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ATR NSUF INSTRUMENTATION ENHANCEMENT EFFORTS

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ABSTRACT

A key component of the Advanced Test Reactor (ATR) National Scientific User Facility (NSUF) effort is to enhance instrumentation techniques available to users conducting irradiation tests in this unique facility. In particular, development of sensors capable of providing 'real-time' measurements of key irradiation parameters is emphasized because of their potential to increase data fidelity and reduce post-test examination costs. This paper describes the strategy for identifying new instrumentation needed for ATR irradiations and the program underway to develop and evaluate new sensors to address these needs. Accomplishments from this program are illustrated by describing new sensors now available to users of the ATR NSUF. In addition, progress is reported on current research efforts to provide users improved in-pile instrumentation.

Key Words: In-pile instrumentation, irradiation sensors

1 INTRODUCTION

The U.S. Department of Energy (DOE) designated the Advanced Test Reactor (ATR) as a National Scientific User Facility (NSUF) in April 2007 to support U.S. leadership in nuclear science and technology. By supporting users from universities, laboratories, and industry, the ATR will support basic and applied nuclear research and development and advance the nation's energy security needs. A key component of the ATR NSUF effort is to develop and implement in-pile instrumentation that is capable of providing real-time measurements of key parameters during irradiation. This paper describes the strategy for identifying instrumentation needed for ATR irradiations and the program initiated to develop and evaluate new sensors and optimized irradiation capsules and test trains to address these needs. Selected new sensors developed from this effort are identified; and the progress of other on-going instrumentation efforts is summarized.

1.1 ATR Design and Irradiation Capabilities

The ATR is a versatile tool for conducting nuclear reactor, nuclear physics, reactor fuel, and structural material irradiation experiments. [1]

The ATR's maximum power rating is 250 MW_{th} with a maximum unperturbed thermal neutron flux of 1 $x10^{15}$ n/cm^2-s and a maximum fast neutron flux of 5 x 10^{14} n/cm^2-s. Because most contemporary experimental objectives do not require the upper limits of its operational capability, the ATR typically operates at lower power levels (nominally 110 MW_{th}). The ATR is available over 70% of the year, in cycles that typically range from 6 to 8 weeks, with outages lasting one or two weeks. The ATR is cooled by pressurized (2.5 MPa/360 psig) water that

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enters the reactor vessel bottom at an average temperature of 52 °C (126 °F), flows up outside cylindrical tanks that support and contain the core, passes through concentric thermal shields into the open part of the vessel, then flows down through the core to a flow distribution tank below the core. When the reactor is operating at full power, the primary coolant exits the vessel at 71 °C (160 °F).

As shown in Figure 1, the ATR core consists of 40 curved plate fuel elements in a serpentine arrangement around a 3 x 3 array of primary testing locations, including nine large high-intensity neutron flux traps. The unique ATR control device design permits large power variations among its nine flux traps using a combination of control cylinders (drums) and neck shim rods. The beryllium control cylinders contain hafnium plates that can be rotated toward and away from the core. Hafnium shim rods, which withdraw vertically, are inserted or withdrawn for minor power adjustments. Within bounds, the power level in each corner lobe of the reactor can be controlled independently to allow for different power and flux levels in the four corner lobes during the same operating cycle. The ratio of fast to thermal flux can be varied from 0.1 to 1.0. In addition to the nine large volume (up to 48" long and up to 5.0" diameter) high-intensity neutron flux traps, there are 66 irradiation positions inside the reactor core reflector tank, and two capsule irradiation tanks outside the core with 34 low-flux irradiation positions.

There are three basic types of test assembly configurations used in the ATR:

- ***Static Capsule Experiment*** – These capsules may contain a number of small sample or engineered components. Static capsule experiments may be sealed or may contain material that can be in contact with the ATR primary coolant (such capsules are in an open configuration without being sealed). Capsules may be any length, up to 122 cm (48 in.) and may be irradiated in any core position, including the flux traps. Irradiation temperature may be selected by providing a gas gap in the capsule with a known thermal conductance. Peak temperatures may be measured using a series of melt wires, temperature-sensitive paint spots, or silicon carbide temperature monitors. Accumulated neutron fluences may be verified using flux wires.

- ***Instrumented Lead Experiment*** - Active control of experiments and data from test capsules during irradiation is achieved using core positions with instrumentation cables and temperature control gases in ATR instrumented lead experiments. Such experiments can have instrumentation, such as thermocouples, connected to individual capsules or single specimens. This instrumentation can be used to control and sample conditions within the capsule. For example, temperature control in individual zones is performed by varying the gas mixture (typically helium and neon) in the gas gap that thermally links the capsule to the water-cooled reactor structure. In addition to temperature, instrumented lead experiments have been used to monitor the gas around the test specimen. In a fueled experiment, the presence of fission gases due to fuel failures or oxidation can be detected via gas chromatography. Instrument leads allow real time display of experimental parameters in the control room.

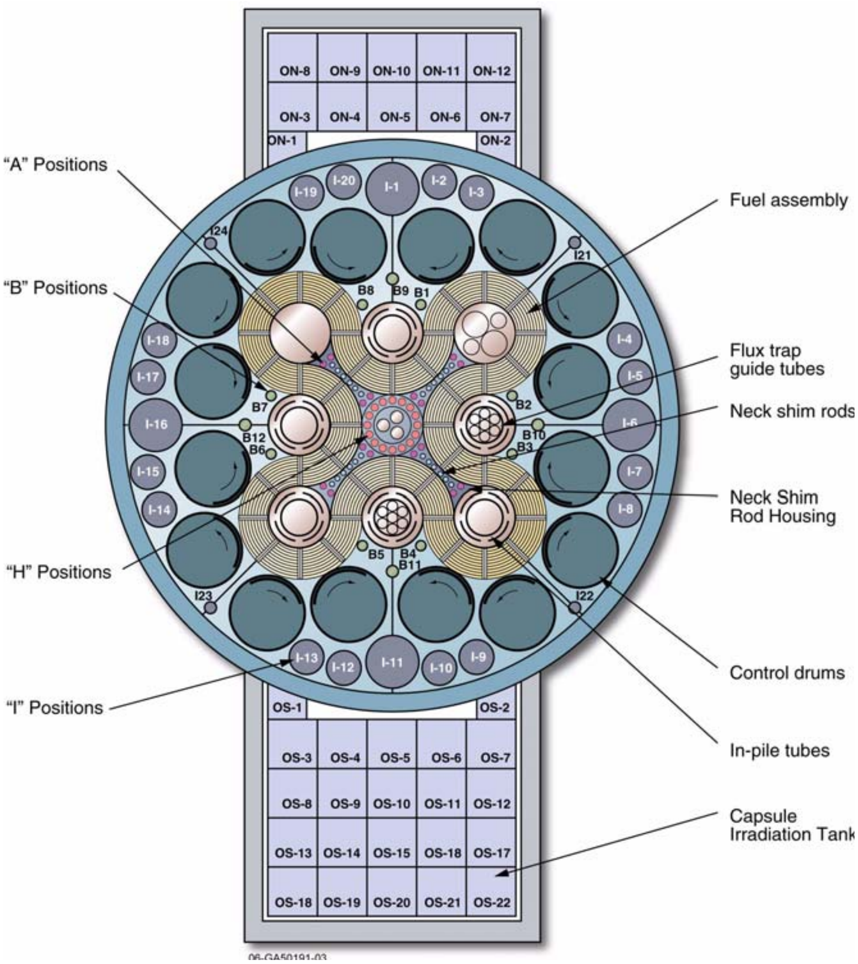


Figure 1. ATR core cross section identifying irradiation locations.

- ***Pressurized Water Loop Experiment*** **-** Five of the nine ATR flux traps used for materials and fuels testing are equipped with pressurized water loops (at the NW, N, SE, SW, and W locations). A sixth loop will be operational in 2010. Each of the water loops can be operated at different temperatures, pressures, flow rates, or water chemistry requirements. These loops can operate above the standard temperatures and pressure of a commercial PWR power plant. The great advantage of loop tests is the ease with which a variety of samples can be subjected to conditions specified for any PWR design. Each pressurized loop in the ATR is instrumented to measure and control (both helium and water) coolant flows, temperatures, pressures and sample test data.

Clearly, the ATR design offers unique advantages for testing. With additional in-pile instrumentation to support these testing capabilities, the features offered by this reactor user facility can be even more fully utilized.

1.2 Approach to Address ATR User Needs for Enhanced Instrumentation

Despite its long history for developing highly specialized instrumentation to meet demands of customers conducting unique tests in one-of-a-kind test facilities, INL instrumentation research funding decreased significantly in the 1980s when large nuclear test facility programs ended. Until recently, ATR irradiations relied primarily on commercial vendors for instrumentation. In 2004, an instrumentation effort was restarted that allowed INL to develop unique instrumentation required for ATR irradiations. Because much of the sensor fabrication and evaluation equipment and expertise were still available, INL's High Temperature Test Laboratory (HTTL) staff quickly developed high temperature thermocouples requested by ATR customers for fuel irradiations. Currently, several INL efforts are underway to enhance in-pile instrumentation for ATR users. This section describes the approach being used by INL to identify and prioritize ATR in-pile instrumentation development research.

INL efforts to enhance ATR instrumentation began by first completing a review (e.g., References [2] through [11]) to identify instrumentation available to users at other test reactors located in the U.S. and abroad. Table I summarizes results from this review. The column labeled "Technology Available at ATR" indicates the types of sensors currently available to ATR users. The column "Proposed Advanced Technology" includes two categories: "Available at Other Reactors" identifies several technologies employed at other test reactors that could be adapted to enhance ATR instrumentation capabilities and "Proposed Instrumentation Advancement" identifies developmental or non-nuclear technologies that could be used in irradiation tests. Blue text denotes the instrumentation currently being pursued as part of ATR NSUF research activities, and red text denotes new instrumentation developed by INL and deployed in the ATR. Note that many of these instrumentation development efforts are in collaboration with other organizations. The instrumentation currently being evaluated for the ATR NSUF (denoted by blue text in Table I) was selected based on anticipated user needs and 'technology readiness' (providing ATR users needed instrumentation in the near-term).

Although not discussed in this paper, efforts are also being initiated to develop standardized instrumented lead and PWR test train designs that incorporate new ATR NSUF instrumentation and instrumentation currently used at test reactors. Data from initially deployed standardized test vehicles will be used to validate the performance of developmental instrumentation.

Table I. Review of instrumentation available at ATR and other test reactors

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.

2 REPRESENTATIVE INL-INSTRUMENTATION DEVELOPMENT EFFORTS

Some examples of efforts to develop new methods for detecting temperature and dimensional changes during ATR irradiations are summarized in this section.

2.1 Temperature

Because of the importance of this key parameter, new methods for detecting temperature during irradiation are required. This section summarizes INL efforts to develop unique new thermocouples that resist decalibration due to high temperatures and neutron transmutation in instrumented lead and loop tests and silicon carbide temperature monitors for static capsule tests. Although not discussed in this paper, INL is also collaborating with Luna Innovations to explore the use of fiber optics as a non-contact temperature sensor. In addition, as discussed in Reference [12], efforts are underway to investigate the use of thermocouples and hot-wire techniques for detecting changes in thermal conductivity during fuel irradiation tests.

2.1.1 High Temperature Irradiation Resistant Thermocouples (HTIR-TCs)

Commercially-available thermocouples drift due to degradation at high temperatures (above 1100 °C) or due to transmutation of thermocouple components. Thermocouples are needed that can withstand both high temperature and high radiation environments. To address this need, INL developed a High Temperature Irradiation Resistant ThermoCouple (HTIR-TC) design that contains commercially-available doped molybdenum paired with a niobium alloy. Battelle Energy Alliance (BEA), the operating contractor for INL, has filed a patent application for this technology, and INL now offers the sensors to ATR and other test reactor customers. HTIR-TC component materials were selected based on data obtained from materials interaction tests, ductility investigations, and resolution evaluations (see [13] through [15]). To demonstrate HTIR-TC long duration performance, long-term testing, in which thermocouples are held at elevated temperatures (from 1200 °C to 1800 °C) for up to 6 months, is being performed. The 1200 °C test included nineteen commercially-available Type N thermocouples, three commercially-available Type K thermocouples, and nine INL-developed swaged HTIR-TCs. As indicated in Figure 2, some Type K and N thermocouples drifted by over 100 °C or 8%. Much smaller drifts (typically less than 20 °C or 2%) were observed in the INL-developed HTIR-TCs. As documented in Reference [13], similar drifts (2%) were observed in HTIR-TCs in a long duration (4000 hour) test completed at 1400 °C. designs. Results from higher-temperature (e.g., 1500°C and 1800 °C) evaluations in a vacuum furnace installed at the HTTL will be used to compare the performance of “swaged,” “drawn,” and “loose assembly” HTIR-TCs.

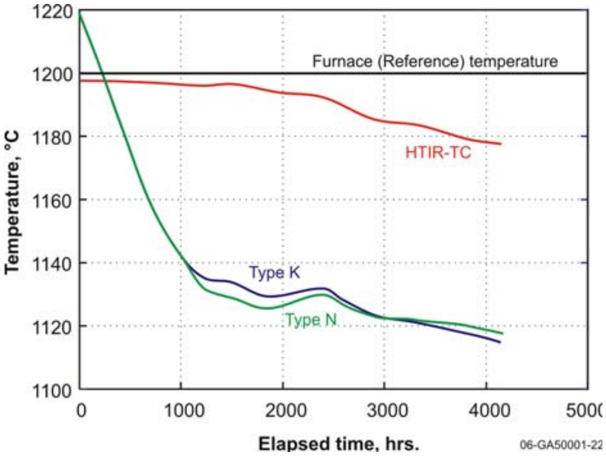


Figure 2. Representative thermocouple response in 1200 °C tests.

HTIR-TCs were installed in a multi-capsule experiment that is currently being irradiated in INL's ATR. This multi-capsule experiment is designed to irradiate samples at temperatures up to 1200 ºC. This test, which started in February 2007, is still underway. Figure 3 shows signals from two INL-developed HTIR-TCs and one Type N thermocouple located at a cooler region within one of the test capsules. Signal variations are due to ATR power fluctuations and outages. As shown in this figure, at the beginning of this irradiation, the HTIR-TC located near the Type N thermocouple is giving a signal consistent with the signal from this Type N thermocouple. In addition, the HTIR-TC located at a higher temperature region within the capsule is yielding a consistent, but higher temperature, signal. However, in October 2008, the Type N thermocouple failed and its signal ceased.

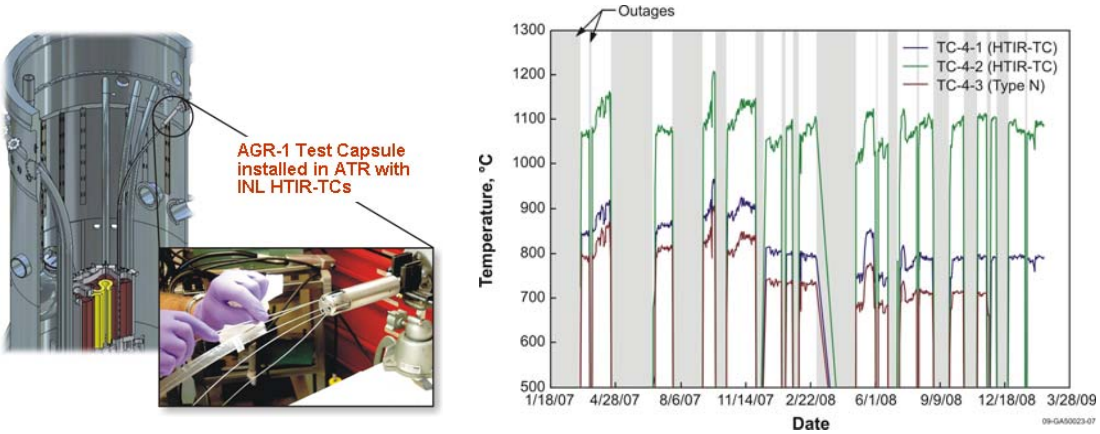


Figure 3. HTIR-TCs installed in AGR-1 test capsule and representative HTIR-TC and Type N data during ATR irradiation.

2.1.2 Silicon Carbide Temperature Monitors

For decades, post-irradiation temperature monitors have been based on the phenomenon that irradiation-induced swelling of silicon carbide (SiC) begins to anneal out at temperatures exceeding its irradiation temperature. These SiC monitors have relied on changes in length, density, thermal conductivity, and electrical resistivity to infer irradiation temperature. However, Snead et al. [11] recommends using changes in resistivity because of improved accuracy, ease of measurement, and reduced costs. Experimental data indicate that accuracies of approximately 20 °C are possible with this technique for dose ranges of 1 to 8 dpa and temperatures from 200 to 800 °C. Absolute limits for this approach are 150 °C (an amorphous threshold) and 875 °C (due to recrystallization). A capability similar to the technique used by Snead et al. [11] is being implemented at INL. Efforts are underway to prepare and checkout the equipment setup at INL’s HTTL. It currently planned to start making measurements with SiC monitors irradiated in the ATR in November 2009.

2.2 Dimensional Changes

Geometry changes of samples irradiated in the ATR are currently evaluated out-of-pile after specified lengths of irradiation time. The labor and time to remove, examine, and return irradiated samples for each measurement makes out-of-pile approaches expensive. In addition, only the sample's endstate is captured after it is removed from the reactor; and multiple removals and reinsertions may disturb the phenomena of interest.

INL is investigating several options that offer the potential to obtain real-time length and diameter data from samples irradiated in the ATR. For lower temperature (up to 500 ºC) applications, efforts are underway to enhance commercially-available Linear Variable Differential Transducers (LVDTs) for ATR applications. Although not discussed in this paper, INL has also developed and completed preliminary demonstrations for a capsule using pushrods in combination with LVDTs for higher temperature elongation measurements. In addition, INL has initiated an effort to investigate the use of non-contact ultrasonic transducers for in-pile detection of sample geometry changes.

2.2.1 High Temperature Linear Variable Differential Transducers

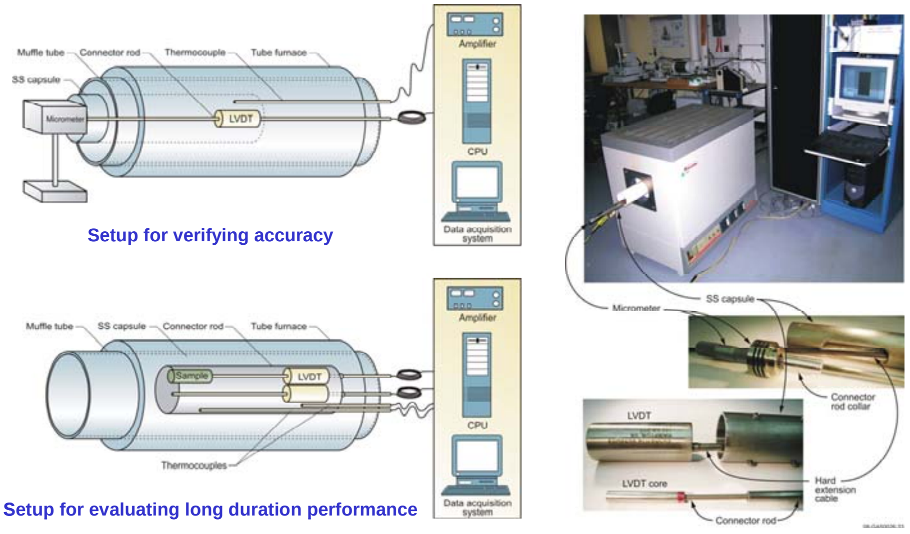
LVDT designs made by vendors offering nuclear grade LVDTs for irradiations in ATR instrumented capsules and in-pile tubes are currently being evaluated at INL. [16] The objective of this effort is to evaluate (and enhance, as needed) the viability of applying commercially available LVDTs as in-pile sensors for detecting dimensional changes of specimens during high temperature (up to 500 ºC) irradiations in ATR instrumented lead capsules and PWR loop tests. Desired LVDT characteristics for ATR irradiations are listed in Table II.

Table II. Desired LVDT characteristics for ATR irradiations

Parameter	ATR Specification
Total LVDT Displacement (e.g., stroke), mm	> +/- 2.5
Resolution, mm	10^{-2}
Sensitivity, V/m	>50
Maximum operating temperature, K	773
Normal operating pressure, MPa	0.1013-15.5
Peak thermal flux, E < 0.625 MeV, neutrons/cm^{2}s	1 x 10^{14}
Integrated thermal fluence, E < 0.625 MeV, neutrons/ cm^{2a}	8 x10^{21}
Peak fast flux, E > 20 MeV, neutrons/cm cm^{2a}	3 x 10^{14}
Integrated fast fluence, E > 20 MeV, neutrons/cm^{2a}	2 x10^{22}
Integrated gamma exposure, γ/cm^{2a}	9 x10^{22}
Maximum LVDT Diameter, mm	<25.4
Maximum LVDT Length, mm	63.8
Test environment	Water and Inert Gas (Neon, Helium)
Distance from test capsule to use of soft extension cable, m	12
Length of leads until T < 200 ºC, m	7

[a] Peak values; based on a NE lobe source power of 18 MW. Fluence is based on 3 years of operation at 75% utilization.

Nuclear-grade commercial LVDTs produced by two vendors were identified as having the potential to meet Table II specifications, if minor modifications were incorporated into their design. One vendor's design requires that the LVDT diameter exceed values desired for ATR applications; while the other vendor’s design has a peak operating temperature of 350 ºC. LVDTs made by each vendor were evaluated at the HTTL using the test setups shown in Figure 4. To verify the accuracy for the range of elongations anticipated, tests were completed between 200 and 500 ºC. Long duration performance evaluations were also completed to monitor signal stability at a temperature of 500 ºC for at least 1000 hours, and results are reported in Reference [16].



Setup for verifying accuracy

Setup for evaluating long duration performance

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Figure 4. Setup for evaluating LVDT performance.

In addition, several options are being considered to enhance the performance of vendor LVDT designs. For example, components used in LVDTs developed for INL’s Loss of Fluid Test [17] were found to produce LVDTs with stable signals up to 500 ºC. Once fabrication efforts of developmental nuclear grade LVDTs that include such components are completed, these LDVTs will be evaluated at INL’s HTTL. Test results from evaluations of developmental and commercially-available nuclear grade LVDTs will be used to select an LVDT vendor and optimized design for ATR irradiations.

2.2.2 High Temperature Diameter Gauges

INL evaluations indicate that the diameter gauge developed by the Norwegian Institutt for Energiteknikk (IFE) at the Halden Reactor Project (HRP) could be adapted for fuel/cladding interaction and axial offset anomaly testing at the ATR. As shown in Figure 5, the diameter gauge contains an LVDT with two feelers on opposite sides of the fuel rod. A ferromagnetic armature is suspended in cross springs parallel to the LVDT coil system in such a way that when the armature moves, one magnet gap will increase while the other one decreases. The diameter gauge travels along the fuel rod by using an in-core hydraulic drive and positioning system on a continuous basis (e.g. during power transients for measuring pellet-cladding interaction) or on a less frequent basis (e.g. once every month for monitoring crud build-up). The diameter gauge accuracy is ± 1 μm, and it can operate at up to 165 bar and 325 °C. INL is investigating options that could enhance the accuracy and high temperature performance of these sensors. If results are promising, a modified diameter gauge design may be recommended for ATR irradiations.

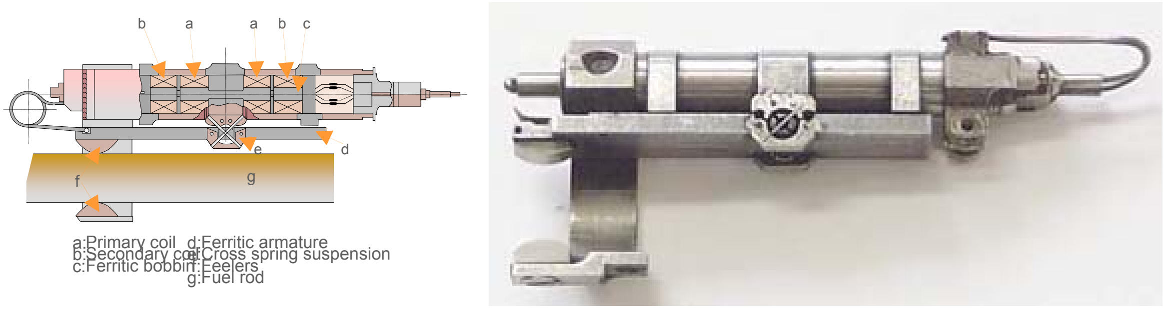

Figure 5. IFE HRP diameter gauge. [3]

3 CONCLUSIONS

An effort is underway to provide enhanced in-pile instrumentation for ATR users. In particular, development of sensors capable of providing real-time measurements of key parameters during irradiation is emphasized because of their potential to offer much-improved irradiation performance data and reduce post-test examination costs. The effort to enhance ATR instrumentation began by first completing a review to identify what instrumentation was available at other test reactors in the world. Developmental or non-nuclear technologies that could be used in ATR irradiation tests were also considered. Instrumentation development activities were then prioritized based on anticipating needs customer needs and technology readiness. In addition, instrumentation development collaborations were begun with other organizations that employ similar sensors in their test facilities. This effort has resulted in several new sensors now being available to ATR NSUF users and other research organizations. Representative results from on-going INL efforts to evaluate sensors for detecting temperature and geometry changes during irradiation testing illustrate the process used within this project. Efforts are also underway to standardize instrumented lead and PWR test train designs that incorporate this instrumentation. Data from initially deployed standardized test vehicles will be used to validate the performance of developmental instrumentation.

4 ACKNOWLEDGMENTS

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