Instrumentation to Enhance ATR NSUF Irradiation Testing

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ATR NSUF User's Week

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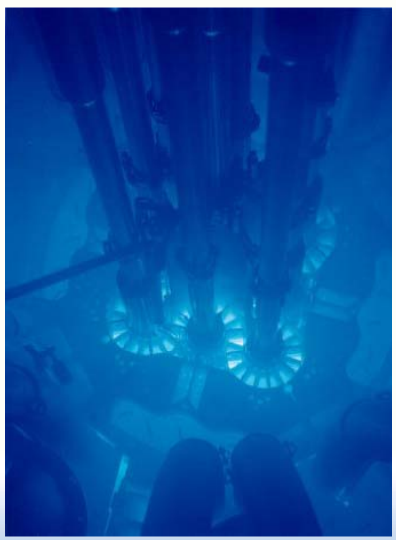
Advanced Instrumentation Needed to Grow ATR Missions



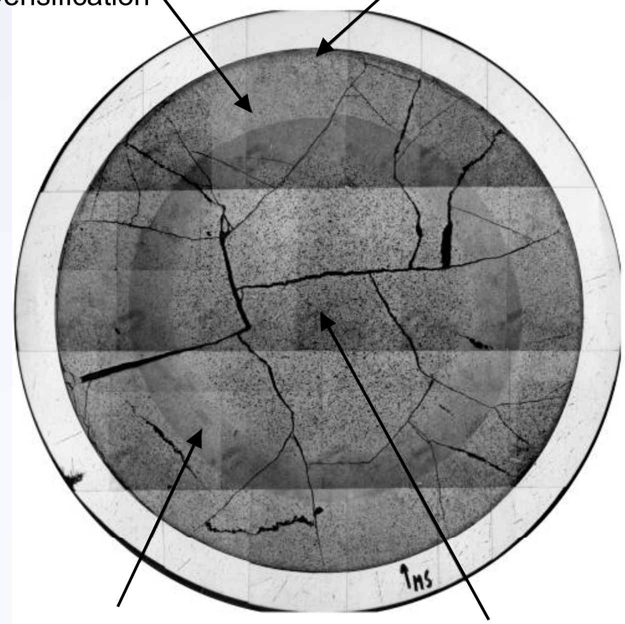
Goal – Provide ATR users real-time measurement of key parameters during irradiation

- Advanced ATR instrumentation needed to grow nuclear program support.
  - Naval reactors
  - DOE (NGNP, FCR&D, 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

Real-time Measurements Needed to Understand Observed Irradiation Phenomena

- **Interrelated phenomena observed during fuel and materials irradiation**
  - **Cracking**
  - **Corrosion**
  - **Creep**
  - **Swelling**
  - **Densification**
  - **Rim formation**
  - **Fission gas release**
  - **Crud deposition**
  - **Axial offset anomaly**
  - **Pellet-Cladding Interactions**

- **Real-time measurements needed to understand and predict phenomena**
  - **Pressure**
  - **Temperature**
  - **Thermal conductivity**
  - **Diameter and length changes**
  - **Thermal and fast flux**
  - **Crack growth**



Data needed to support FC R&D, NGNP, ATR NSUF, and LWRS programs

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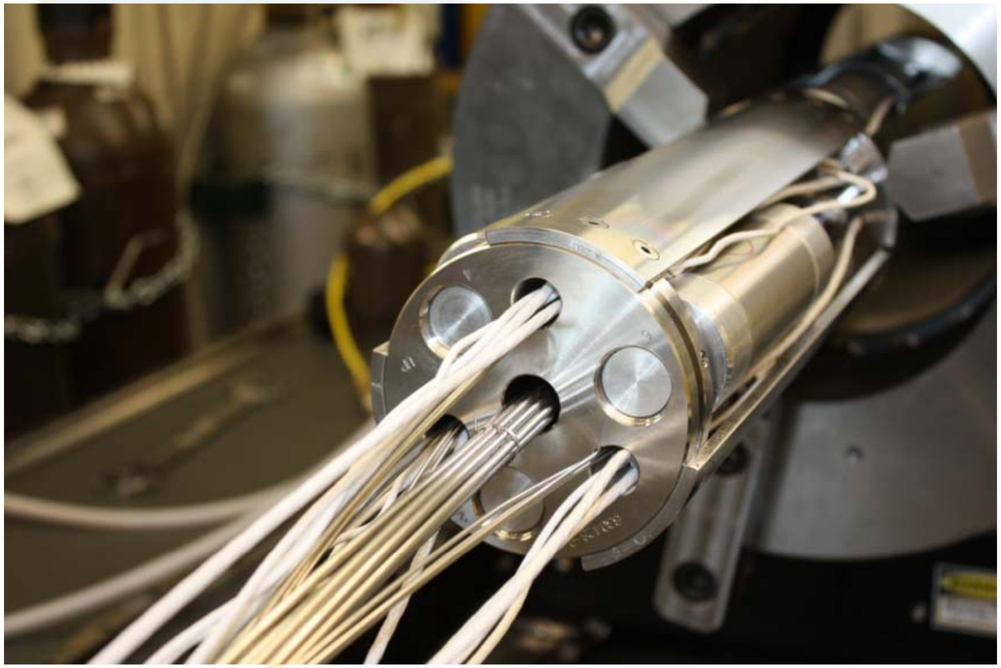
In-Pile Instrumentation Must Meet Several Design Requirements

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



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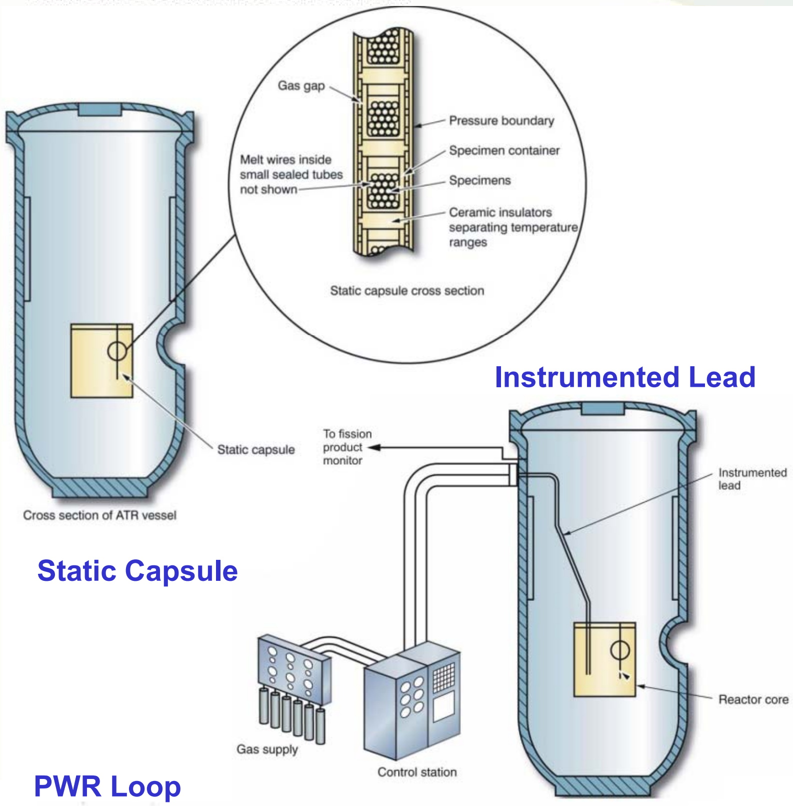
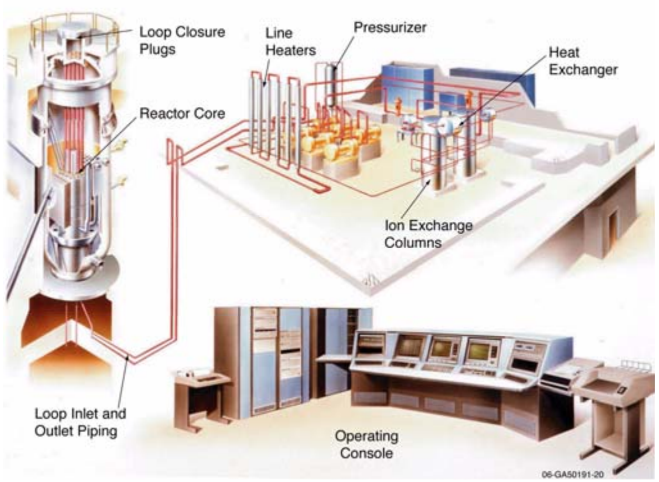
Several Instrumentation Enhancements Available for Various ATR Test Locations



PWR Loop



Parameter	Parameter: Static Capsule	Parameter: Instr. Lead	Parameter: PWR Loop	ATR Technology	Proposed Advanced Technology: Available at Other Reactors	Proposed Advanced Technology: 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		√	√		• Degradation using signal changes in thermocouples	
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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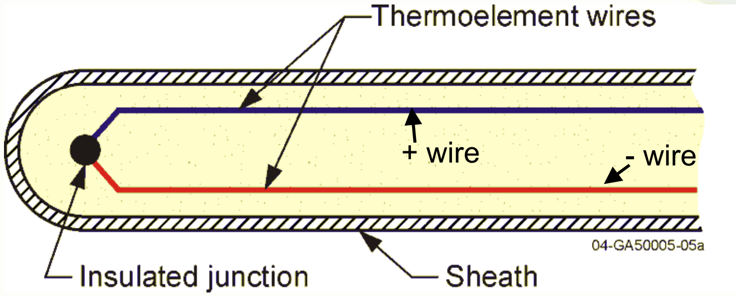
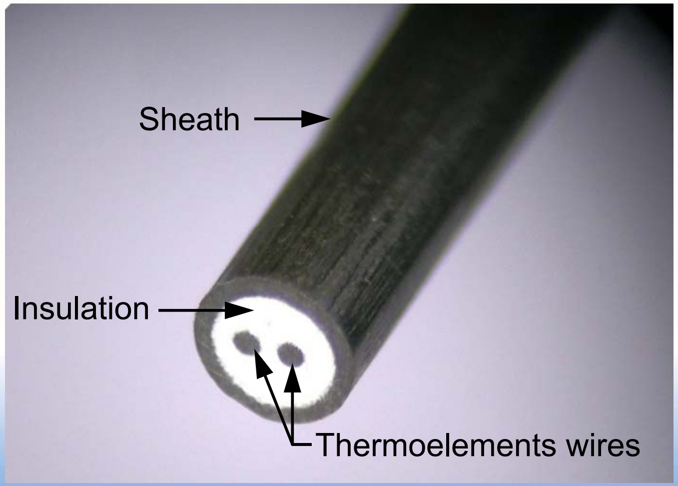
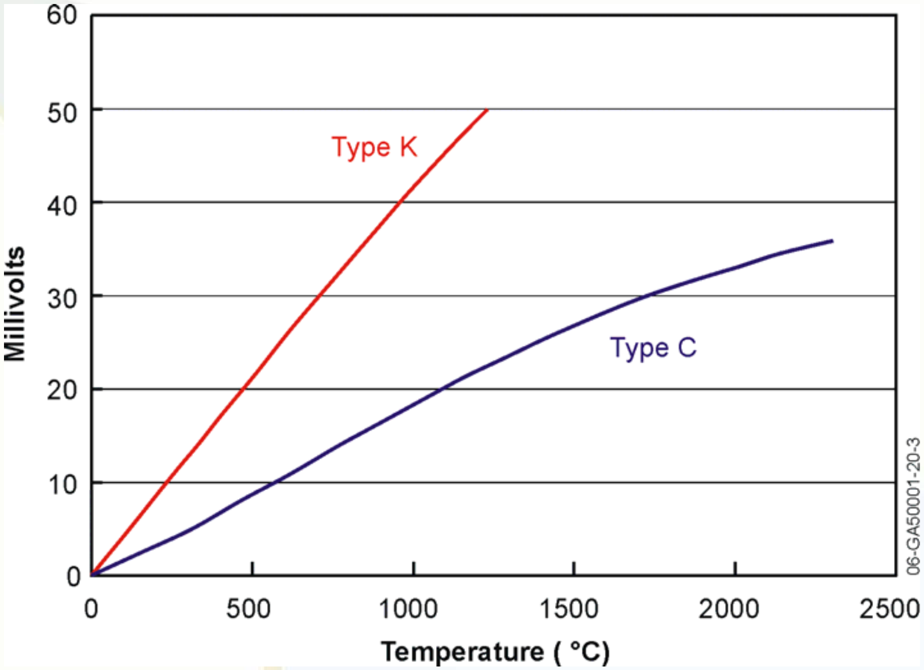
HTIR-TCs Build Upon Established Easy-to-use Measurement Method



Thermocouples

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





Design Options

- Material selection
- Fabrication

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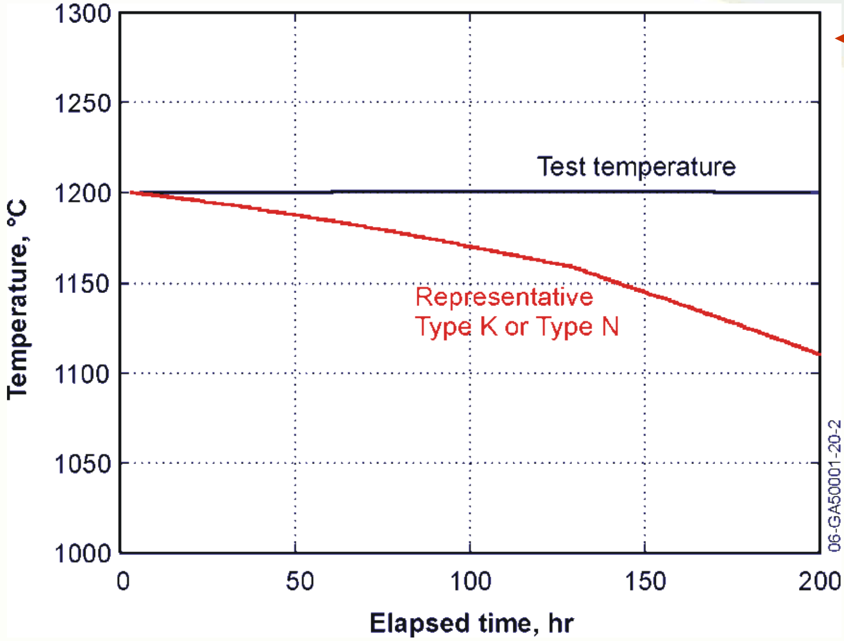
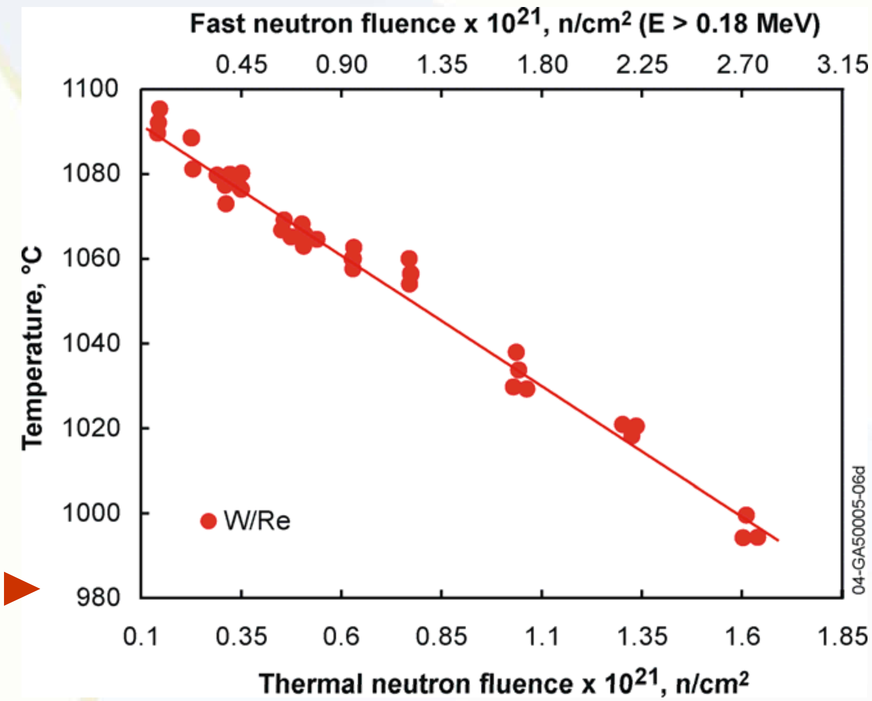
High Temperature Thermocouples Needed to Support Fuels and Materials Irradiation Programs



◀ **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/cm^2 ▶

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

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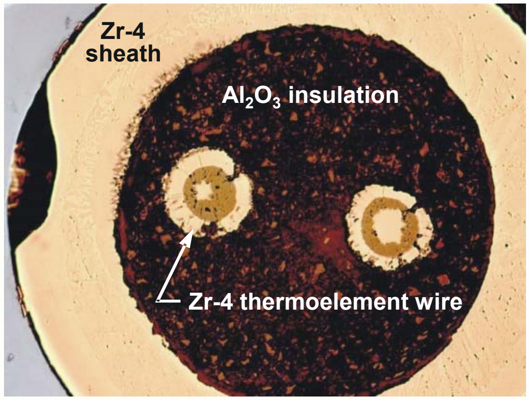
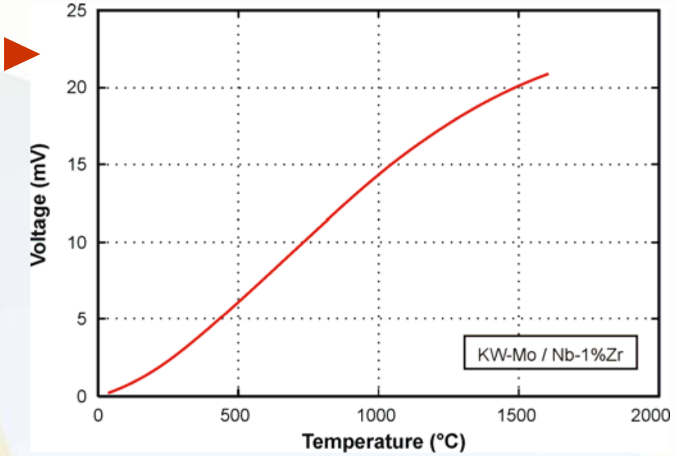
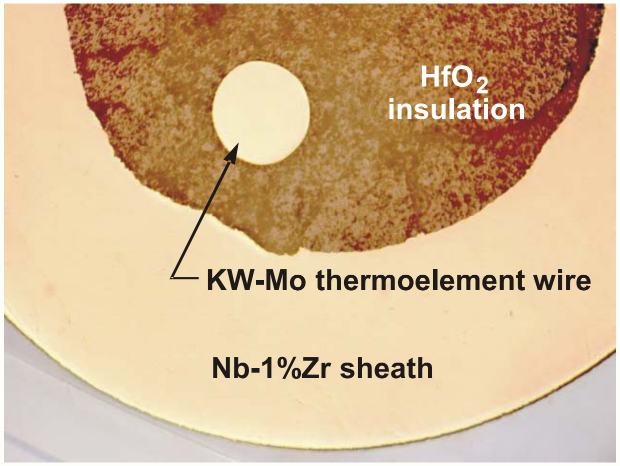
Initial HTIR-TC Development Considered High Temperature Material Compatibility, Ductility and Resolution



Al_2O_3 attacks wire and sheath after heating at 1300°C

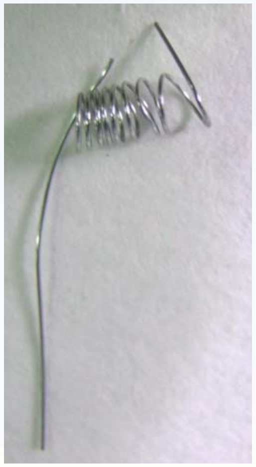
Selected KW-Mo and Nb-1%Zr combination has suitable resolution up to at least 1700 °C

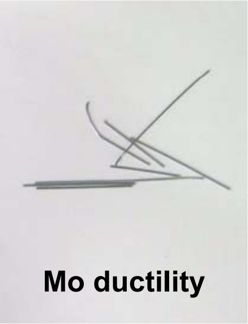




Selected materials resist interactions after heating at 1600 °C

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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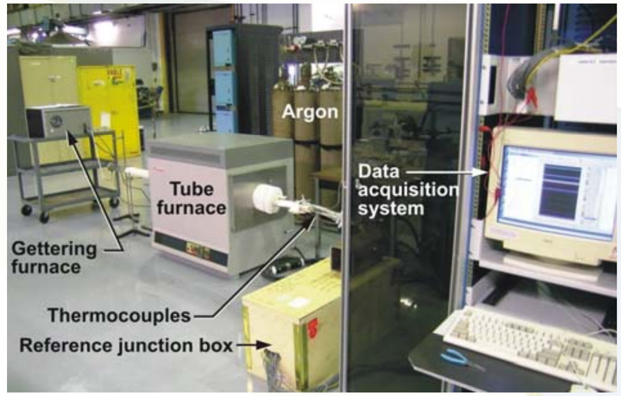
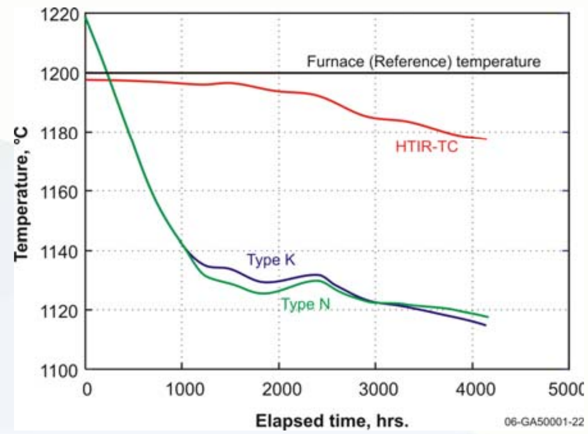
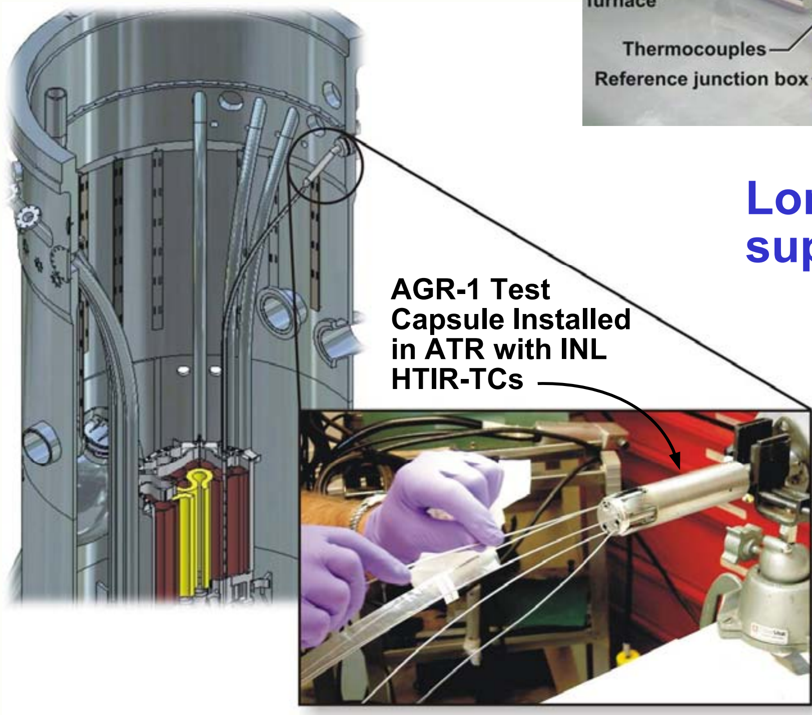
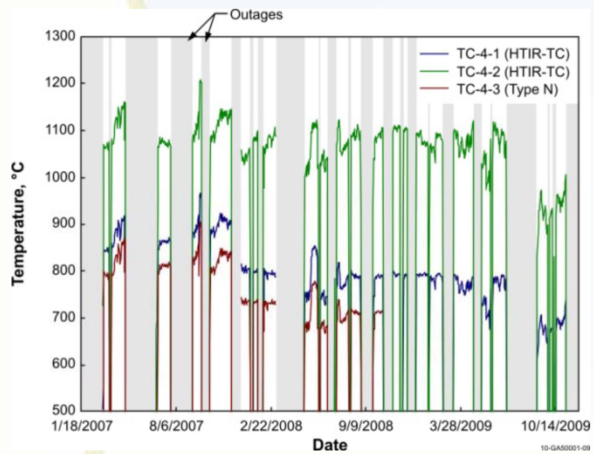
Subsequent HTIR-TC Development Included Long Duration and Radiation Testing





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, HFR, and HBWR

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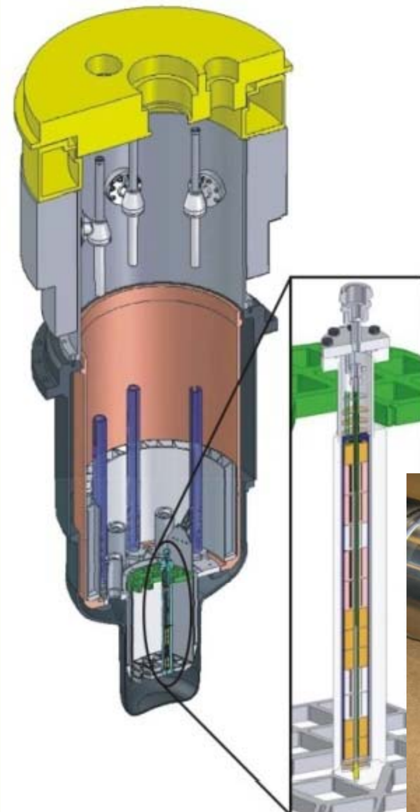
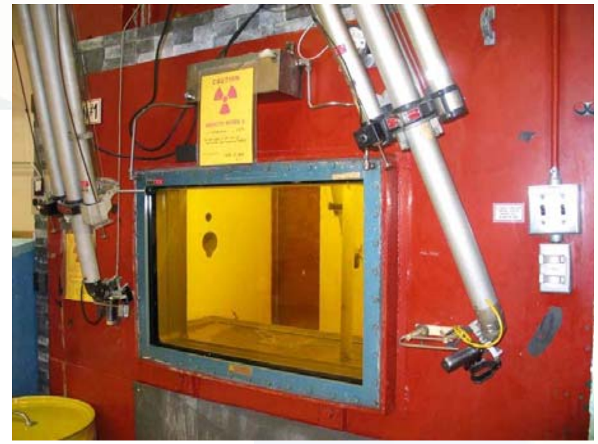
Optimized HTIR-TCs Fabricated for MITR Irradiations

MITR High Temperature Irradiation Facility for 1400 °C irradiations





Hot cell on reactor floor area for test disassembly and transfer to SEM for examinations

MITR HTIF facilitates high temperature HTIR-TC irradiations and post test examinations

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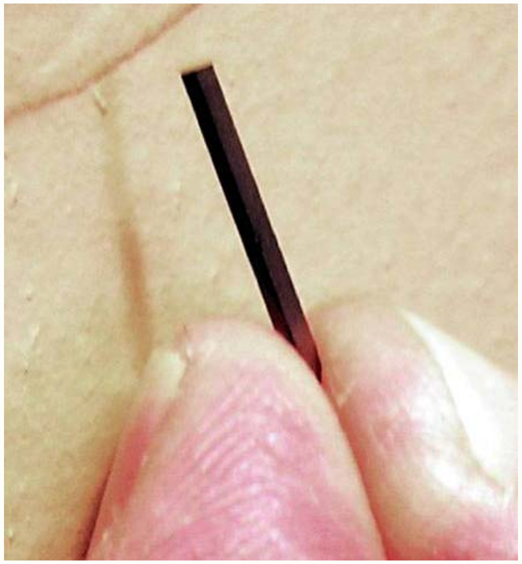
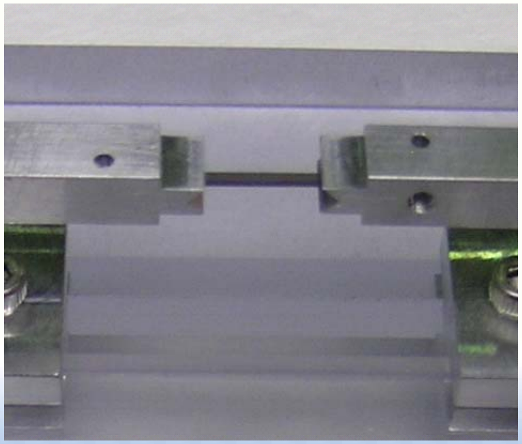
Single SiC Monitor Offers Detection for Temperature Range in Static Capsules





- Static capsule temperature detection limited to single-temperature sensors (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 (e.g., minimize dopant impurities)
  - resistance measurements with SiC at same orientation and temperature

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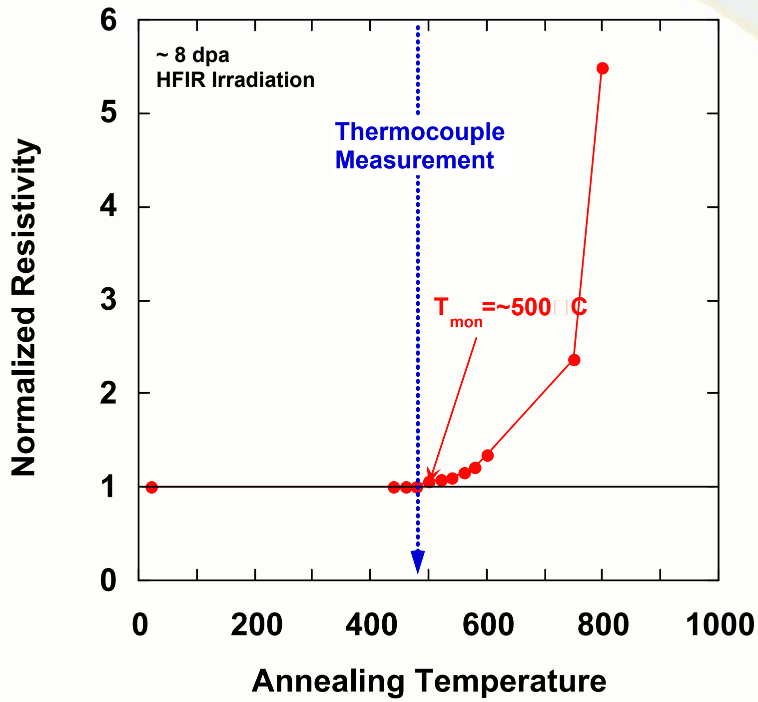
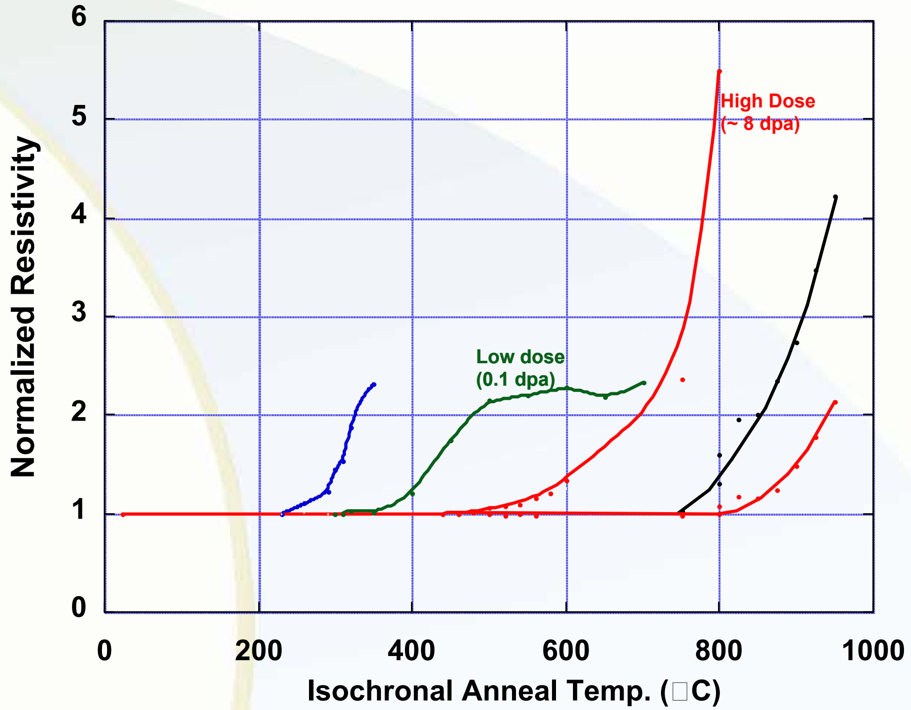
Resistivity Increases in SiC Monitors Reliable Indicator of Peak Irradiation Temperature (cont.)





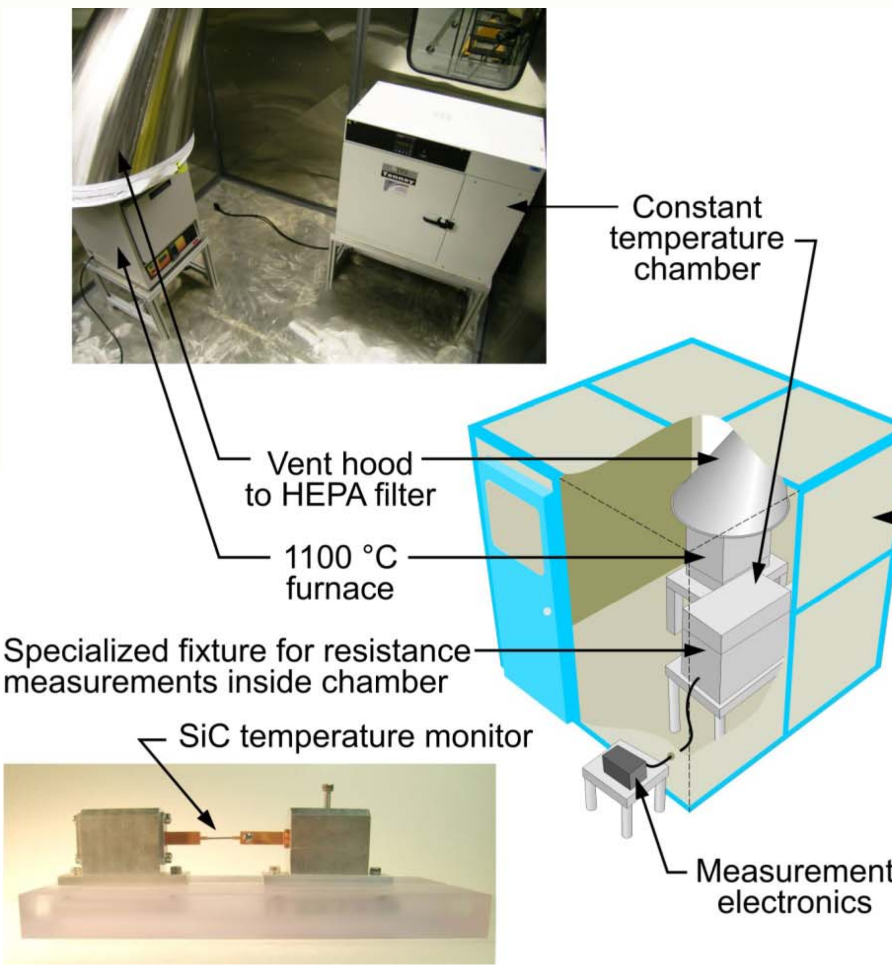
ORNL evaluations indicate

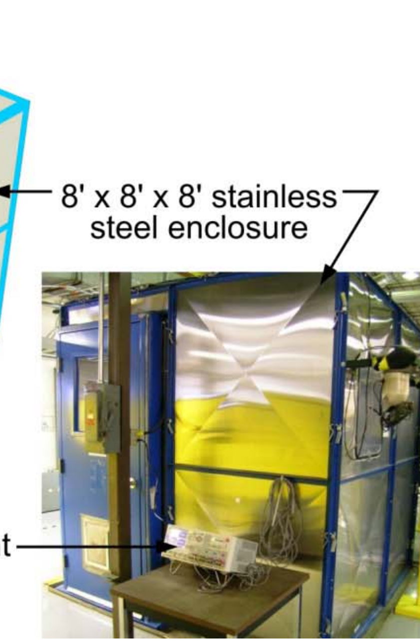
- **accuracies of 20°C with thermocouple comparisons**
- **similar accuracies for wide range of temperatures (200 - 800 °C) and doses (1.1 to 8 dpa)**

HTTL Prepared for Measuring Resistivity of SiC Monitors Irradiated at ATR

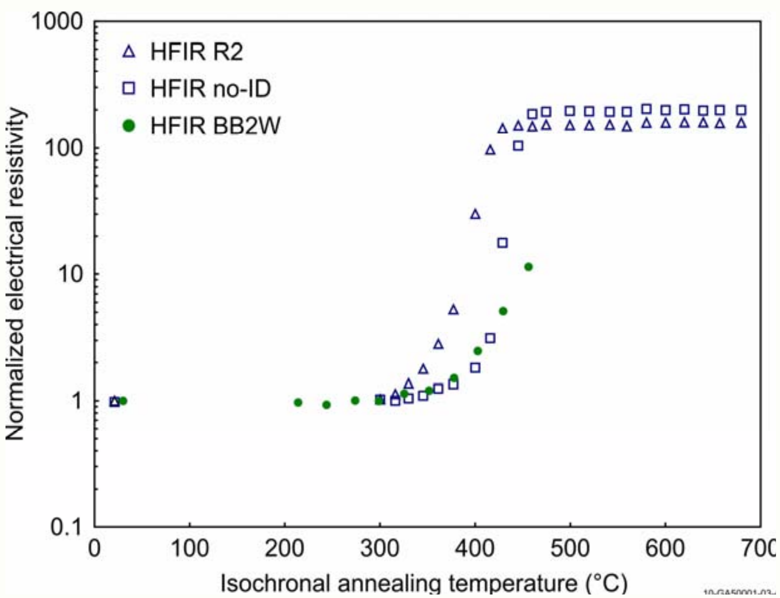
- Small (1 mm x 1 mm x 10 mm) monitors of high density CVD SiC
- SiC monitors heated for 30 minutes in furnace with NIST-traceable thermocouples

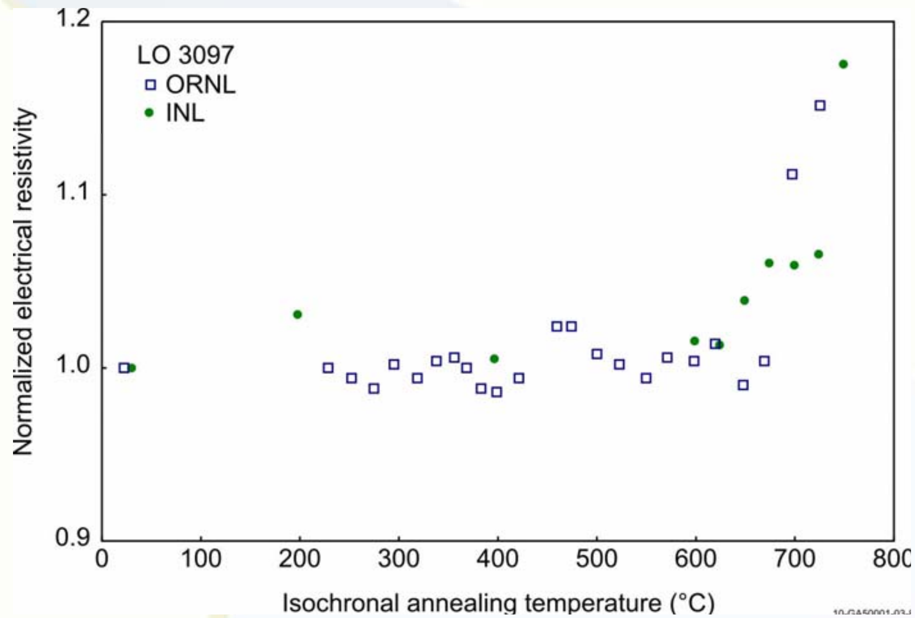
- Specialized fixturing developed for resistance measurements
- Measurements made in constant temperature chamber at 30 °C
- High accuracy (9 digit) electronics





Comparison Results Indicate INL Successfully Implemented ORNL Approach





Less than 5% difference in peak temperature estimates.

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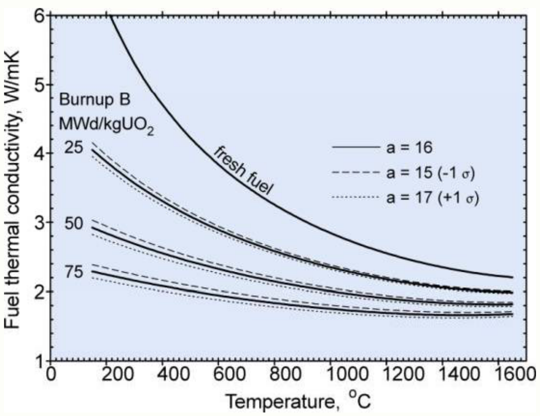
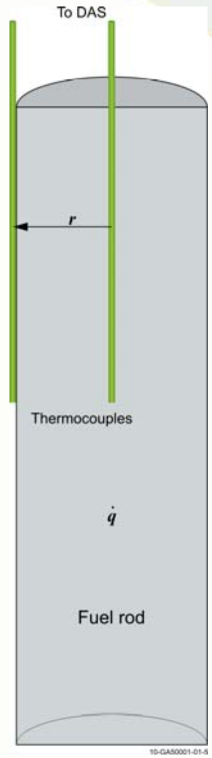
Hot Wire Method Offers Significant Improvement for In-Pile Thermal Conductivity Detection

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

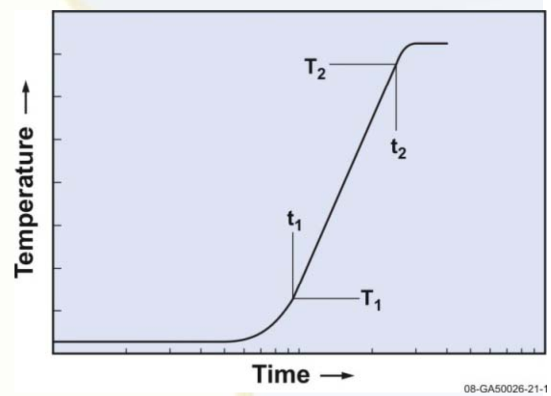


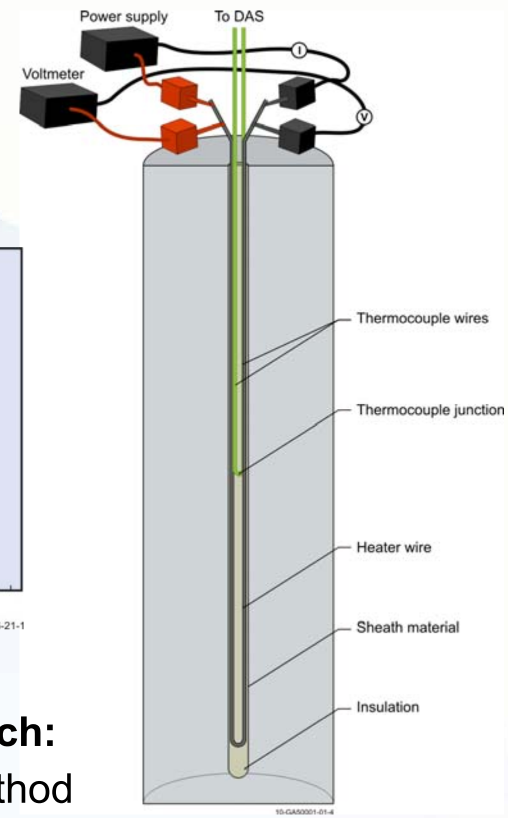


Two thermocouple approach:

- Used by IFE/HRP (previously used by Bettis and ANL)
- Steady-state, longer duration, measurement
- Two probes – one in the fuel and one outside the fuel

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





Transient hot-wire approach:

- Adaptation of ASTM method
- Transient, quick, measurement
- Single probe in the fuel

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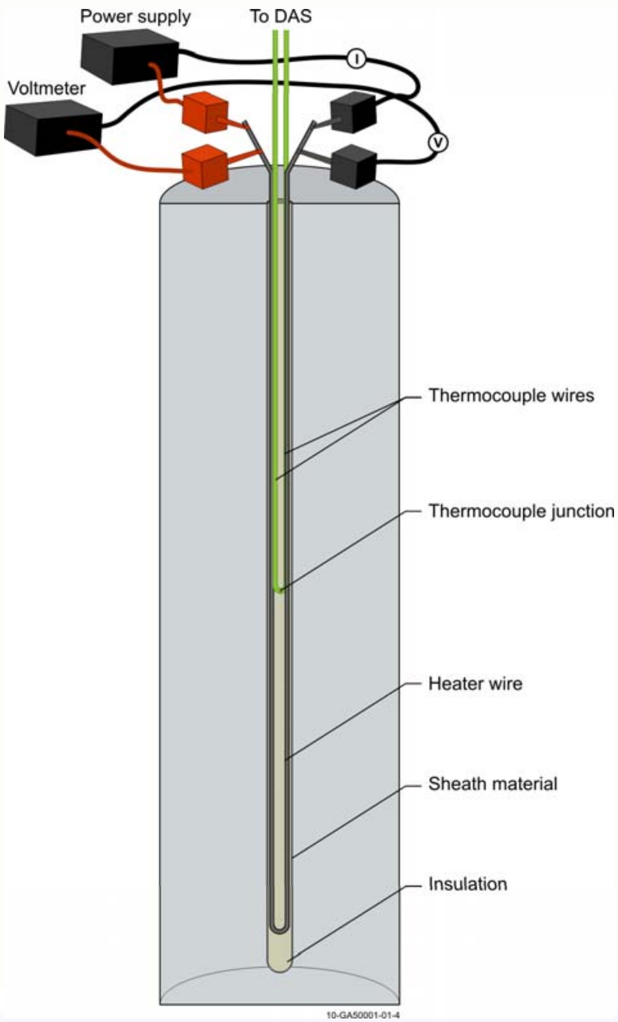
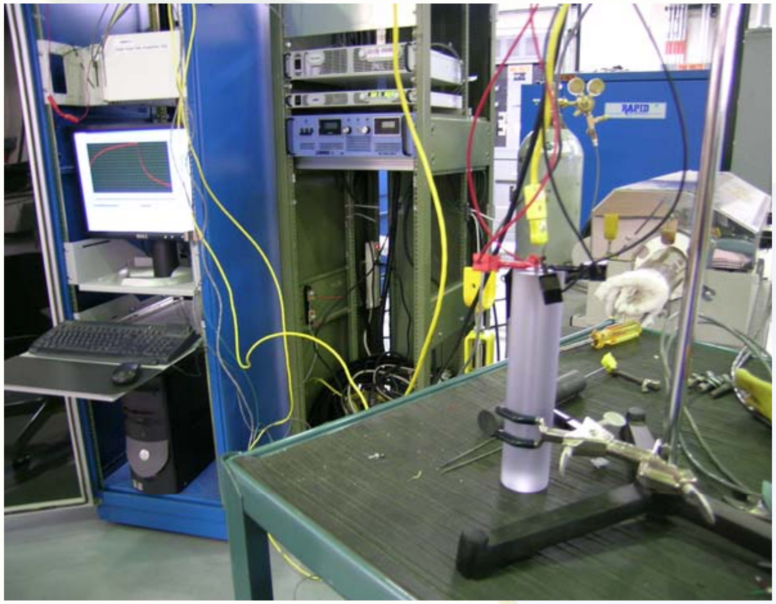
Initial INL/USU Investigations Support that Needle Probe Superior Method for In-pile Thermal Conductivity Detection





Room temperature data within 5% of reported values

Material	USU/INL Probe Average Measured Effective Thermal Conductivity (W/m^2K)	Average Reported Value (W/m^2K)	Ratio of Reported to USU/INL Measured Values
SiO_2	**1.353**	**1.380**	**1.02**
Delrin	**0.281**	**0.295**	**1.05**
Acrylic	**0.215**	**0.216**	**1.01**

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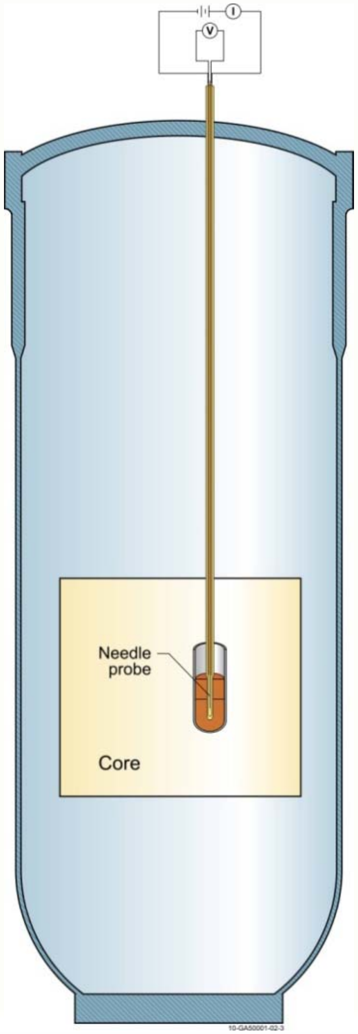
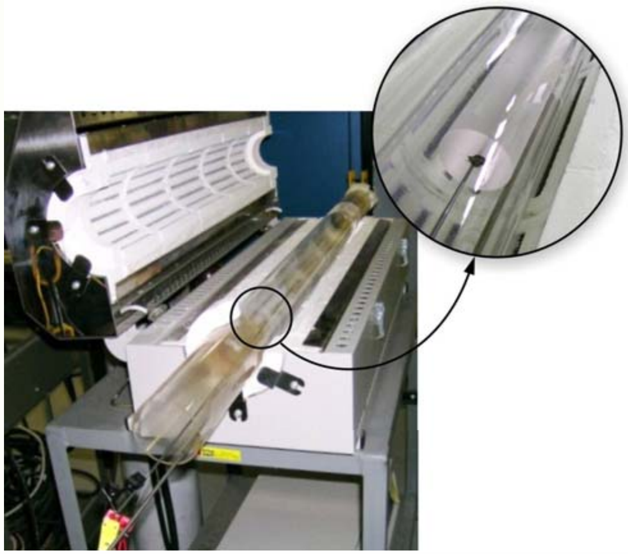
INL/USU Needle Probe Design Overcome Obstacles Associated with In-Pile Applications



Unique combination of materials, geometry, and fabrication techniques make hot wire method suitable for in-pile applications.

- Minimize sensor geometry/influence
- Maximize fuel hot-wire heating
- 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
- HTIR-TC included for high-temperature detection during irradiation



BEA considering filing patent on this technology:

- Evaluations indicate optimized probe design yielding 1% accuracies at high temperatures (up to 600 °C in quartz).
- Several candidate facilities (e.g., ATR, OSIRUS, HBWR, and MITR) for irradiation testing

Subject of MOU-defined exchanges in ATR NSUF:

- Institute for Energy Technology/Halden Reactor Project (IFE/HRP)
- French Commission for Atomic Energy (CEA)

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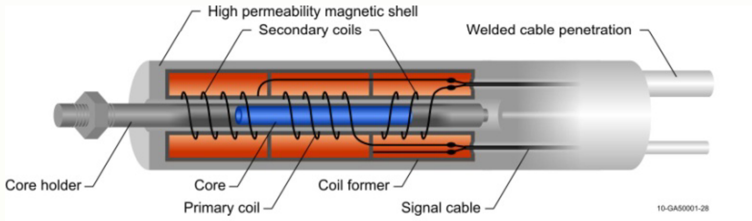
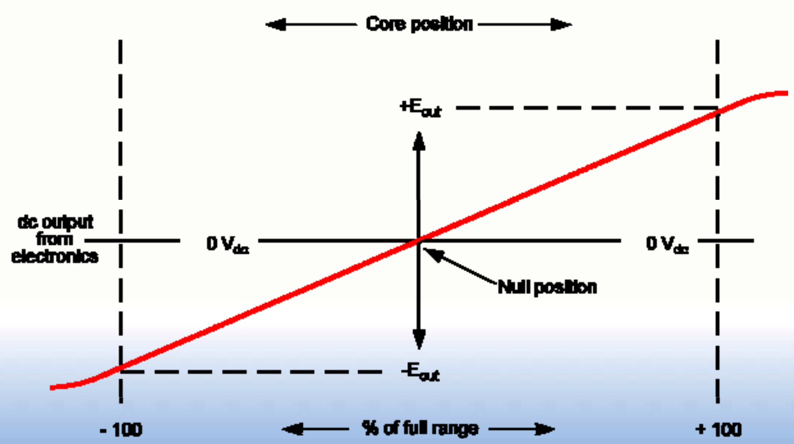
Initial Efforts for In-Pile Geometry Detection Focus on Nearer-term LVDT Technology





- Linear Variable Differential Transformers (LVDTs) used for many types of displacement measurements
- Advantages include high resolution, wide range of sensitivity, absolute output
- Electronics can be placed far from LVDT
- Development needed to increase temperature capability of current sensors

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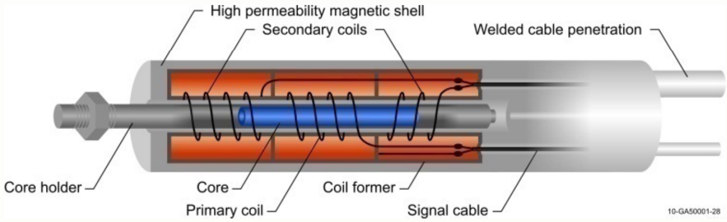
Typical ATR Test Conditions Challenging for LVDT Inpile Applications



Parameter	ATR Specification
Minimum LVDT displacement, mm	± 2.5
Resolution, mm	< 1e-2
Minimum sensitivity, mV/mm	50
Maximum LVDT diameter, mm	25
Maximum LVDT length, mm	64
Maximum operating temperature, ^{o}C	500
Normal operating pressure, MPa	0.10 – 16
Test environment	Water (to 350°C) and inert gas (to 500°C)
Peak thermal flux, neutrons/cm^2-s	1.8e14
Thermal fluence, neutrons/cm^2	8.5e21
Peak fast flux, neutrons/cm^2-s (E > 1 MeV)	1.2e14
Fast fluence, neutrons/cm^2 (E > 1 MeV)	5.7e21
Gamma flux, γ/cm^2-s	1.1e15
Integrated gamma exposure, γ/cm^2	5.2e22

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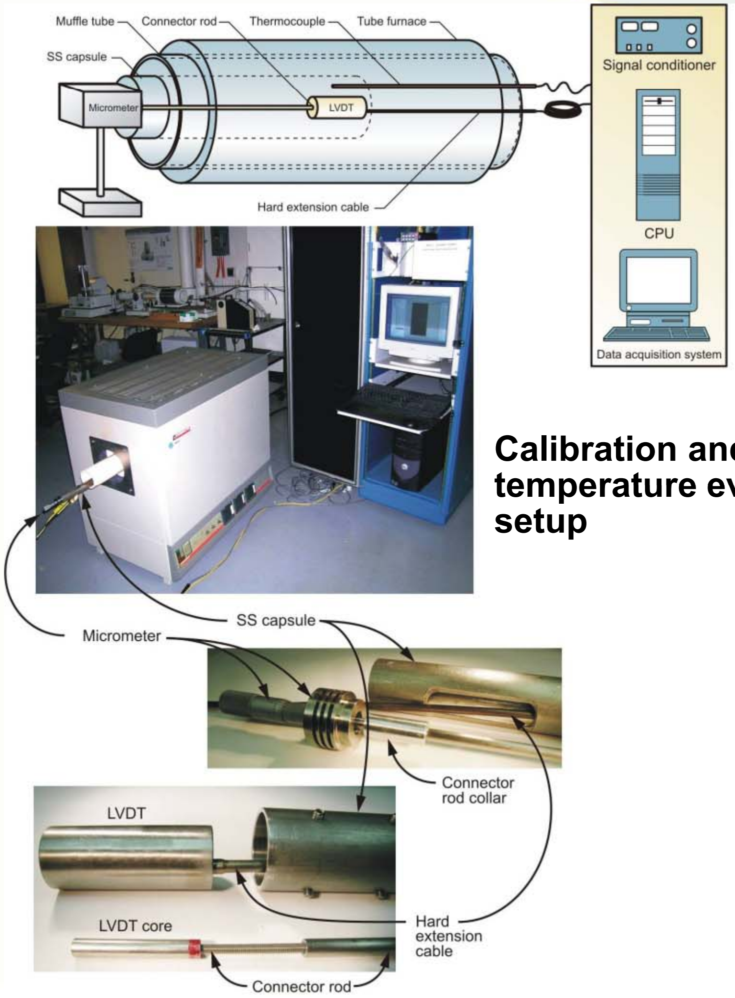
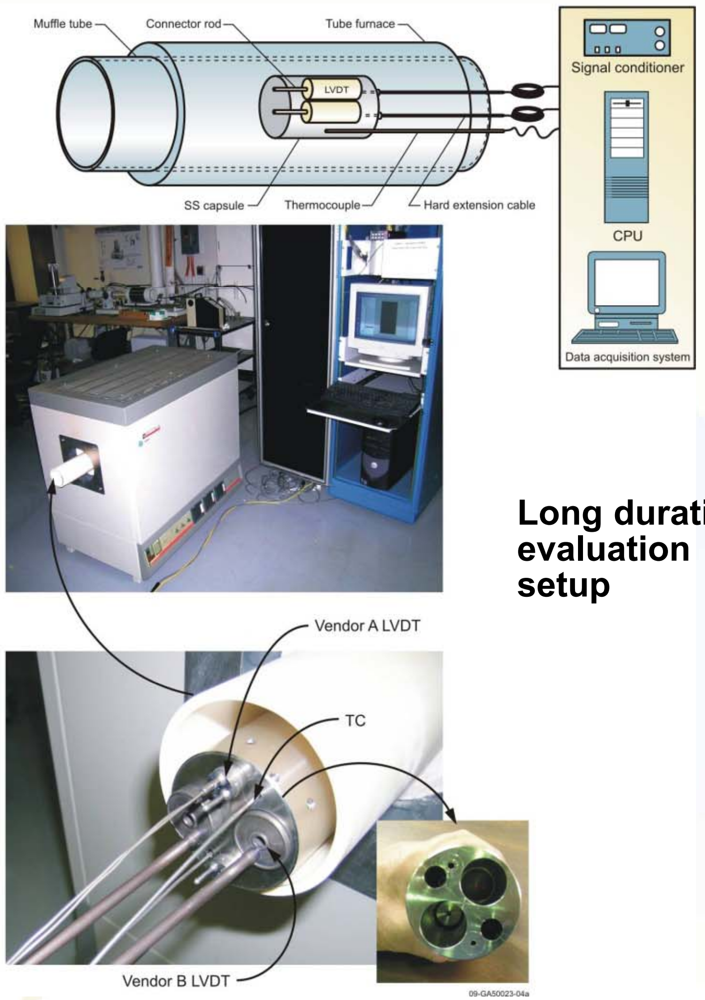
Investigations Completed to Evaluate LVDT Performance for ATR Conditions



Calibration and Curie temperature evaluation setup



Long duration evaluation setup

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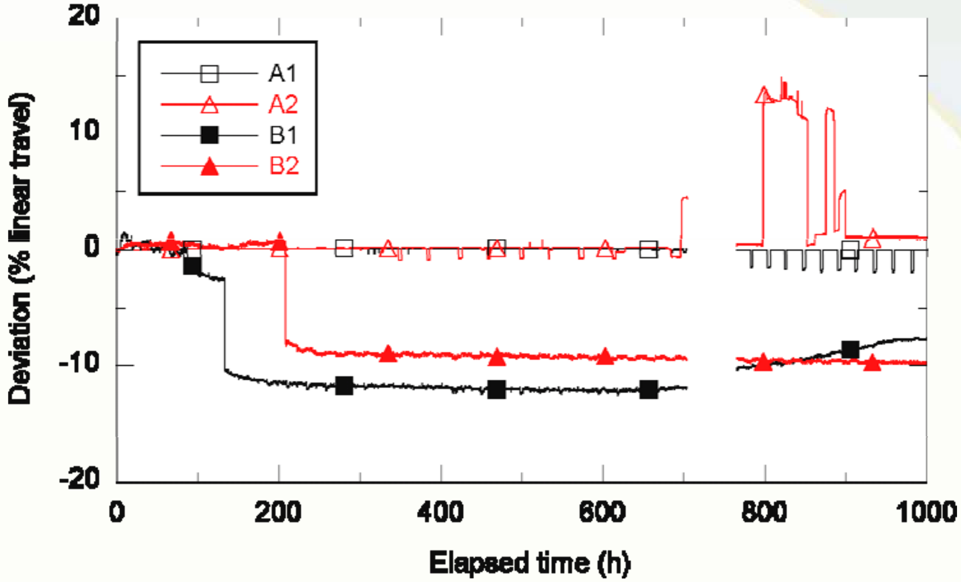
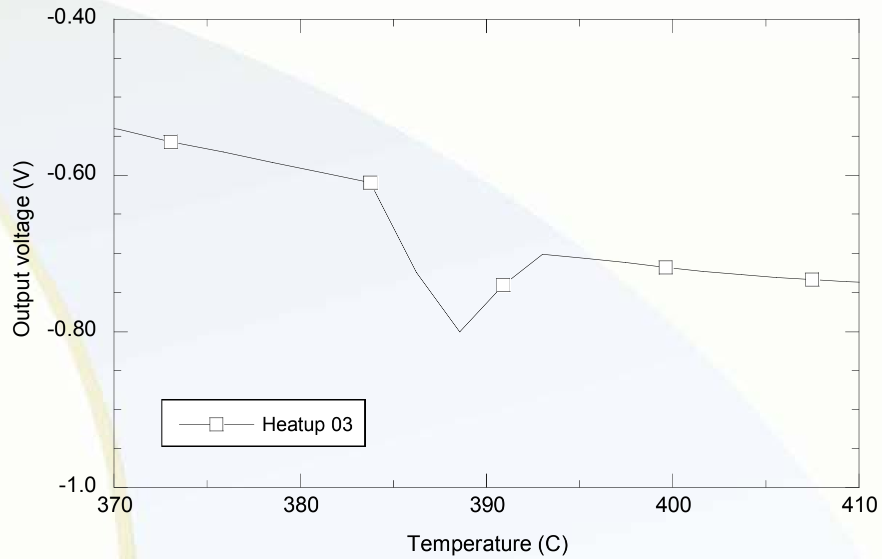
IFE/HRP LVDTs Superior At High Temperature but Less Accurate Near Curie Temperature



Smaller diameter IFE/HRP LVDTs (Vendor A) exhibit superior long duration high temperature response



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

- IFE/HRP and INL exploring alternate LVDT coil materials with superior high temperature performance
- HTTL evaluations of optimized LVDTs (with alternate coil materials) show exceptional high temperature stability!

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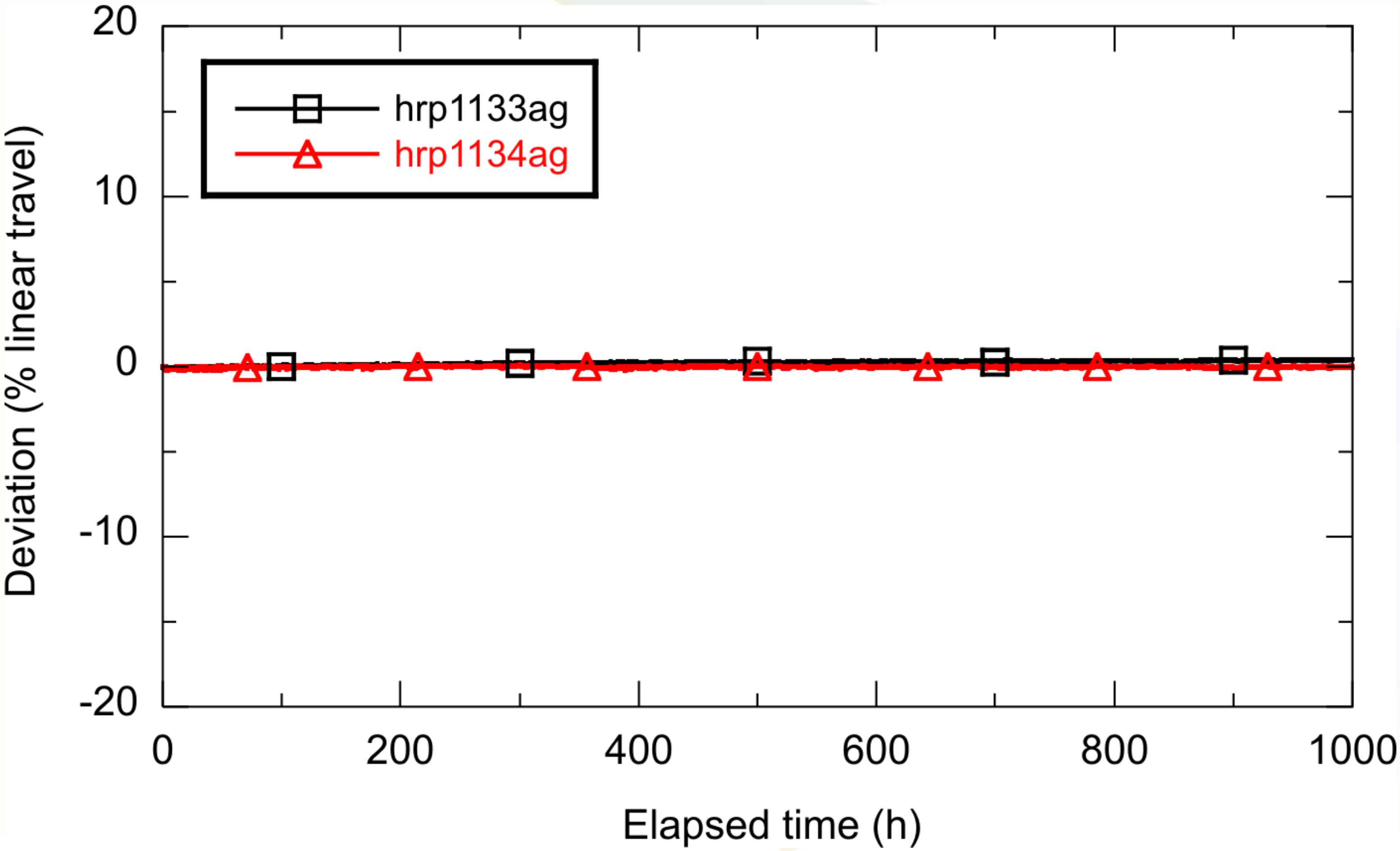
INL evaluations of Developmental IFE/HRP LVDTs indicate Exceptional High Temperature Stability



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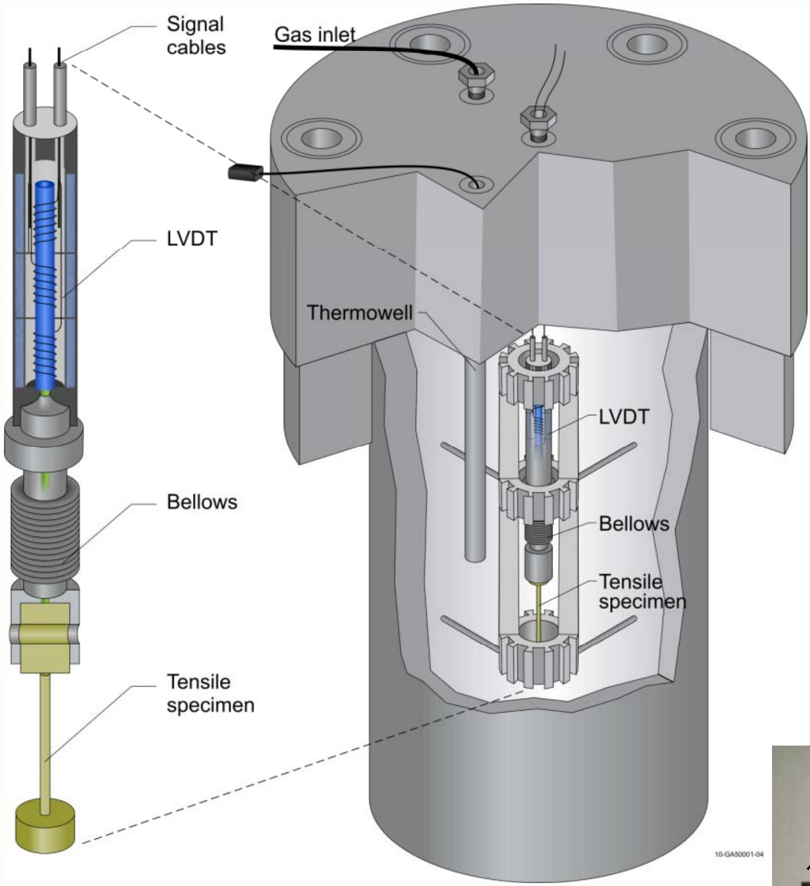
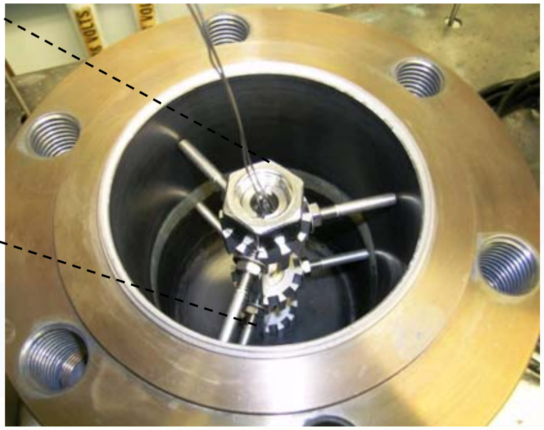
LVDTs offer Potential for Real-time Creep Measurements



INL rig for creep testing in PWR loops

Test rig facilitates creep testing in PWR coolant loop

- External pressure compresses bellows applying constant load to specimen
- Real time elongation detected using IFE/HRP LVDT
- Fixture design completed in FY09.
- IFE/HRP welded bellows and LVDT to fixture
- Autoclave testing initiated in January 2010.



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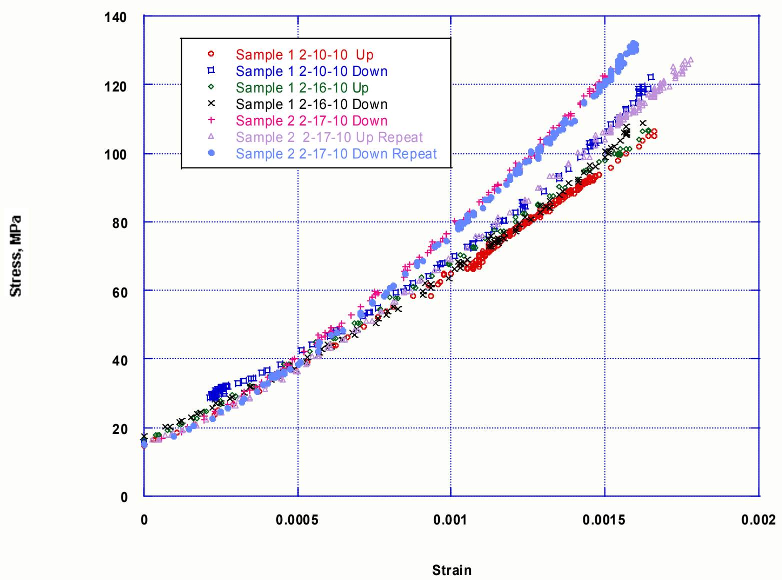
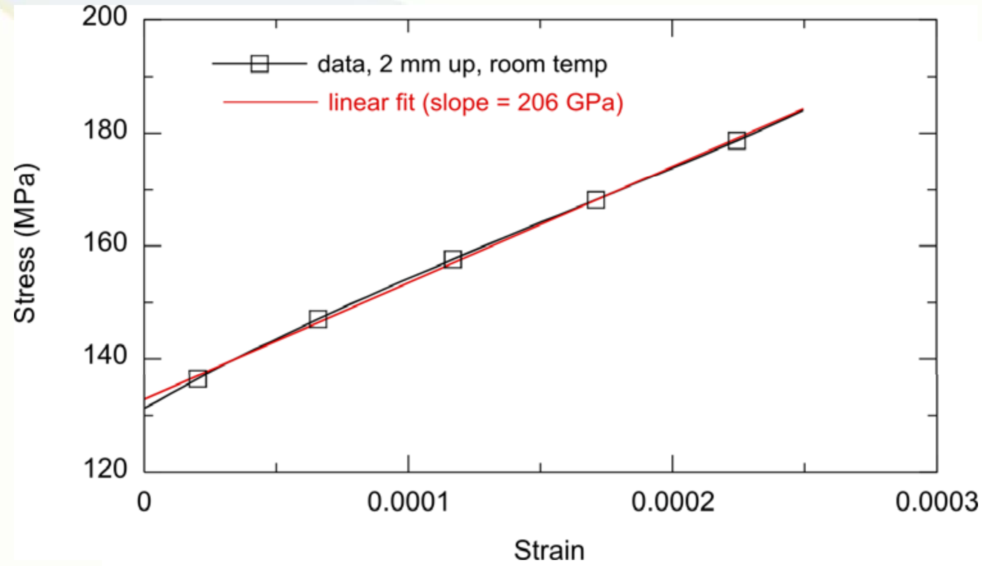
Initial evaluations indicate test rig yields consistent repeatable results





Initial autoclave tests yield consistent results for various specimens

Initial comparisons with load frame tests yield consistent results

Rig design to be finalized for ATR PWR loop deployment in 2011.

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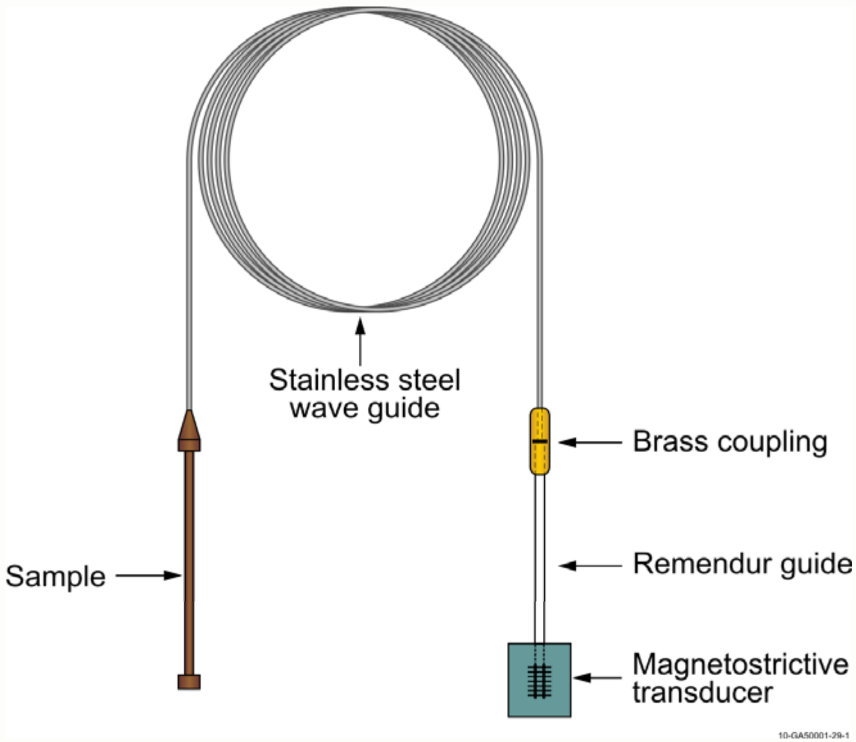
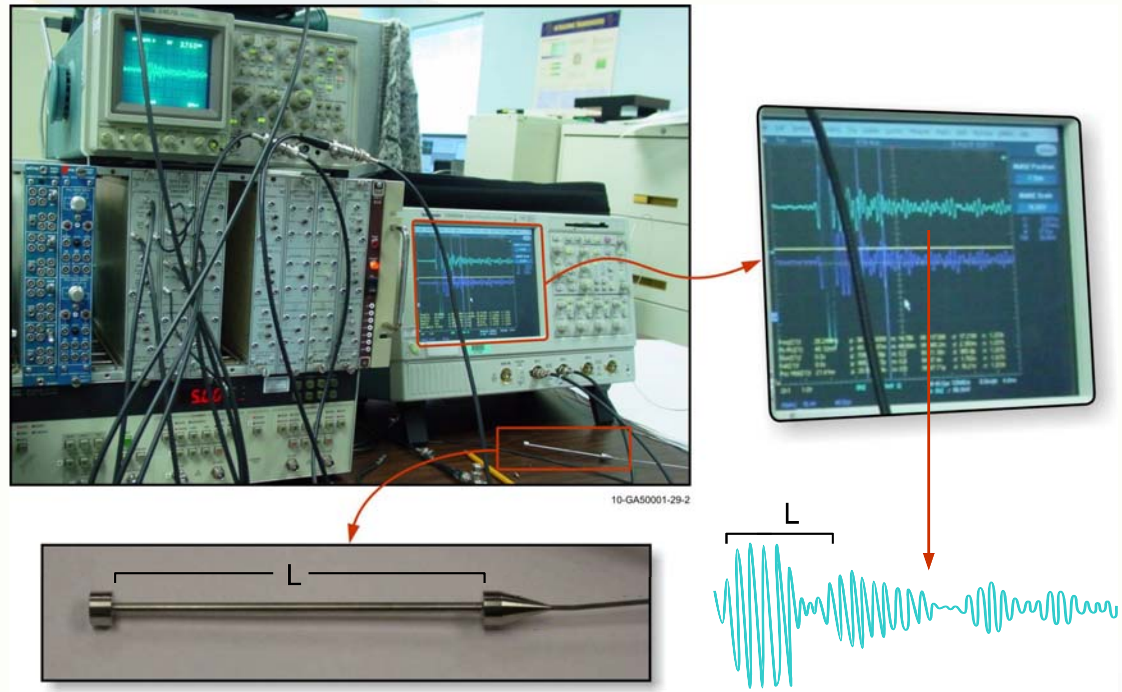
Ultrasonic Techniques Offer Several Advantages for Real-time Detection of Geometry Changes





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

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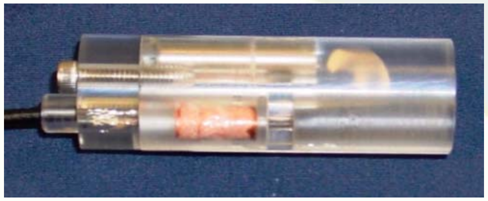
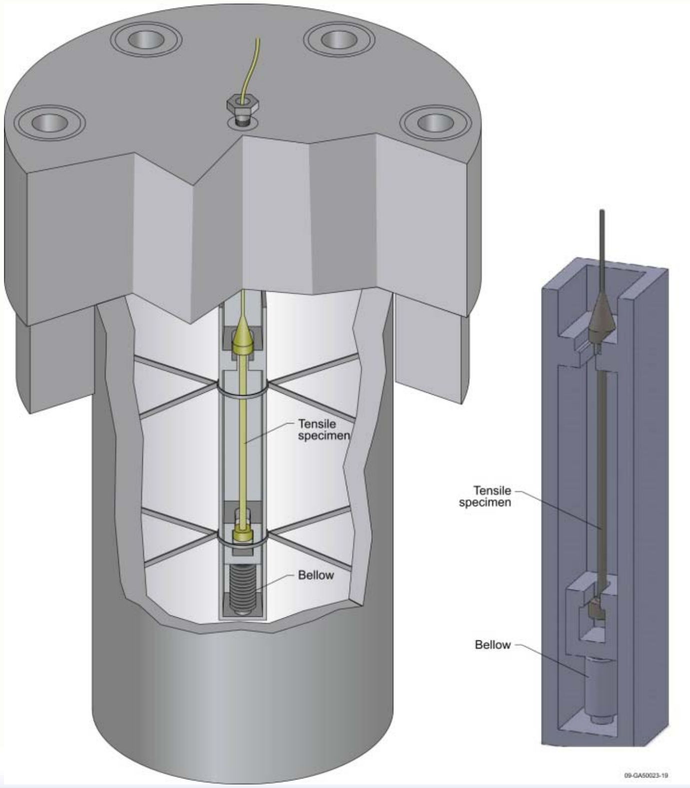
INL/PSU Effort Exploring Ultrasonic Techniques for Real-time Detection of Geometry Changes





- 3-year effort initialized in FY10
- Optimized designs developed for:
  - Driver coil
  - Coupling
  - Remendur guide
  - Acoustic horn/sample
- Benchtop, furnace, and autoclave evaluations to be completed
  - Autoclave test setup design developed and procurement underway.
  - Benchmark evaluations underway

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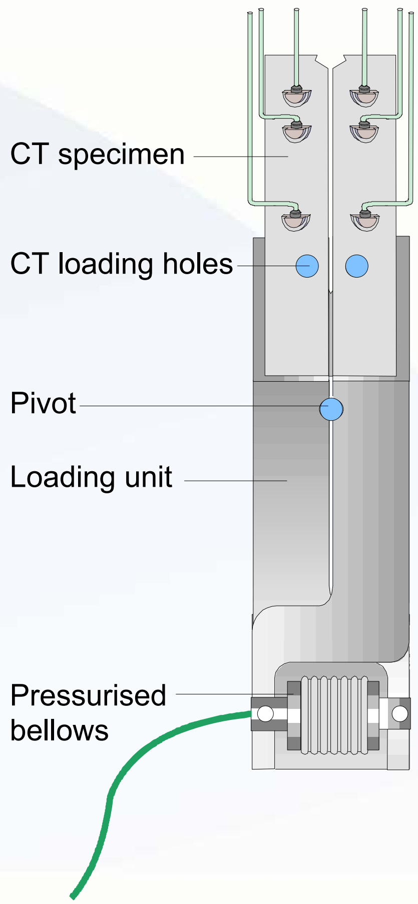
In-core Crack Growth Measurement

- **Shown is a Halden Reactor Project compact tension specimen with a pivoting bellows load system**
- **Crack growth is measured by passing a current through the sample using the upper pair of contacts and measuring the potential across the lower two pairs**
- **A similar system with passively loaded samples has been used in power reactor and research reactor testing, generally in conjunction with in situ ECP measurement**



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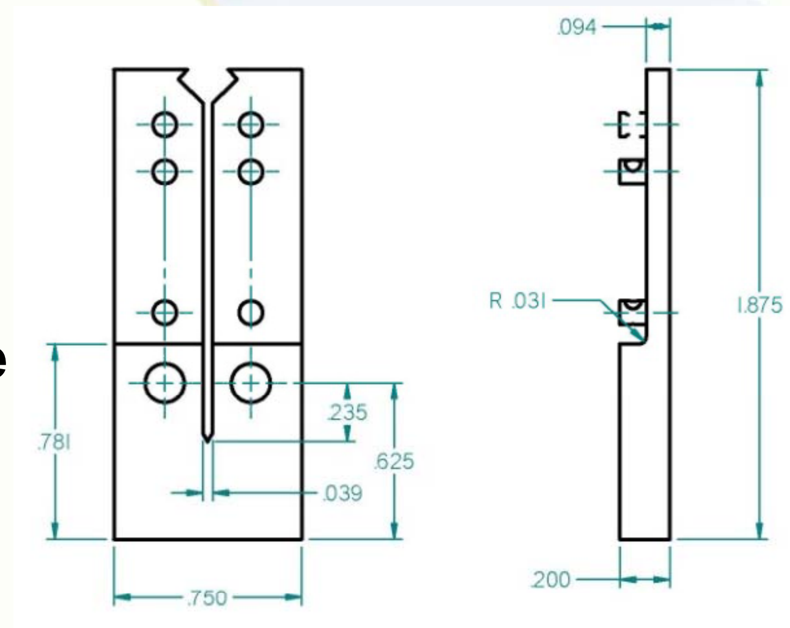
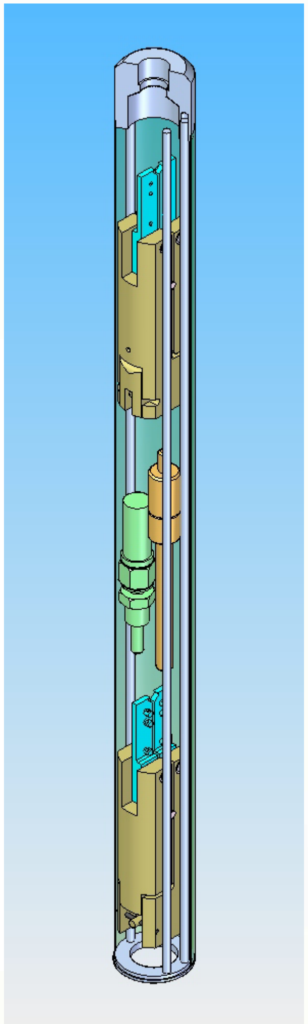
ICCGM Development at MIT

- MIT reviewed in-core crack growth measurement systems for the NSUF
- Halden system from previous slide was chosen as a basis for NSUF design
- Specimen and loading fixture were re-engineered for a planned irradiation test in the MITR
- Pending funding, MIT/INL will continue to collaborate and proceed to prototype specimen manufacturing, out-of-core testing and in-core demonstration





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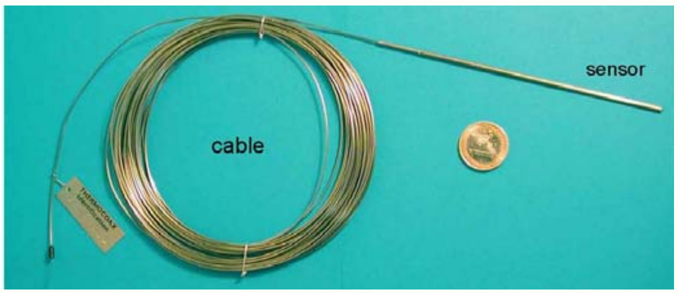
ISU/CEA/INL Project Investigating Use of Real-time In-core Flux Detectors in ATRC

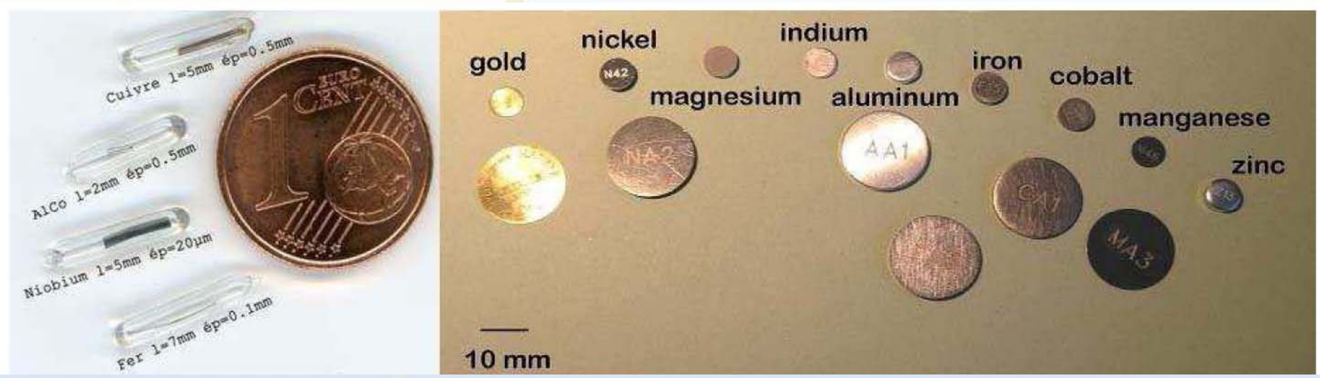
CEA fission chambers



SPNDs

BTB fission chambers

- Fast and thermal flux measurements obtained from foils, wires, SPNDs, and fission chambers
- Sensors cross-compared for response time, accuracy, and longevity.
- Data ultimately will allow development of real-time 3D ATRC core map



Flux wires and foils

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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 (A/nv)**
  - **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**

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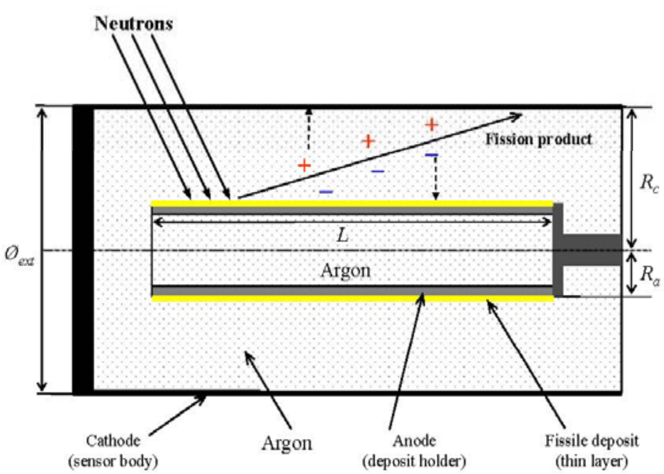
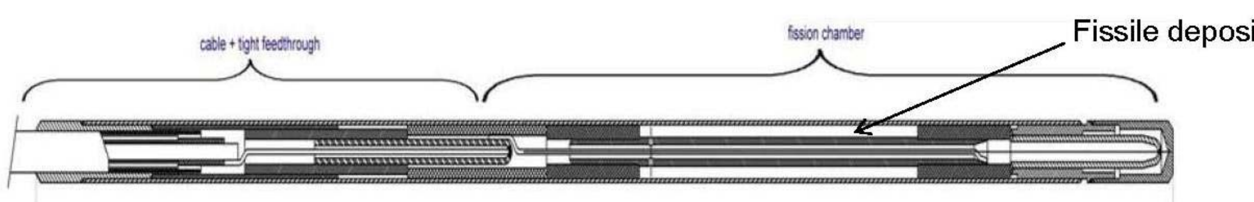
ISU/CEA/INL Project Also Evaluating Fission Chambers

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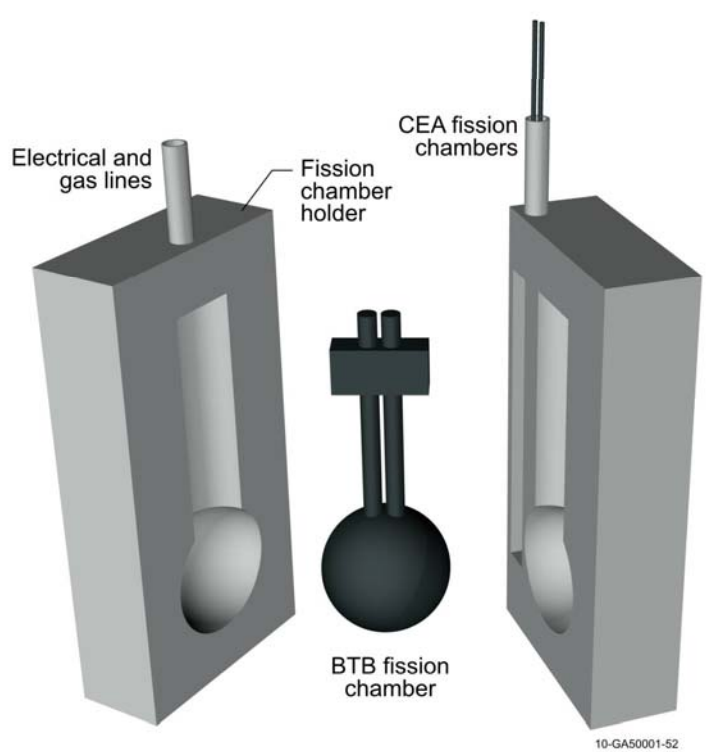
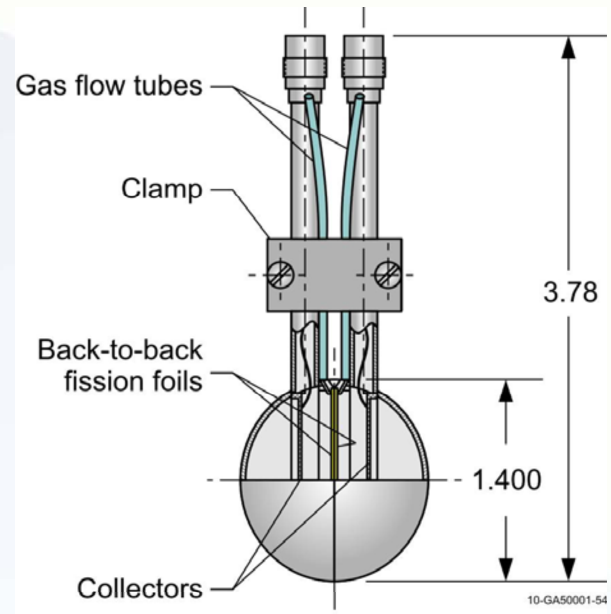
ISU/CEA/INL Project Comparing Detectors to Back-to-Back Fission Chambers





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

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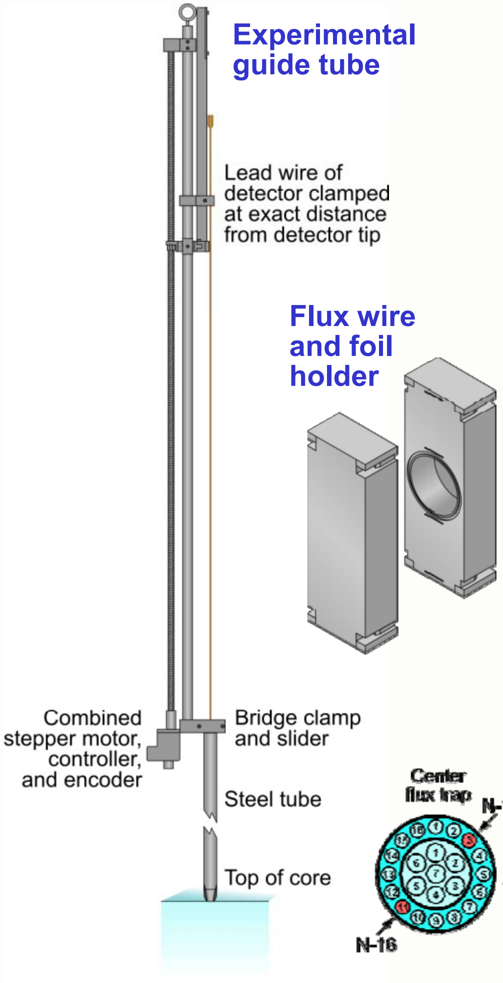
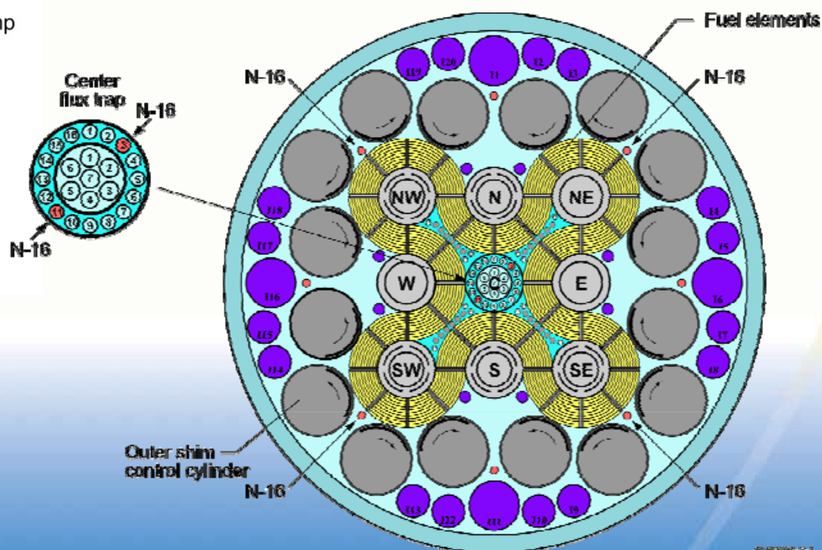
Initial Efforts Investigating Real-time Thermal and Fast Flux Detectors Underway





- Three-year project initiated January 2010.
- Sensors identified and procured (some detectors from CEA, CNEA, and prior ANL evaluations).
- Signal processing equipment identified and procured.
- Test fixture designs developed to allow insertion of sensors in NW flux trap and six N-16 positions.
- Real time detector position control, position indication, and detector signal readout simultaneously controlled and recorded via Labview.
- Initial tests planned for May through July 2010 timeframe.

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Summary

- 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.

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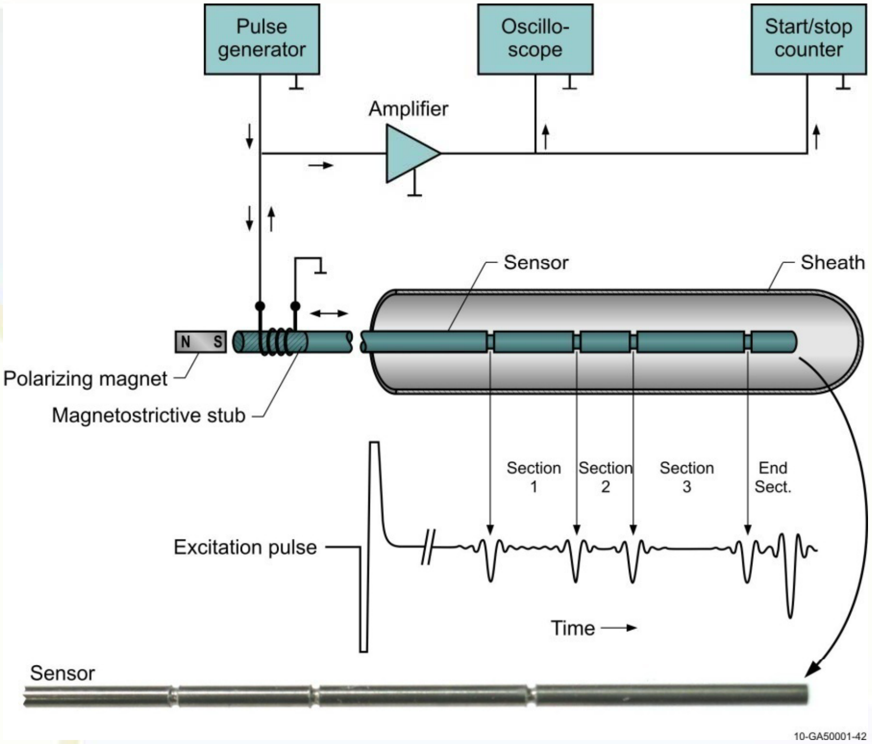
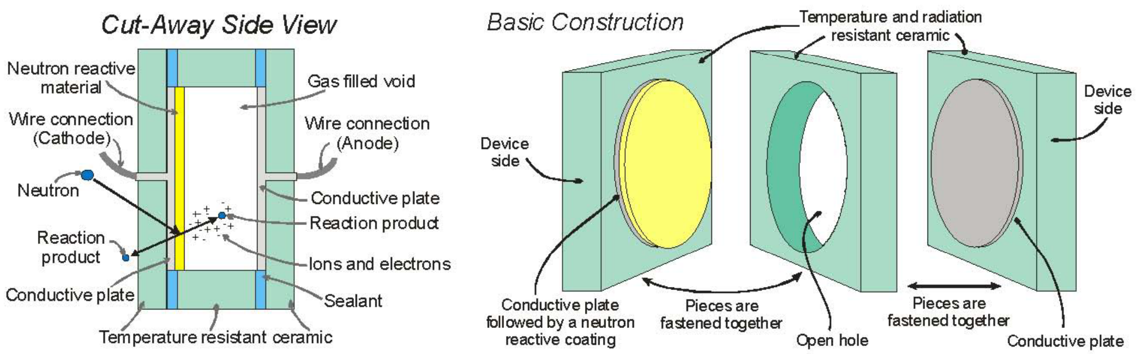
Future R&D to Focus on Sensor Technologies Not Available at MTRs

Fiber optics offer simultaneous temperature, pressure, length, and morphology detection



Ultrasonic thermometers offer multipoint temperature detection with a single miniature sensor



Micro-Pocket Fission Detectors (0.5 mm x 1.0 mm) offer more miniature neutron detection options

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