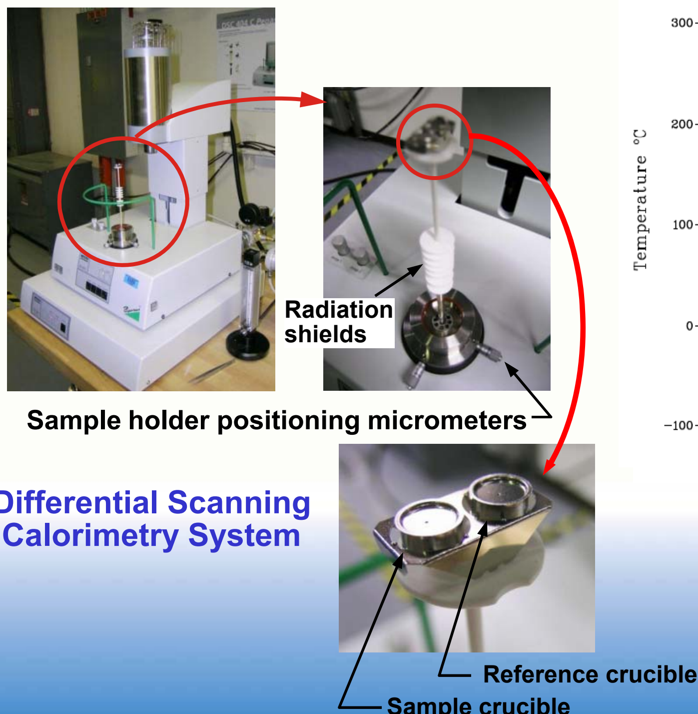
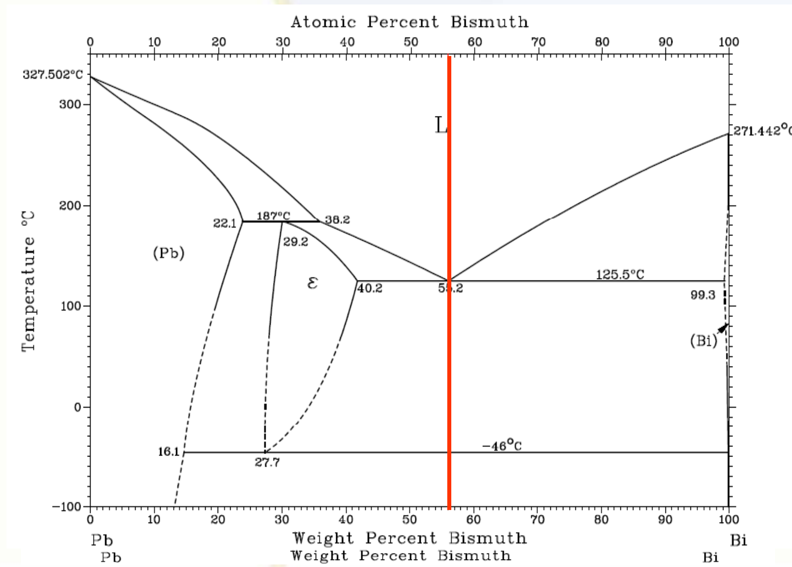
Melt Wires Inexpensive Approach for Estimating Peak Test Temperature

INL qualified supply of melt wires encapsulated in quartz for irradiation testing:

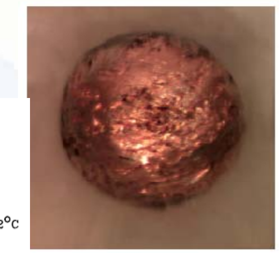
- **Range of melting temperatures (100-1000 °C)**
- **Low neutron capture cross-section**
- **Easily handled**
- **Visible deformation**



Differential Scanning Calorimetry System



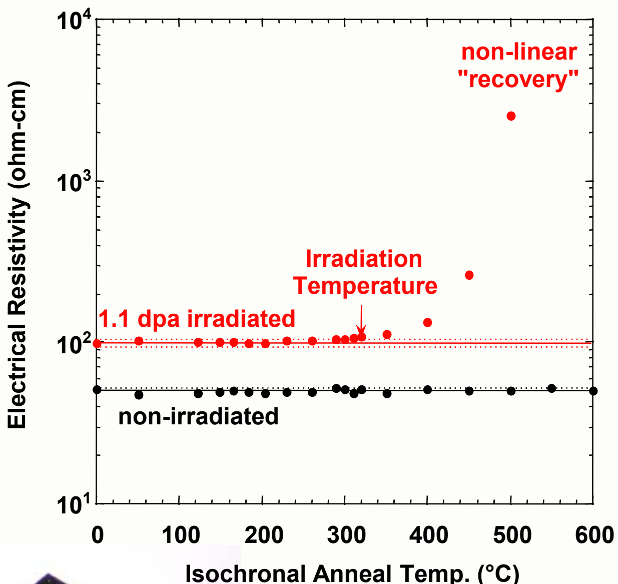
Lead/Bismuth Phase Diagram



Copper/Gold Alloy Post Melt

Ag/Cu/Zn/Mn/Ni Alloy Post Melt

Single SiC Monitor Offers Detection for Temperature Range in Static Capsules



1 x 1 x 10 mm

- ATR static capsule temperature detection previously limited to single temperature sensors (paint spot, melt wires, etc.)
- Post-irradiation annealing of SiC to detect peak irradiation temperature used since 1960
  - Heating above peak irradiation temperature reduces irradiation-induced lattice expansion (swelling from defect and void formation)
  - Swelling reduction detected by changes in length, density, thermal diffusivity and resistance
- ORNL evaluations indicate more accurate peak irradiation temperature detection with
  - fully dense, CVD SiC
  - resistance change measurements

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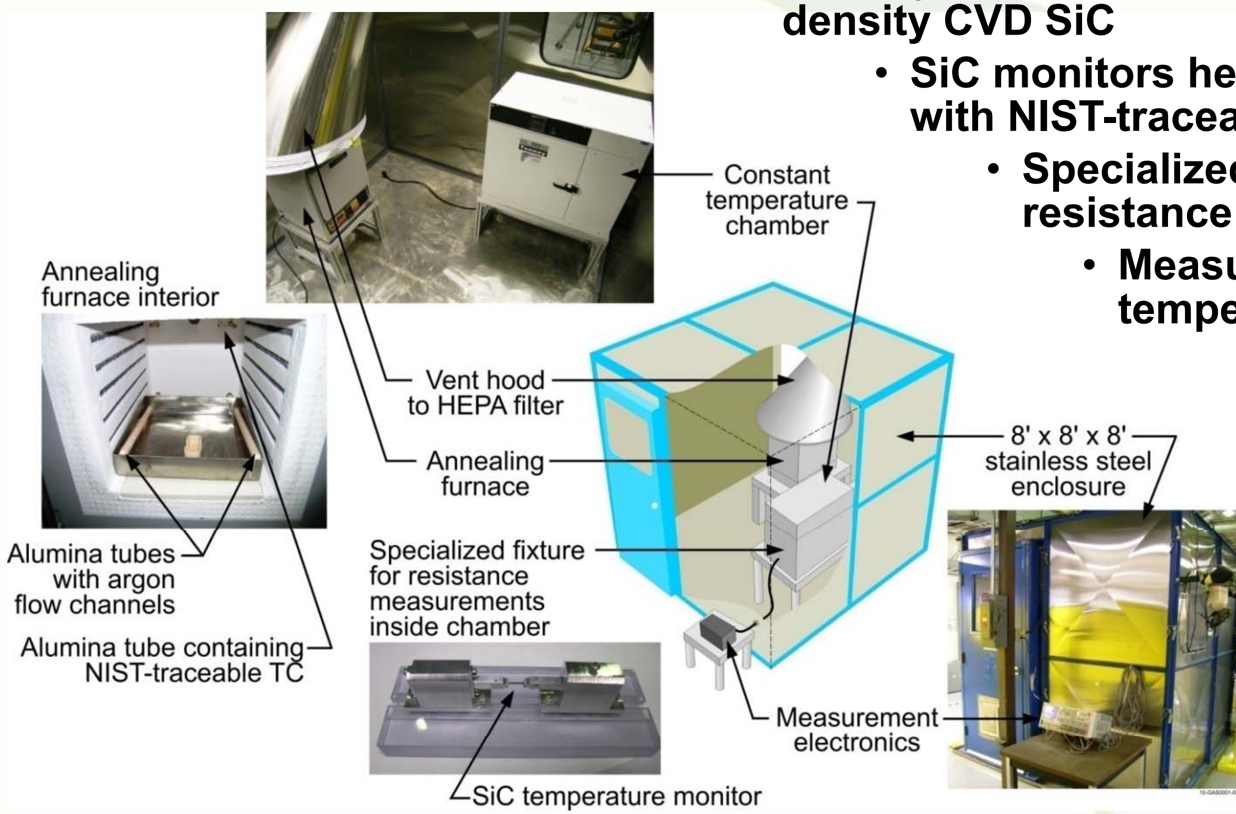
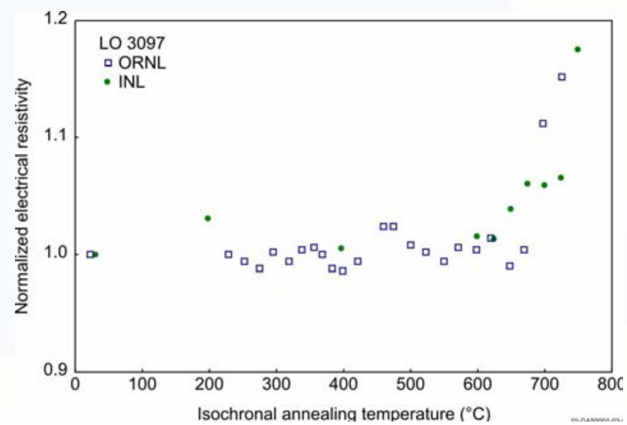
HTTL Developed Viable Approach for Measuring Resistivity of SiC Monitors

- **Small (1 mm x 1 mm x 10 mm) monitors of high density CVD SiC**
  - **SiC monitors heated for 30 minutes in furnace with NIST-traceable thermocouples**
    - **Specialized fixturing developed for resistance measurements**
      - **Measurements made in constant temperature chamber at 30 ° C**
        - **High accuracy (9 digit) electronics**





- **INL approach agrees within 5% of ORNL results**
- **Thermocouple comparisons indicate accuracies of 20 °C**
- **Similar accuracies for wide range of temperatures (200 – 800 °C) and doses (1.1 to 8 dpa)**

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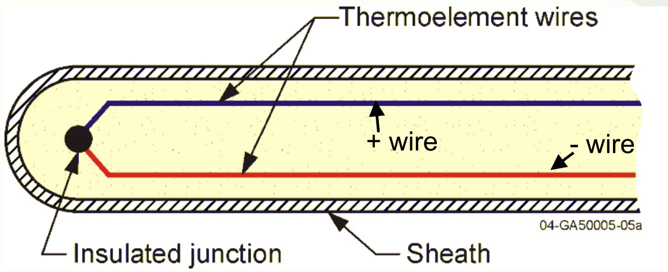
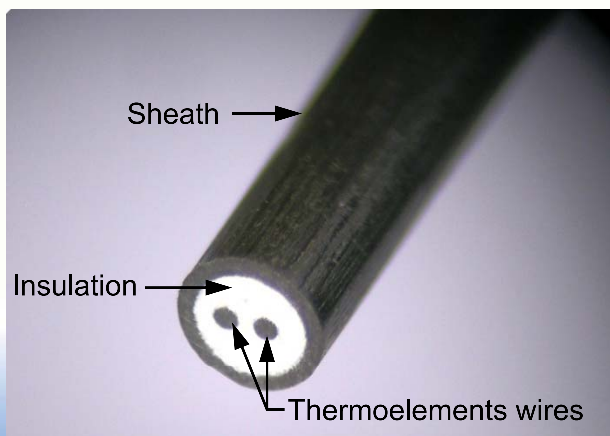
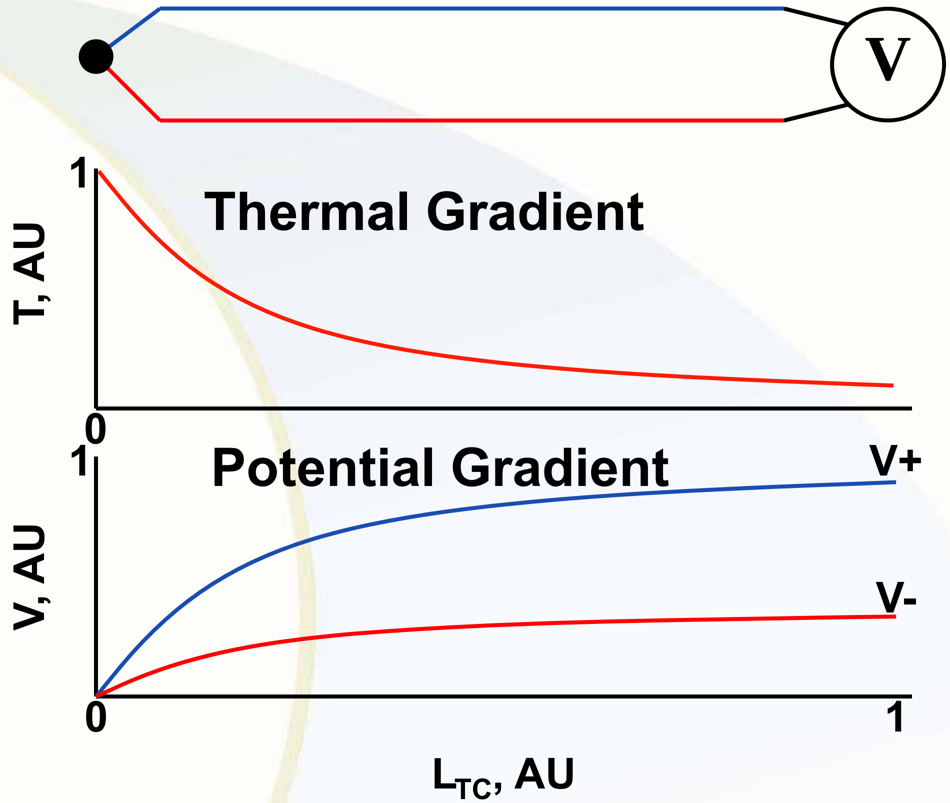
Thermocouples are an Established Easy-to-Use Measurement Method



Thermocouples –

- Simple construction
- Easily understood
- Low-cost signal processing





Design Options:

- Material selection
- Fabrication method

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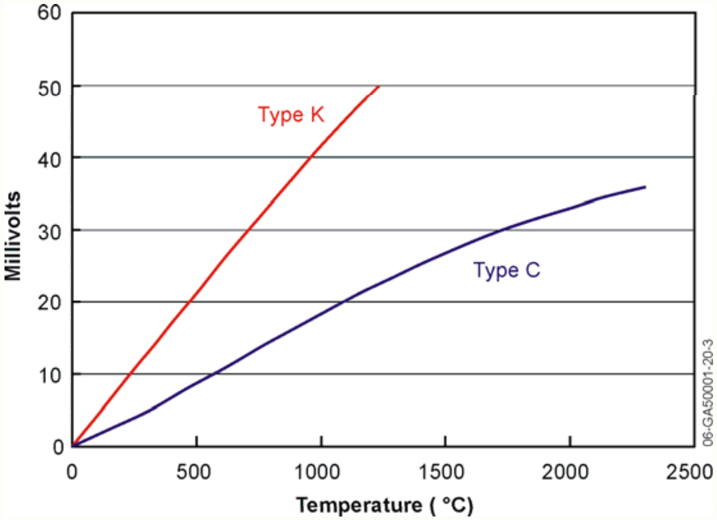
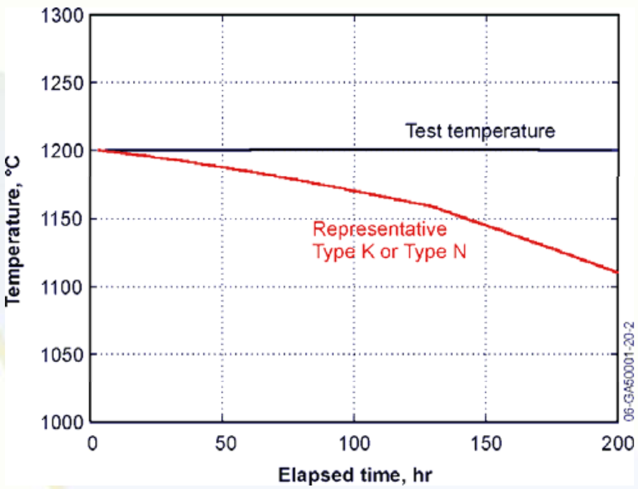
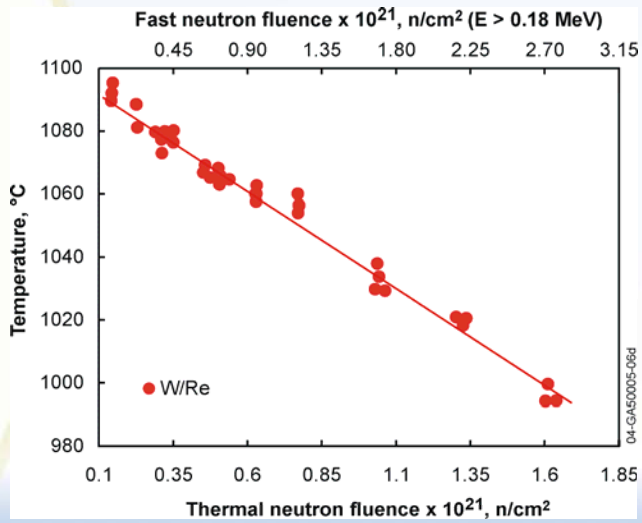
High Temperature Thermocouples Needed to Support Fuels and Materials Irradiation Programs







Drift exceeds 100 °C in Type N and K thermocouples within 200 hours

Drift of nearly 100 °C in Type C thermocouples in fluences exceeding 10^{21} n/cm²

Commercial thermocouples degrade at temperatures above 1100 °C or transmute during irradiation.

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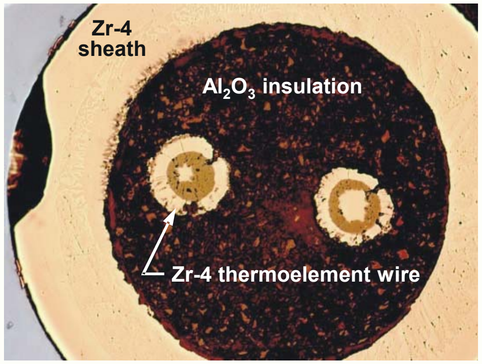
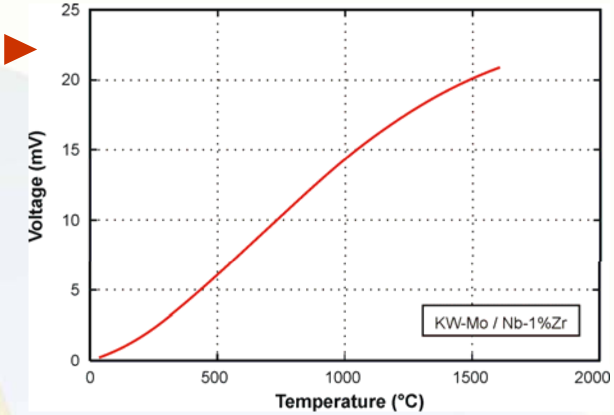
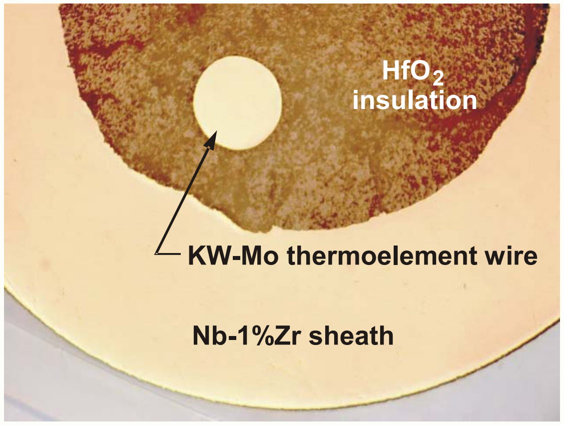
Initial HTIR-TC Development Considered High Temperature Material Compatibility, Ductility, and Resolution



Al_2O_3 attacks wire and sheath after heating at 1300°C

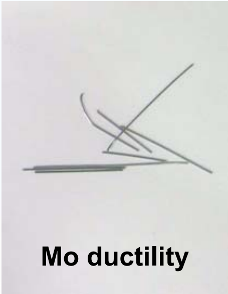
Selected KW-Mo and Nb-1%Zr combination has suitable resolution up to at least 1700 °C





Selected materials resist interactions after heating at 1600 °C

Selected KW-Mo ductile after heating at 1600 °C



Evaluations suggest doped Mo/Nb-1%Zr thermoelements with HfO_2 insulation and Nb1%Zr sheaths most suitable combination for HTIR-TCs.

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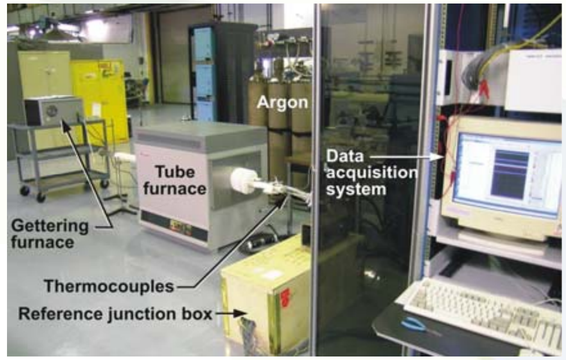
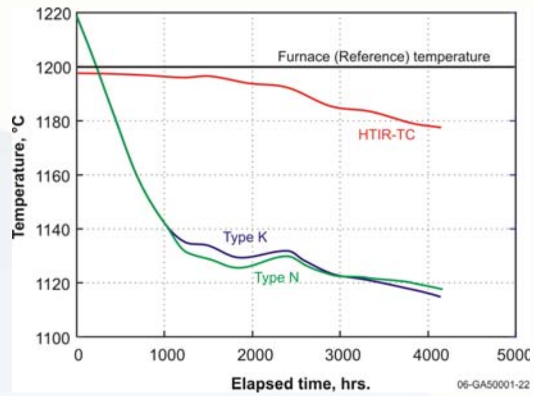
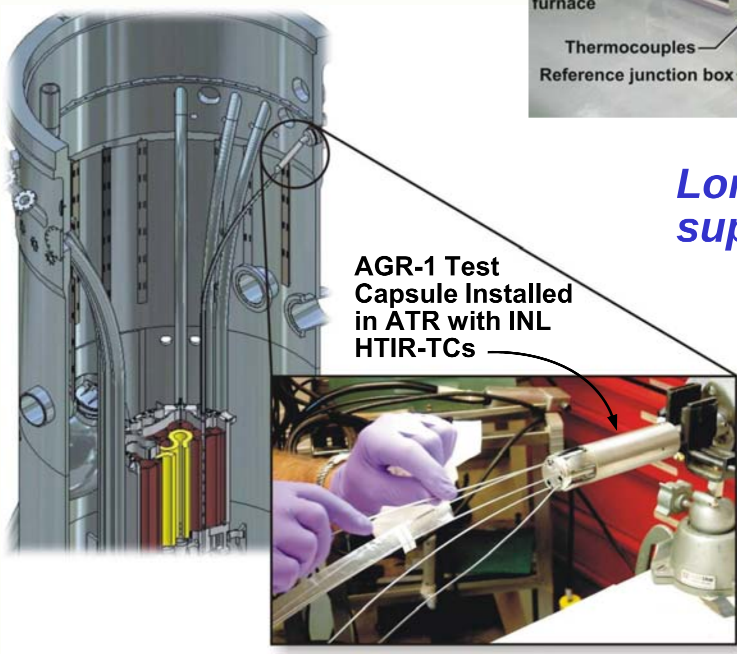
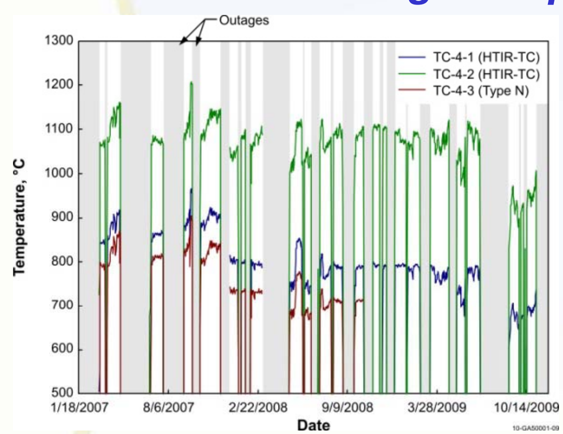
Subsequent HTIR-TC Development Included Long Duration and Radiation Testing





Long duration laboratory testing show HTIR-TCs superior to commercial TCs at high temperatures





HTIR-TCs performed well throughout AGR-1 irradiations (while commercial TCs failed)

HTIR-TCs patented by BEA and soon to be deployed in MITR and HBWR

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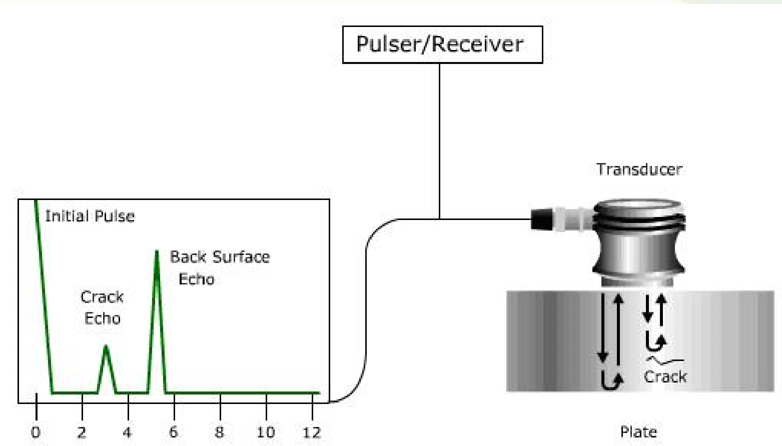
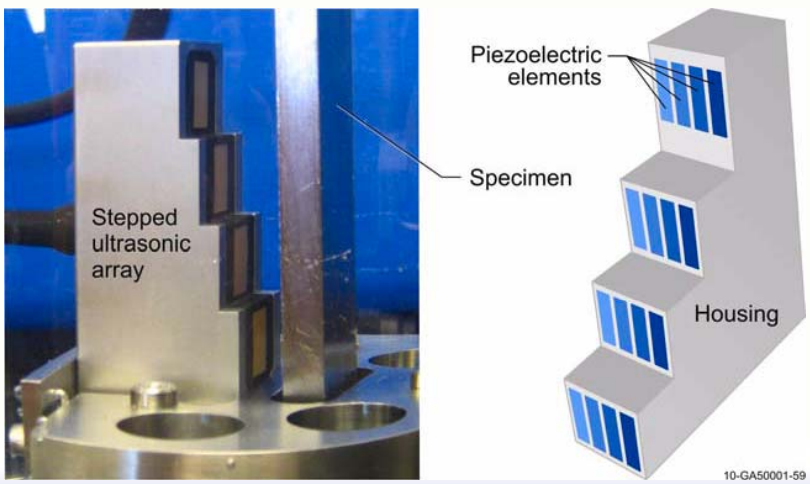
Ultrasonic Technology is Widely Used in Industry for Non-Destructive Evaluation





Advantages

- Small Size: Waveguide may be small diameter wire
- Multiple parameters can be sensed
- Many methods of sending/sensing signals
- Virtually any low attenuation material may be used to carry signals
- Resistant to harsh environment
- Well developed technology for industry/medical applications
- Low cost transducers

Issues

- Complicated signal processing
- Lack of transducer testing in neutron radiation environment
- Possible signal attenuation at pressure seals

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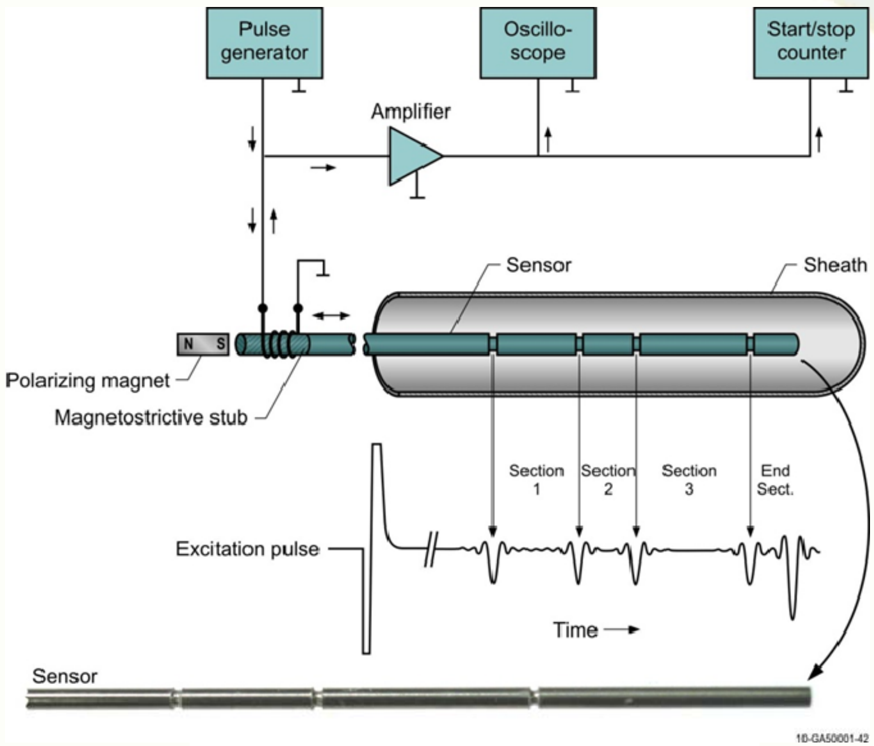
Ultrasonic Thermometer Offers Potential for Improved Accuracy and Temperature Profiling



$$v(T) = \sqrt{\frac{E(T)}{\rho(T)}}$$

- **Small Diameter**
  - **Down to 0.010”**
    - **Minimal Impact On Sample**
  - **Minimizes Wave Dispersion/Mode Conversion**
- **Very High Temperatures**
  - **Previously Tested to ≈3000 °C**
- **Suitable for Harsh Conditions**
  - **High Temperature**
  - **Radiation**
  - **Corrosive Environment**
- **High Resolution**
  - **Multi-Segment Design**
- **High accuracy (e.g., 1% or better)**
- **High durability**

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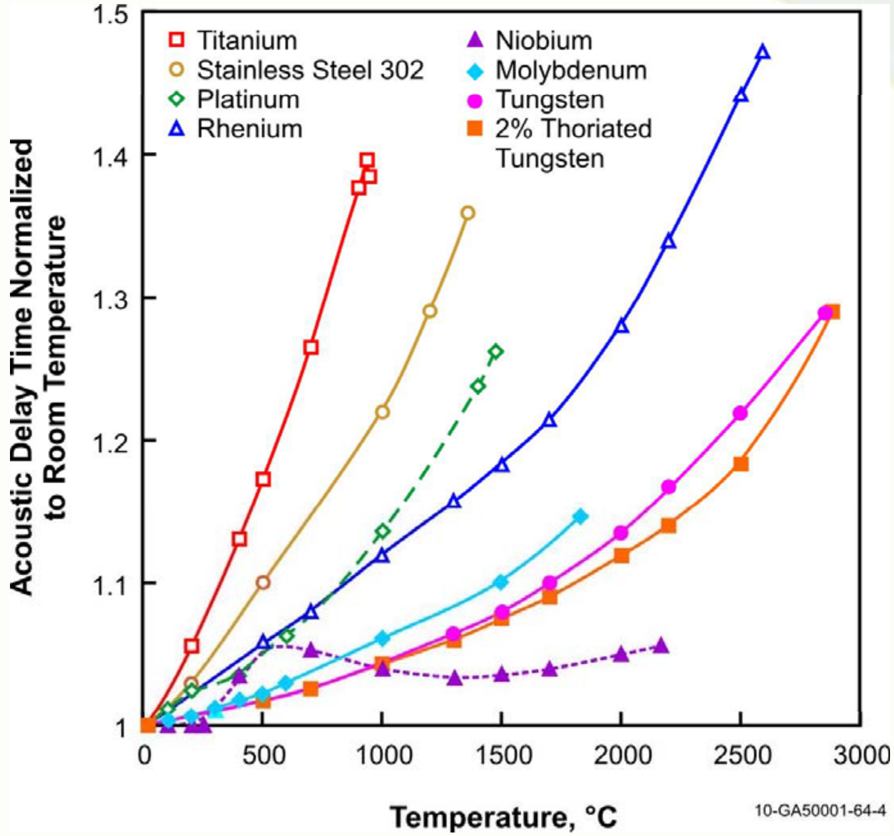
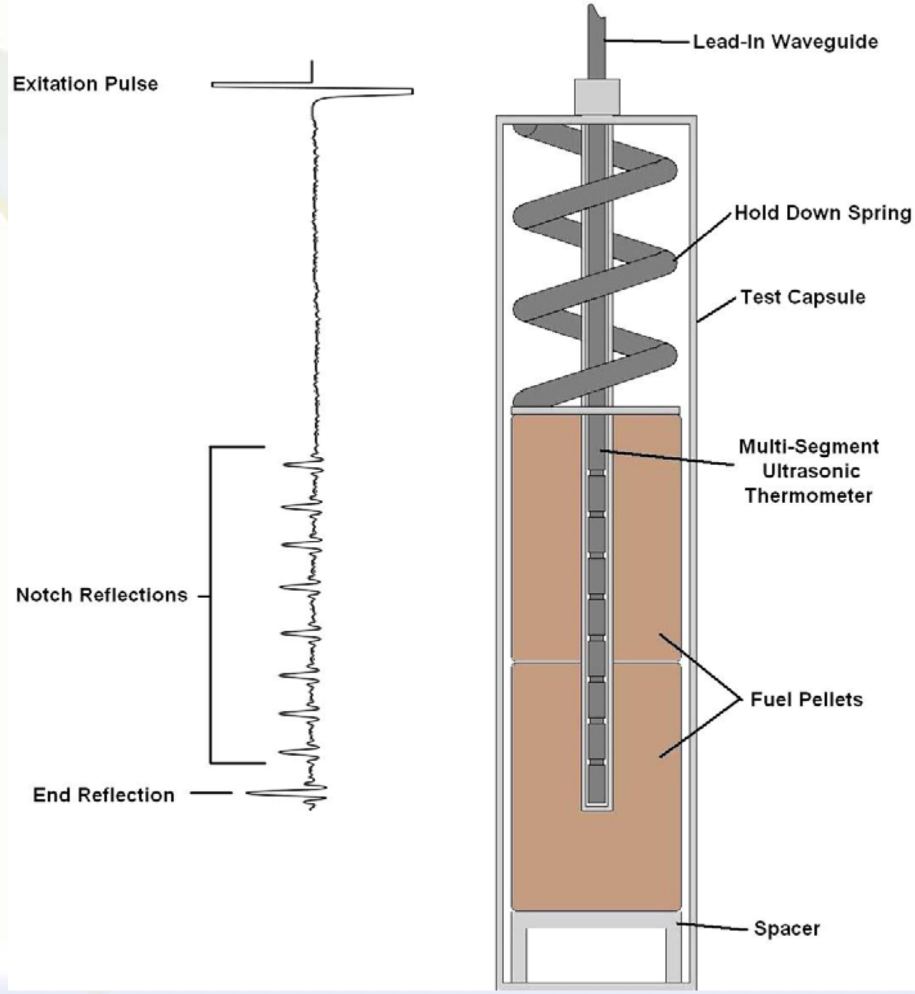
Ultrasonic Thermometer Offers Potential for Improved Accuracy and Temperature Profiling Continued





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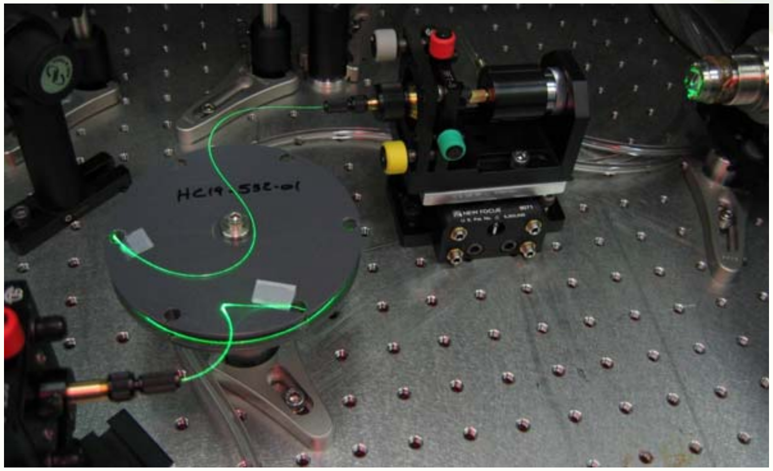
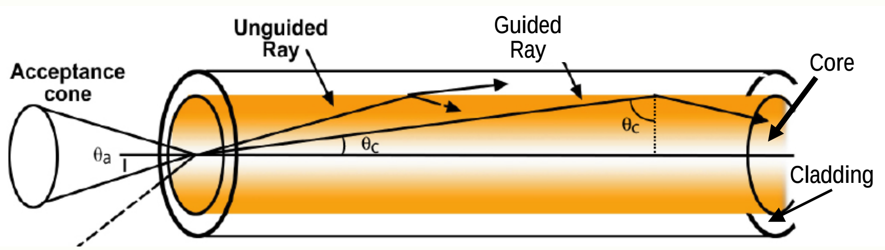
Fiber Optic Sensor Measurements Based On Changes in Light Intensity, Spectrum, Phase, or Polarization





Advantages

- **Small Size: ~20 fibers in single 1/16" diameter tube**
- **Multiple parameters sensed simultaneously**
- **Distributed sensing**
- **Resistant to harsh environment**
- **Unaffected by electromagnetic interference**
- **Low cost**

Issues

- **Fiber darkening due to irradiation**
- **Temperature limited (~700ºC,~1000ºC with appropriate clad)**
- **Optical path issues (extrinsic measurements require re-coupling light back into the fiber)**
- **Pressure boundary seals/fiber protection**
- **Complex signal processing**

Typical Core diameter: 5 – 200 µm

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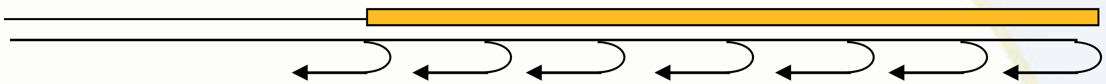
Fiber Optics Offer Point, Multiplexed, and Distributed Options for Temperature Detection

Distributed measurement using stimulated scattering

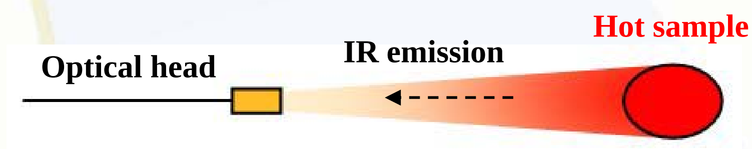
-Raman → temperature distribution , chemical composition, dispersive spectrometer (ex : monitoring primary coolant circuit)

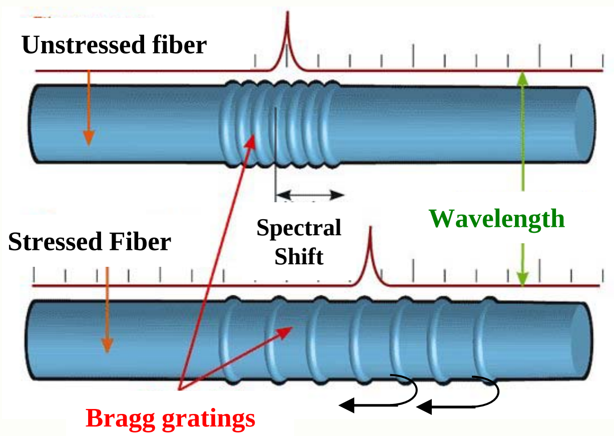
- Brillouin → temperature / deformation, interferometer



Point measurements

Optical Pyrometry

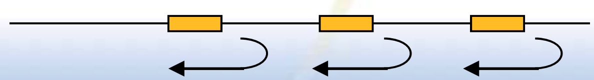




Figures from CEA\Villard ATR-NSUF 2010 Presentation

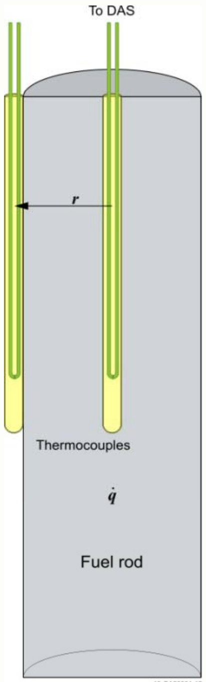
Distributed measurements

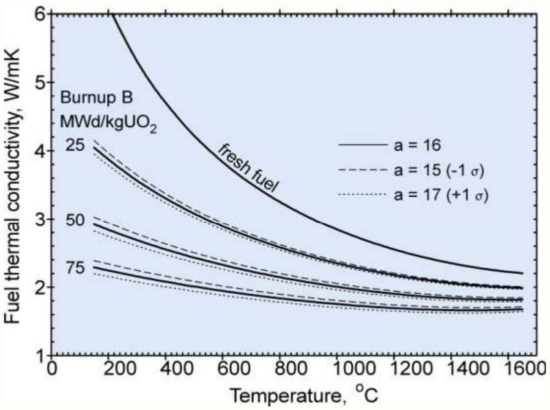
Bragg gratings → temperature, deformation, pressure, etc.



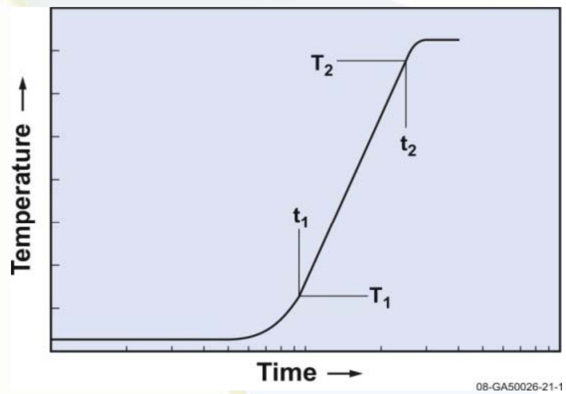
Fiber strain causes shift in reflected wavelength

Two Approaches Investigated for In-Pile Thermal Conductivity Detection

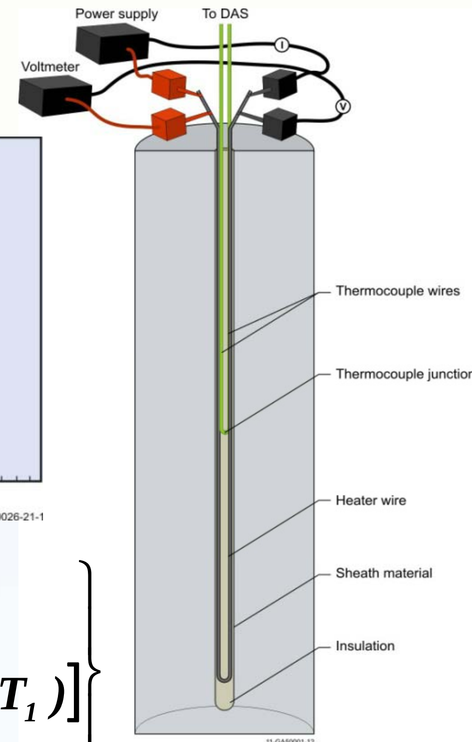




$$k = \frac{\dot{q} \cdot r^2}{4 \cdot \Delta T}$$



$$k = Q_w \left\{ \ln\left(\frac{t_2}{t_1} \right) \Big/ \left[4\pi (T_2 - T_1) \right] \right\}$$



Multiple Thermocouple (MTC) :

- **Adaptation of IFE-HRP method**
- **Steady-state measurement**

Transient Hot-Wire Method (THWM) Needle Probe:

- **Adaptation of ASTM method**
- **Transient measurement**

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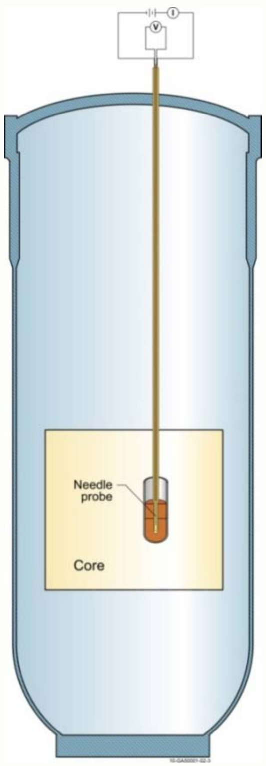
THWM Needle Probe Designed to Overcome Obstacles Associated with In-Core Applications

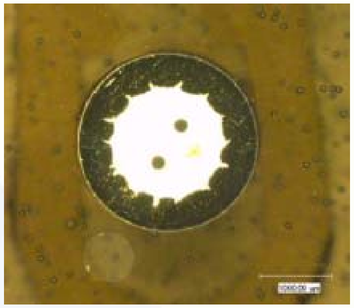


IDR filed on unique probe design

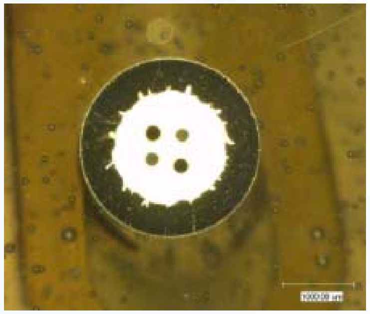
Unique combination of materials, geometry, and fabrication techniques make THWM needle probe more suitable for in-core applications

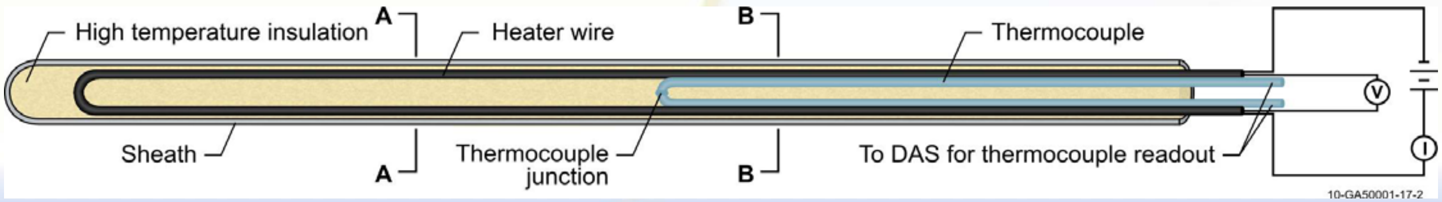
- **Minimize sensor geometry/influence**
- **Maximize fuel hot-wire heating**
- **Ex-capsule/ex-vessel transition to 4 wires for power supply and detection**
- **Thermocouple-like construction with high temperature materials that remain ductile while resisting transmutation and materials interactions**
- **Multiple combinations of materials possible; HTIR-TC included for high-temperature detection during irradiation**

Cross-section A-A



Cross-section B-B





Innovative research on THWM thermal conductivity probe subject of MOUs with IFE/HRP and CEA

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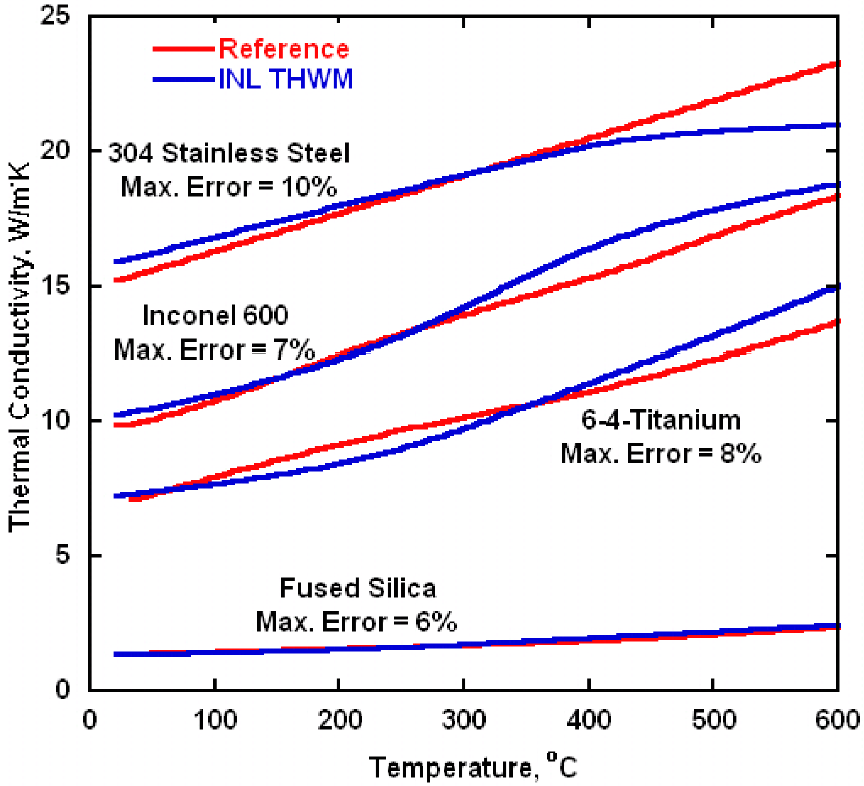
THWM Values Consistent with Published Values for Range of Materials and Temperatures



Material	Thermal Conductivity (W/m·K)		% Diff
	INL	Reference	
Acrylic	0.21	0.20	5.0
Delrin	0.33	0.34	2.9
Fused Silica	1.4	1.4	0
Titanium-6%Al-4%V	7.3	7.2	1.3
Inconel 625	10.3	9.9	3.7
304L Stainless Steel	15.9	15.3	3.5

Elevated Temperature Results **Room Temperature Results**

Material thermal conductivities selected to bound possible fuel thermal conductivities

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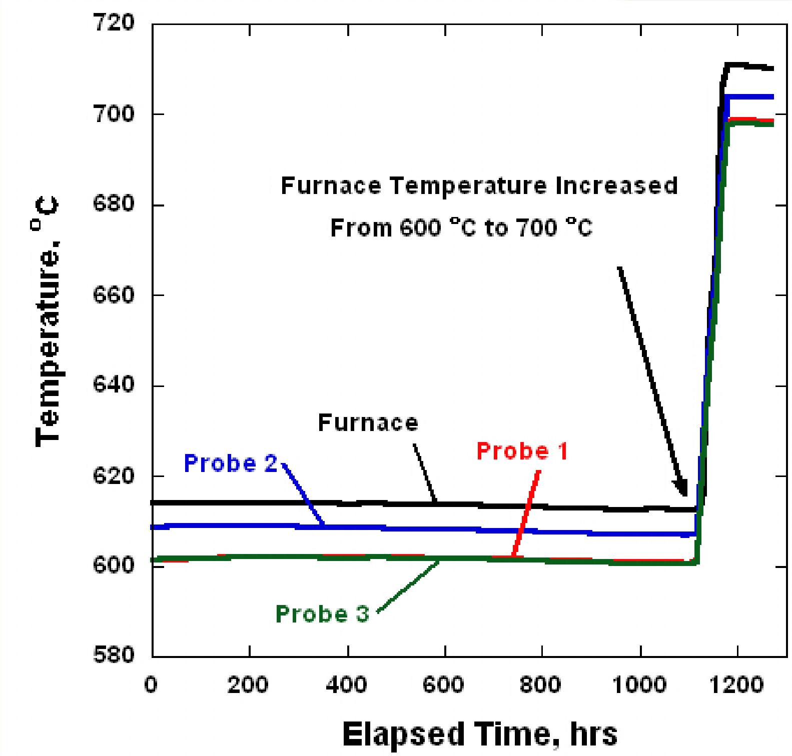
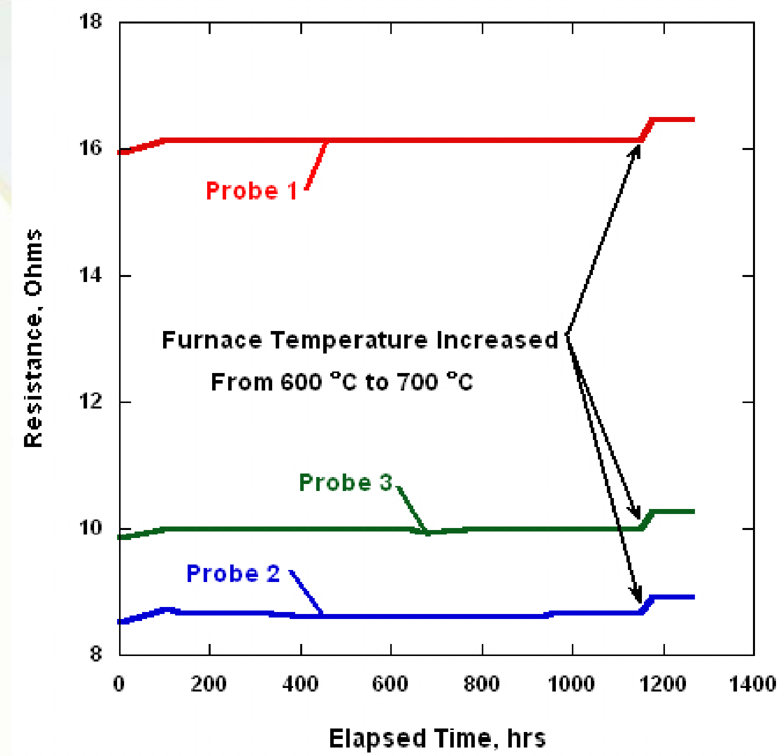
Long Duration Test High Temperature Testing Confirms THWM Needle Probe Stability





Less than 1% drift or insulation resistance degradation in 1000 hour test at 600 °C (evaluation temperature selected to be consistent with conditions for MITR irradiation).

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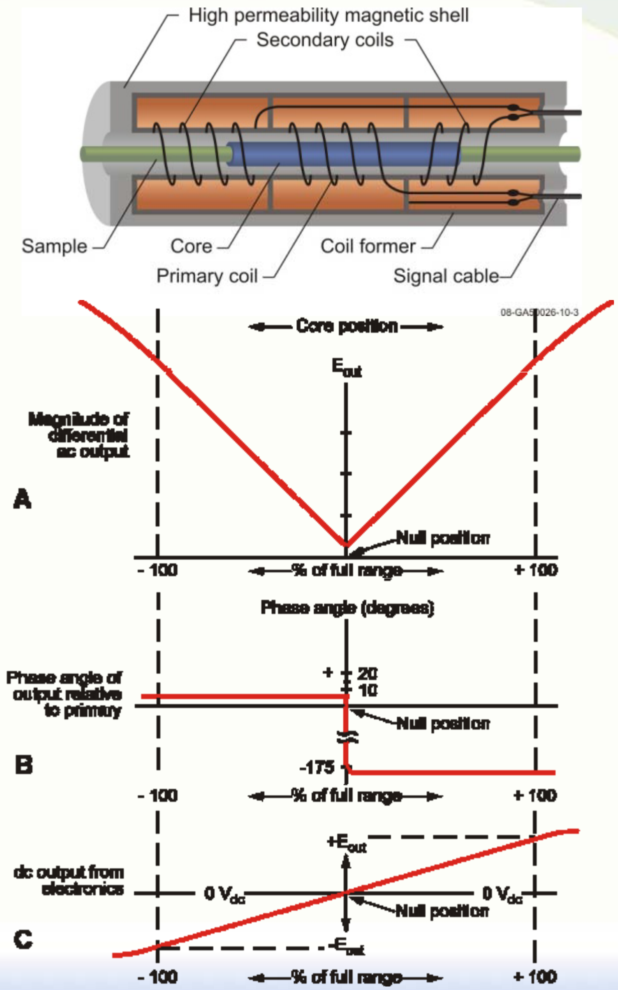
Initial Efforts for In-Pile Geometry Detection Focus on Nearer-Term LVDT Technology



Parameter	ATR Specification
Total LVDT Displacement (stroke), mm	> ± 2.5
Resolution, mm	10^{-2}
Sensitivity, V/m	>50
Maximum operating temperature, K	773
Normal operating pressure, MPa	0.101-15.5
Peak thermal flux, neutrons/cm^{2}s[a]	1.8 x 10^{14}
Thermal fluence, neutrons/ cm^2[a]	8.5 x10^{21}
Fast flux, E > 1 MeV, neutrons/cm^{2}s[a]	1.2 x 10^{14}
Integrated fast fluence, E > 1 MeV, neutrons/cm^2[a]	5.7 x10^{21}
Gamma flux, γ/cm^2[a]	1.1 x 10^{15}
Integrated gamma exposure, γ/cm^2[a]	5.2 x10^{22}
Maximum LVDT Diameter, mm	<25.4
Maximum LVDT Length, mm	63.8
Test environment	Water and Inert Gas (Neon, Helium)

a. Peak values based on 24.3 MW center lobe power. Fluence is based on 2 years of operation at 75% utilization. These conditions are expected to bound anticipated test conditions.

b. Smaller diameter and lengths preferred.

Slide 26

JED2 What is DNB (in notes)?
JED, 6/7/2011

JED4 Were LVDTs used in LOFT for DNB? How? I have seen references to LDVs (Laser Doppler Velocimeters), but not LVDTs. I know LVDTs are used for a lot of things, but I don't understand how this works.
JED, 6/7/2011

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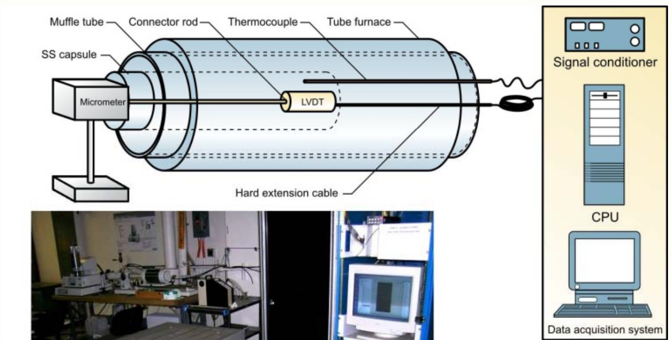
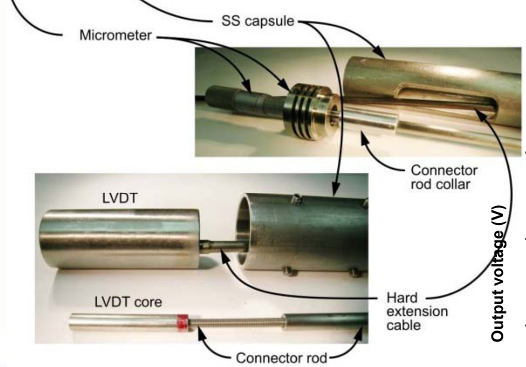
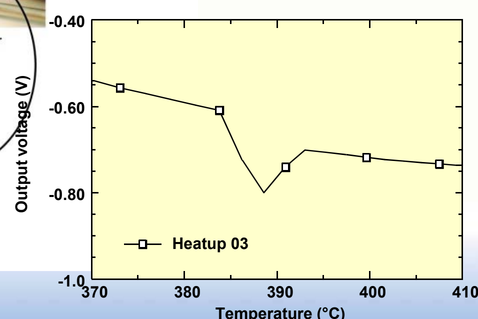
LVDT Enhancements Needed Prior to Deploying in ATR Conditions

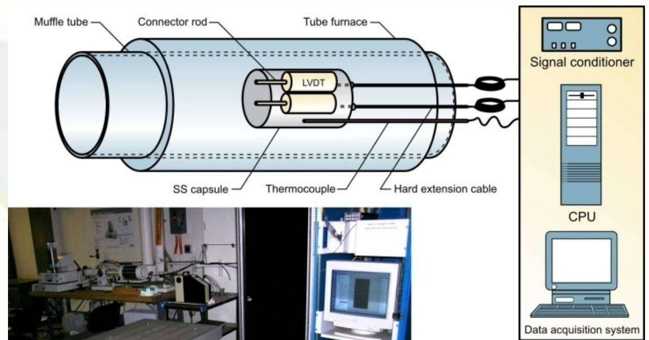


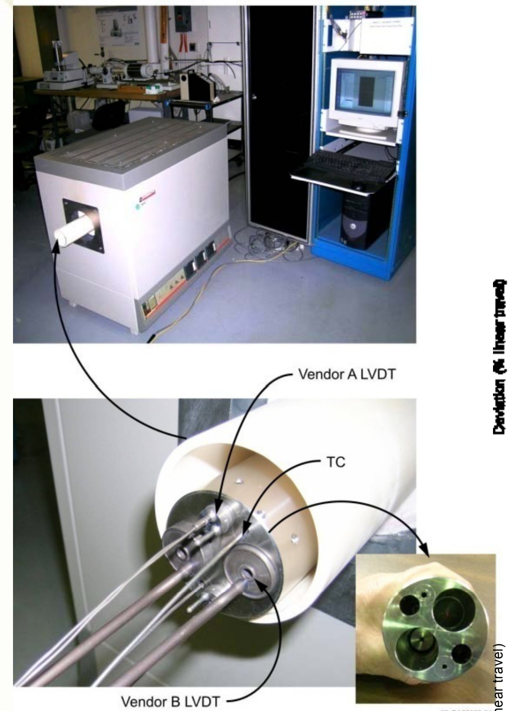


Calibration and Curie temperature evaluations

Curie effect may alter LVDT output by as much as ~60% over limited temperature range (± 2 °C)

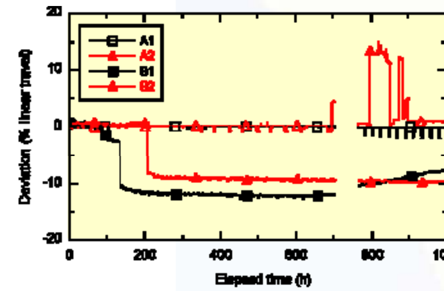




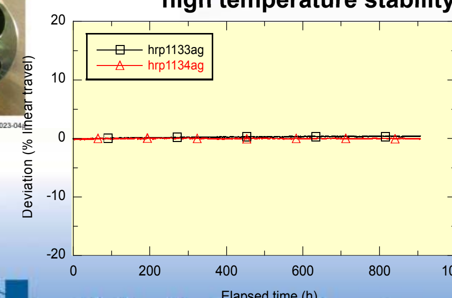


Long duration evaluations

Initial INL long duration high temperature LVDT evaluations exhibited instability after 700 hours



INL evaluations of optimized IFE/HRP LVDTs indicate exceptional high temperature stability



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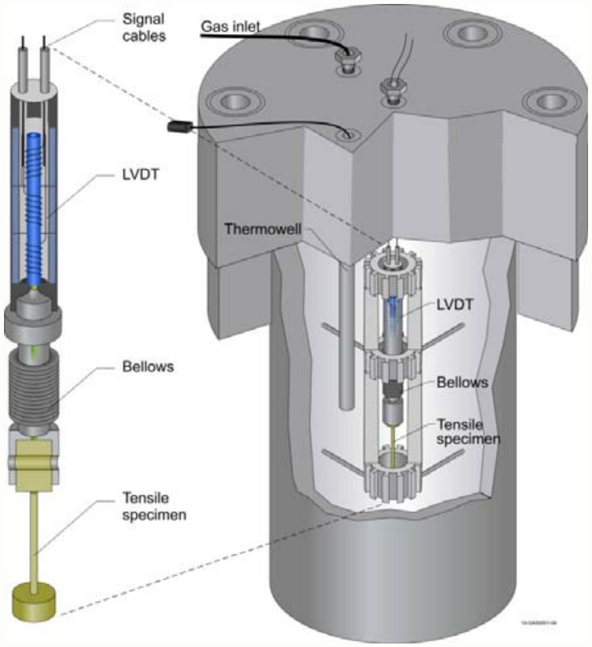
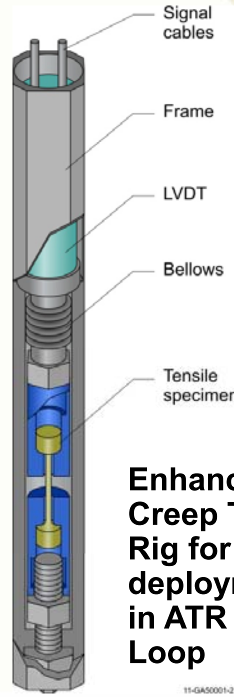
LVDTs Offer Potential for Real-Time Creep Measurements

Test rig facilitates creep testing in PWR coolant loop

- **External pressure contracts bellows applying load to specimen**
- **Real time elongation detected using IFE/HRP LVDT**
- **Fixture design completed in FY09, autoclave testing completed in 2010**
- **Stainless steel and copper results verify creep test rig accuracy within 1%**



Initially-proposed creep test rig evaluated in HTTL Autoclave

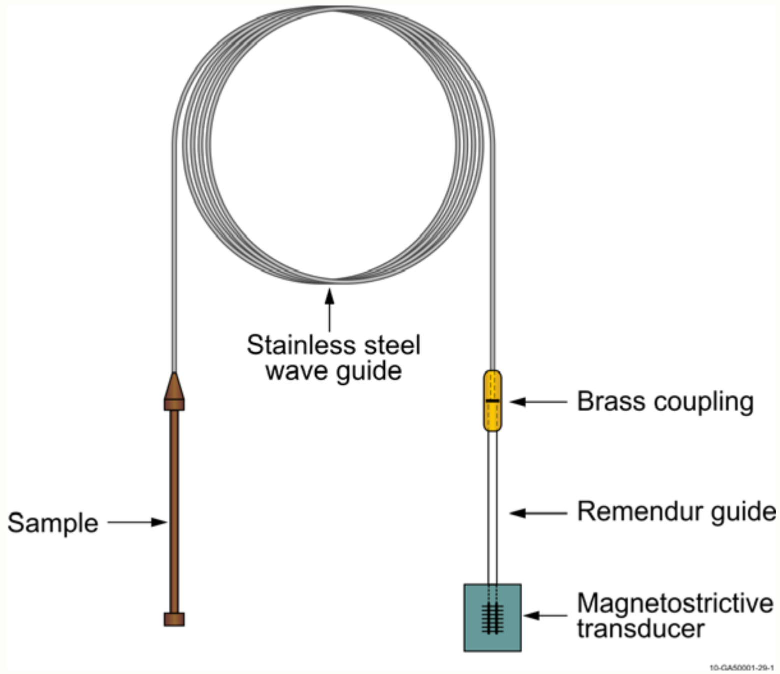


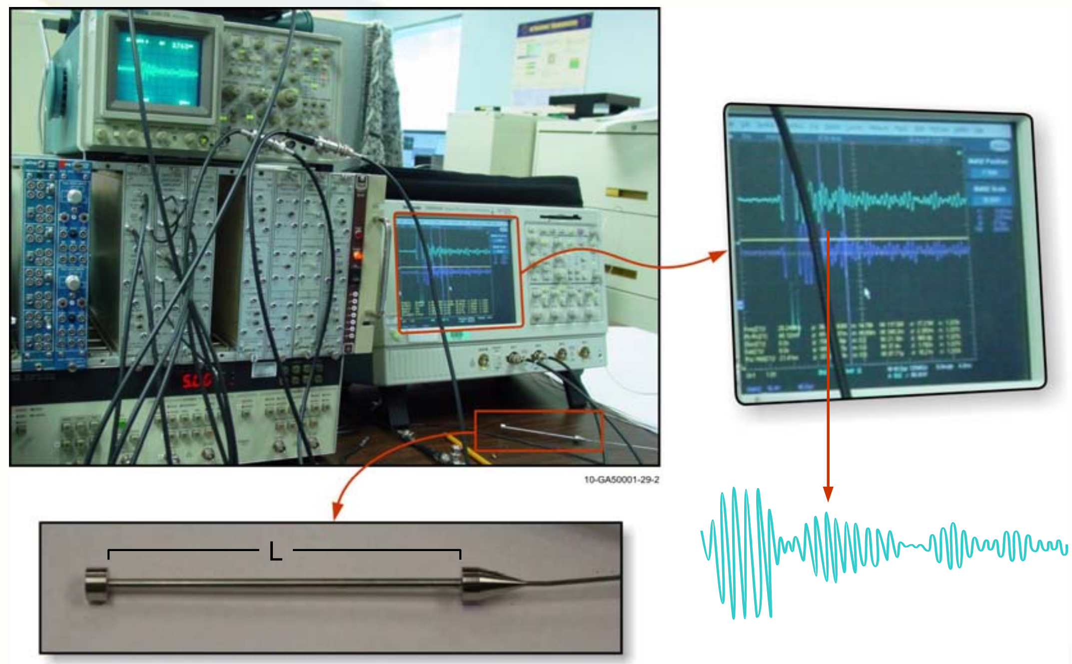
Enhanced Creep Test Rig for deployment in ATR PWR Loop

Specimen	Measured Length (mm)		% Diff
	LVDT	Micrometer	
SSX	29.16	29.25	0.31
SS01	29.85	30.05	0.65
SS02	29.67	29.85	0.61
SS03	29.90	29.95	0.17
SS04	29.83	29.93	0.33
Cu01	30.32	30.36	0.13
Cu02	30.21	30.32	0.36
Cu03	28.98	29.24	0.90
Cu04	28.55	28.64	0.31

Design to be finalized for ATR PWR loop deployment

Ultrasonic Techniques Offer Several Advantages for Real-time Detection of Geometry Changes





Possible advantages include more compact, higher temperature, more accurate, multi-dimension methods

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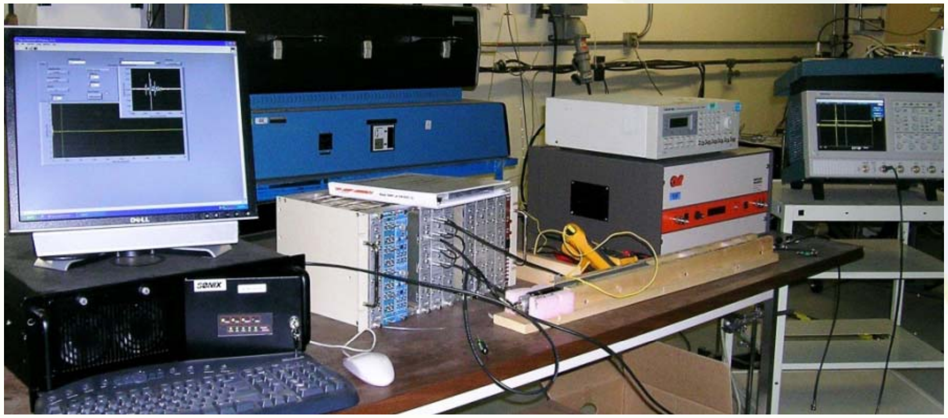
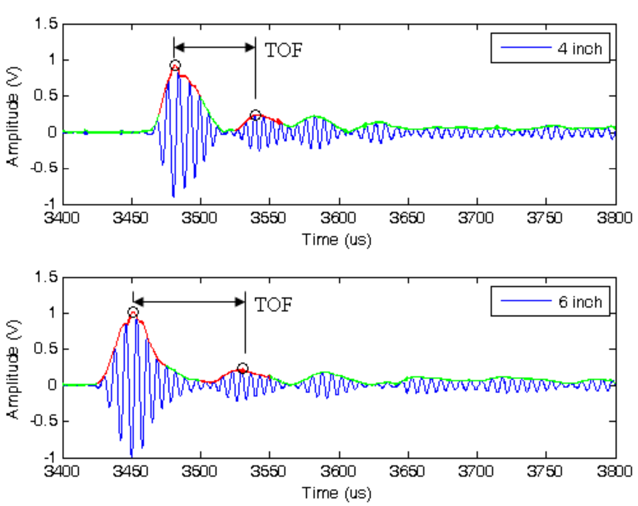
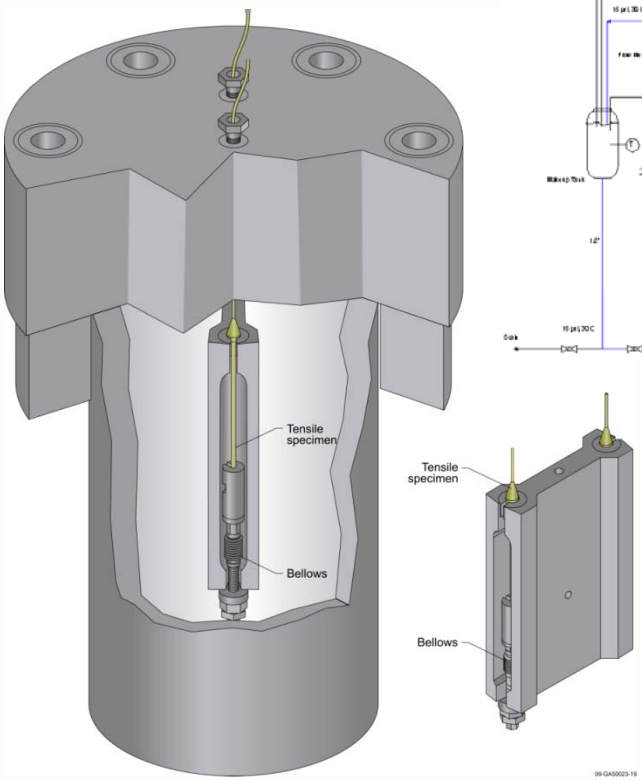
Completed Laboratory Testing of Ultrasonic Components and Analysis Comparisons

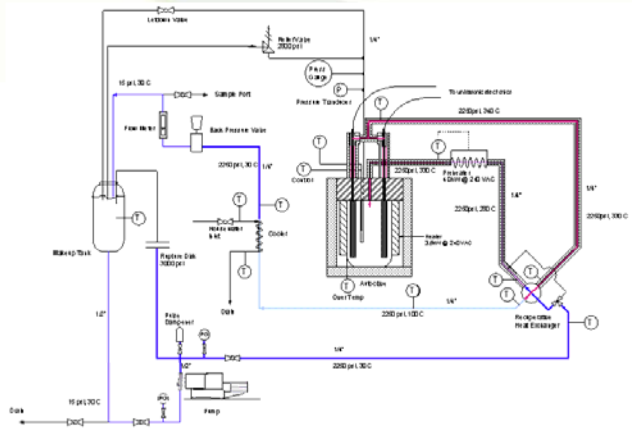


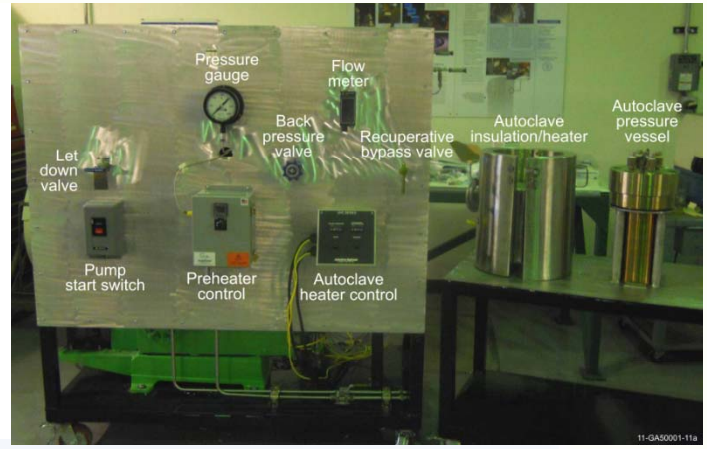


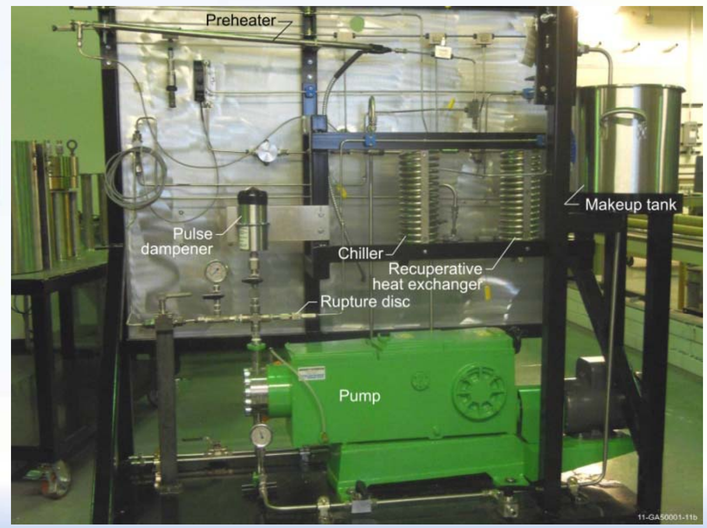
- **Time-of-flight (TOF) measurements completed on two stainless steel creep specimens (gauge length of 4 and 6 inches) at 300°C**
- **Signal reflection for both specimens yielded 5mm/μs ultrasonic velocities indicating results are**
  - **Viability of transmission through 30 ft waveguide**
  - **Independent of specimen length**
  - **Consistent with guided wave theory predictions**

Current Ultrasonic Activities Focused on Test Rig Design and Autoclave Testing









New autoclave system and test rig allows multiple specimen evaluation with temperature and pressure control and water chemistry evaluation

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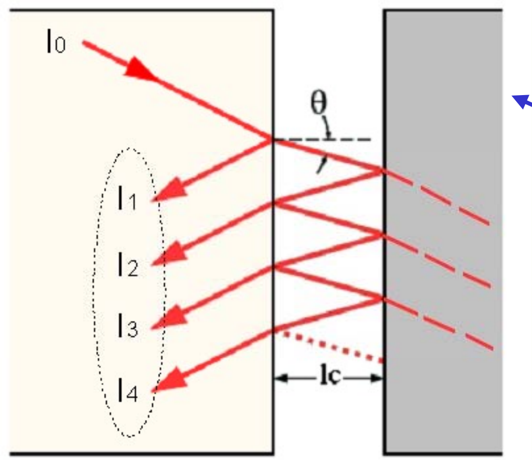
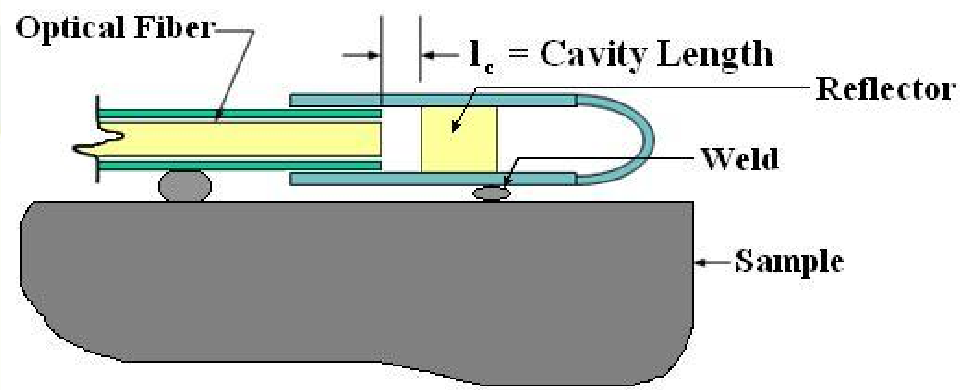
White Light Interferometer for Elongation Measurement

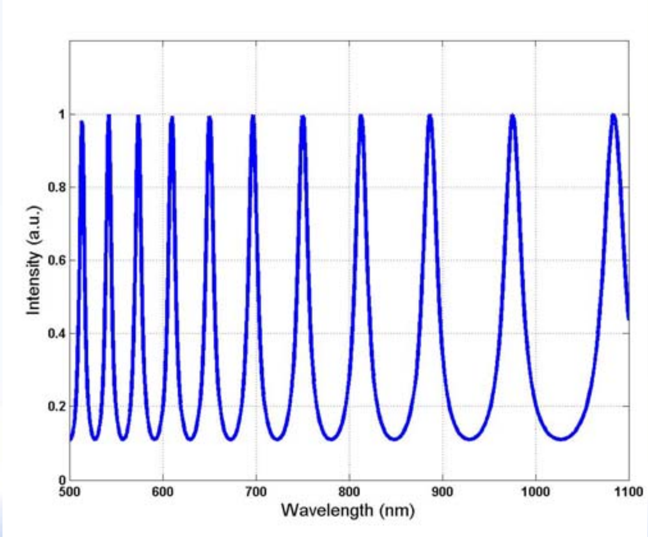
A white light interferometer can be used to accurately measure a gap or "cavity length"





Figures from CEA\Villard, ATR-NSUF 2010 Workshop

Reflections from the fiber face and the surface across the gap interfere to create a fringe pattern in the return spectrum



The cavity length can be determined from the fringe spacing by:

$$l_c = \frac{\lambda_1 \cdot \lambda_2}{2(\lambda_2 - \lambda_1)}$$

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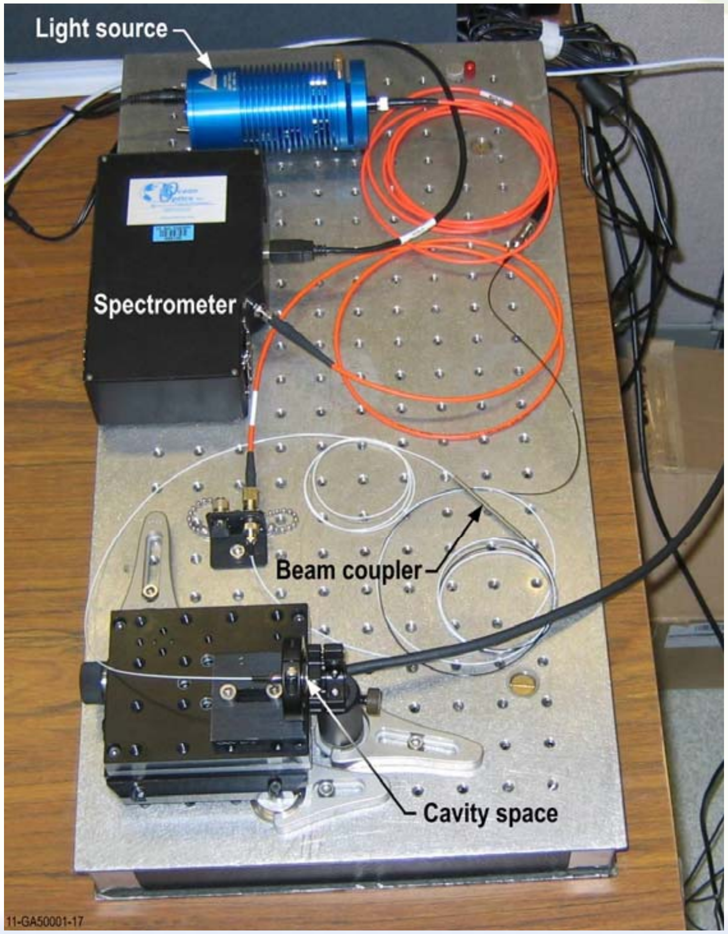
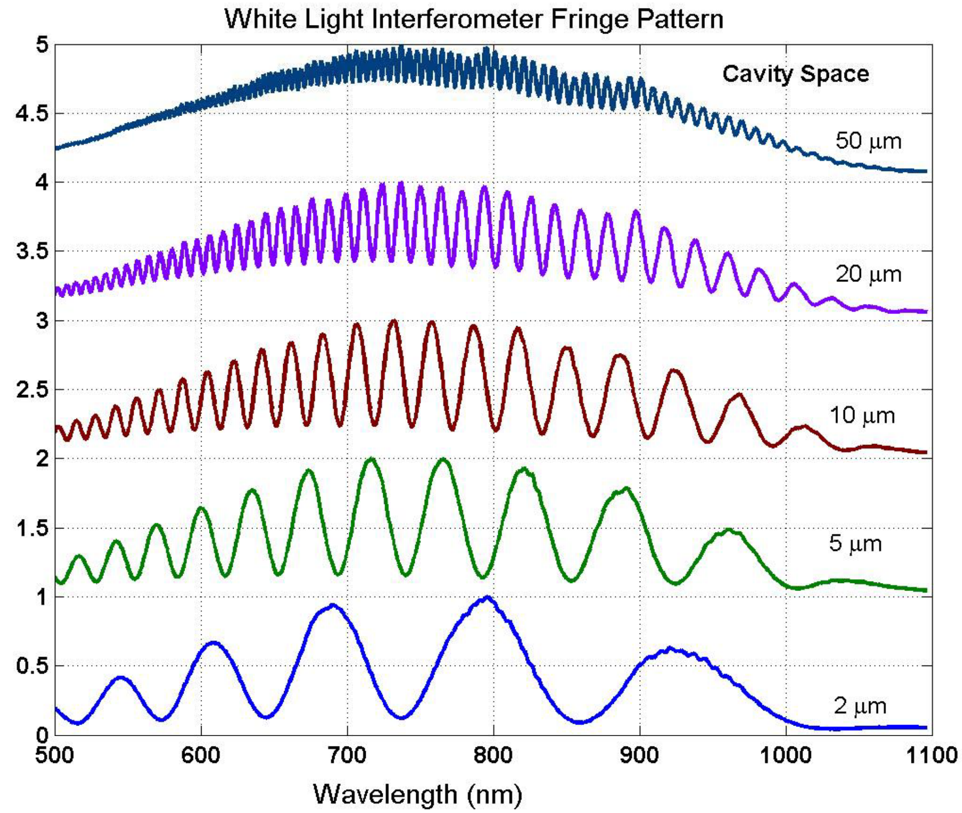
Bench-top Qualification of Cavity Length Measurement

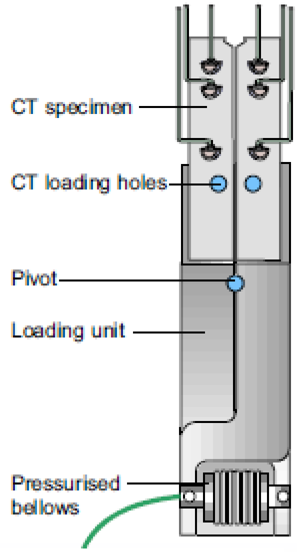




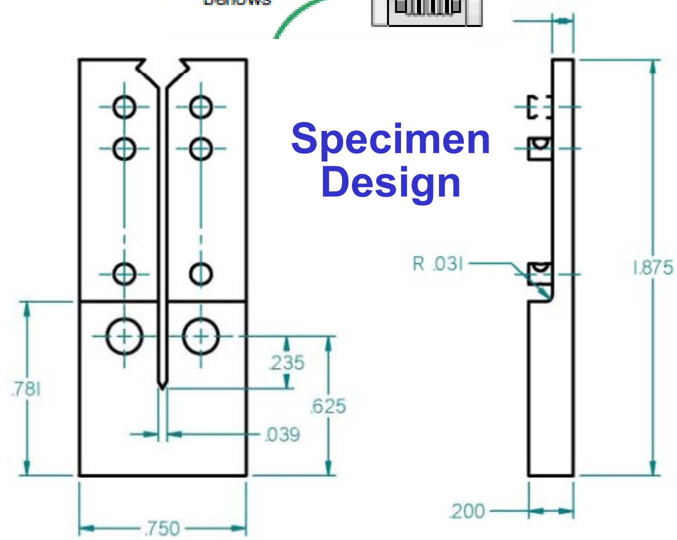
Current Work Based on Research Conducted at CEA (France)

In-Core Crack Growth Measurement Through Collaboration with MIT

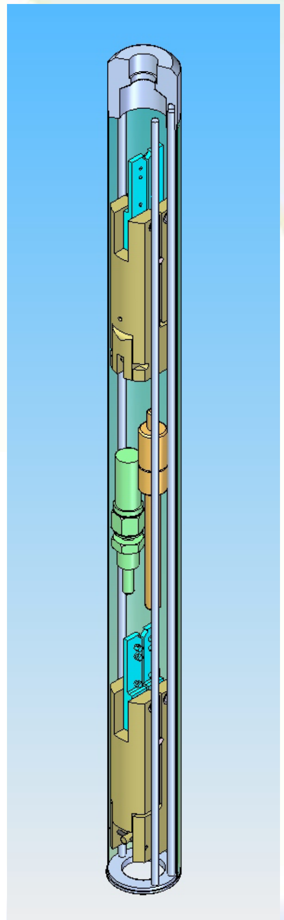
IFE/HRP Design



Specimen Design



Test Train



- MIT reviewed in-core crack growth measurement systems
- IFE/HRP system selected with variable load applied via pivoting bellows
- Specimens and test train engineered for planned irradiation test in MITR
- Pending funding, MIT/INL will continue collaboration through prototype specimen manufacturing, laboratory testing, and in-pile demonstration

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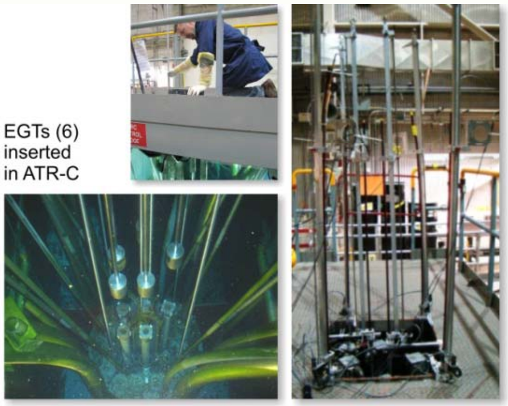
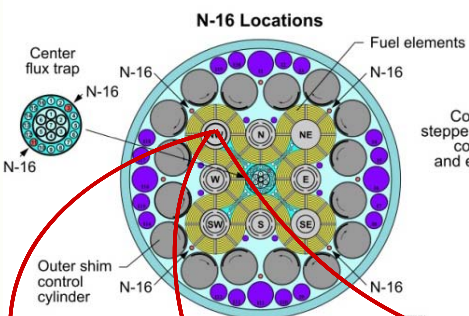
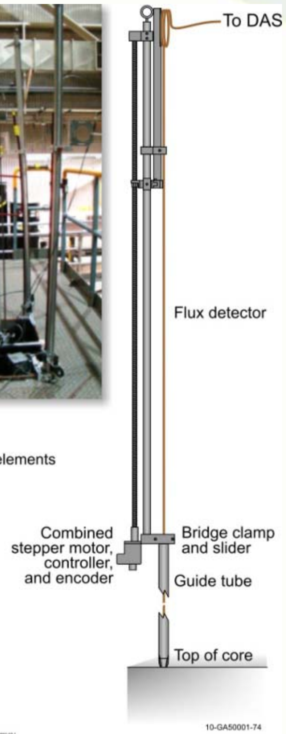
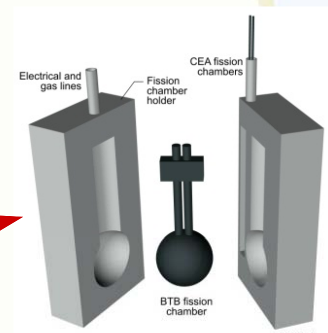
ISU/CEA/INL Project Investigating Use of Real-Time In-Core Flux Detectors in ATRC

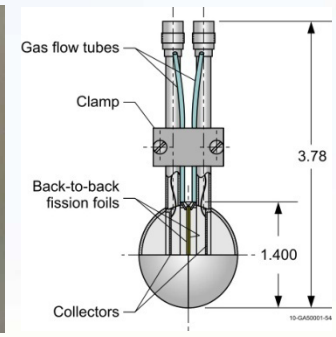


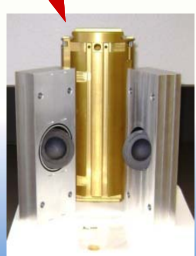




- **Sensors compared for response time, accuracy, and durability**
- **Installed EGTs accommodate 6 sensors in as many as 6 axial positions**
- **Data ultimately to allow development of real-time 3D ATRC core flux map**
- **Provides insights for selecting ATR flux sensors**







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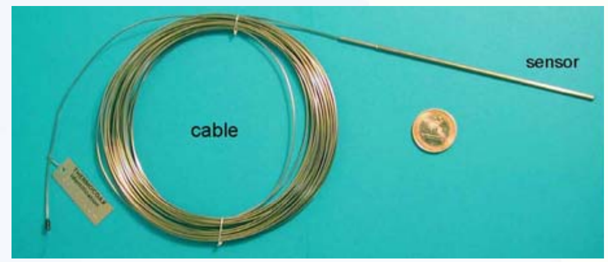
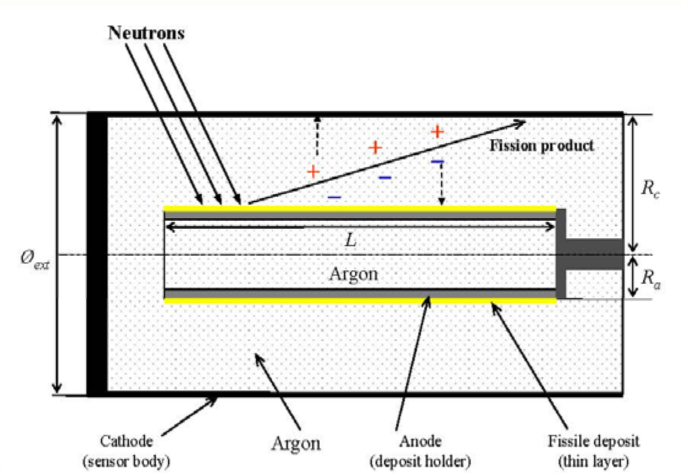
ISU/CEA/INL Project Comparing Various Types of SPNDs

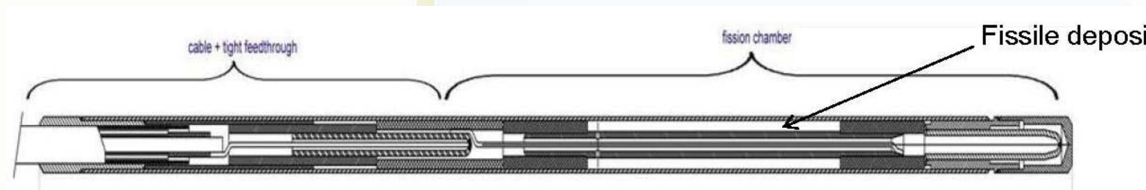
- **Incident neutron flux proportional to measured current from emitter to collector (sheath); Characterized by:**
- **Response time:**
  - **Delayed (e.g., Vanadium, Rhodium and Silver emitters)**
  - **Prompt (e.g., Cobalt, Platinum, Hafnium, Gadolinium)**
- **Burnup rate**
  - **High: Rhodium**
  - **Low: Vanadium, Platinum**
- **Sensitivity**
  - **High: Hafnium, Silver, Rhodium**
  - **Low: Platinum, Cobalt, Vanadium**
- **Advantages**
  - **No power supply needed**
  - **Simple and robust structure**
  - **Small (OD typically 0.062" /1.52 mm)**
  - **Good stability at high temperatures and pressures**
  - **Generate reproducible linear signal**
- **Disadvantages**
  - **Require calibration**
  - **Only detect thermal flux**



ISU/CEA/INL Project Also Evaluating Fission Chambers



- **Measure current generated by fission reactions in fissile material deposited on electrode**
- **Thermal or fast neutron flux monitoring, depending on deposited fissile material (thermal: U-235; fast: U-238, Pu-242)**
- **Small (OD typically 0.062" /1.52 mm)**
- **Good stability at high temperatures and pressures**
- **Reproducible linear signal**
- **Lifetime considerations**



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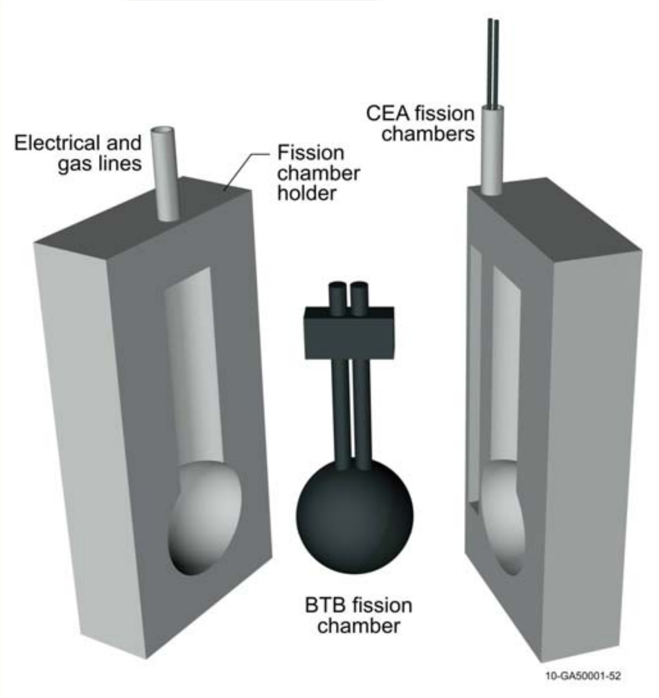
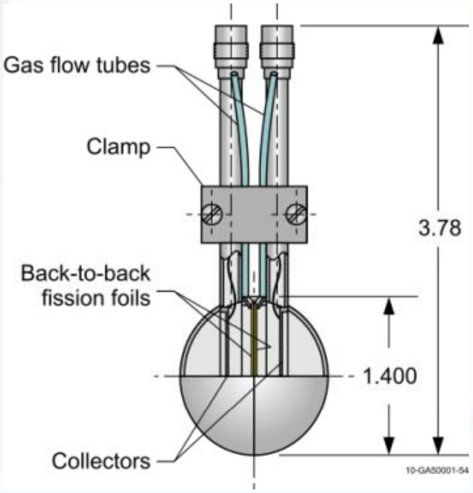
ISU/CEA/INL Project Comparing Detectors to Back-to-Back Fission Chambers





- **Bisected hollow aluminum spheres with "back-to-back stainless steel foils with fissile material deposits.**
- **Allow accurate '2π' measurement of fission rate.**
- **Provide 'absolute' calibration for co-located flux detectors**

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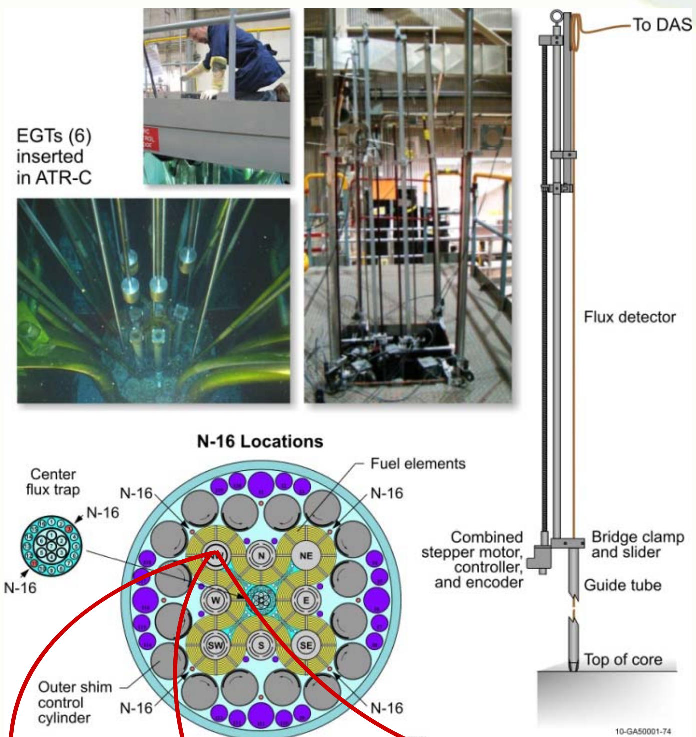
Fixturing for Evaluations Fabricated and Installed at ATRC



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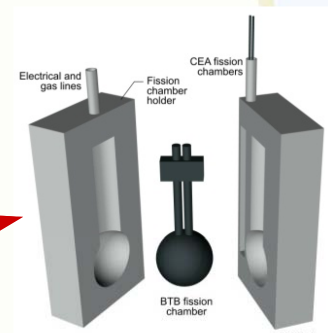
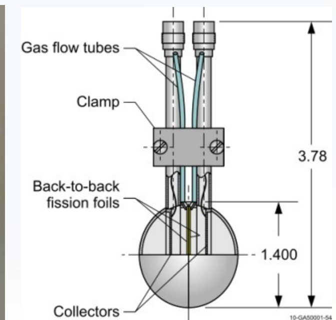
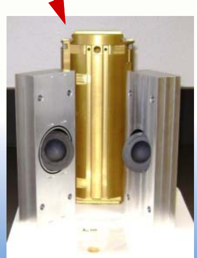
- Provides insights for selecting ATR flux sensors







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Summary

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- Efforts underway to provide ATR users new in-pile instrumentation
- New sensors for detecting temperature available
- New sensors for real-time detection of thermal conductivity, elongation, and neutron flux under evaluation for near-term deployment
- Future activities include:
  - Evaluate and deploy remaining sensors currently available at other test reactors
  - Evaluate new sensor technologies not available at other test reactors
  - Strong opportunities to explore and deploy developmental sensors in science-based DOE-NE program initiatives.