Instrumentation development for in-core experiments at the ATR NSUF

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Outline

- **Introductory comments on in-core measurements and instrumentation: typical measurements and challenges**
- **NSUF instrumentation selection and prioritization strategy**
- **Collaborative instrumentation development programs**
- **Key accomplishments and ongoing research**

Typical In-core Measurements: Experimental Condition

- **Physical: temperature, pressure, flow rate, position**
- **Irradiation: neutron flux (thermal and fast), spectrum, gamma dose rate (nuclear heating rate)**
- **Chemical: pH, ECP, conductivity, gas composition**

Typical In-core Measurements: Sample behavior

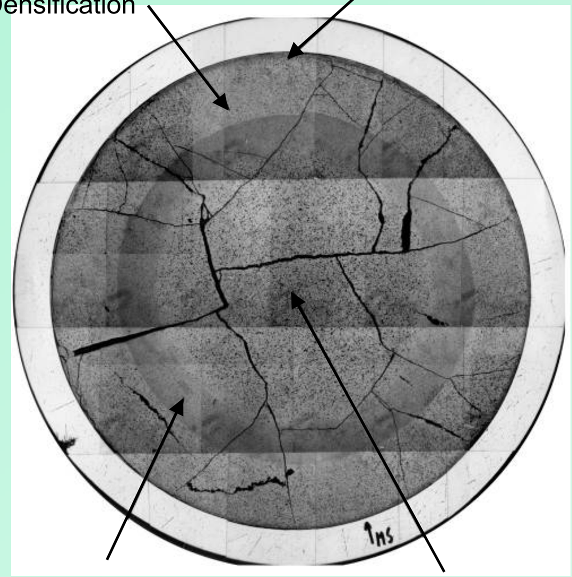
- **Materials testing: displacement (strain, crack growth, specimen failure), crack length, thermal conductivity, corrosion**
- **Fuel testing: temperature, pressure, fuel and clad dimensional changes, neutron flux and power, fission gas release, thermal conductivity**

Why Do In-core Measurements?

- **Determine time/fluence response of parameters**
- **Investigate interrelationship between parameters**
- **Better characterize irradiation conditions**
- **Avoid multiple irradiate/remove/measure cycles in order to:**
  - **Avoid disturbing phenomena of interest**
  - **Save time and money**

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**



What Are the Challenges for In-core Measurements?

- Demanding environments – neutron and gamma irradiation, high temperatures and pressures, aggressive coolants (requires careful qualification)
- Limited space, difficult access
- Additional constraints including: reactivity and activation considerations, design for remote assembly and disassembly, avoiding perturbation of environment

Typical Approaches to Probing In-core Spaces

- **Passive or active electrical signals – thermocouples, potential drop or eddy current measurements directly on samples, LVDTs**
- **Sampling for coolant/environment conditions**
- **Newer methodology being evaluated and developed includes: fiber optics, ultrasonic transducers, acoustic methods and wireless technology**

Overcoming the Difficulties: Some Generic Approaches

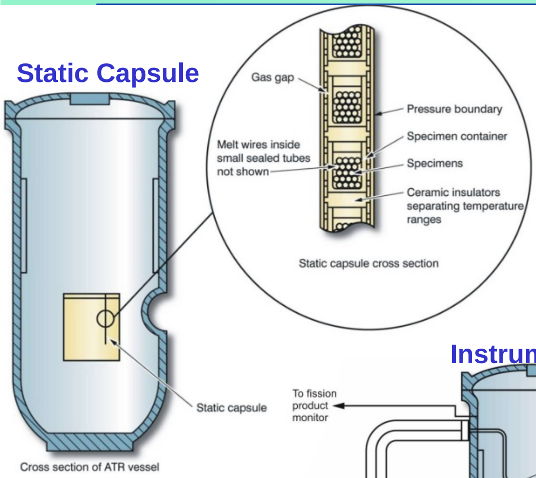
- **Develop radiation and temperature hardened insulation materials: wide use of mineral insulated (MI) cable, e.g. sheathed thermocouples**
- **Improve and qualify metal to ceramic seal technologies**
- **Mechanically translate displacements to lower-dose environments**
- **Calibrate for radiation effects using post-irradiation standardizations, provide *in situ* reference specimens or develop sensors with minimal irradiation drift**
- **Correlate results at "extreme" and "moderate" locations**

NSUF Instrumentation Selection and Prioritization Strategy

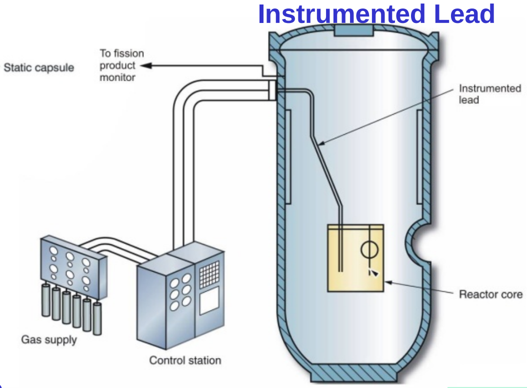
- Review of available instrumentation at research and test reactors worldwide and existing NSUF capabilities
- Identification of non-nuclear instrumentation with potential for application in-core
- Survey of user needs
- Selection of near term projects based on anticipated user needs and technology readiness
- Selection of longer-term projects including development of new technologies to provide world-class instrumentation to NSUF users
- Note that many of these developments are in collaboration with other institutions

NSUF Instrumentation Development Plan

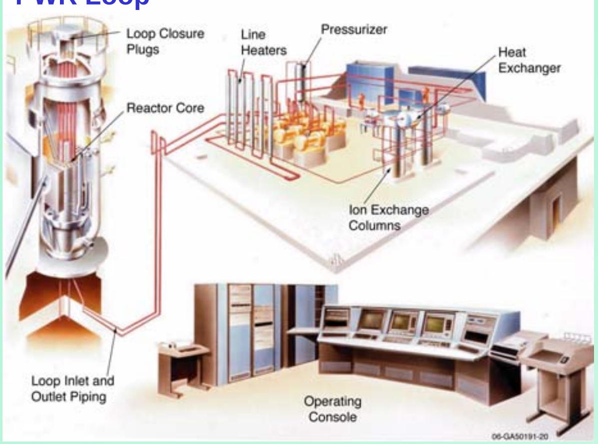
Static Capsule



Instrumented Lead



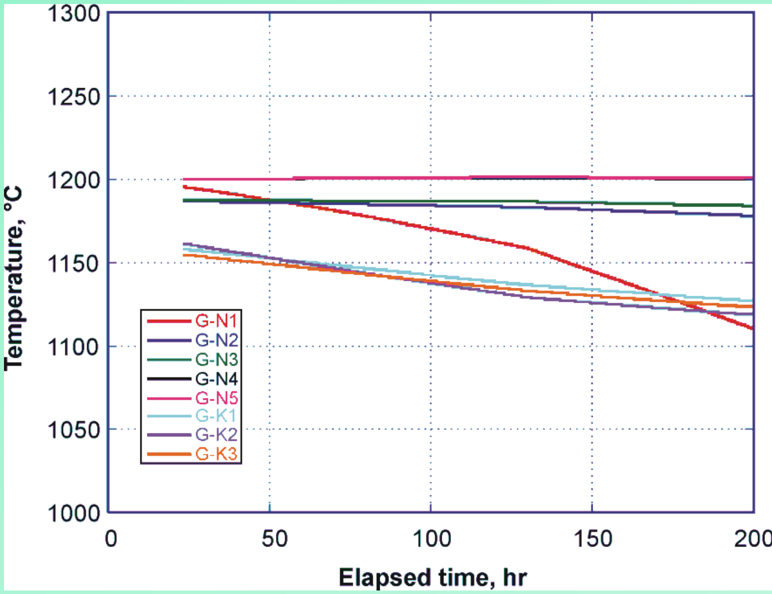
PWR Loop



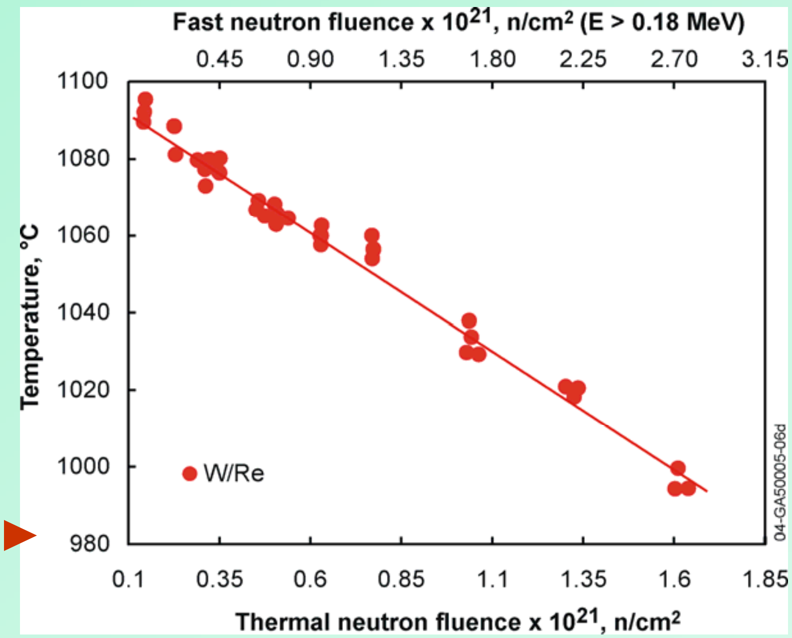
Parameter	Parameter			ATR Technology	Proposed Advanced Technology	
	Static Capsule	Instr. Lead	PWR Loop		Available at Other Reactors	Developmental
Temperature	√	√	√	• Melt wires (peak) • Paint spots (peak) • SiC Temperature Monitors (range)		• Wireless (range)
		√	√	• Thermocouples (Type N, K, C, and 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) • Subminiature fission chambers	• Moveable SPNDs
Gamma Heating		√	√		• Degradation using signal changes in thermocouples	
Dimensional	√	√	√	• Out-of-pile examinations		
		√	√		• LVDTs (stressed and unstressed) • Diameter gauge • Hyper-frequency resonant cavities	• 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.

In-Pile High Temperature Instrumentation Needed to Support Fuels and Materials Irradiation Programs



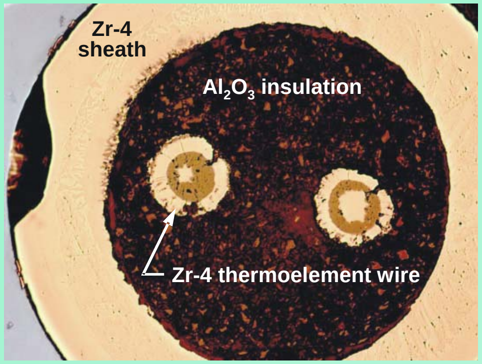
◀ **Drift exceeds 50 °C in 4 out of 8 Type N and K thermocouples within 200 hours**



Drift of nearly 100 °C in Type C thermocouples at fluences exceeding 10^{21} n/cm^2 ▶

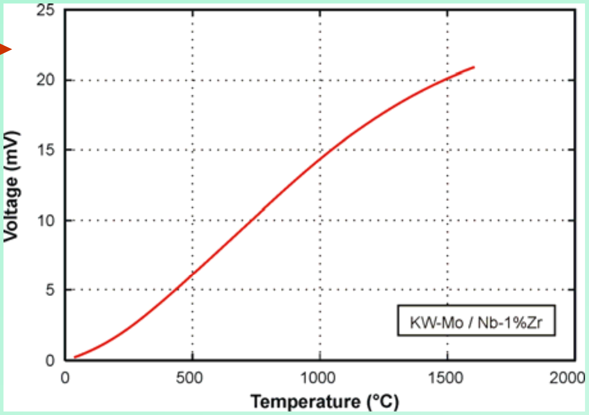
Commercial thermocouples degrade at temperatures above 1100 °C or transmute during irradiation.

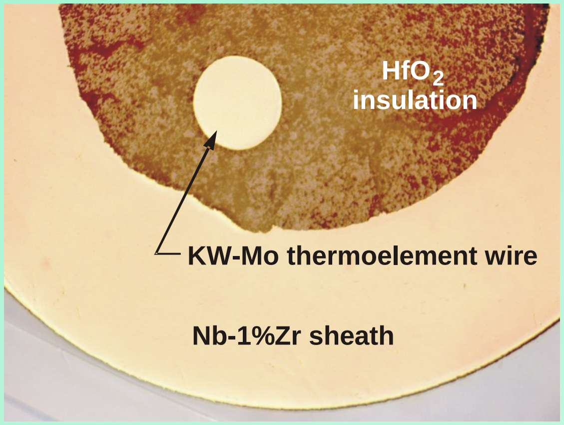
Initial HTIR-TC Development Considered Radiation and High Temperature Performance



Al_2O_3 attacks wire and sheath after heating at 1300°C

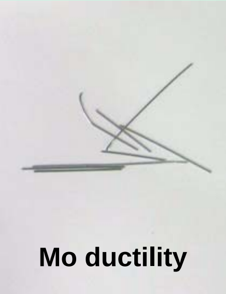
Selected KW-Mo and Nb-1%Zr combination has suitable resolution up to 1700 °C





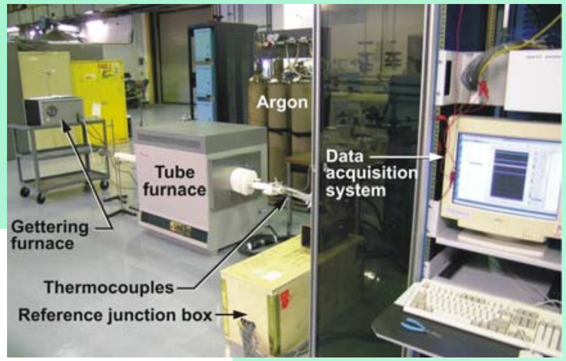
Selected materials resist interactions after heating at 1600 °C

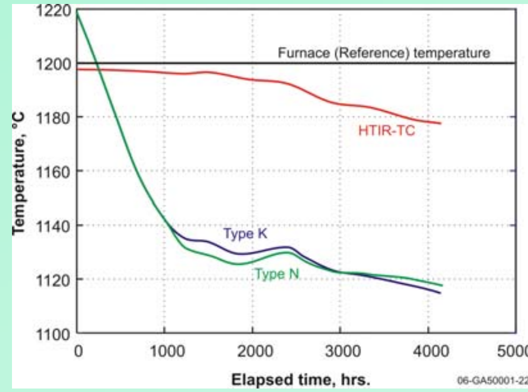
Selected KW-Mo ductile after heating at 1600 °C

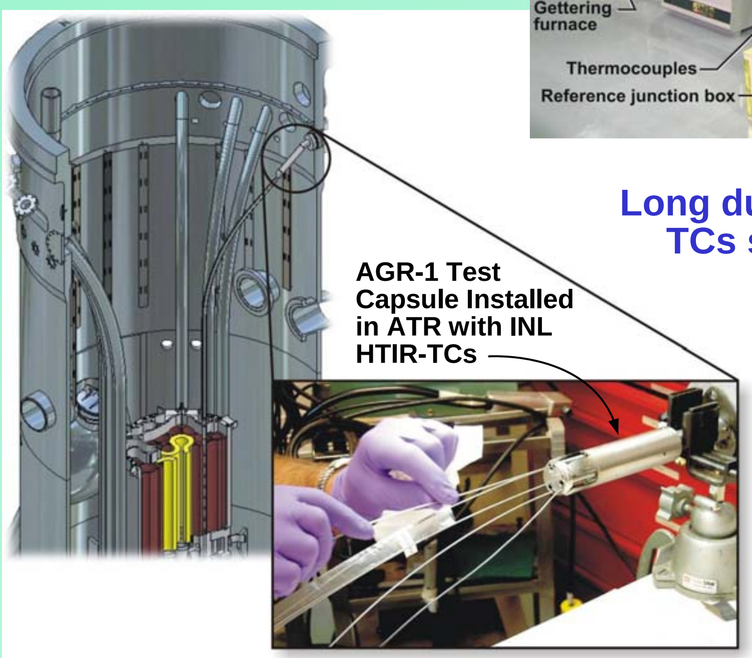


Evaluations suggest doped Mo/Nb-1%Zr thermoelements with HfO_2 insulation and Nb1%Zr sheaths most suitable combination for HTIR-TCs.

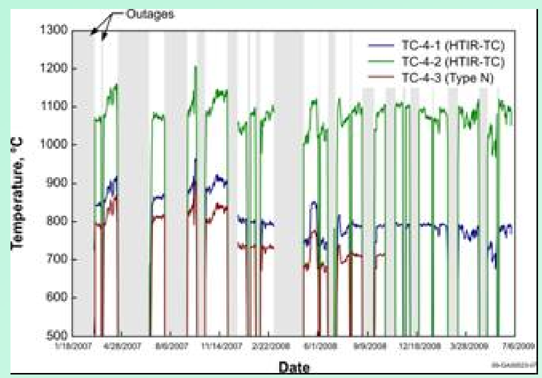
Final HTIR-TC Development Included Long Duration Testing and Radiation Testing







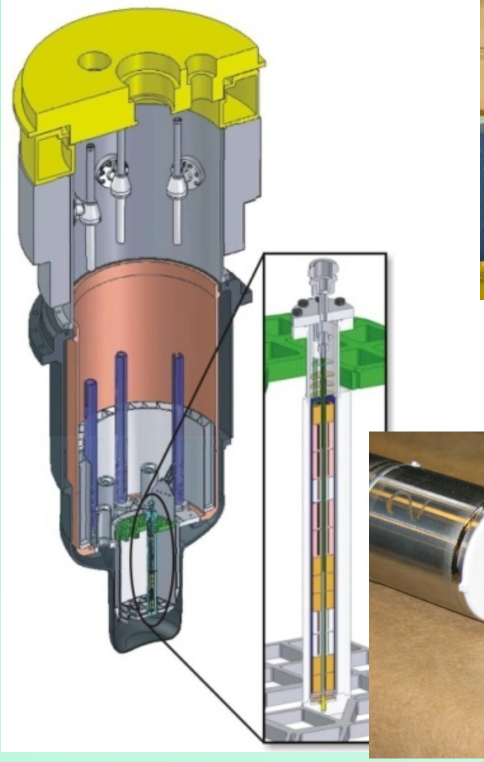
Long duration laboratory testing up to 1500 ºC show HTIR-TCs superior to commercial TCs at high temperatures



HTTL-developed in-pile instrumentation yielding reliable data for on-going ATR irradiations.

Optimized HTIR-TCs Fabricated for MITR Irradiations

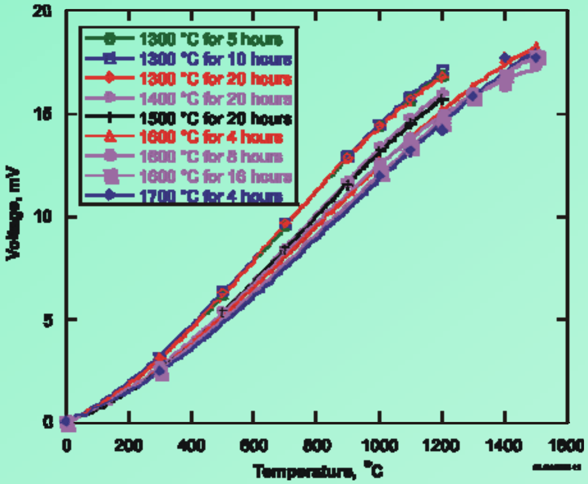
MITR High Temperature Irradiation Facility for 1400 °C irradiations



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

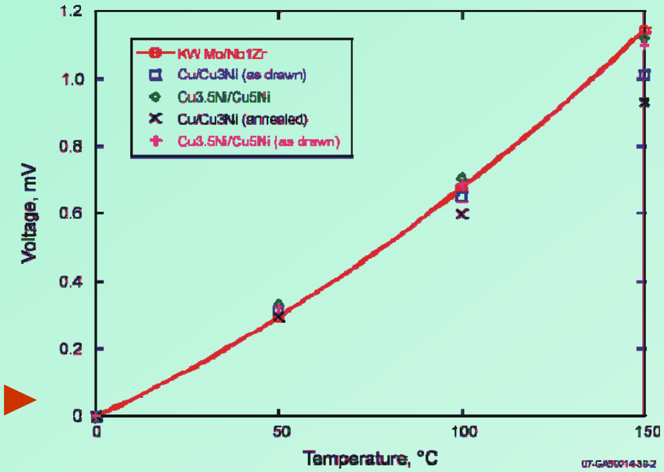
MITR HTIF facilitates high temperature HTIR-TC irradiations and post test examinations

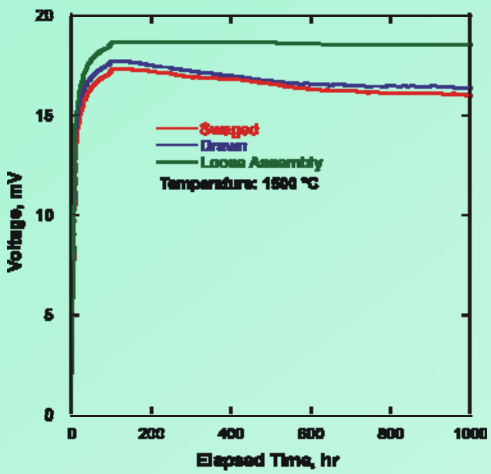
INL Continuing to Look for Ways to Optimize HTIR-TC Performance and Fabrication



◄ ***Optimized heat treatment***

Alternate extension cable materials ►



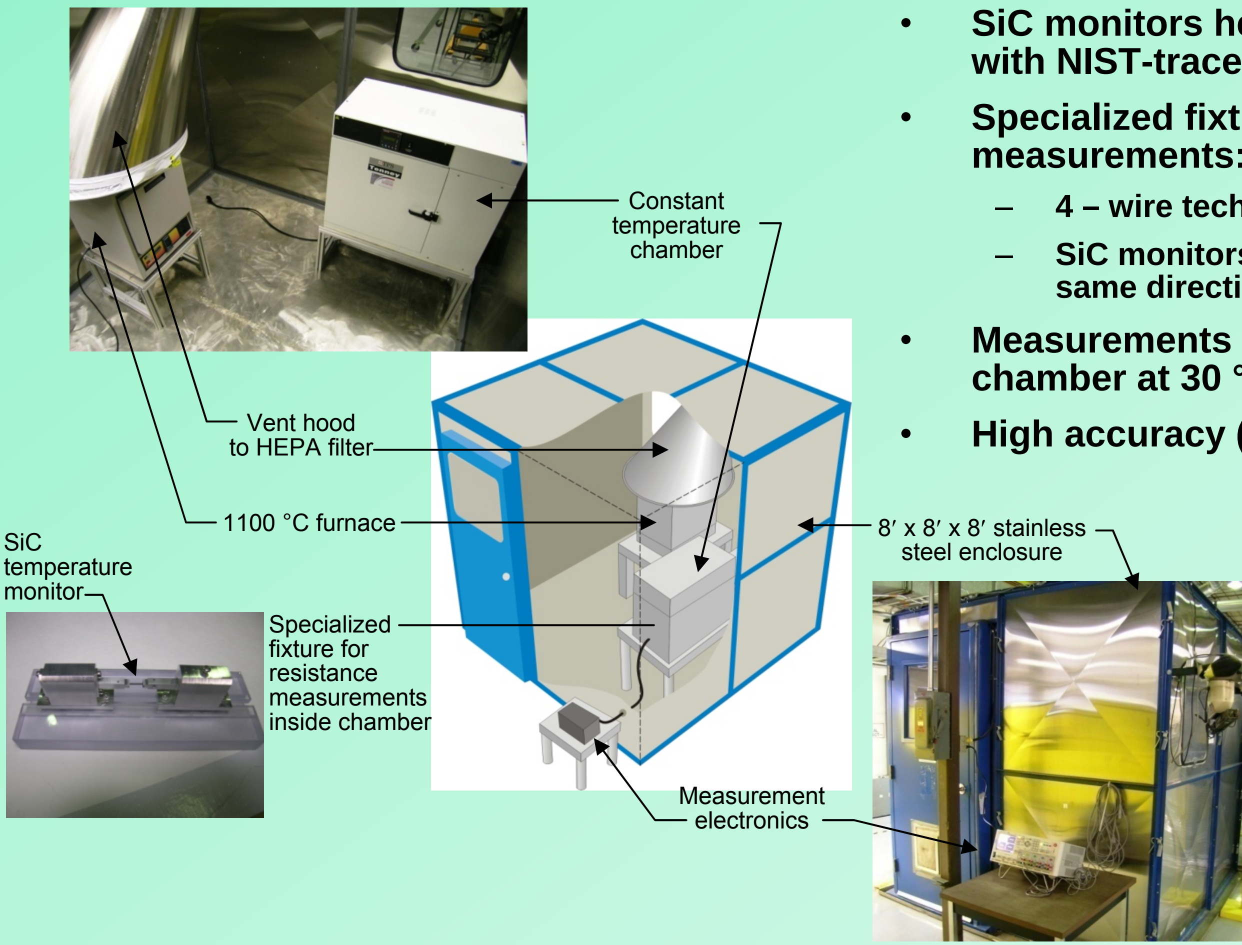


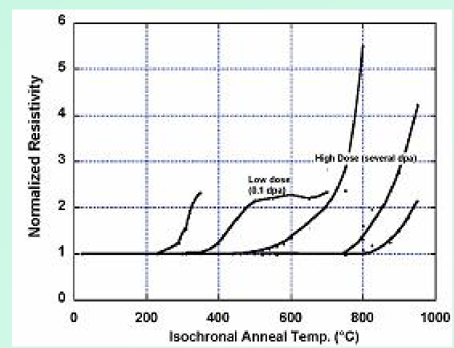
◄ ***Alternate designs***

Development activities focus on existing and anticipated needs of customers at ATR, MITR, and international test reactors

HTTL Prepared for Measuring Resistivity of SiC Monitors Irradiated at ATR

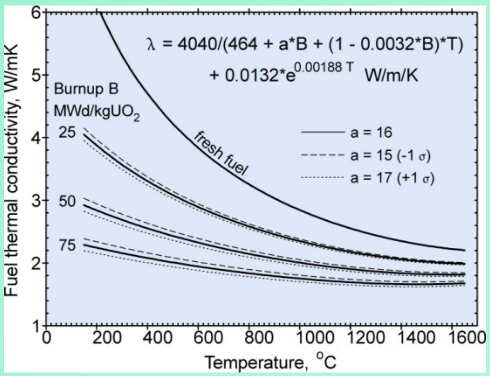
- Small (1 mm x 1 mm x 10 mm) monitors of high density CVD SiC
- SiC monitors heated for 30 minutes in furnace with NIST-traceable thermocouples
- Specialized fixturing developed for resistance measurements:
  - 4 – wire technique applied
  - SiC monitors held at same location and oriented in same direction
- Measurements made in constant temperature chamber at 30 °C
- High accuracy (9 digit) electronics

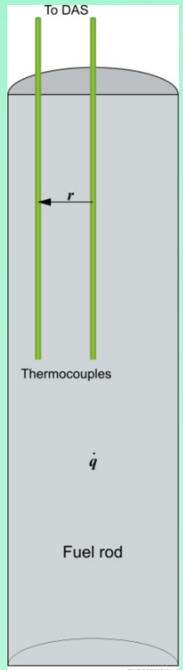




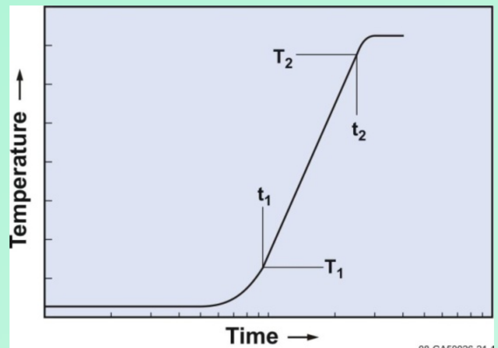
INL/USU Investigating Two Methods for In-pile Thermal Conductivity Detection

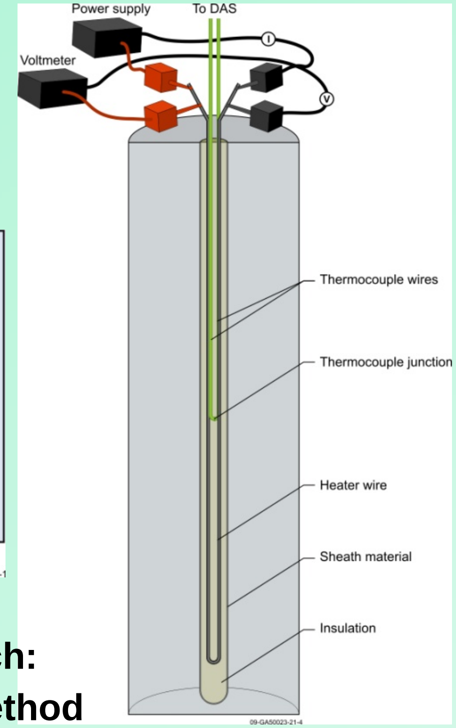
$$k = \frac{\dot{q}\cdot r^2}{4\cdot \Delta T}$$





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





Two thermocouple approach:

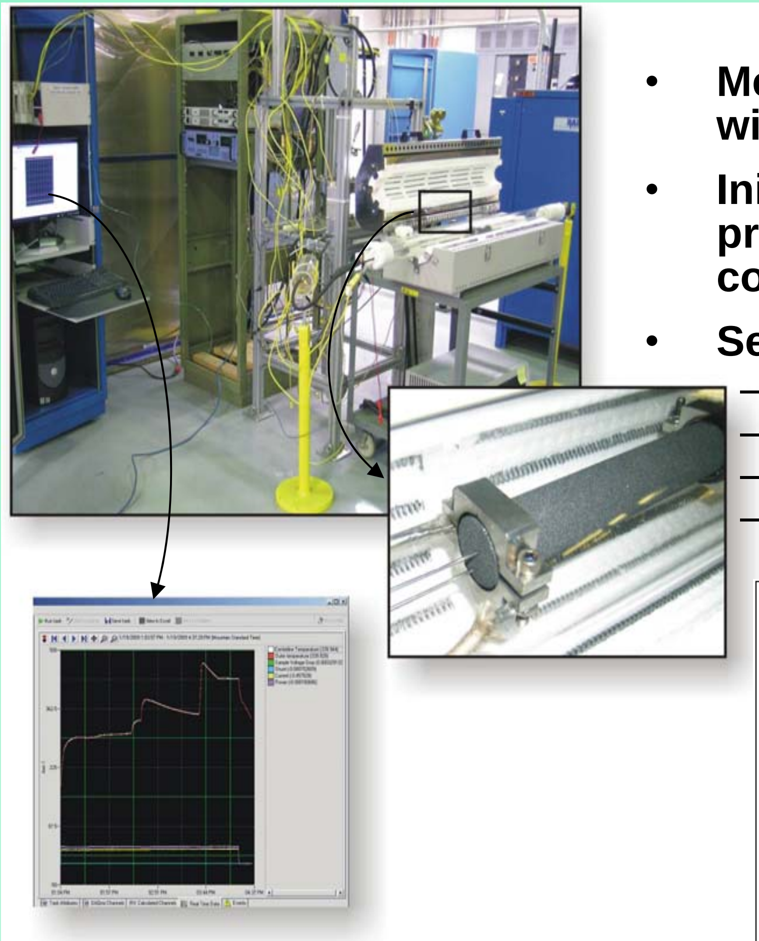
- Adaptation of IFE-HRP method
- Steady-state measurement

Transient hot-wire approach:

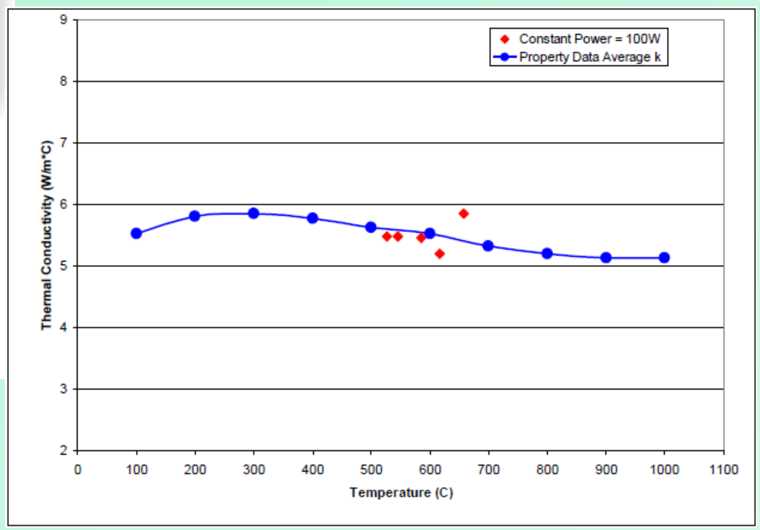
- Adaptation of ASTM method
- Transient measurement

"Average" value obtained from either method impacted by fuel irradiation phenomena (e.g, porosity, grain structure, fissile species redistribution, fission gas release, fuel pellet/cladding interactions, helium gas accumulation, etc.)

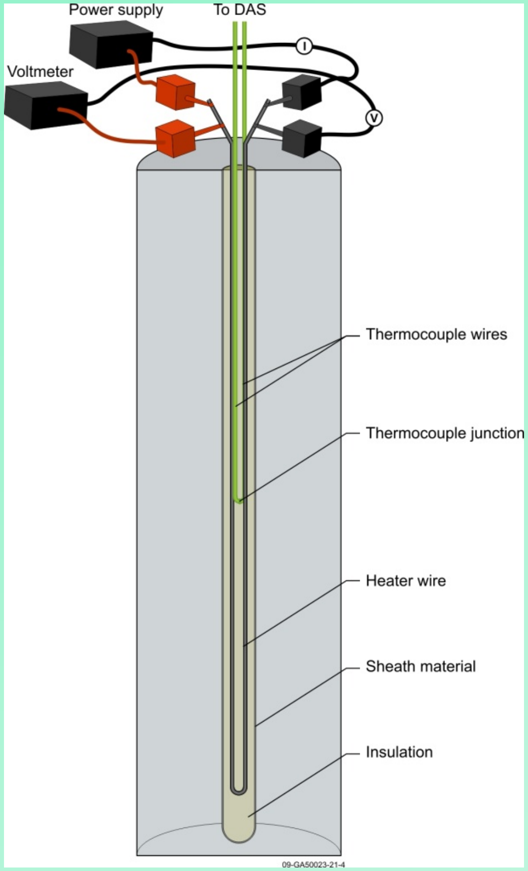
INL/USU Efforts Underway to Quantify Operational Limits for IFE-HRP Two-Thermocouple Technique



- **Methods evaluated using surrogate fuel materials with resistance heating in tube furnace**
- **Initiated first surrogate rod (CFOAM) material property and two thermocouple thermal conductivity testing**
- **Sensitivities underway to optimize results**
  - **Power**
  - **TC orientation**
  - **Outer heat transfer**
  - **Gap conductance**



THWM Offers Possible Improved Method for In-pile Thermal Conductivity Detection



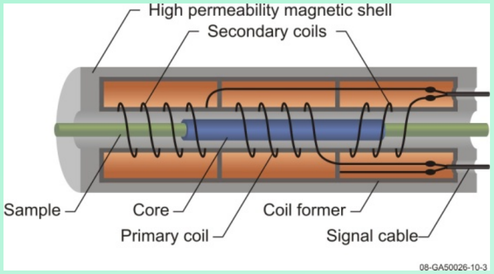
Room temperature data typically within 10% of reported values

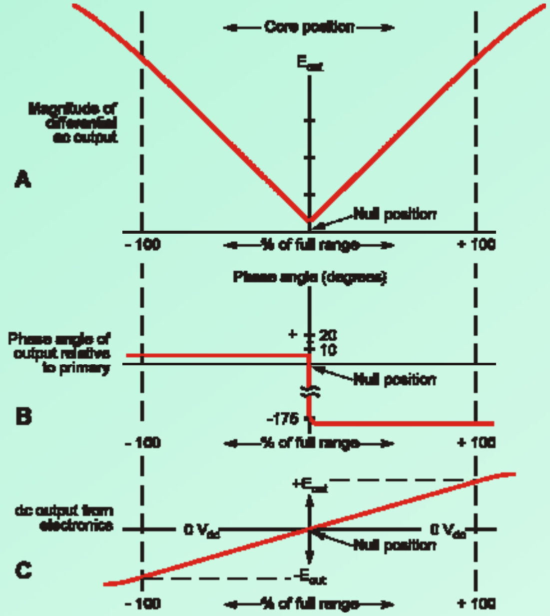
Material	USU/INL Probe Average Measured Effective Thermal Conductivity (W/m^2K)	Average Reported Value (W/m^2K)	Ratio of Reported to USU/INL Measured Values
SiO_2	1.353	1.38	1.020
Delrin	0.281	0.295	1.050
Lexan	0.247	0.207	0.838
Acrylic	0.215	0.216	1.005
Particle Board	0.149	0.135	0.906

INL/CEA efforts initiated to develop prototype design for in-pile evaluation.

Irradiation Hardened LVDTs

- **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**

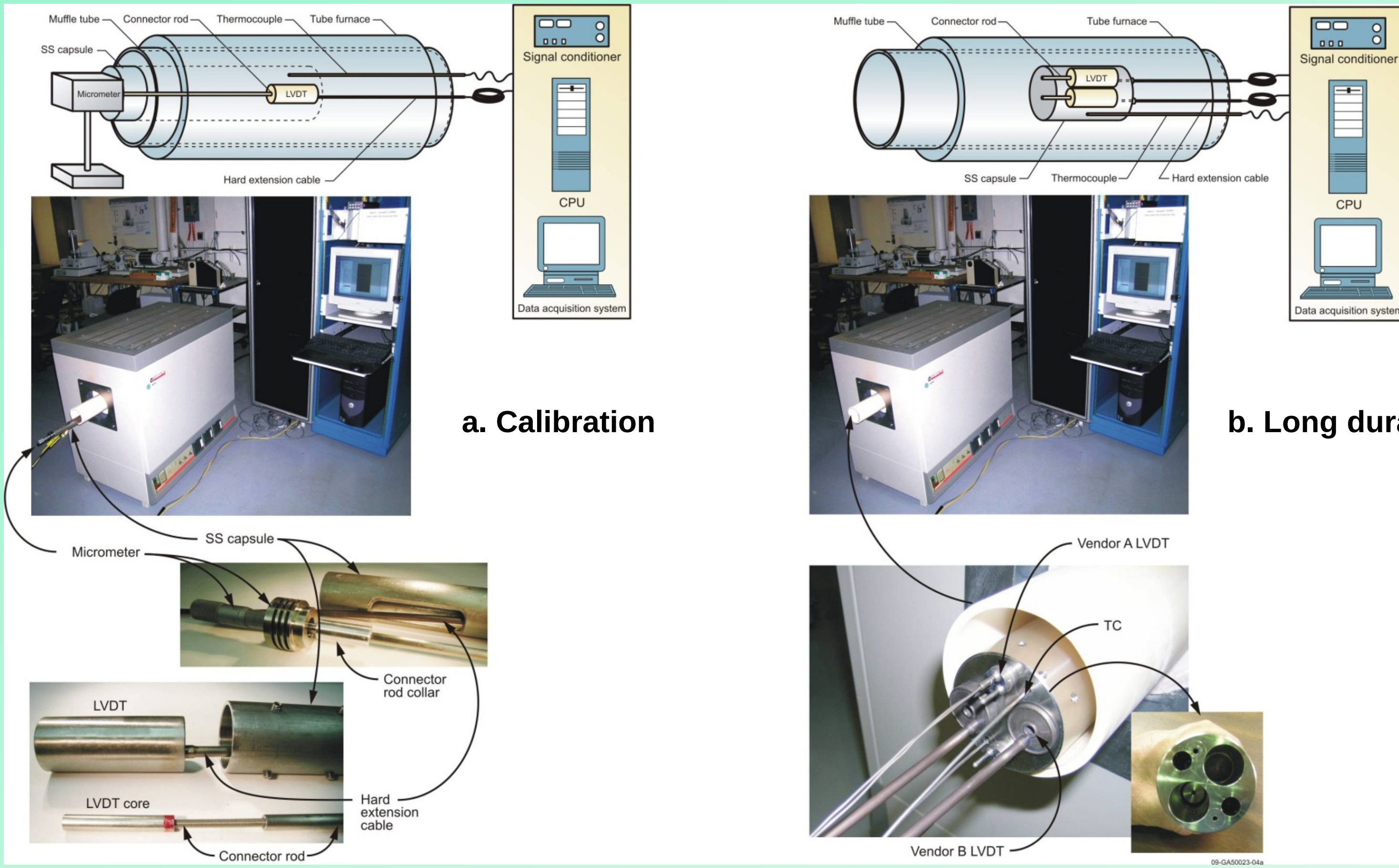




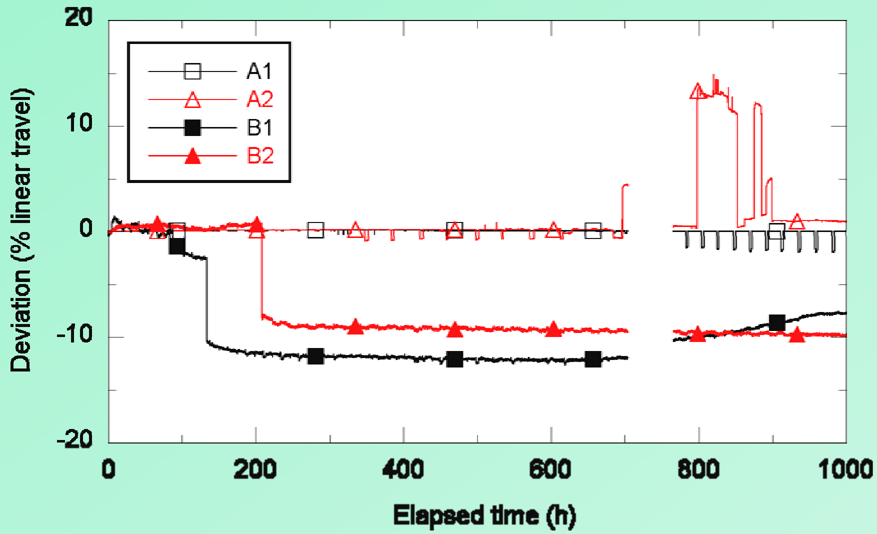
LVDTs Initially Investigated for Real-time In-pile Detection of Dimensional Changes

Parameter	Vendor A	Vendor B	Desired ATR
LVDT Length, mm	66	63.8	63.8
LVDT Outer Diameter, mm	12	25.4	≤ 25.4
Test environment	Water or Inert Gas	Water or Inert Gas	Inert Gas (Neon, Helium)
Length of leads from transducer until T < 200 ºC, cm	>12	>12	12
Total LVDT Displacement (stroke), mm	+/- 2.5-6.0	> +/- 2.5	> +/- 2.5
Sensitivity, V/m	60	51	
Normal operating temperature, K	620	820	< 773
Maximum operating temperature, K	>773[a]	920	773
Normal operating pressure, MPa	15.5	16.5	0.1013-0.3039
Peak thermal flux, E < 0.625 MeV, neutrons/cm^2-s [a]	3 x 10^{13}[d]	NA[c]	1 x 10^{14}
Integrated thermal fluence, E < 0.625 MeV neutrons/cm^2[a]	NA[e]	> 1 x 10^{19}[c]	8 x10^{21}
Peak fast flux, E > 20 MeV, neutrons/cm^2-s[a]	3 x 10^{13}[d]	NA[c]	3 x 10^{14}
Integrated fast fluence, E > 20 MeV, neutrons/cm^2[a]	NA[e]	NA[c]	2x10^{22}
Integrated gamma exposure, γ/cm^2[a]	NA[e]	NA[c]	9x10^{22}
Integrated radiation, rads/cm^2[a]	NA[e]	NA[c]	2 x 10^{13}

Investigations Initiated to Obtain Real-time Geometry Sensors for ATR Conditions

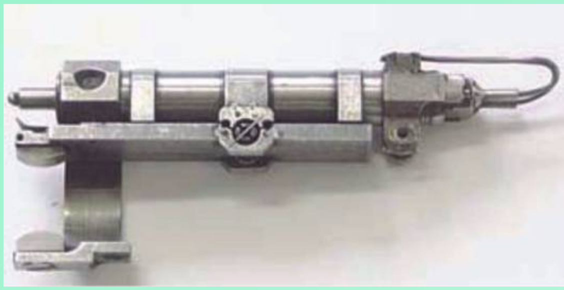


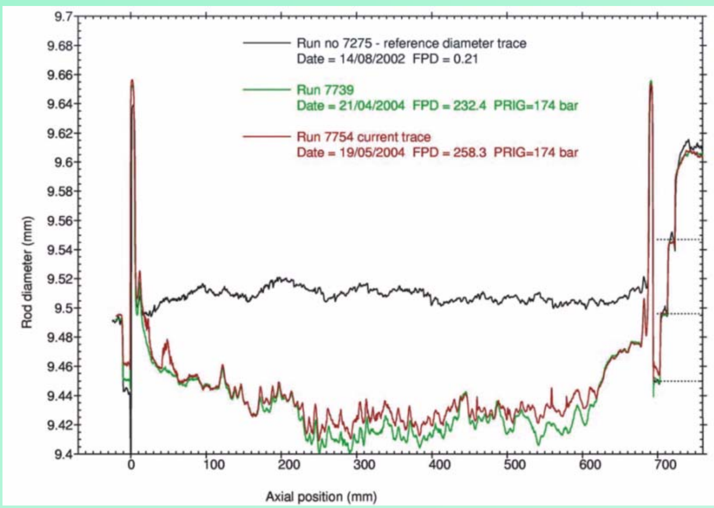
High Temperature Long Duration Tests show Vendor A (Halden) LVDTs Superior



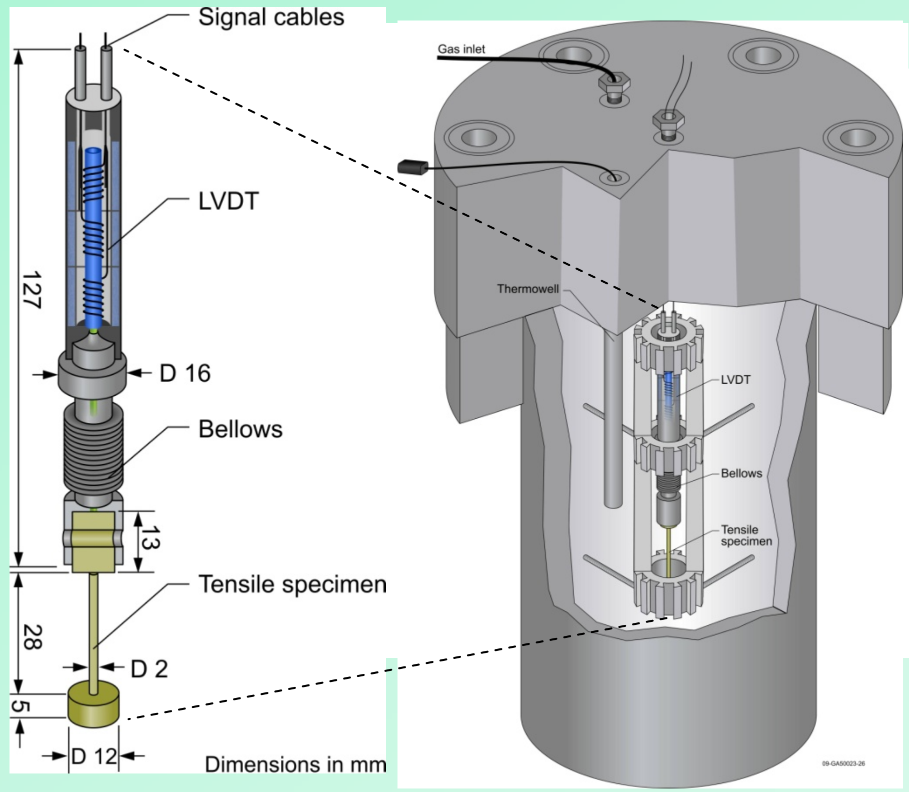
- *Vendor A LVDTs have smaller diameter and exhibit superior long duration high temperature response*
- *Efforts underway to assess Vendor A LVDT Curie temperature behavior and to explore alternate coil materials with superior high temperature performance*
- *Joint IFE-HRP/INL effort underway to evaluate optimized LVDT design.*

LVDT Applications:
Crud deposition monitor, creep testing rig





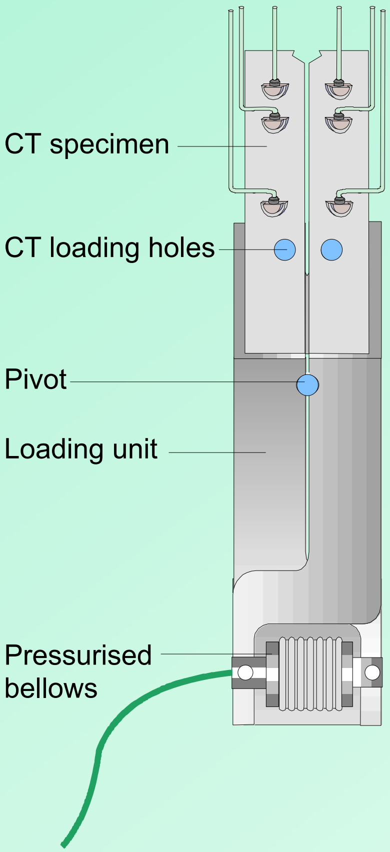
HRP-developed diameter gauge detects crud deposition



Autoclave evaluations of INL proposed test rig for creep testing in PWR loops

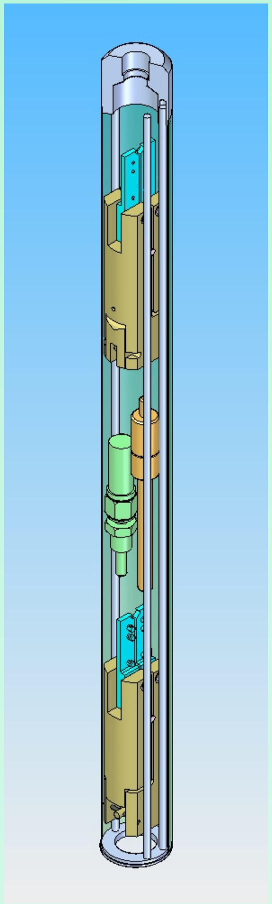
In-core Crack Growth Measurement

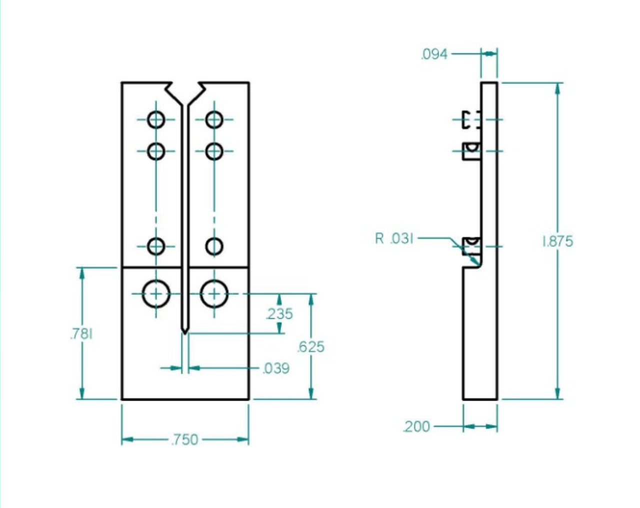
- **Shown is a Halden Reactor Project compact tension specimen with a pivoting bellows load system**
- **Crack growth is measured by passing a current through the sample using the upper pair of contacts and measuring the potential across the lower two pairs**
- **A similar system with passively loaded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



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**





INL/CEA/ISU efforts initiated to explore various flux detection options for NSUF

- **INL/ISU evaluations to consider several options**
  - **flux wires**
  - **SPNDs**
  - **CEA-developed fission chambers**
- **Initial efforts to focus on ATR-C testing**
- **Subsequent efforts to focus on ATR**

Summary

- **Additional instrumentation needed to support existing and new ATR NSUF missions.**
- **In-pile instrumentation enhancement wise investment.**
- **Preliminary instrumentation enhancement plan developed with initial efforts focusing on higher priority tasks for near-term instrumentation adaptations.**
- **Collaborations encouraged!**