Current Techniques for Length Detection - Linear Variable Differential Transformers and Applications for In-Pile Testing

Darrell Knudson
Idaho National Laboratory

Bong Goo Kim
Korea Atomic Energy Research Institute

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HANARO
High-flux Advanced Neutron Application Reactor

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- Introduction
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- INL LVDT evaluations
- Hands-on demonstration/instruction

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Introduction

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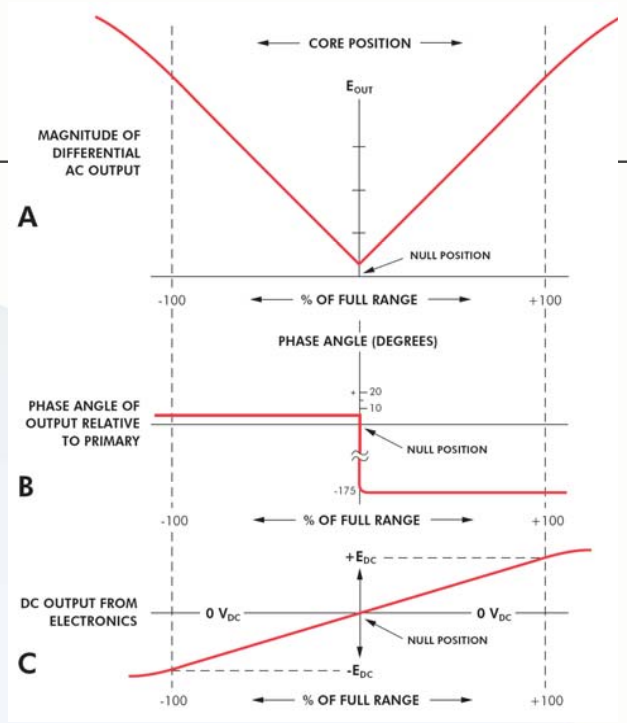
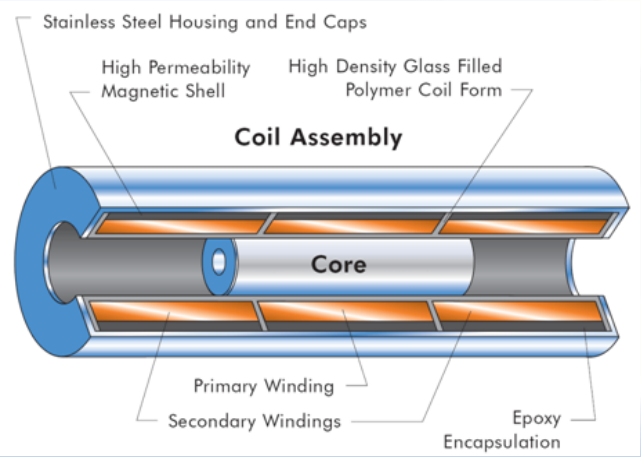
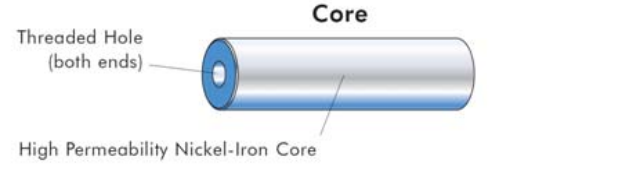
What is an LVDT?

- LVDT : Linear Variable Differential Transformer
- Electromechanical transducer that converts rectilinear motion of object to which it is coupled mechanically into corresponding electrical signal
- Robust method for measuring wide range of phenomena
- Many phenomena produce, or can be used to produce, length changes which in turn can be measured and converted into a measure of the phenomenon
- The LVDT device has proved to be robust and versatile







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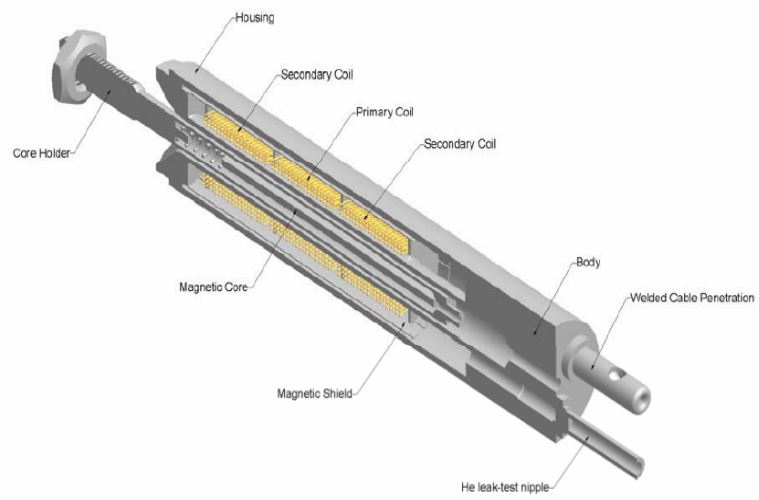
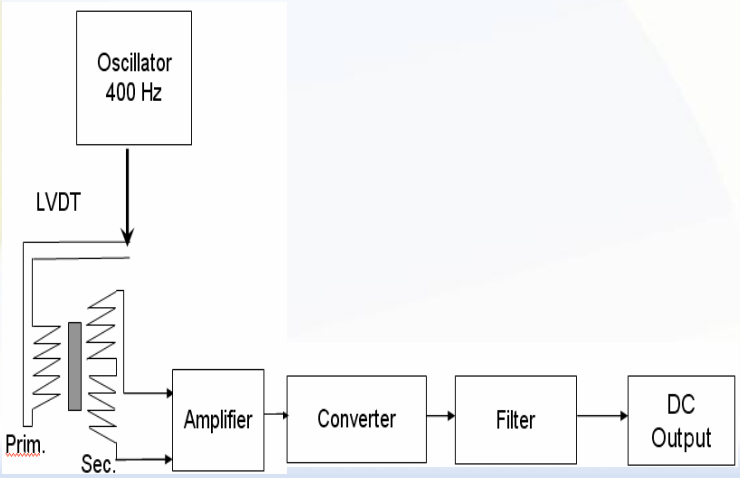
INL and KAERI Investigations Indicate IFE/HRP (Halden) LVDTs Superior for In-Pile Testing

- Developed for measuring fuel rod pressure, temperature, fuel stack and cladding elongation
- Primary coil with two secondary coils
- Movable magnetically-permeable core concentrically located inside coil system
- Core movement affects balance of the secondary coils and generates signal output



Part	Materials
Core	Iron
Housing	Inconel 600
Coil form	Inconel 600, plasma sprayed with Al_2O_3
End caps	Inconel 600
Magnetic shield / bore liner	Fe-Si foil
Coil wire	Nickel clad Copper with vitreous enamel film
Primary / secondary signal cable (outer diameter)	Inconel 600sheath with Al_2O_3 insulation and nickel wires (1.0 mm)
Cement (for coil, after forming)	None required



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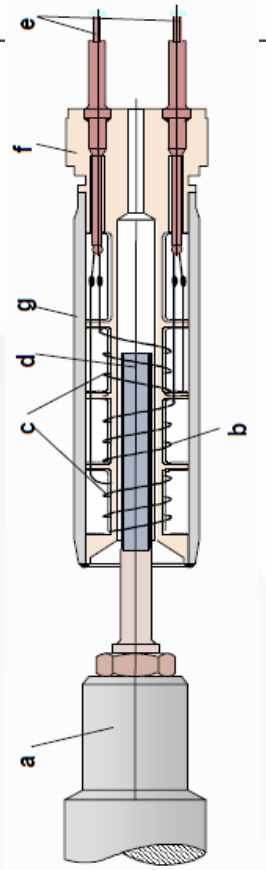
IFE-HRP (Halden) offers wide range of specialized LVDTs

- Primary coil activated by 400 Hz constant-current generator
- Mechanical movement changes position of core and corresponding signal can be measured
- LVDTs designed for PWR conditions (350°C, 150 bar) but can be operated for shorter periods up to 500°C
- LVDTs made in many different sizes at customers request; most common size designated "type 5" LVDT
  - linear range: ± 2.5 mm
  - diameter: 11.5 mm
  - length: 55 mm
  - 2 signal cables; mineral insulated (Al_2O_3) with Inconel 600 sheath; diameter: 1.0 mm
- LVDTs for higher temperature operation (up to 600°C) developed using alternate coil wire



a: Test rod end plug assembly
b: Primary coil
c: Secondly coil
d: Ferritic core
e: Twin-led signal cables
f: Body
g: Housing

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In-Pile Applications

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IFE/HRP has applied LVDTs in wide Range of Sensors

- Measurement applications include:
  - pressure transducer (fission gas release)
  - fuel temperature (expansion thermometer)
  - fuel stack length (densification, swelling)
  - cladding elongation (axial PCMI)
  - cladding diameter (radial PCMI)
  - crack growth (crack mouth opening displacement)
  - creep and stress relaxation

Advantage: no cable penetration into the fuel rod

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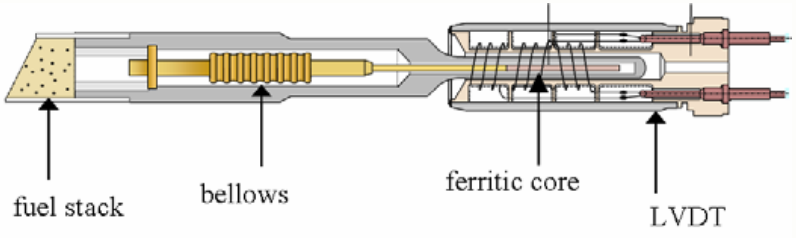
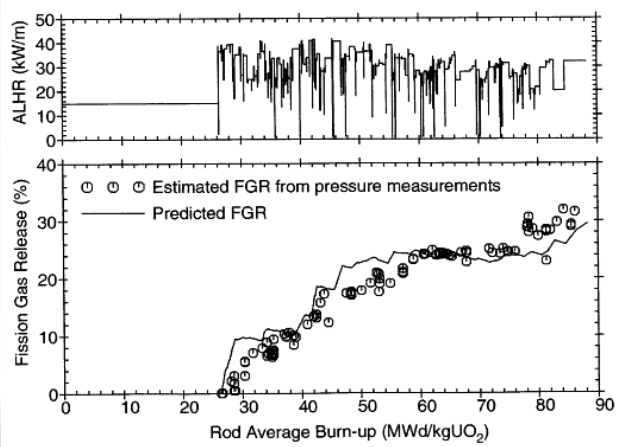
Pressure transducer

- Provides data on fission gas release by means of measurements of fuel rod inner pressure
- Miniaturized bellows with access to fuel rod plenum mechanically fixed in fuel rod end plug
- Core fixed to free moving end of bellows
- Core movement sensed by LVDT
- Pre-conditioned and pre-pressurized bellows in order to reduce creep due to high temperature and radiation
- Often used in conjunction with fuel temperature measurements (TF)





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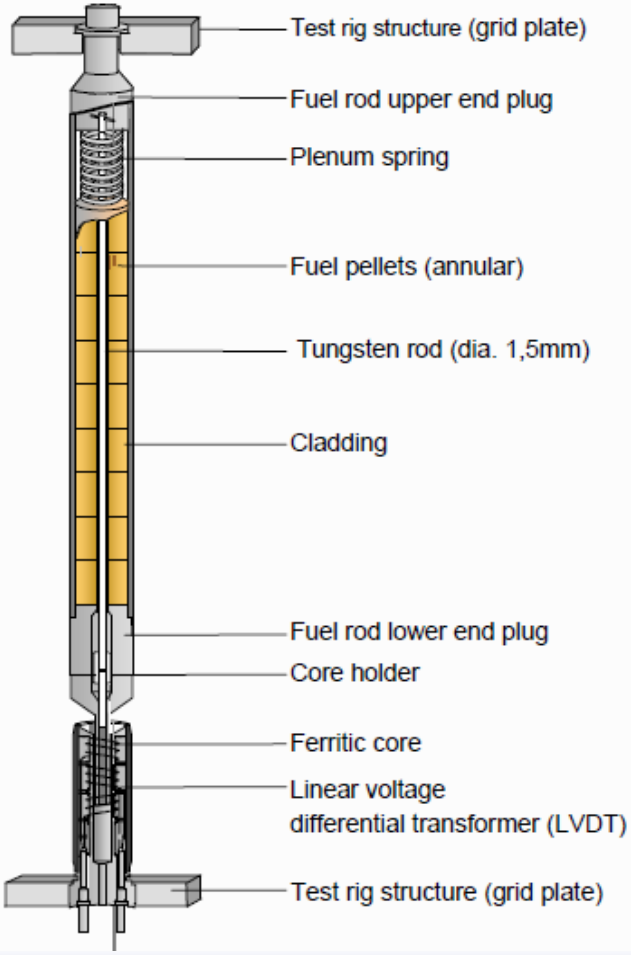
Expansion thermometer (1/2)

- Two types of fuel temperature measurements available:
  - fuel thermocouple (designated by "TF")
  - expansion thermometer (designated by "ET")
- IFE/HRP uses tungsten-rhenium fuel thermocouple that are susceptible to drift from neutron induced transmutation
- Expansion thermometer based on measuring thermal expansion of tungsten rod inserted through center hole drilled through entire fuel stack (avoids drift associated with tungsten-rhenium thermocouples)
- Tungsten rod thermal expansion measured with LVDT. ET often used for long duration tests and for very high temperature measurements



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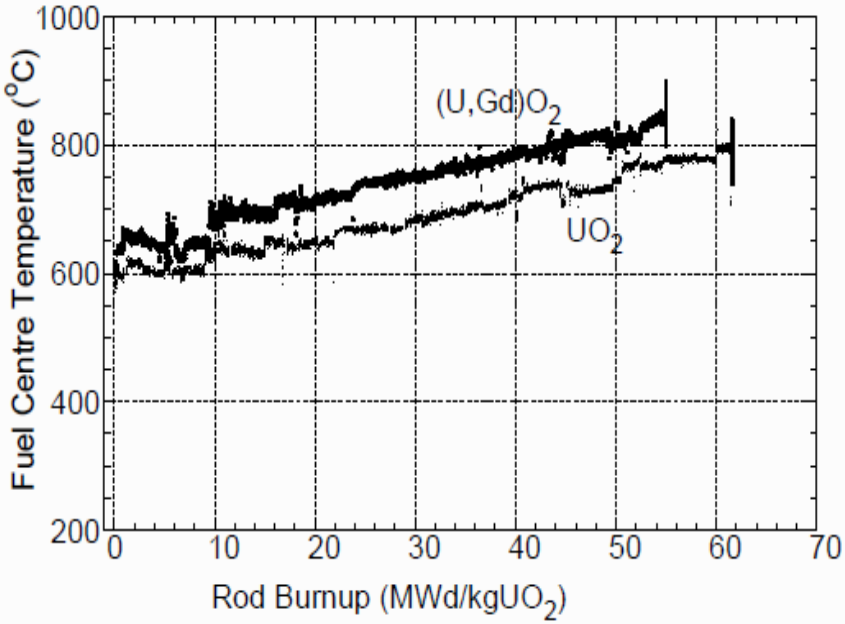
Expansion thermometer (2/2)

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



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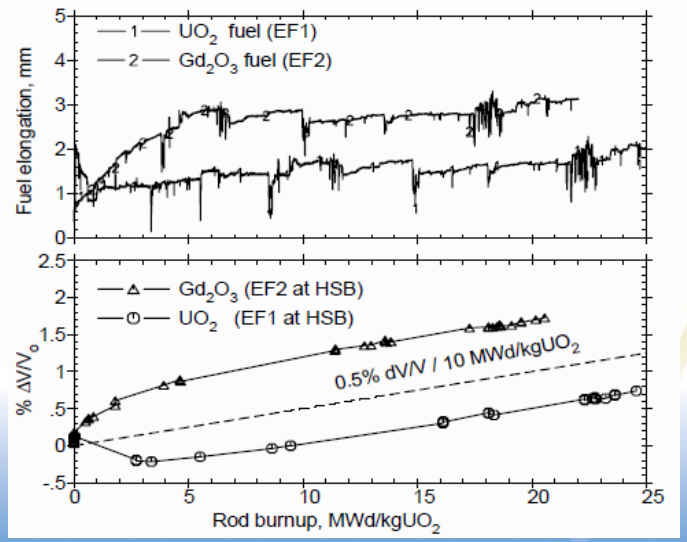
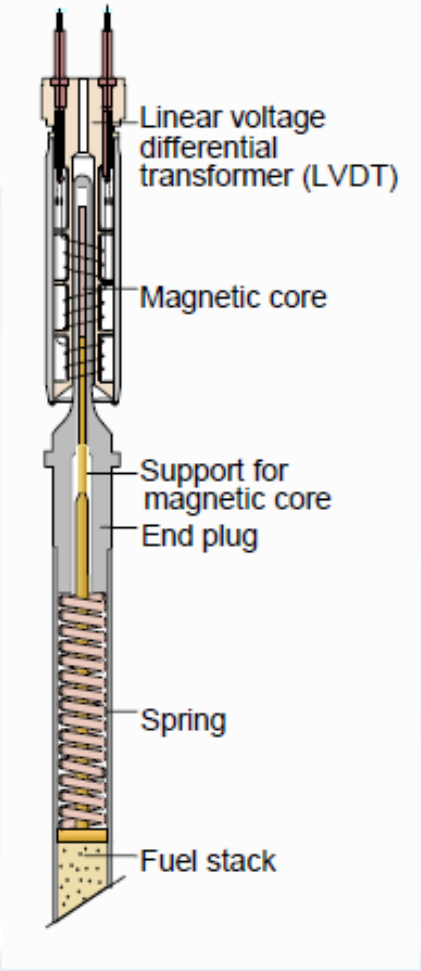
Fuel stack elongation

- Provides swelling data in terms of fuel stack axial expansion
- Magnetically-permeable core spring loaded against fuel column end pellet in rod plenum
- Core movement sensed by LVDT





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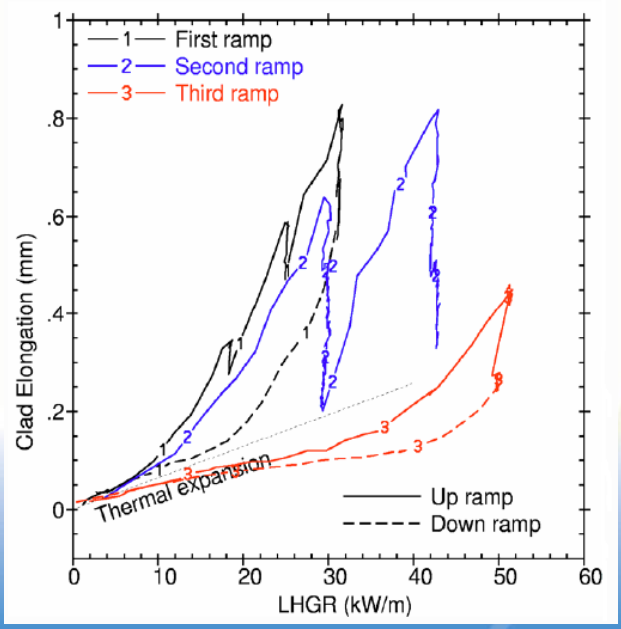
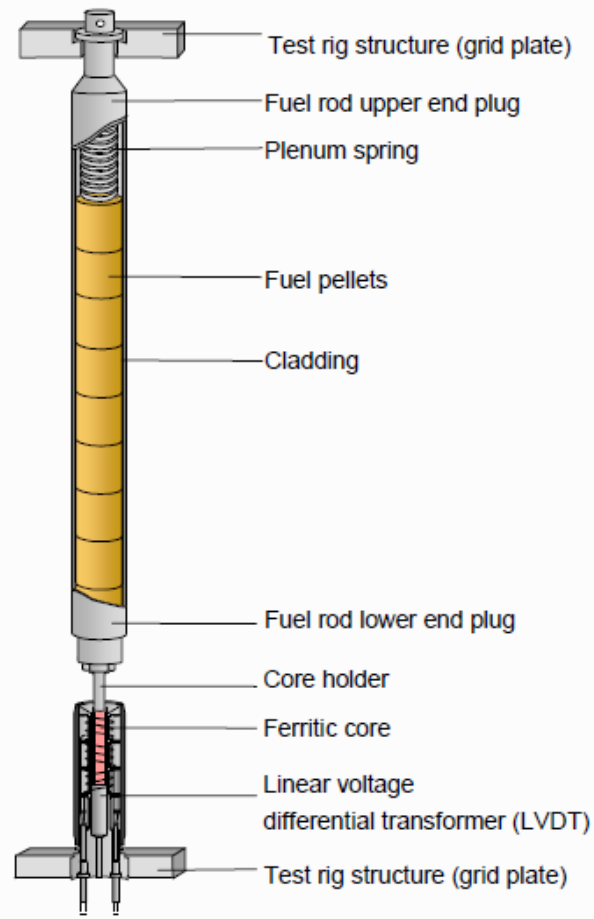
Cladding extensometer

- **Provides data on pellet-cladding interaction and cladding axial deformation**
- **Movement of magnetically-permeable core (fixed to the fuel rod end) sensed by LVDT**





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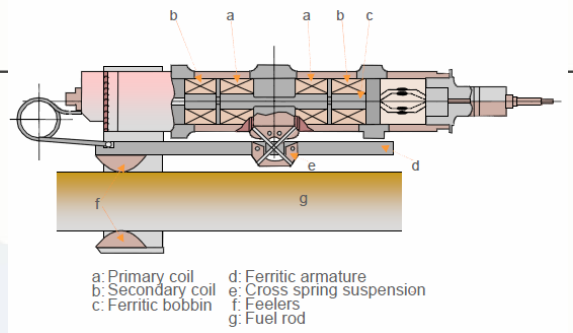
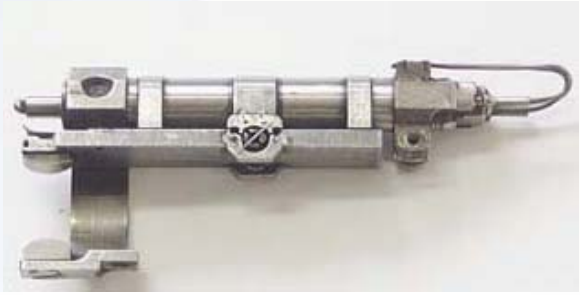
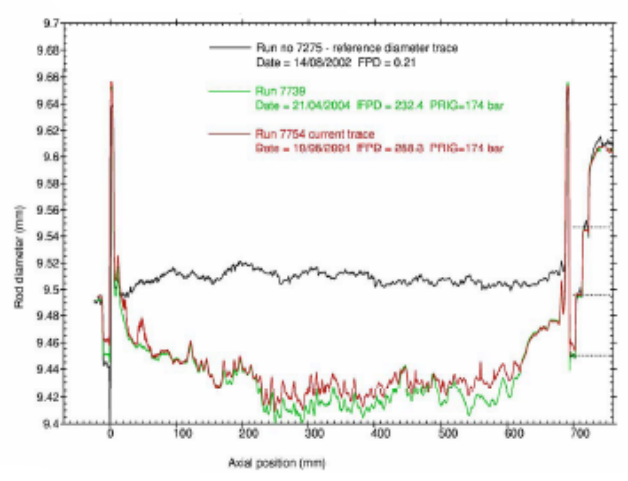
Diameter gauge (DG)



- Based on LVDT principle, but several differences:
  - Primary coil and two secondary coils are wound on ferritic bobbin as opposed to an Inconel bobbin
  - DG uses ferritic armature instead of ferritic core used in LVDT
  - Change in air gaps in two secondary loops changes balance between signals generated in two secondary loops, leading to change in output signal (difference of two secondary coil signals) from DG.
- Provides data on fuel rod diameter profile
- Instrument based on LVDT principle
- Differential transformer with two feelers on opposite sides of fuel rod
- DG moved by hydraulic system while position sensor senses the axial position along rod
- Operating conditions: 165 bar, 350°C





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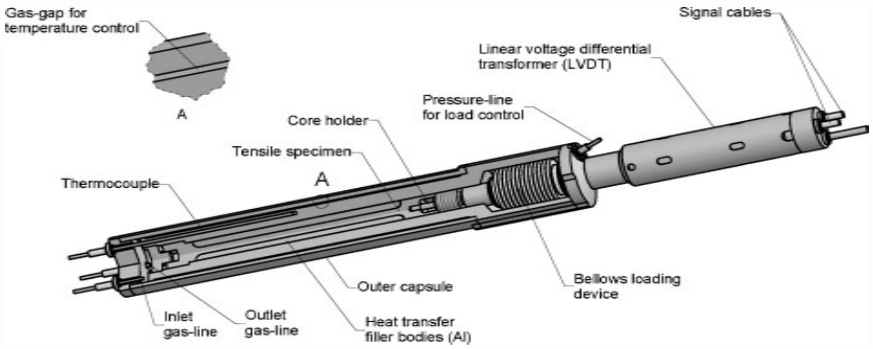
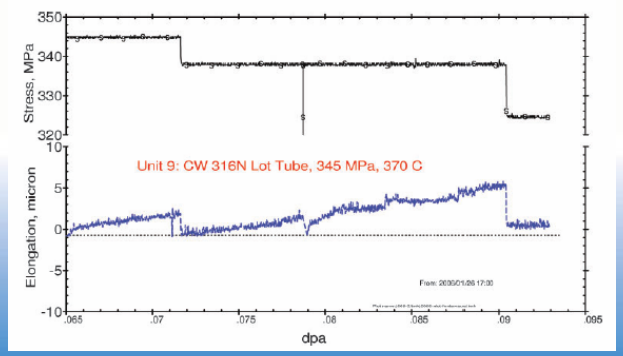
Creep/Tensile Tests (Dry Condition) - HBWR

- The effects of irradiation on the creep/stress relaxation in austenitic stainless steels commonly employed in commercial PWR reactors was evaluated
- The test materials are small tensile specimens (2.5 mm diameter and a gauge length of ~50 mm) prepared from unirradiated, solution annealed 304 and cold worked 316 stainless steels





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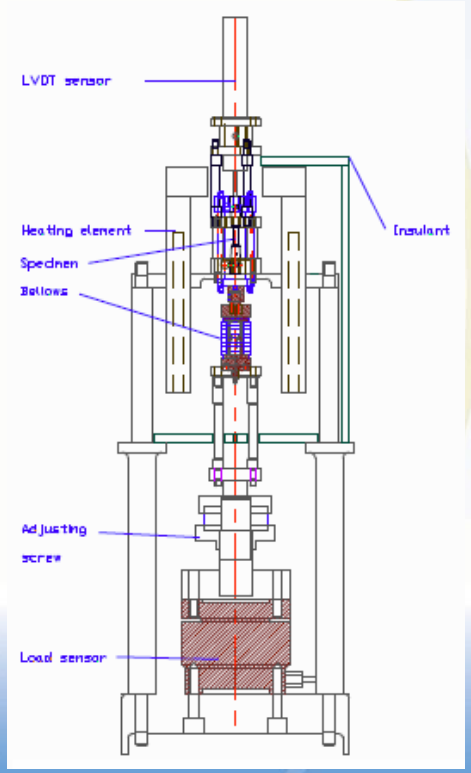
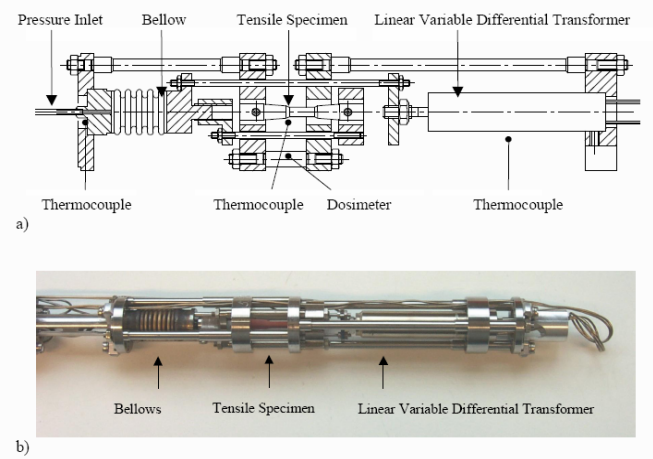
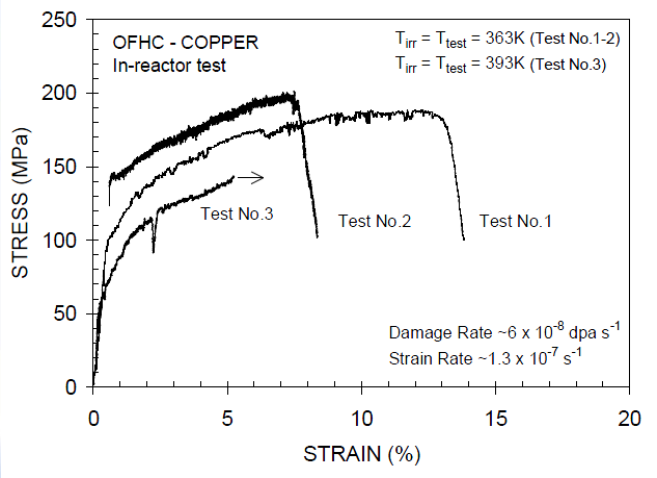
Creep/Tensile Tests (Wet Condition) - BR2

- In-reactor uniaxial tensile tests with constant strain rate
- Tensile loading module calibrated prior to insertion into BR2
- Tested thin (0.3 mm) sheets of oxygen free high conductivity (OFHC) and CuCrZr alloy (for ITER applications)







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INL LVDT Evaluations

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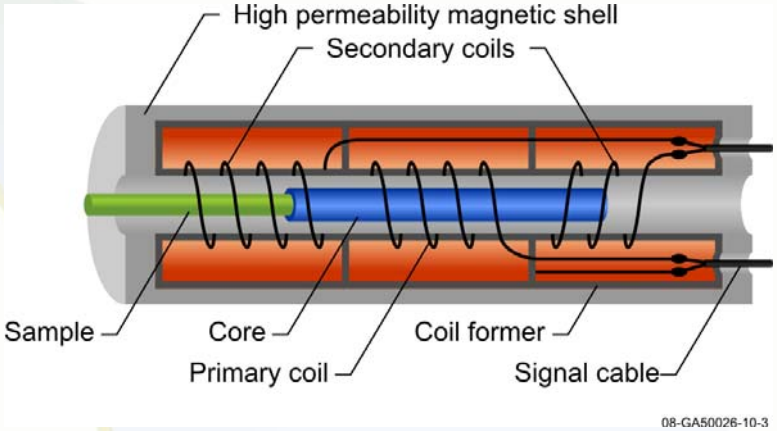
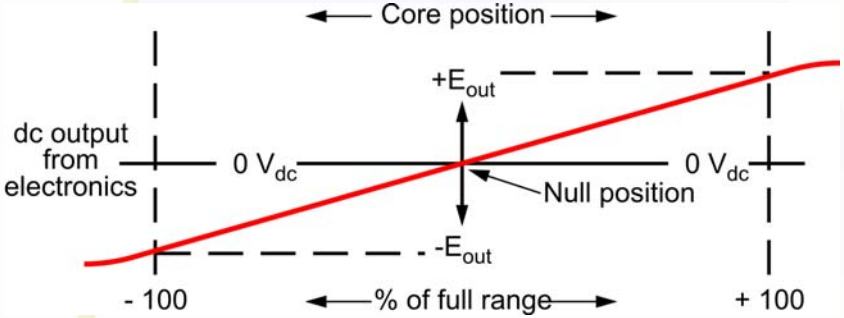
Evaluations Motivated by ATR NSUF Designation and General Nuclear Resurgence

- Issues
  - Instrumentation needed to support ATR users
  - Dimensional changes in ATR currently quantified using “cook and look”
  - Current ATR approach expensive and may not reveal behavior of interest
  - New materials must be characterized before use in next generation and existing reactors
- Solution
  - Evaluate LVDTs for anticipated high temperature, high power, in-pile use at ATR

Why Use LVDTs?

- Key features yield advantages
  - Simple
  - Reliable and accurate
  - Relatively inexpensive
  - Mature technology
- Good fit in INL reactor in-pile instrumentation program – near term deployment





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Candidate LVDTs Must Meet ATR Specifications

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

LVDTs must function continuously for ATR operating cycles of ~1000 h

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Scope of Initial Evaluations

- Two candidate LVDTs identified for evaluation
  - Vendor A, with Curie effect considerations
  - Vendor B, with size considerations
- Evaluation focused on potential degradation in sensitivity / electrical properties following
  - Calibration to 500°C
  - Long duration testing at 500°C for 1000 h

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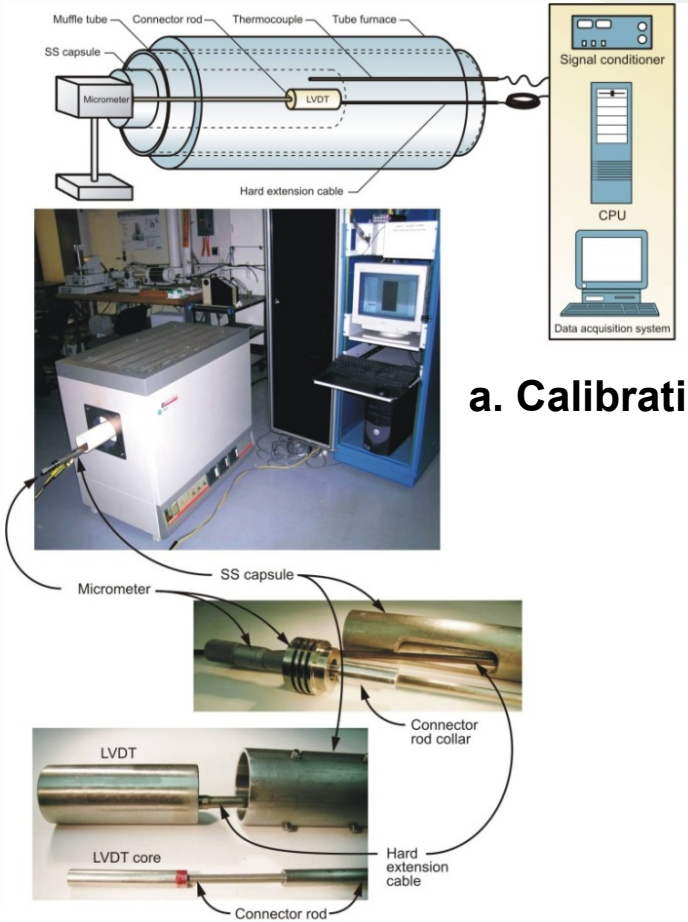
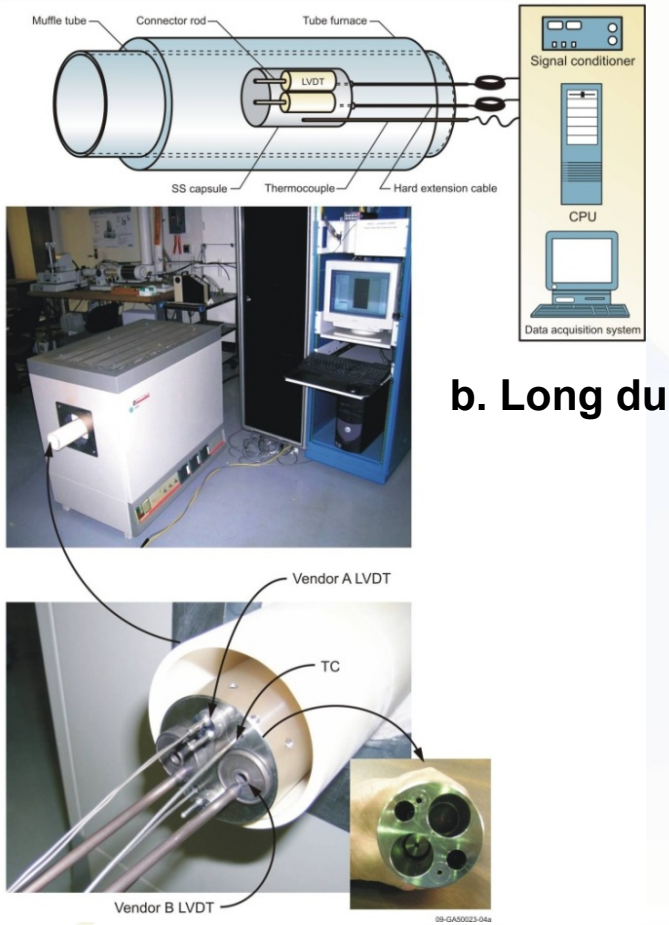
Evaluation of Candidate LVDTs for Use in ATR Irradiation Experiments



a. Calibration



b. Long duration

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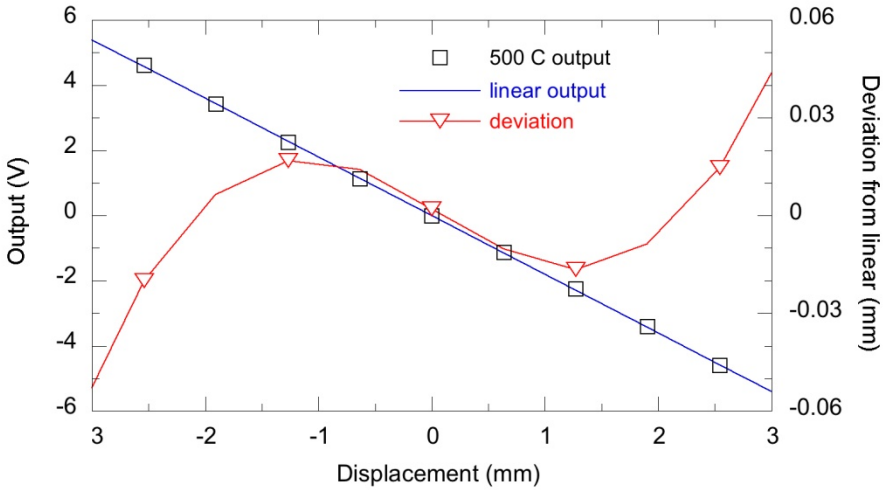
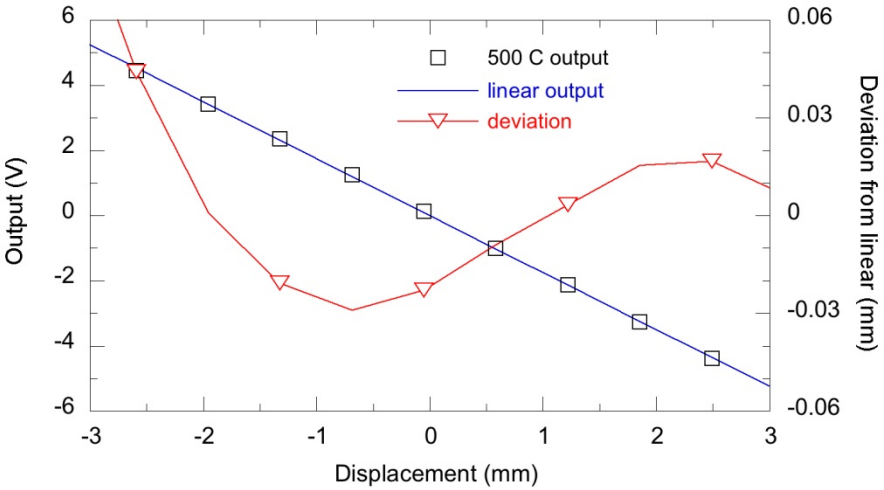
Calibration Results Favor Vendor A

Vendor A LVDT

- Maximum linear deviation: ± 0.02 mm (± 0.8%) @ 500°C
- Symmetric output





Vendor B LVDT

- Maximum linear deviation: - 0.044 mm (- 1.8%) @ 500°C
- Non-symmetric output

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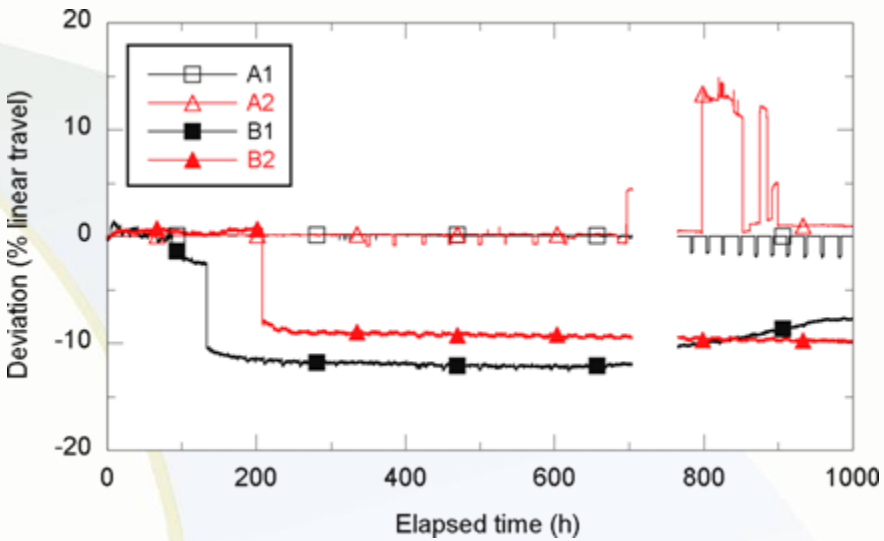
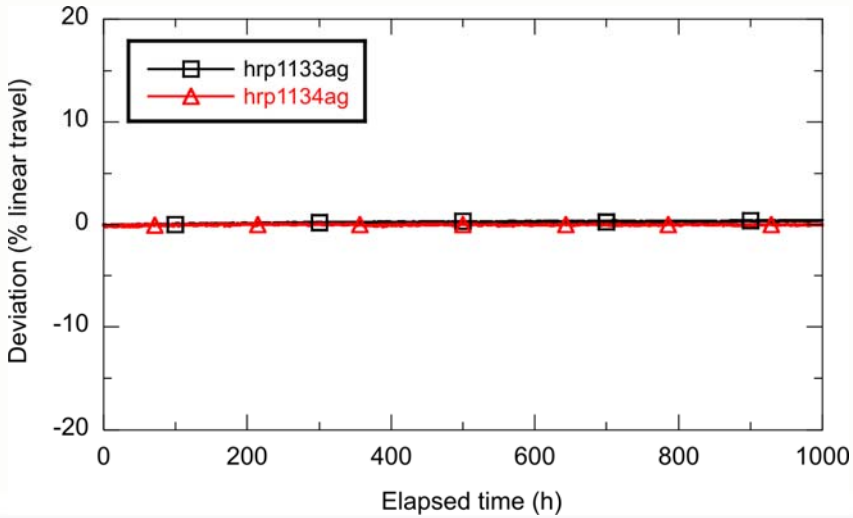
Long Duration Results Favor Vendor A

- Vendor A LVDTs have superior long duration, high temperature response





- Vendor A (HRP) LVDTs with alternate wire and fabrication techniques show exceptional long duration, high temperature stability

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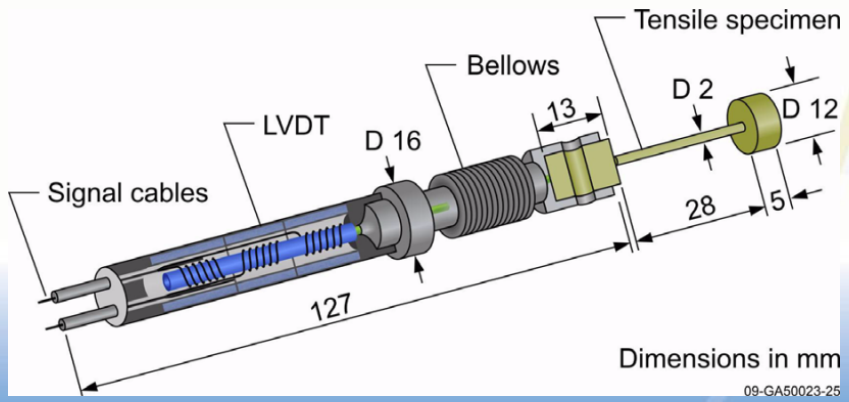
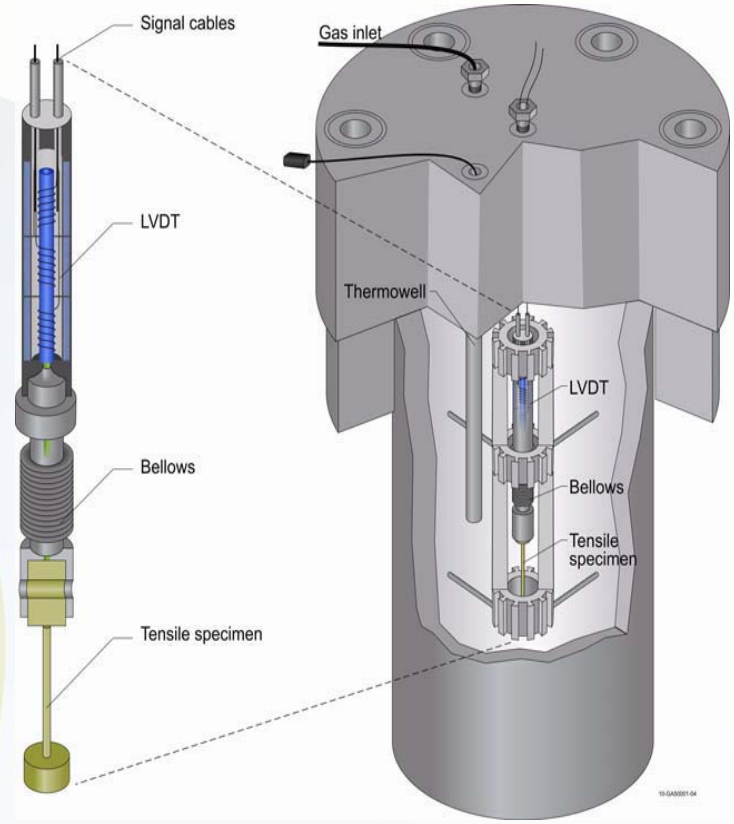
Creep Test Rig with LVDT Developed and Evaluated for ATR Testing

- Major components: an LVDT, a bellows, a tensile specimen, a creep frame
- LVDT/bellows assembly fabricated by HRP
- INL fabricated tensile specimen and creep frame to accommodate LVDT/bellows assembly
- Assembled components positioned in HTTL autoclave for lab testing





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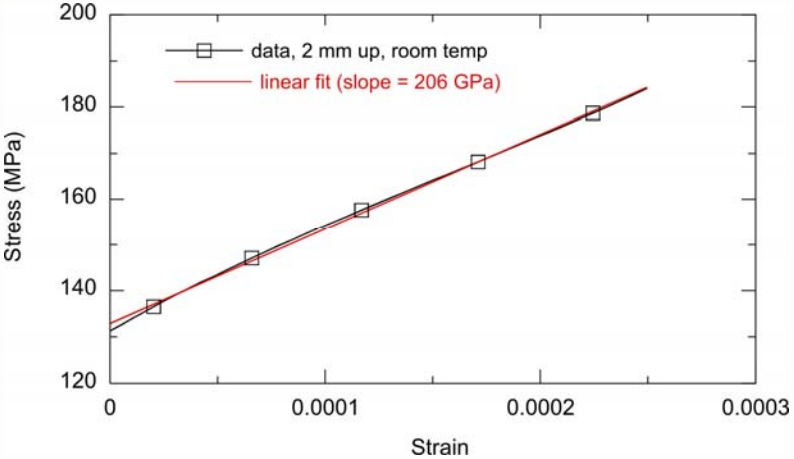
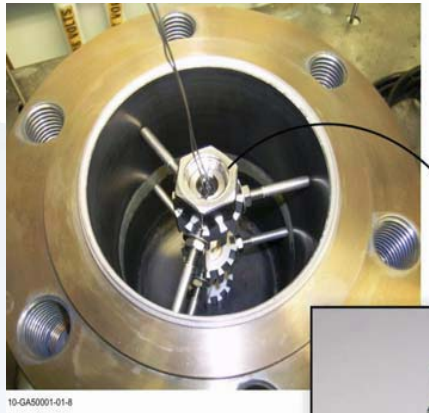
Initial Test Rig Evaluations Underway

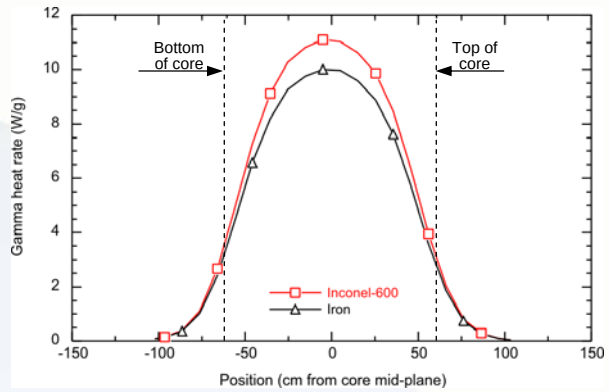
- Tensile testing in HTTL underway
- Preliminary results (in elastic region) agree with independent load frame testing

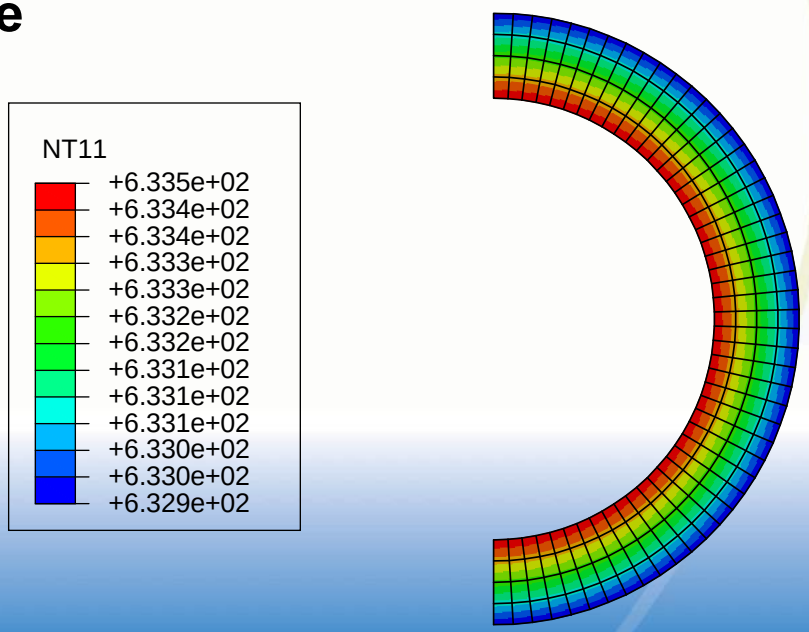


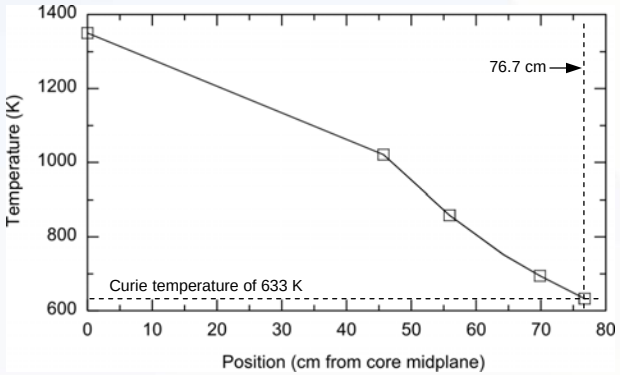


Gamma Heating Analyses to Establish Acceptable LVDT In-Core Position

- Gamma heating ranges from ~3 to ~11 W/g in ATR active core
- Maximum coil temperatures limited to 633 K (in standard sensor)
- Acceptable LVDT position ~16 cm above top of core
- Resulting flat core temperature profile







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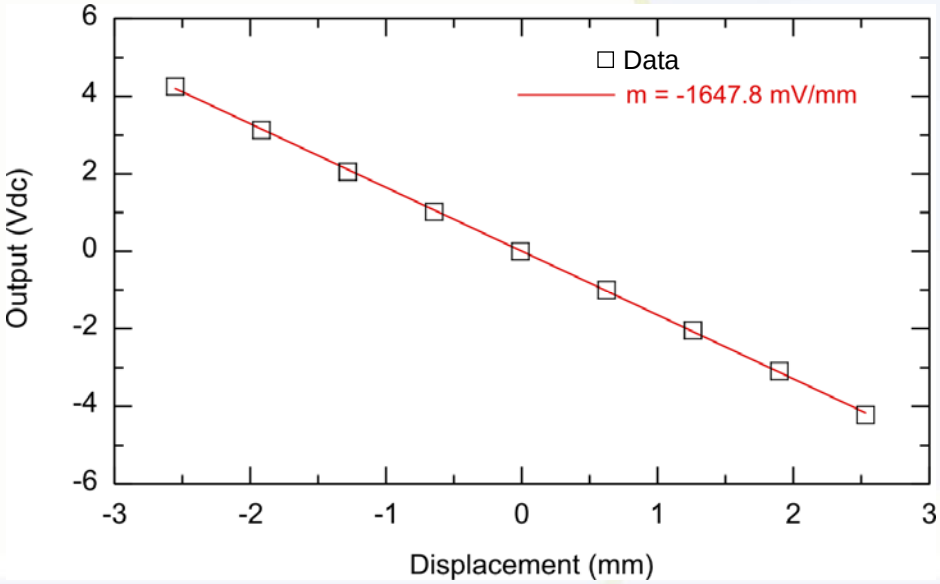
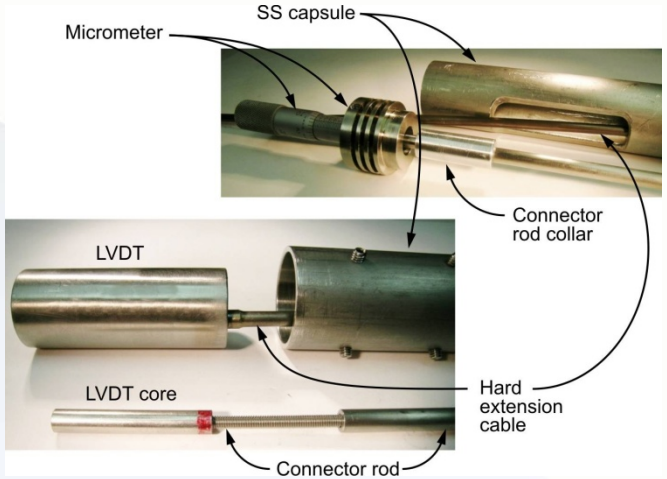
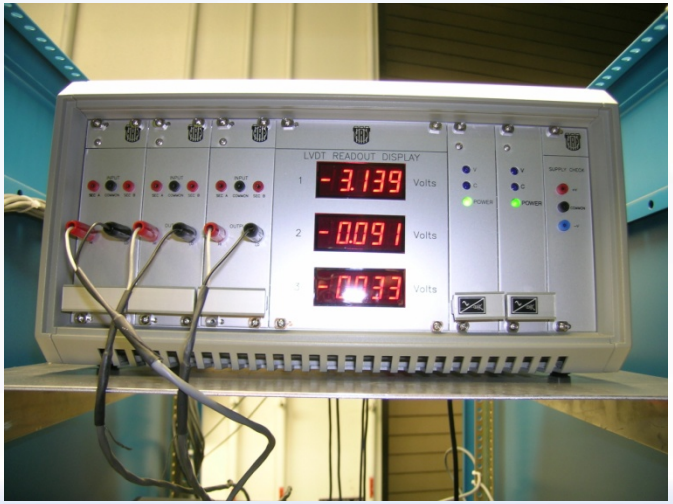
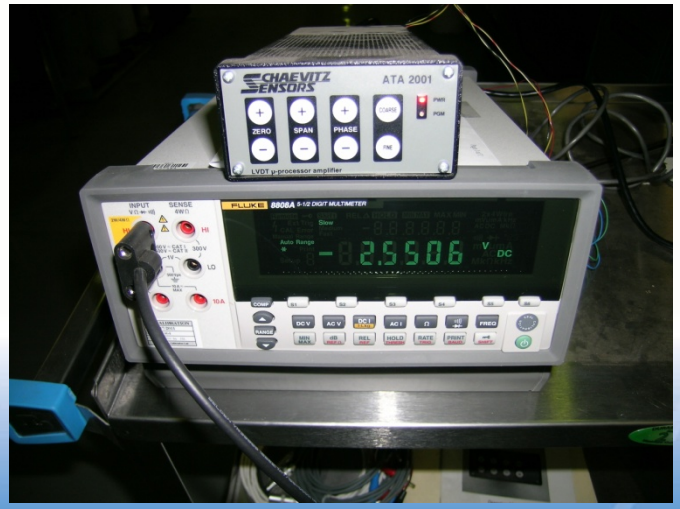
Hands-On Demonstration/Instruction

Objectives

- Observe and test LVDT operation
- Record position and LVDT output
- Determine LVDT sensitivity (mV/in is acceptable)



Setup

- LVDT, connecting rod, and micrometer assembled inside SS capsule
- Assembly mounted on lab stands
- Connections to signal conditioner and voltmeter