In-core Instrumentation: Motivation, Approaches, and Examples

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ATR NSUF User Week 2009

Experimenter Course, Thursday June 4, 2009

MIT Nuclear Reactor Laboratory

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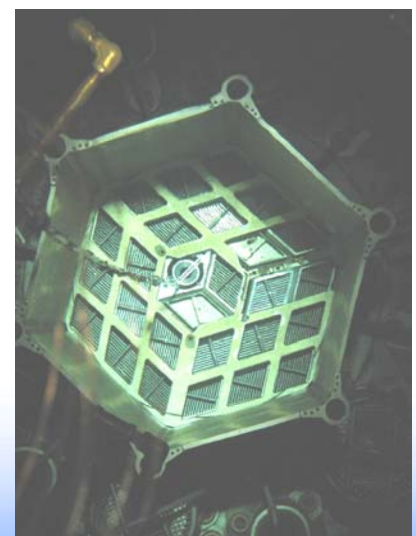


Objectives

- **Introduce general considerations about in-core measurements (what, why, how)**
- **Discuss challenges and generic approaches**
- **Highlight some examples of well-established, cutting edge and potential future in-core instrumentation**
- **Introduce NSUF in-core instrumentation capabilities**

What Constitutes "In-core Instrumentation"?
(for purposes of today's discussion)

- Any system to measure irradiation experiment parameters with instrumentation originating in-core or within the reactor vessel
- Emphasis will be on real-time measurements but some post-irradiation measurements will also be discussed
- Measurements may be made continuously or intermittently, at power or shut down
- In-core measurements can be used to determine irradiation conditions or sample response

Typical In-core Experimental Condition Measurements

- **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 Sample Measurements

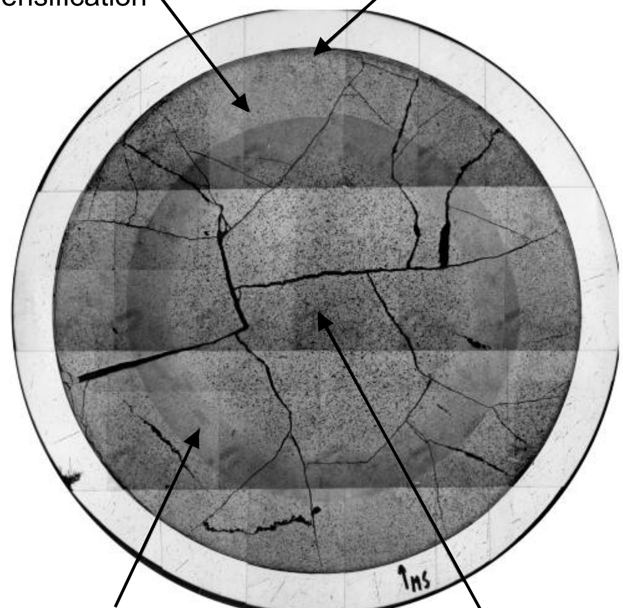
- **Materials testing: displacement (strain, crack growth, specimen failure), crack length, thermal conductivity, corrosion**
- **Fuel testing: temperature, pressure, fuel and clad dimensional changes, neutron flux and power, fission gas release, thermal conductivity**

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



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Why Not In-core Measurements?

- In-core measurements often reduce the number of samples that can be irradiated
- Instrumentation and leads can perturb in-core conditions
- If conditions are well-characterized there may be no need for the expense of in-core instrumentation

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

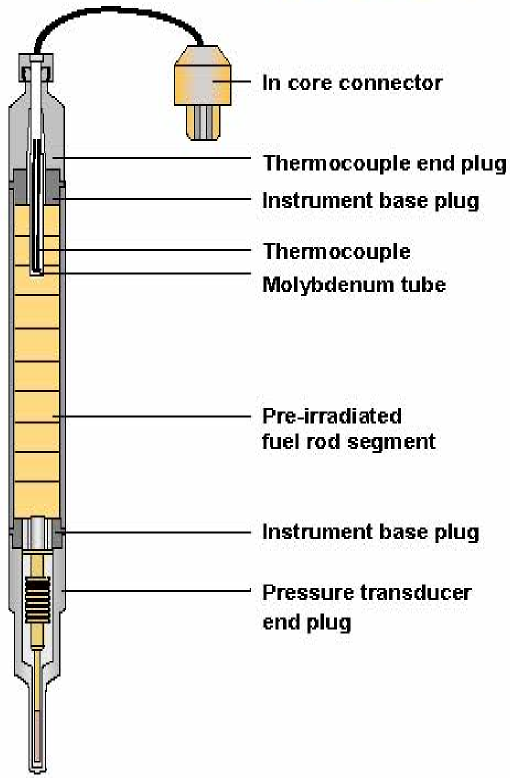
- Passive or active electrical signals – thermocouples, potential drop or eddy current measurements directly on samples, LVDTs
- Sampling for coolant/environment conditions
- Newer methodology being evaluated and developed includes: fiber optics, ultrasonic transducers, acoustic methods and wireless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

Overcoming the Difficulties: Connectors

In-core connectors



- Connection of MI cables for thermocouples and / or gas lines
- Mechanical sealing
- Operating conditions : 165 bar, 325°C
- Designed and fabricated by the HRP

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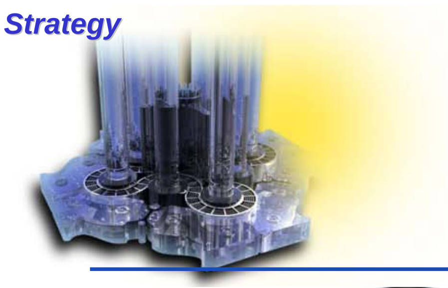
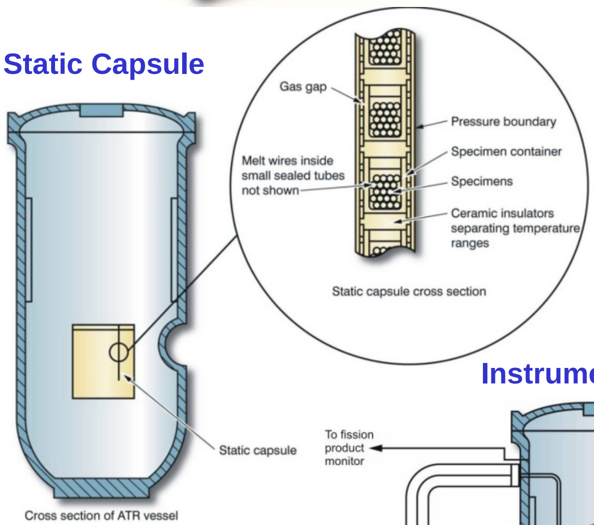
“Case Studies”: Examples of Development and Application of In-core Instrumentation

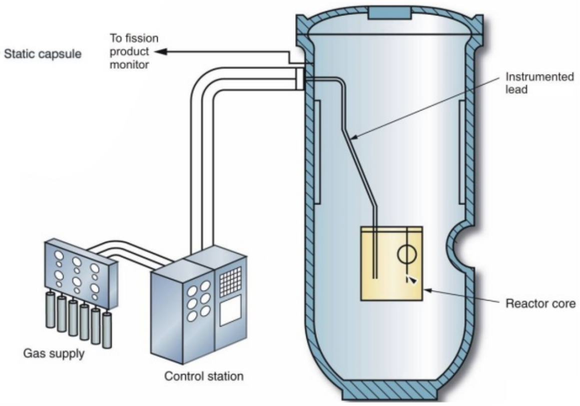


Several Instrumentation Enhancements Available for Various ATR Test Locations

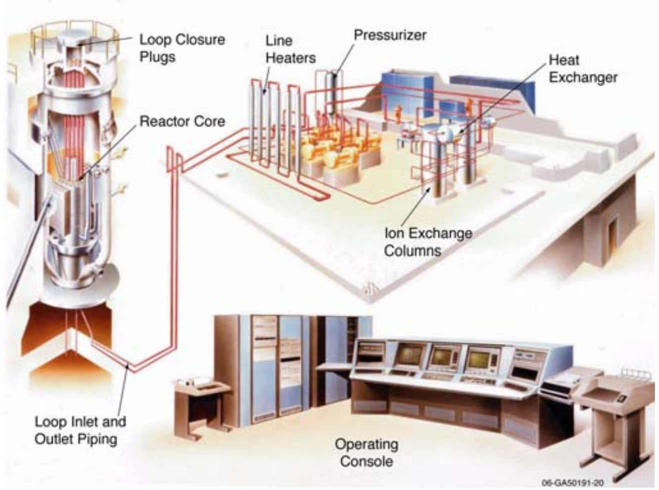
Static Capsule



Instrumented Lead



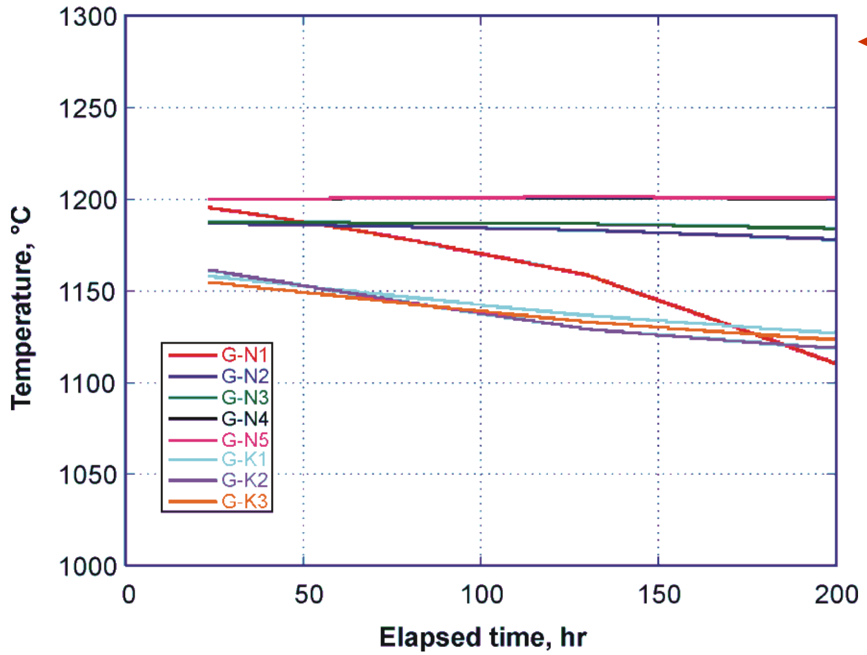
PWR Loop



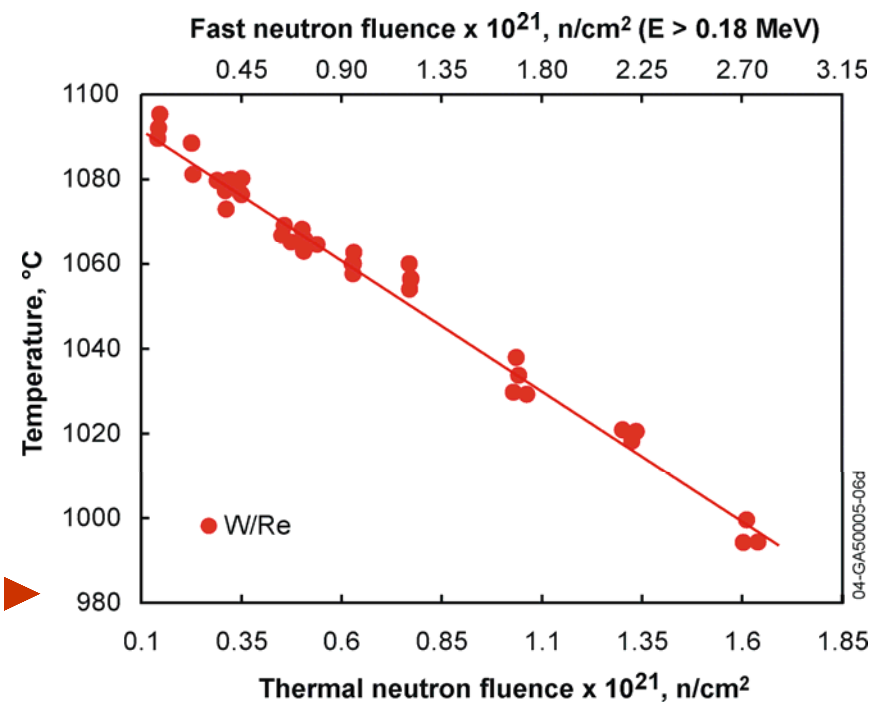
Parameter	Parameter			ATR Technology	Proposed Advanced Technology	
	Static Capsule	Instr. Lead	PWR Loop		Available at Other Reactors	Developmental
Temperature	√	√	√	• Melt wires (peak) • Paint spots (peak)	• SiC Temperature Monitors (range)	• Wireless (range)
		√	√	• Thermocouples (Type N, K, C, and 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.

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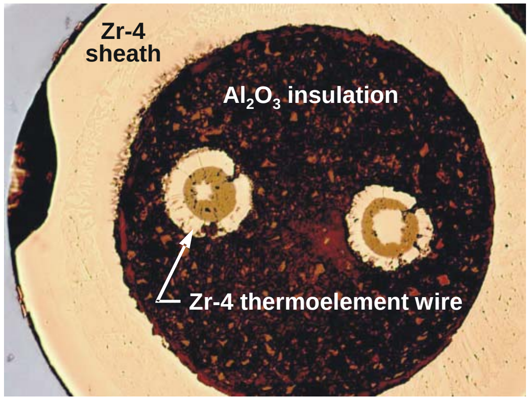
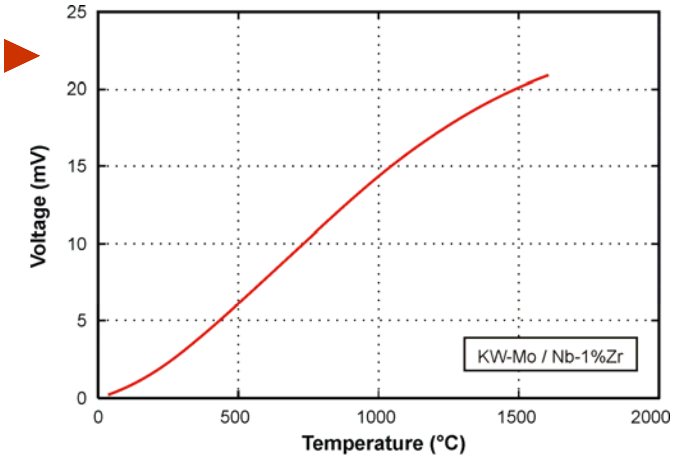
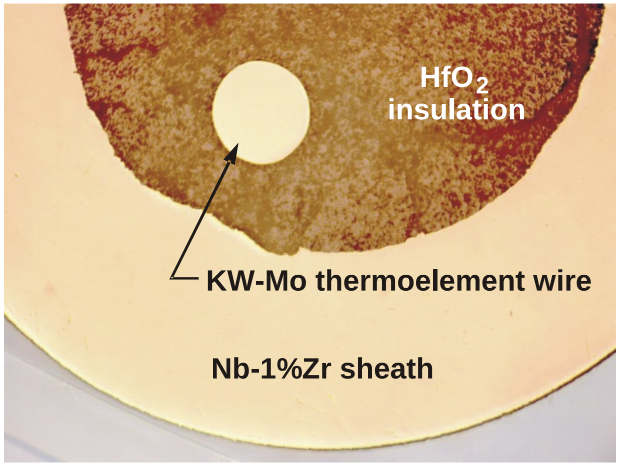
Initial HTIR-TC Development Considered Radiation and High Temperature Performance



Al_2O_3 attacks wire and sheath after heating at 1300°C

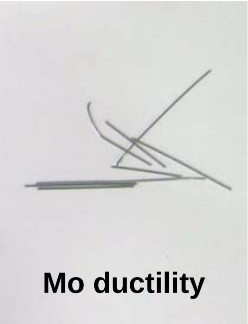
Selected KW-Mo and Nb-1%Zr combination has suitable resolution up to 1700 °C





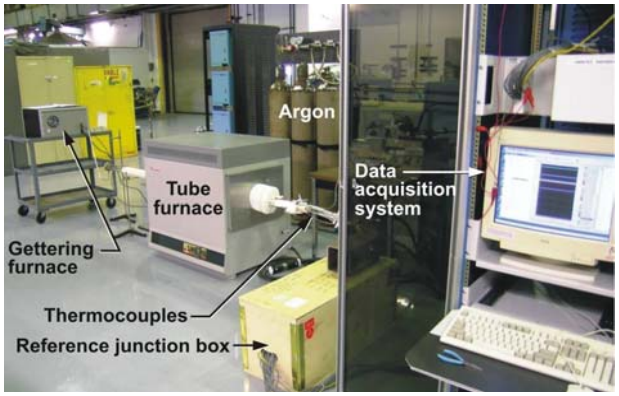
Selected materials resist interactions after heating at 1600 °C

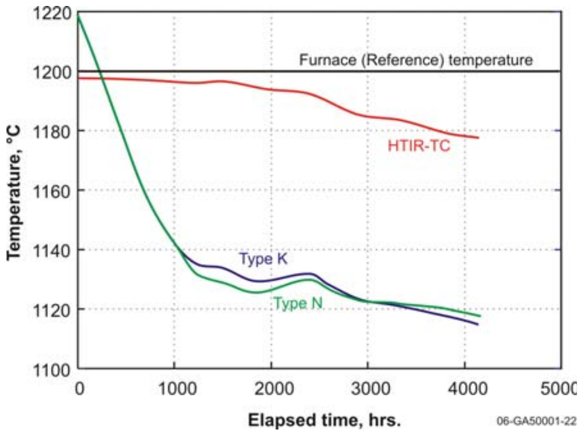
Selected KW-Mo ductile after heating at 1600 °C



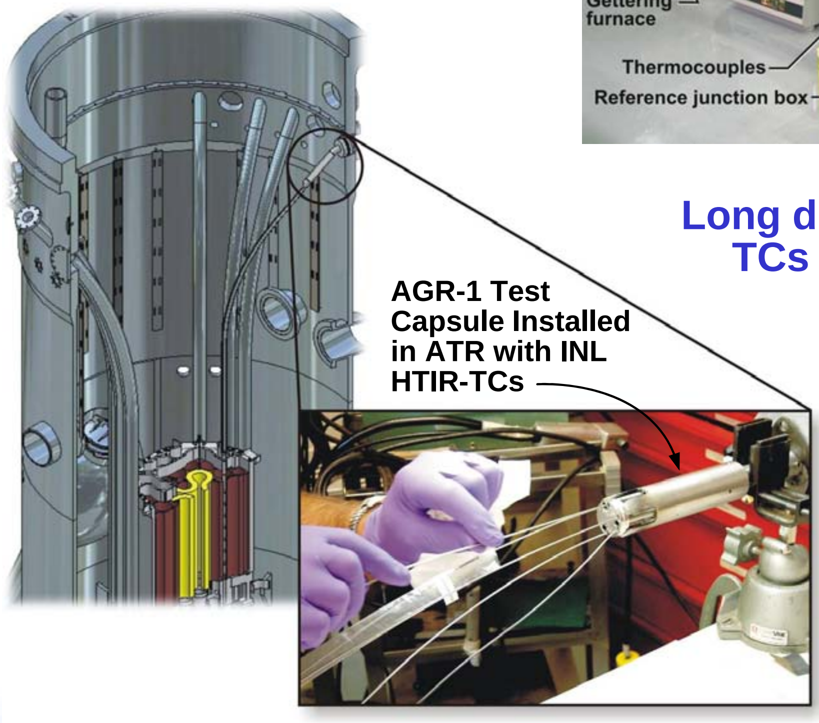
Evaluations suggest doped Mo/Nb-1%Zr thermoelements with HfO_2 insulation and Nb1%Zr sheaths most suitable combination for HTIR-TCs.

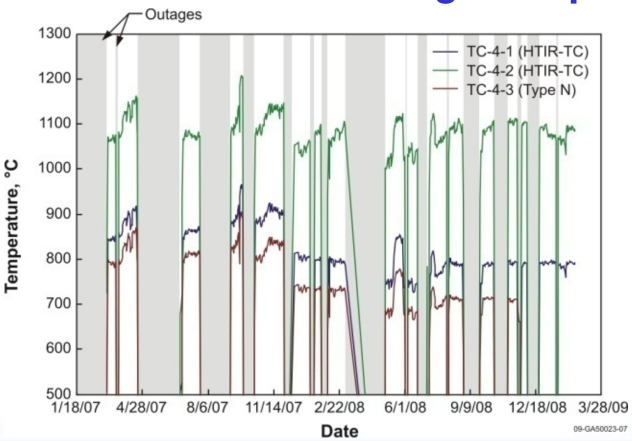
Final HTIR-TC Development Included Long Duration Testing and Radiation Testing





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.

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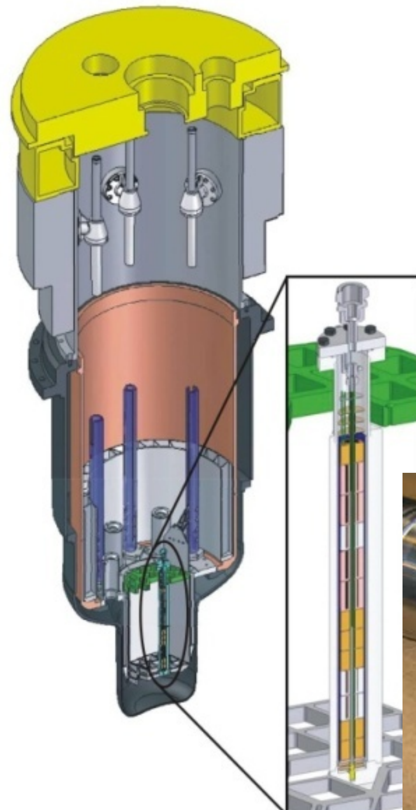
Optimized HTIR-TCs Fabricated for MITR Irradiations

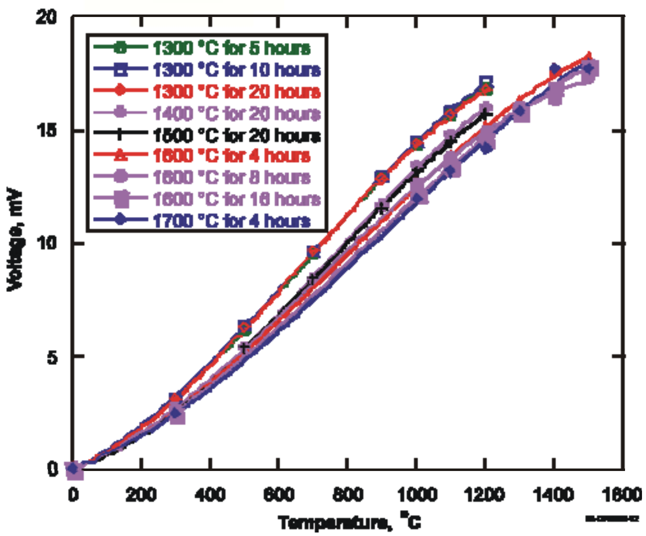
MITR High Temperature Irradiation Facility for 1400 °C irradiations



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

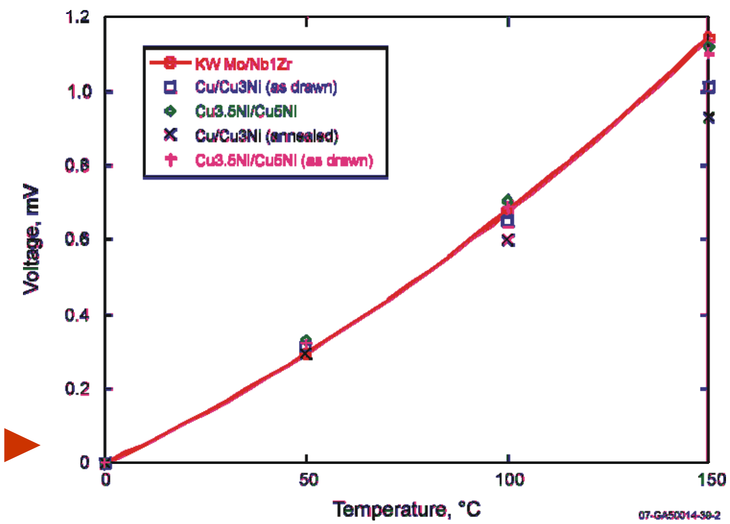
MITR HTIF facilitates high temperature HTIR-TC irradiations and post test examinations

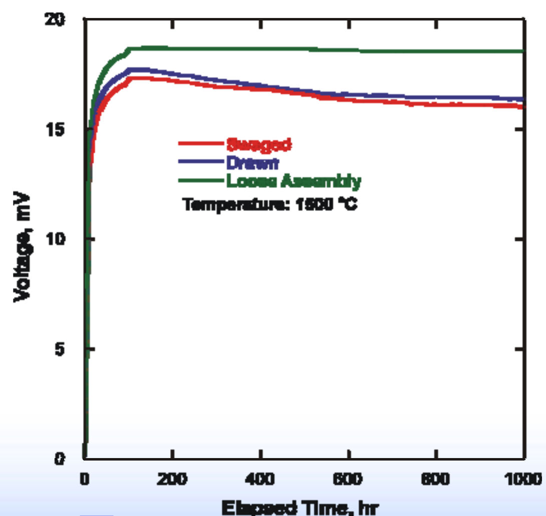
INL Continuing to Look for Ways to Optimize HTIR-TC Performance and Fabrication



◀ *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

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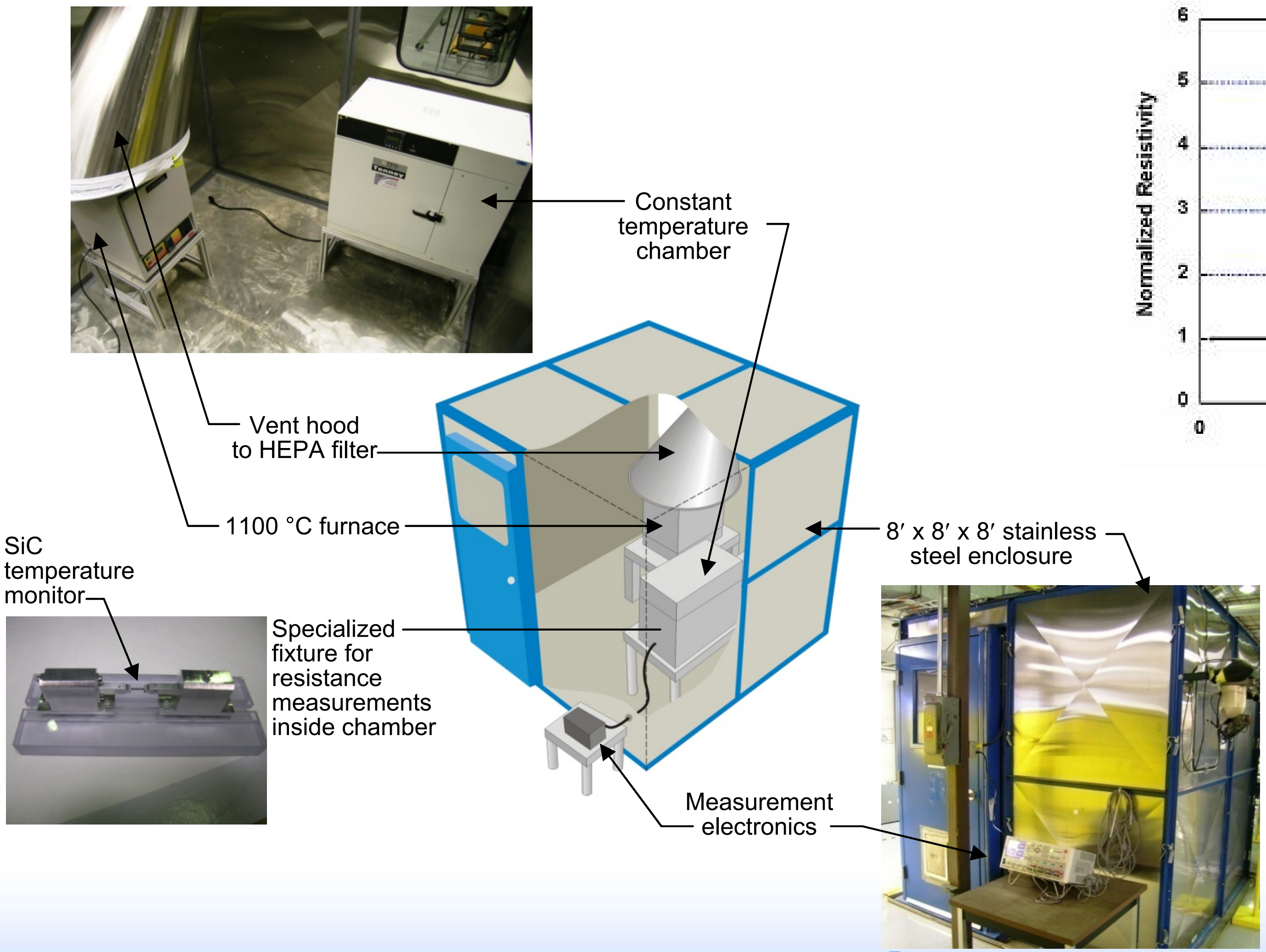
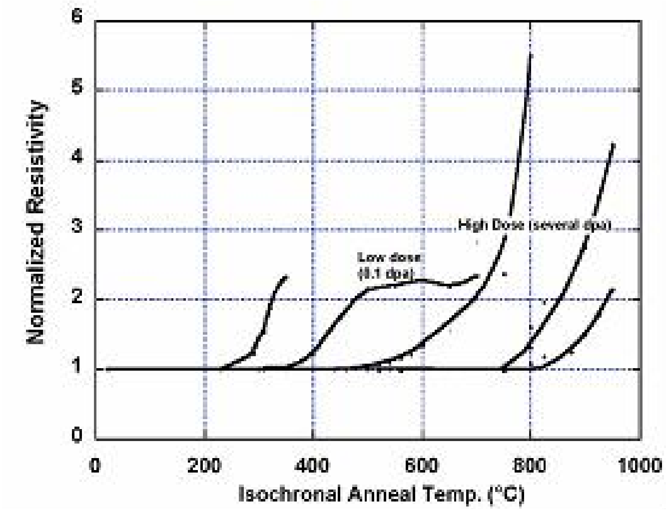
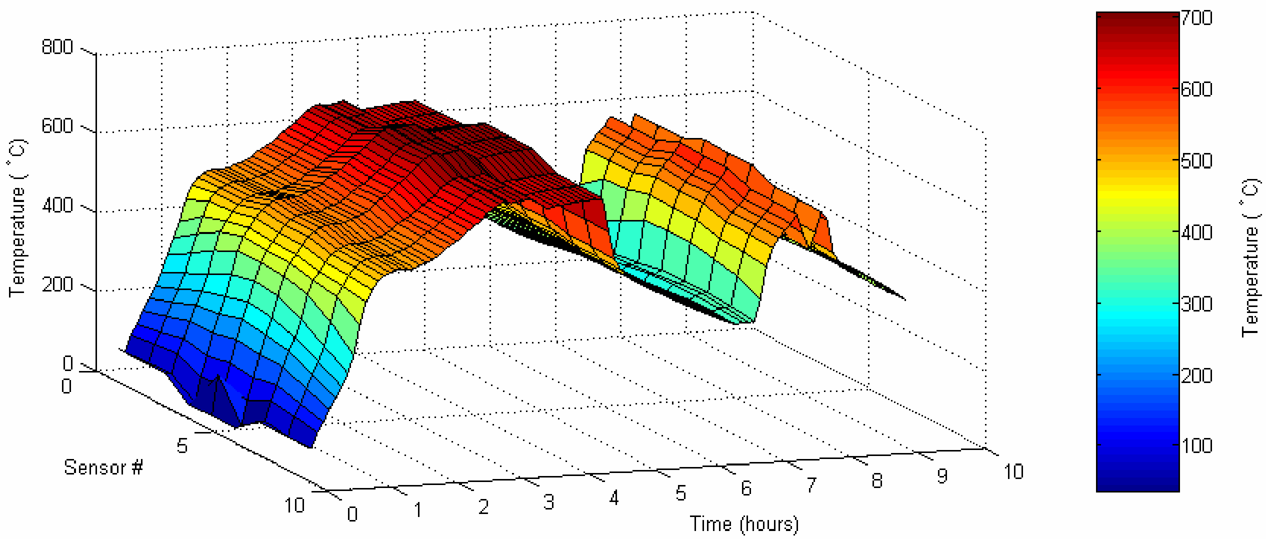
HTTL Prepared for Measuring Resistivity of SiC Monitors Irradiated in ATR Static Capsules

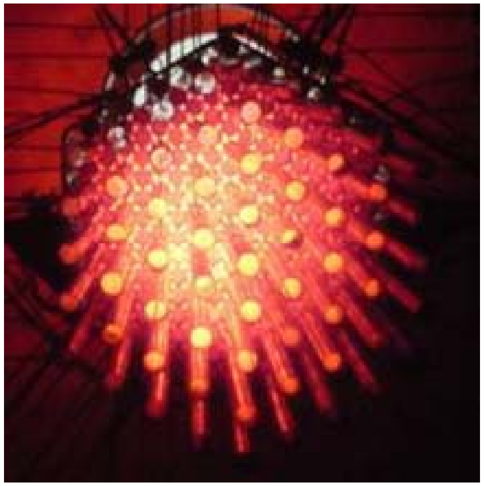




INL to apply ORNL-developed resistance measurement method to SiC monitors irradiated in ATR

STTR Phase I funding INL and Luna Innovations for Fiber Optic Sensor Feasibility Studies





Luna developed FBG-based fiber optic probes proven for spatially dense NASA space-based nuclear reactor temperature measurements

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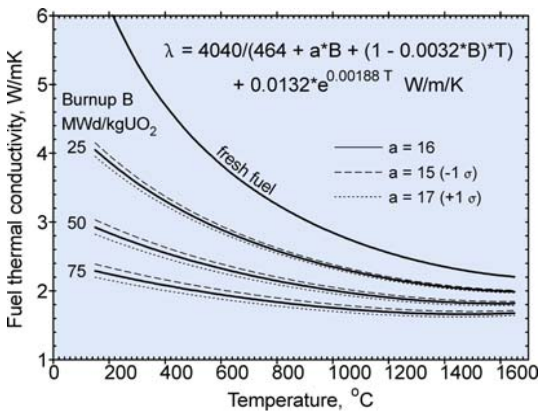
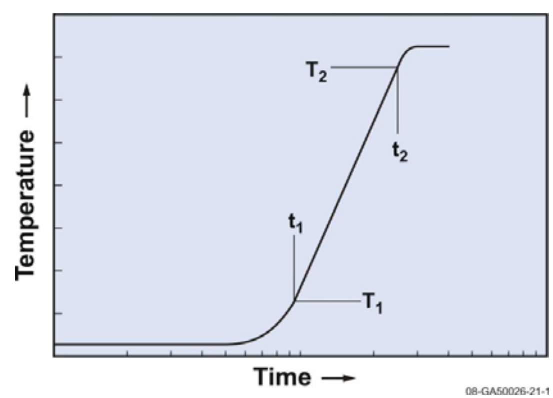
Two Approaches Investigated for In-pile Detection of Thermal Conductivity



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



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

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.)

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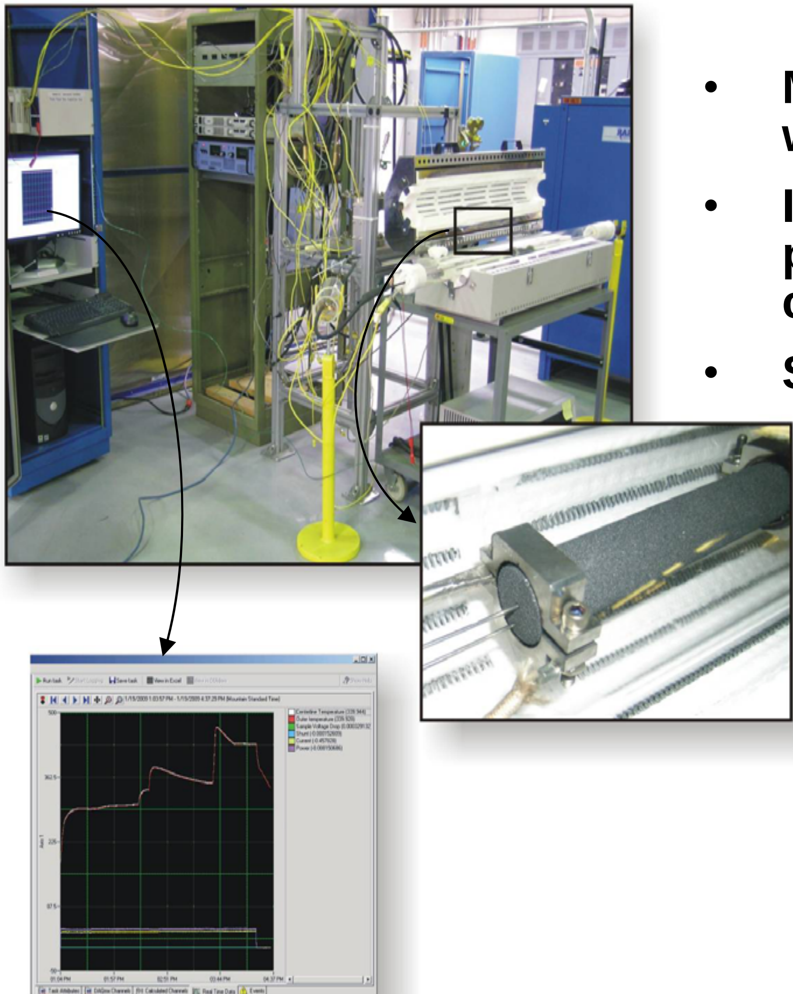
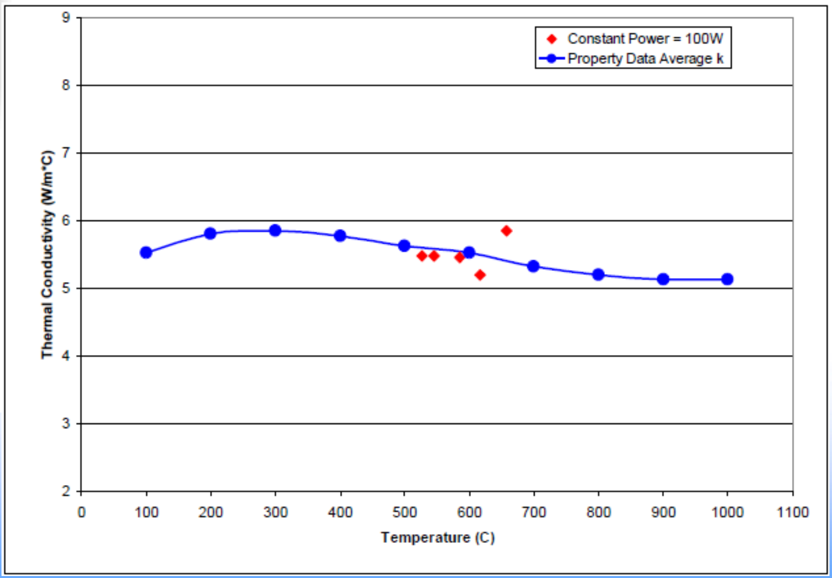
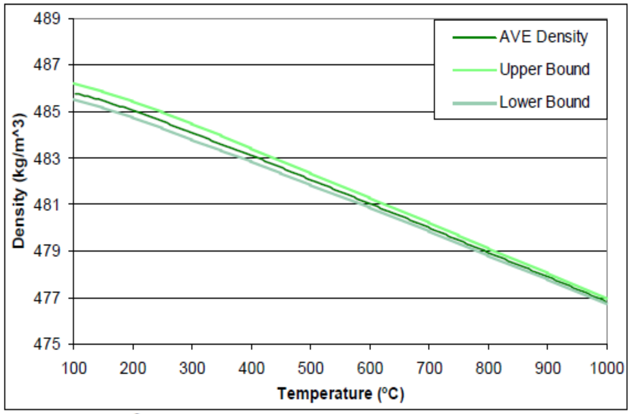
Efforts Underway to Quantify Operational Limits for Two-Thermocouple Techniques

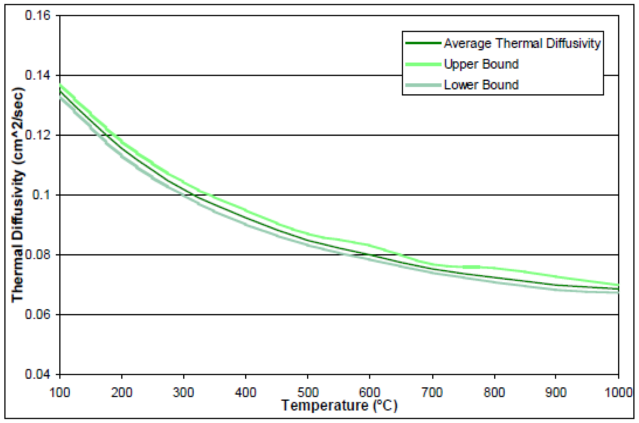


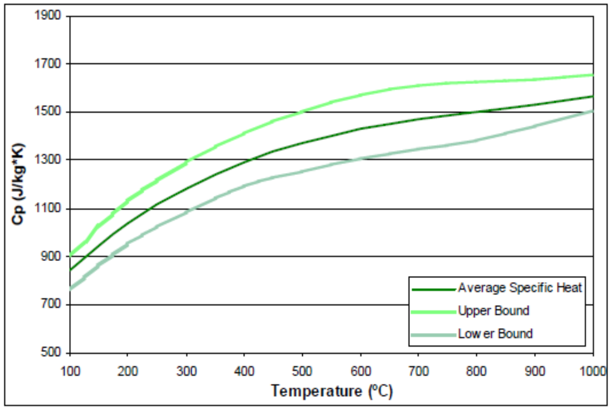
- Methods evaluated using surrogate fuel materials with resistance heating in tube furnace
- Initiated first surrogate rod (CFOAM) material property and two thermocouple thermal conductivity testing
- Sensitivities underway to optimize results
  - Power
  - TC orientation
  - Outer heat transfer
  -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

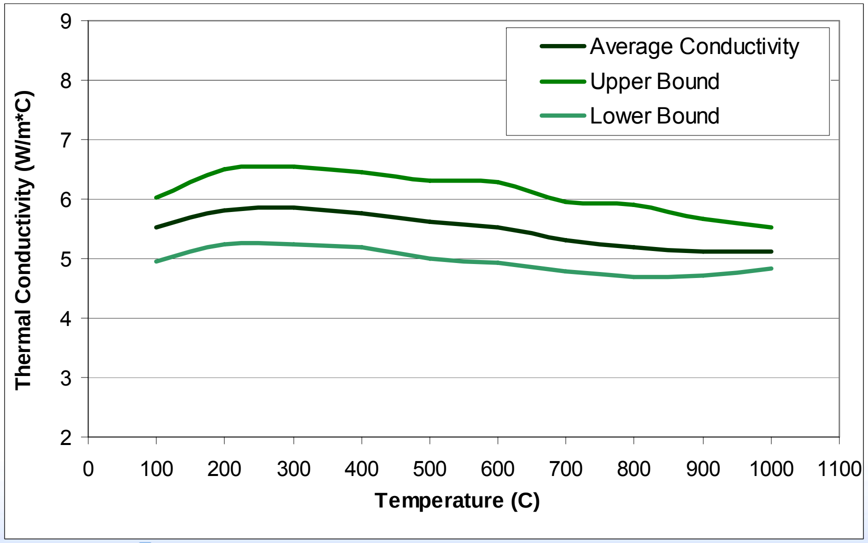


HTTL Material Property Measurement Systems used to Obtain Thermal Conductivity Data









CFOAM vendor material property data limited

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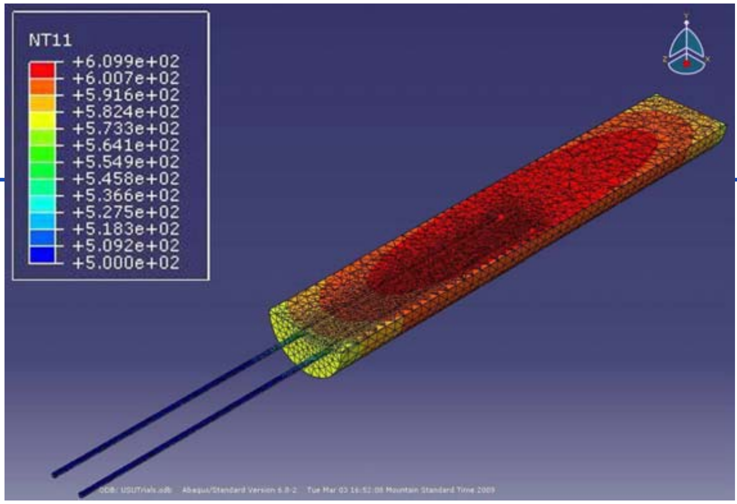
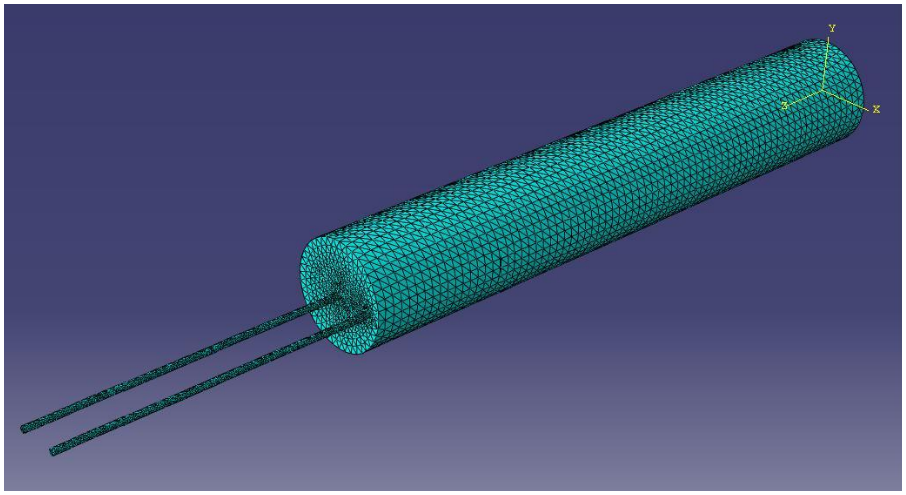
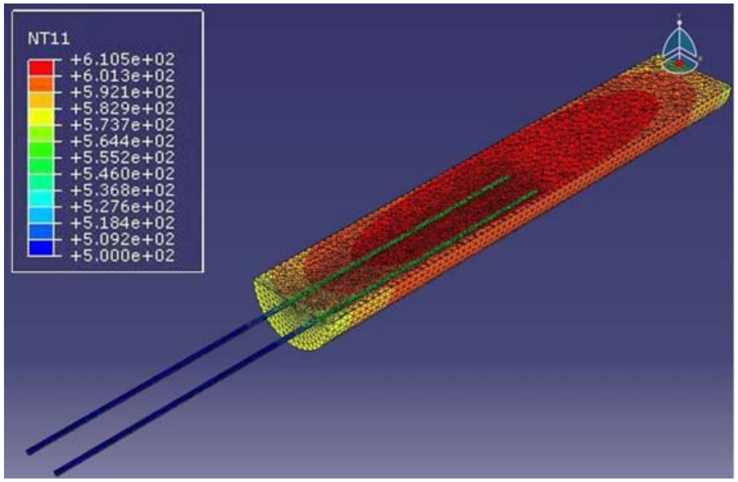
ABAQUS Comparisons Provide Key Insights



9376 W/m^2-°C effective gap heat transfer coefficient



ABAQUS Mesh



308 W/m^2-°C effective gap heat transfer coefficient

Impact of assumed thermocouple-to-fuel gap effective heat transfer coefficient

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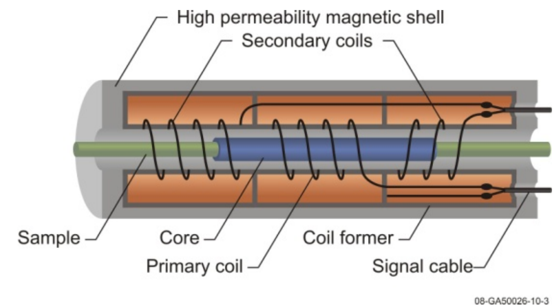
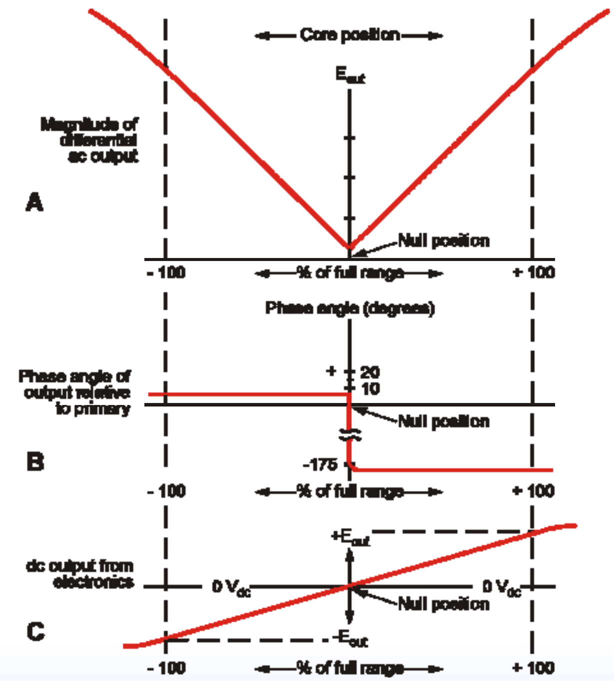
Irradiation Hardened LVDTs

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

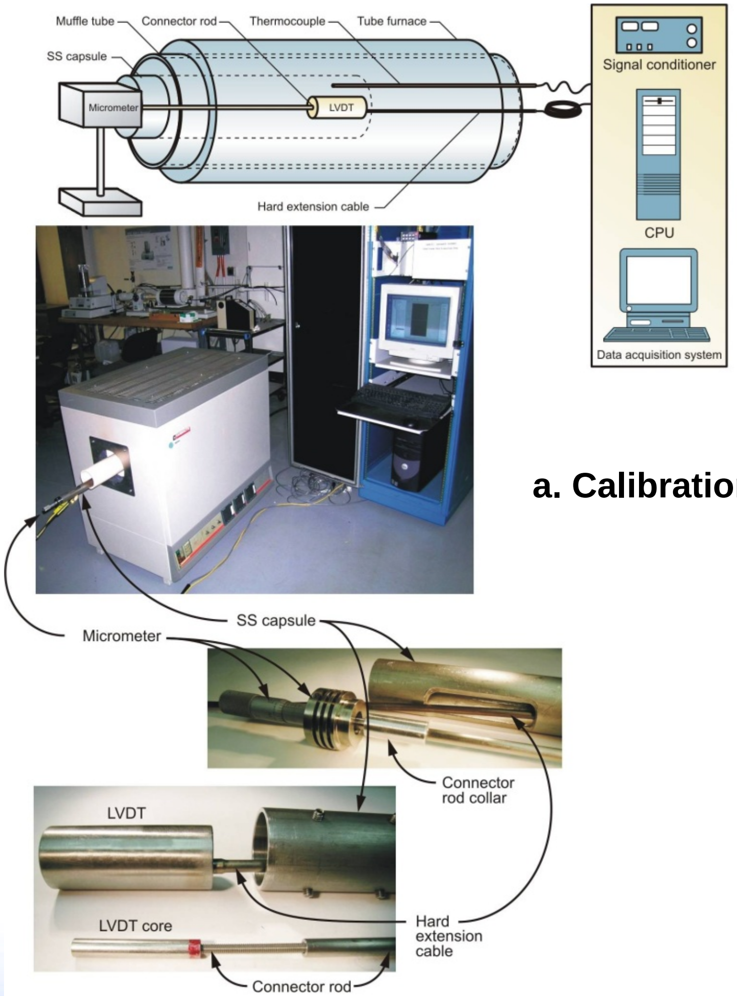




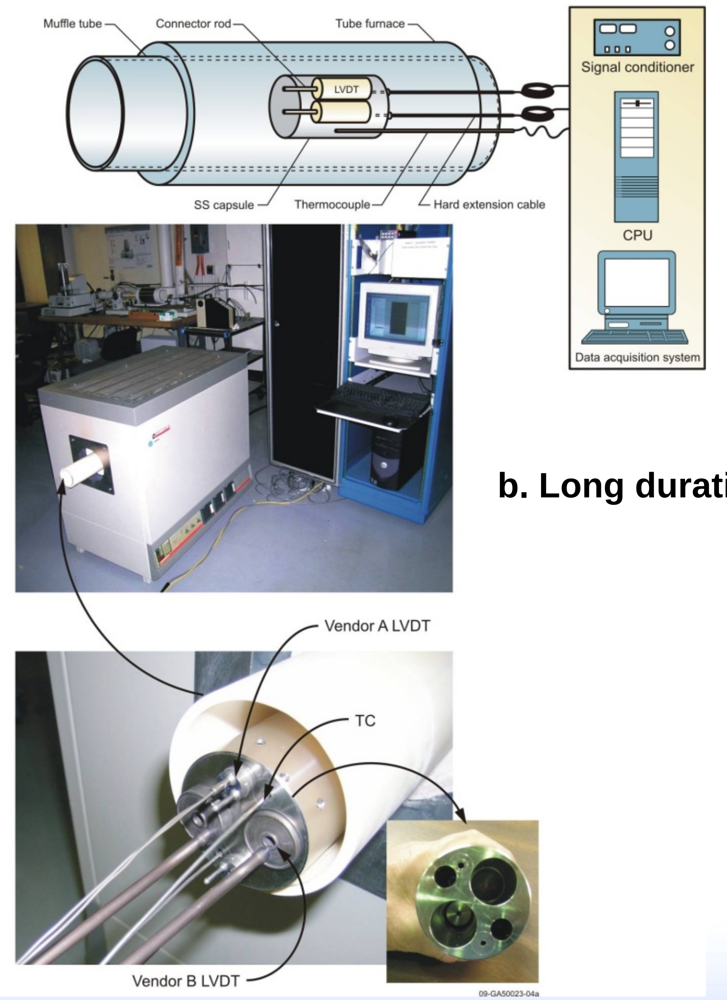
LVDTs Initially Investigated for Real-time In-pile Detection of Dimensional Changes

Parameter	Vendor A	Vendor B	Desired ATR
LVDT Length, mm	66	63.8	63.8
LVDT Outer Diameter, mm	12	25.4	$\leq$ 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 Underway to Obtain Real-time Geometry Sensors for ATR Conditions

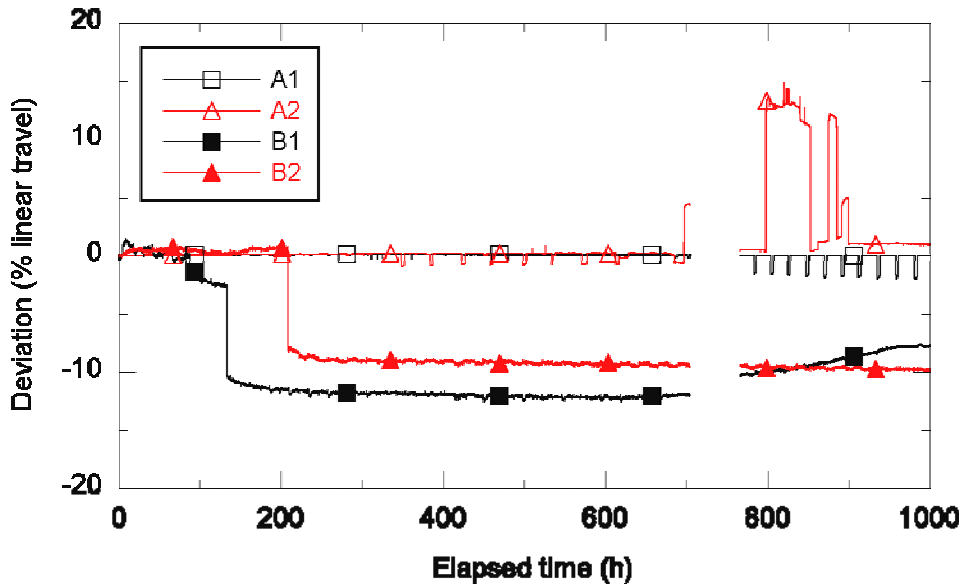


a. Calibration



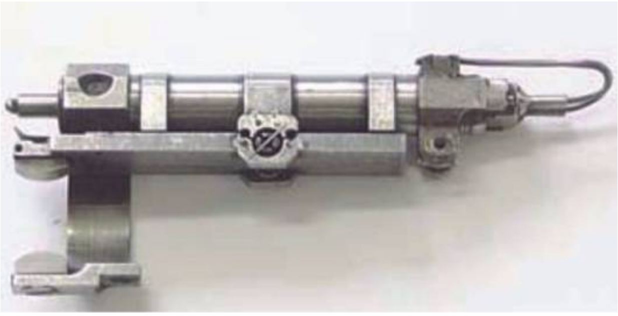
b. Long duration

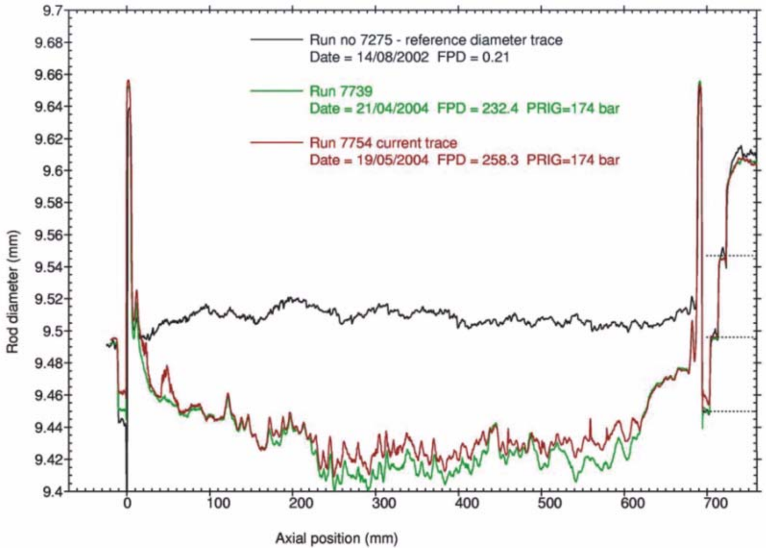
High Temperature Long Duration Tests show Vendor A (Halden) LVDTs Superior



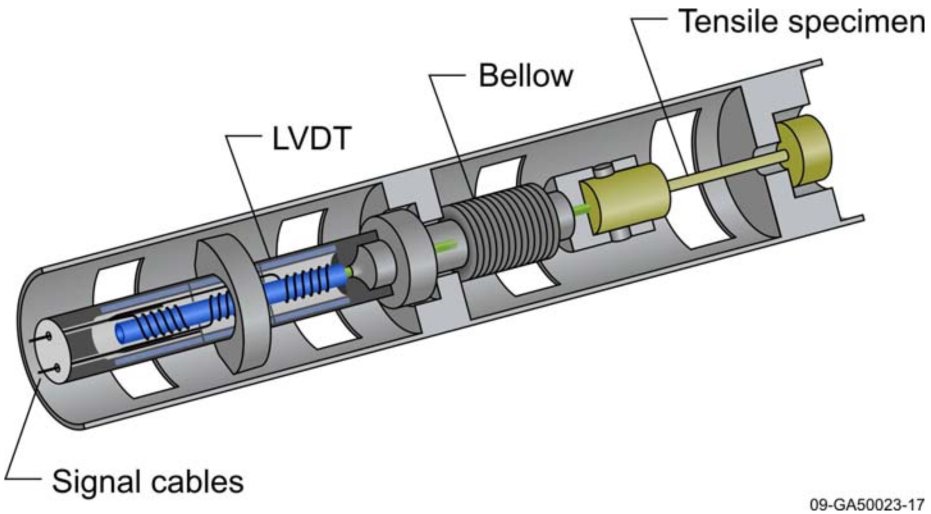
- *Vendor A LVDTs have smaller diameter and exhibit superior long duration high temperature response*
- *Efforts underway to assess Vendor A LVDT Curie temperature behavior and to explore alternate coil materials with superior high temperature performance*
- *Optimized LVDT to be evaluated at HTTL*

LVDT Applications: Crud deposition monitor, creep testing rig





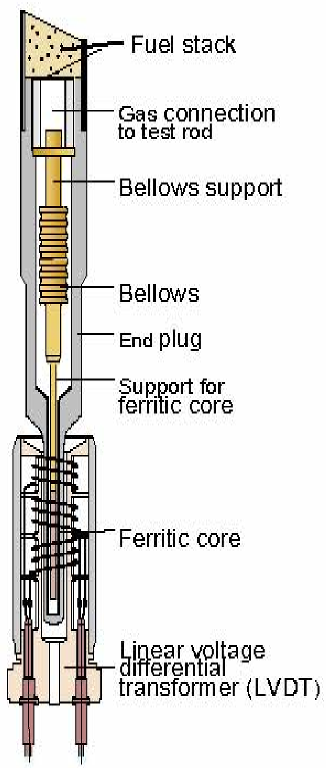
HRP-developed diameter gauge detects crud deposition



INL proposed test rig for creep testing in PWR loops

LVDT applications: In-situ pressure measurement

Pressure Gauge



- Provides data on fission gas release by means of measurements of the fuel rod inner pressure.
- Miniaturised bellows with access to the fuel rod plenum mechanically fixed in the fuel rod end plug.
- Magnetic core fixed to the free moving end of the bellows. Core movement sensed by LVDT.
- Pre-conditioned and pre-pressurised bellows in order to reduce creep due to high temperatures and radiation.
- Bellows types: Range 15, 30 or 70 bar DP.
- Often used in conjunction with fuel temperature measurements (TF).

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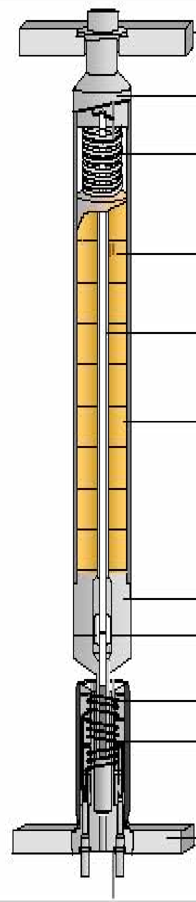
LVDT applications: Temperature measurement

Expansion Thermometer

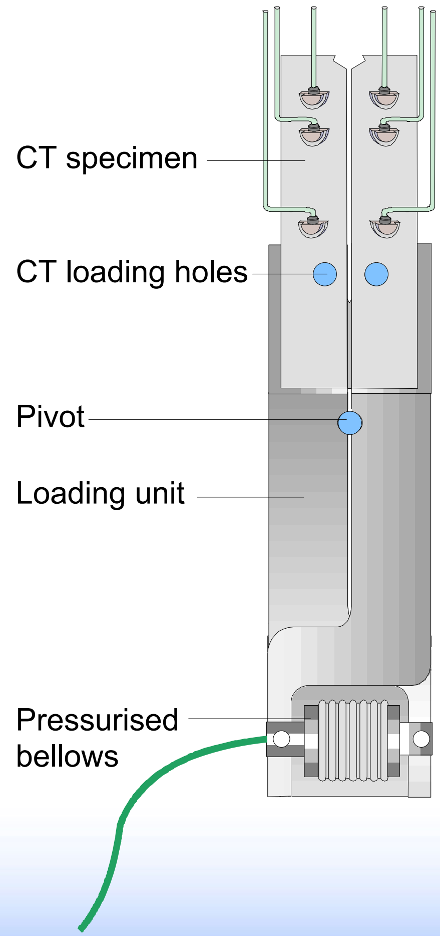
- Alternative to Fuel Thermocouple.
- Provides data on fuel rod average centre-line temperature.
- Magnetic core fixed to a tiny refractory metal rod penetrating the centre-line of the whole fuel stack. Core movement is sensed by the LVDT.
- Recommended for high-temperature measurements.
- No decalibration with time.



11/14/2007

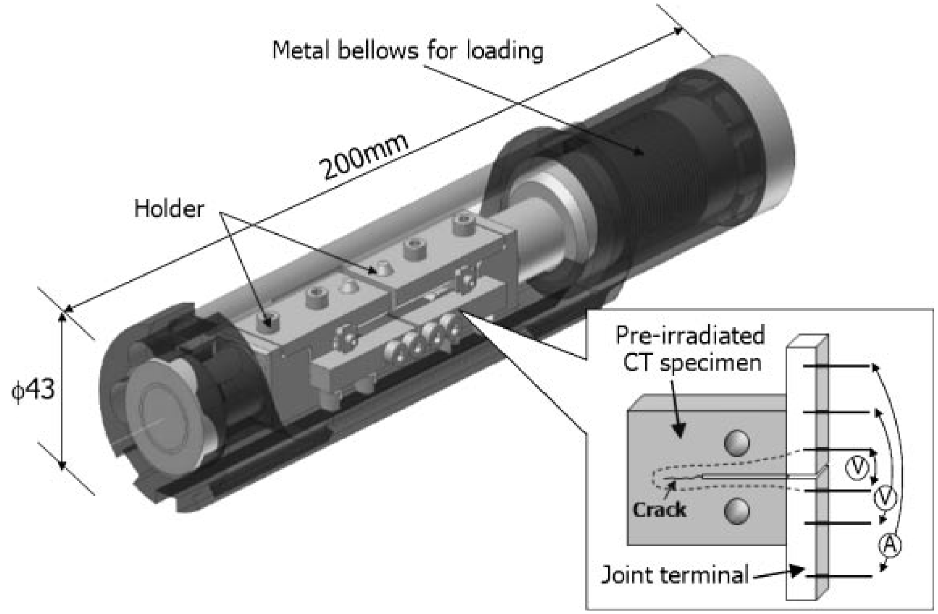
In-core Crack Growth Measurement

- 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



In-core Crack Growth Measurement

- Alternative CT testing design used at JMTR
- DCPD is again used to measure crack growth
- Specimen is loaded by collapse of the bellows when external pressure exceeds controlled inner pressure



Some Possible Future Directions

- Fiber optics for temperature sensing
- Hot wire thermal conductivity measurement
- Acoustic measurements for fission gas release
- In-core application of electrochemical impedance spectroscopy and electrochemical noise monitoring for corrosion measurement
- In-core eddy current measurements for crack detection
- Extension of current techniques to new environments (liquid metals, supercritical water, molten salt)