Enhanced In-Pile Instrumentation at the Advanced Test Reactor

Joy L. Rempe, *Member, IEEE*, Darrell L. Knudson, Joshua E. Daw, Troy Unruh, Benjamin M. Chase, Joe Palmer, Keith G. Condie, and Kurt L. Davis

***Abstract*—Many of the sensors deployed at materials and test reactors cannot withstand the high flux/high temperature test conditions often requested by users at U.S. test reactors, such as the Advanced Test Reactor (ATR) at the Idaho National Laboratory. To address this issue, an instrumentation development effort was initiated as part of the ATR National Scientific User Facility in 2007 to support the development and deployment of enhanced in-pile sensors. This paper provides an update on this effort. Specifically, this paper identifies the types of sensors currently available to support in-pile irradiations and those sensors currently available to ATR users. Accomplishments from new sensor technology deployment efforts are highlighted by describing new temperature and thermal conductivity sensors now available to ATR users. Efforts to deploy enhanced in-pile sensors for detecting elongation and real-time flux detectors are also reported, and recently-initiated research to evaluate the viability of advanced technologies to provide enhanced accuracy for measuring key parameters during irradiation testing are noted.**

***Index Terms*—In-pile detectors, radiation resistant sensors.**

I. INTRODUCTION

An increasing number of U.S. nuclear research programs are requesting enhanced in-pile instrumentation that can provide real-time measurements of key parameters during irradiations. For example, fuel research and development funded by the U.S. Department of Energy (DOE) now emphasize approaches that rely on first principle models to develop optimized fuel designs that offer significant improvements over current fuels. To facilitate this approach, high fidelity, real-time data are essential for characterizing the performance of new fuels during irradiation testing. Furthermore, sensors that obtain such data must be miniature, reliable and able to withstand high temperature, high irradiation conditions. Depending on user requirements, sensors may need to obtain data in inert gas, pressurized water, or liquid metal environments.

The U.S. DOE designated the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL) as a National Scientific User Facility (NSUF) in April 2007 to support U.S. research in nuclear science and technology. By supporting users from universities, laboratories, and industry, the ATR will promote 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 capable of providing real-time measurements of key parameters during irradiation. This paper describes the strategy for identifying instrumentation needed for ATR irradiation tests and the program initiated to obtain these sensors. New sensors developed from this effort are identified, and the progress of other development efforts is summarized.

A. 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 $\mathrm{MW_{th}}$ with a maximum unperturbed thermal neutron flux of $1 \times 10^{15}\ \mathrm{n/cm^2-s}$ and a maximum fast neutron flux of $5 \times 10^{14}\ \mathrm{n/cm^2-s}$. Because most contemporary experimental objectives do not require the upper limits of its capability, the ATR typically operates at lower power levels (nominally 110 $\mathrm{MW_{th}}$). 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 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 Fig. 1, the ATR core consists of 40 curved plate fuel elements in a serpentine arrangement around a 3 × 3 array of primary testing locations, including nine large high-intensity neutron flux traps. The unique ATR 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 or 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 1.22 m long and up to 0.13 m diameter) high-intensity neutron flux traps, there are 66 irradiation positions inside the reactor core reflector

---

Manuscript received June 16, 2011; revised October 10, 2011; accepted October 19, 2011. Date of publication January 23, 2012; date of current version August 14, 2012. This work was supported by the U.S. Department of Energy, Office of Nuclear Energy, under DOE-NE Idaho Operations Office Contract DE AC07 05ID14517.

The authors are with the Idaho National Laboratory, Idaho Falls, ID 83415 USA (e-mail: joy.rempe@inl.gov).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNS.2011.2174066

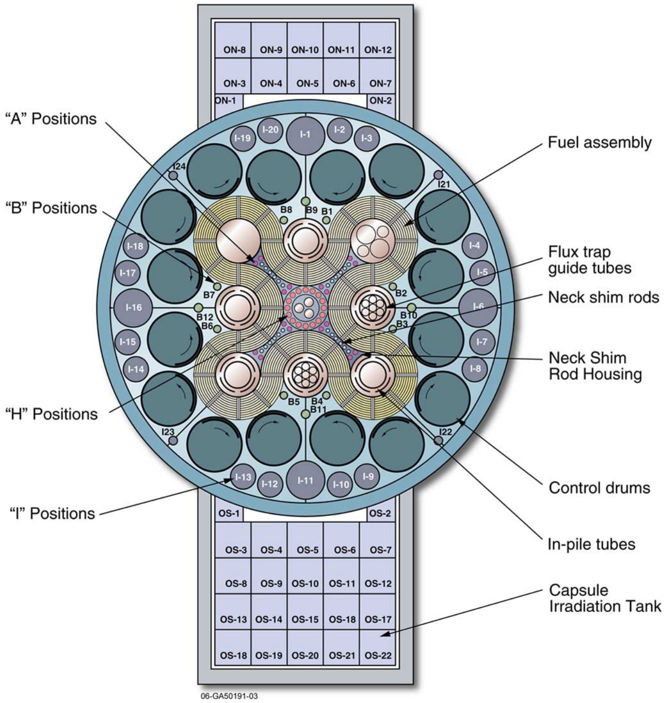


Fig. 1. ATR core cross section showing irradiation locations.

tank, and two capsule irradiation tanks outside the core with 34 low-flux irradiation positions.

There are several ATR test assembly configurations:

- *Static Capsule Experiments*—These capsules may contain several small samples or engineered components. Static capsule experiments may be sealed or may contain material that can be in contact with 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 (within limits) by providing a gas gap in the capsule with a known thermal conductance. Instrumentation is currently limited to sensors that detect peak temperature or accumulated neutron fluence.
- *Instrumented Lead Experiments*—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 measure and control 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 reactor coolant. In addition to temperature, sensors can 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 on control consoles.
- *Pressurized Water Loop Experiments*—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 2012. 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 pressurized water reactor (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 ATR pressurized loop is instrumented to measure and control coolant flows (both helium and water), temperatures, pressures and sample test data.
- *Hydraulic Shuttle Irradiation System (HSIS)*—The HSIS or "rabbit" enables insertion and removal of experiment specimens during ATR during operational cycles. The HSIS is installed in the B-7 reflector position, which is one of the higher flux positions in the reactor with typical thermal and fast (>1 MeV) fluxes of $2.8\mathrm{E}+14\ \mathrm{n/cm^2{-}s}$ and $1.9\mathrm{E}\ +\ 14\ \mathrm{n/cm^2{-}s}$, respectively. The titanium experiment capsules, or shuttles, are approximately 16 mm in diameter × 57 mm in length with interior usable dimensions of 14 mm in diameter x 50 mm long. Up to 14 capsules can be used for irradiations simultaneously, although one does not need to fill all 14 capsules for a test. The maximum allowable weight of each shuttle contents is 27.0 grams.

In addition to these testing locations, the ATR is co-located with the ATR Critical (ATRC), a full-size nuclear mock-up of the ATR core that allows researchers to characterize in advance, with precision and accuracy, the expected changes in ATR core reactivity due to a proposed test. This facility generally operates at a thermal power of less than 5 kW (with associated peak thermal fluxes of around $10^{10}\ \mathrm{n/cm^2{-}s}$ and a maximum fast neutron flux of around $10^9\ \mathrm{n/cm^2{-}s}$).

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.

B. Addressing ATR User Needs for Enhanced Instrumentation

As noted above, the ATR is unique with respect to irradiation testing capabilities. The test volumes and flux levels in each of its irradiation locations [Static Capsules, the HSIS, Instrumented Lead Tests, and PWR loops] are unsurpassed by few, if any, test reactors in the world.

In 2007, the ATR NSUF initiated an effort to develop unique instrumentation required for ATR irradiations. As part of this effort, a review was first completed to identify instrumentation available to users at other materials and test reactors (MTRs) located in the US and abroad. Table I summarizes results from this review [2].

In Table I, the column labeled "ATR Technology" indicates sensors currently available to ATR users. The column "Proposed Advanced Technology" includes two categories: "Available at Other Reactors," which identifies technologies employed

TABLE I
INSTRUMENTATION AVAILABLE AT ATR AND OTHER TEST REACTORS

Parameter	**Parameter**			**ATR Technology**	**Proposed Advanced Technology**	
	Static Capsule/ HSIS	**Instr. Lead**	**PWR Loop**		**Available at Other Reactors**	**Developmental**
Temperature	√	√	√	-**Melt wires** (peak)[a,b] -**SiC Temperature Monitors** (peak temperature for range of values)	-Paint spots (peak)	-Wireless (range)[c]
		√	√	-Thermocouples (Type N, K, C, and **HTIR-TCs**)[d]		*- Fiber optics* -Noise thermometry *-Ultrasonic thermometers*
Thermal Conductivity		√	√		*-Degradation using signal changes in thermocouples*	*-Hot wire techniques*
Fluence (neutron)	√	√	√	-Flux wires and activating foil dosimeters		
		√	√		*-Self-Powered Neutron Detectors (SPNDs)* *-Subminiature / miniature fission chambers*	-Moveable SPNDs
Gamma Heating		√	√		-Calorimeters -Gamma thermometers	
Dimensional		√	√		*-LVDTs (stressed and unstressed)* -Diameter gauge -Hyper-frequency resonant cavities	*-Ultrasonic transducers* *-Fiber optics*
Fission Gas (Amount, Composition)		√	√	-Sampling ('near' real-time) and evaluation using detectors	-LVDT-based pressure monitors -Counter-pressure monitor	-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	-Electrical chemical potential probes	
Crud Deposition			√	-Out-of-pile examinations	-Diameter gauge with neutron detectors and thermocouples	
Crack Growth Rate			√		-Direct Current Potential Drop Technique	-Ultrasonic transducers

[a] Italic text denotes instrumentation being investigated for ATR applications; bold text denotes new instrumentation currently deployed at the ATR.
[b] Although melt wires have been used at ATR, recent efforts have expanded the types offered to our users, allowing more accurate estimates of peak temperature, and enhanced encapsulation methods.
[c] Although listed under temperature, wireless technologies could be pursued for many parameters.
[d] Type C thermocouple use requires a "correction factor" to correct for decalibration during irradiation.

at other MTRs that could be adapted to enhance ATR instrumentation capabilities; and "Developmental," which lists developmental or non-nuclear technologies that could be used in ATR irradiation tests. Technologies listed in this column are considered to be less "ready" for implementation. Italic text denotes sensors currently being pursued as part of instrumentation research activities, and bold text denotes new or enhanced sensors recently developed and deployed by INL. It should be noted that many of these instrumentation development efforts are in collaboration with organizations that develop and deploy instrumentation at other MTRs, such as the French Atomic Energy Commission (CEA), the Institute for Energy Technology at the Halden Reactor Project (IFE/HRP), the Korea Atomic Energy Research Institute (KAERI), and the Massachusetts Institute of Technology (MIT).

The instrumentation currently being evaluated for the ATR was selected based on anticipated user needs and "technology readiness" (providing ATR users needed instrumentation in the near-term). For example, other MTRs have sensors available for real-time detection of parameters such as neutron flux (thermal and fast) and geometry changes (length and diameter). As indicated by the italic text in Table I, efforts are underway to explore using these technologies at the ATR. However, adapting instrumentation used at other test reactors often requires demonstrations because of ATR-specific irradiation conditions (e.g., higher neutron fluxes, higher temperatures, etc.) and test capsule geometries. As indicated by the bold text in Table I, three new or enhanced sensors are now available to ATR users as a result of this instrumentation development effort. Although most instrumentation development efforts are focused on nearer-term technologies that already exist at other test reactors, some exploratory efforts to investigate the use of fiber optic and ultrasonic technologies have also been initiated. The use of these developmental technologies is being explored because of their potential to offer more compact, higher resolution and accuracy instrumentation. For example, it may be possible to obtain a temperature profile within fuel during an irradiation tests using a single, small diameter (~0.25 mm) mult-segment ultrasonic thermometer. The ultimate goal of this effort is to provide ATR users enhanced sensors for detecting all of the parameters listed in Table I.

Fig. 2. Quartz tube containing four melt wires in separated compartments.

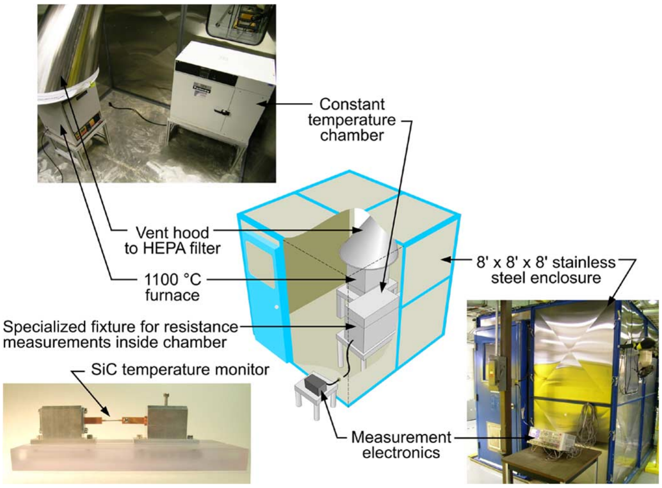


Fig. 3. Setup to anneal and measure electrical resistivity of SiC temperature monitors.

II. Representative Development Efforts

Selected examples of efforts to develop new methods for detecting temperature, thermal conductivity, geometry, and flux during ATR irradiations are summarized in this section.

A. Temperature

As indicated in Table I, temperature detection sensors available to ATR NSUF users are comparable, if not superior, to those used at other MTRs. To meet recent customer requests, an increased selection of melt wires with enhanced encapsulation and SiC temperature monitors are available for all irradiation locations; and doped molybdenum/niobium alloy thermocouples are available for instrumented lead and PWR loop applications. Although not discussed in this paper, INL has recently started exploring the use of fiber optics and ultrasonic techniques as a non-contact temperature sensor.

1) Melt Wires: Metal wires of a known composition and melting temperature are placed in an irradiation test to determine if a specific peak temperature is reached. A post-test examination of the wire is required to determine if melting actually occurred indicating that the corresponding melting temperature was reached (or exceeded). As described in ASTM E 1214-06, [3] melt wire materials should consist of metals with 99.9% purity or be eutectic alloys such that their measured melting temperatures are within ±3°C of the recognized values. Transmutation-induced changes of these wires should not be considered significant even after exposure to fluences up to $1 \times 10^{20}\ \mathrm{n/cm^2}\ (\mathrm{E} > 1\ \mathrm{MeV})$. As noted in [3], melt wires should be selected to measure temperature at 5 to 12°C intervals, with at least one melt wire that possesses a melting temperature greater than the highest anticipated temperature. As part of the ATR NSUF effort, INL has developed in-house capabilities to verify the melting temperature of candidate wire materials (ranging from ~85 to 1500°C) and to encase multiple melt wires into a single small diameter unit for irradiation testing. Fig. 2 shows a quartz tube containing multiple melt wires. Metallic tubes are also available for use in ATR tests.

2) Silicon Carbide Temperature Monitors: In recent years, several organizations have explored the use of SiC temperature monitors for peak temperature detection because these monitors can be used to detect the maximum temperature reached within a range of temperatures. For example, Snead *et al.* (ORNL) [4] successfully used changes in resistivity to detect peak irradiation temperatures with accuracies of approximately 20°C for dose ranges of 1 to 8 dpa and temperatures between 200 and 800°C. Experimental data suggest that upper and lower bounds for this range may be extended.

The technique implemented by Snead *et al.*, is now also available at INL. Specialized equipment at INL's High Temperature Test Laboratory (HTTL) now allows peak temperature detection in all test locations using SiC monitors. In this technique, the SiC sensor electrical resistivity is measured after heating in a furnace located within a stainless steel enclosure at the HTTL (see Fig. 3). After heating, cooled samples are placed into a constant temperature environmental test chamber to ensure electrical resistivity measurements are taken within 0.2°C of a predetermined temperature, 30°C. A high accuracy (9 digit) multimeter, which is placed outside the stainless steel enclosure, is used to obtain resistance measurements. Specialized fixturing (see Fig. 3) was developed to ensure that measurements are always taken with the SiC sensors placed in the same orientation. A four point probe technique is used with the points connected to the sample through spring-loaded angled electrodes that hold the SiC temperature monitor in place. Current and voltage are provided to the sample via wires that are threaded through the holes in the electrodes.

The accuracy of this new INL capability was verified by completing tests with unirradiated samples of various grades of SiC temperature monitors (which vary in resistivity) and by completing comparison measurements with ORNL on identical

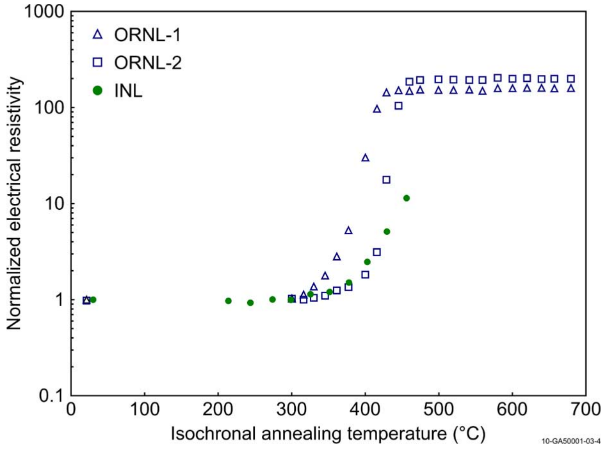


Fig. 4. Electrical resistivity measurement comparison on SiC monitors irradiated at 320°C.

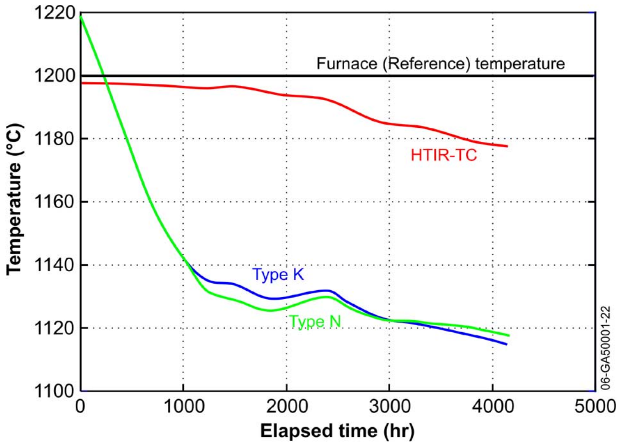


Fig. 5. Representative thermocouple response in INL 1200°C tests.

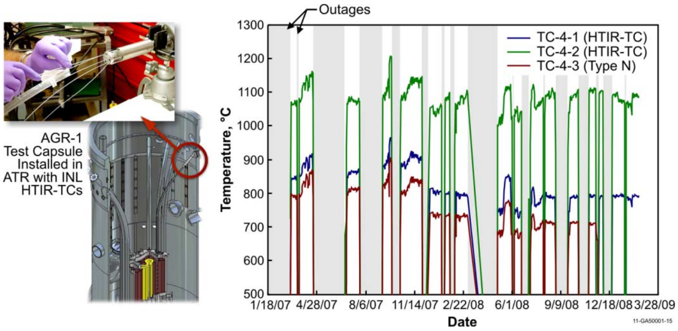


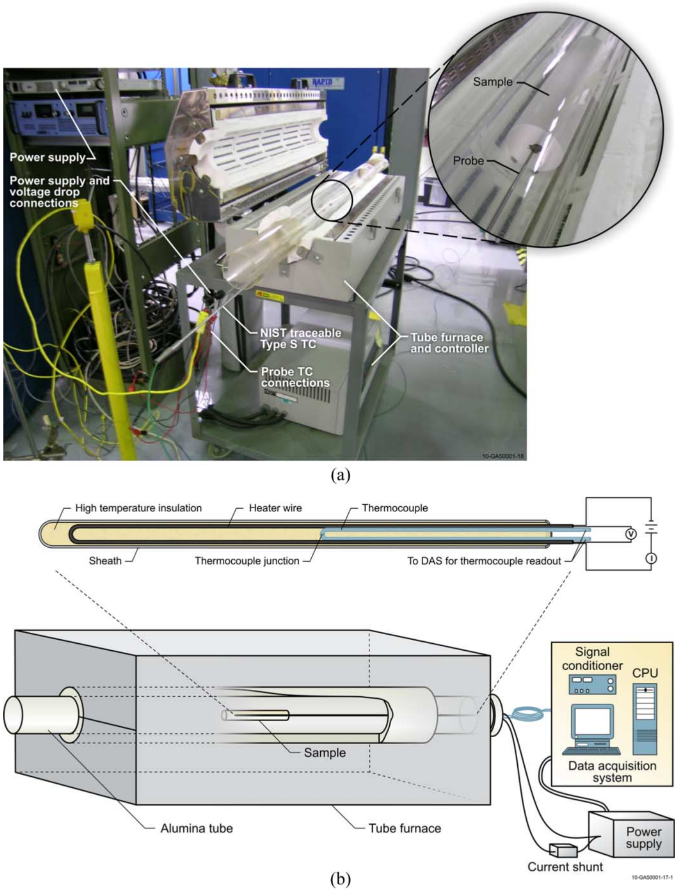
Fig. 6. HTIR-TCs installed in AGR-1 test capsule and representative HTIR-TC and Type N data during ATR irradiation.

sensors that had been subjected to identical irradiation conditions [5]. Increases in normalized electrical resistivity were observed to occur at approximately the same temperature in these evaluations (as shown by representative results in Fig. 4). Hence, evaluations indicate that similar peak irradiation temperatures are inferred from ORNL and INL measurements.

3) High Temperature Irradiation Resistant Thermocouples (HTIR-TCs): For decades, real-time temperature measurements during irradiation tests have been made with commercially-available, mineral insulated, metallic sheathed thermocouples. These thermocouples are used to monitor and/or control the temperature achieved during irradiation. For temperatures below 1000°C, experimental needs are typically met using Type K or Type N thermocouples, which have demonstrated excellent reliability and signal stability under irradiation, even for very high neutron fluences exceeding $10^{22}\ \mathrm{n/cm^2}$ (thermal neutrons). However, these thermocouples decalibrate when exposed to temperatures above 1100°C. High temperature thermocouples, such as Type C or D thermocouples, decalibrate due to transmutation when their tungsten-rhenium thermoelements, with high absorption cross sections, are exposed to a thermal neutron flux. Hence, thermocouples were 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) that contains commercially-available doped molybdenum paired with a niobium alloy. HTIR-TC component materials were selected based on data obtained from materials interaction tests, ductility investigations, and resolution evaluations (see [6]–[11]). HTIR-TC long duration performance has been demonstrated through testing, in which thermocouples were held at elevated temperatures (from 1200°C to 1800°C) for up to 6 months. 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 Fig. 5, 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. Similar drifts (2%) were observed in HTIR-TCs in a long duration (4000 hour) test completed at 1400°C, and smaller drifts (less than 1%) have been observed in HTIR-TCs with enhanced fabrication techniques for higher temperatures (up to 1800°C).

HTIR-TCs were also installed in a multi-capsule experiment where gas reactor fuel samples were irradiated at temperatures up to 1200°C in INL's ATR. The test started in February 2007 and ended in October 2009. Fig. 6 shows signals from two INL-developed HTIR-TCs and one Type N thermocouple located within one of the capsules (Capsule 4). Signal variations are due to ATR power fluctuations and outages (e.g., gray regions correspond to when the ATR was shutdown). As shown in this figure, the HTIR-TC (TC-4-1) located near the Type N thermocouple (TC-4-3) yielded a signal consistent with the signal from this Type N thermocouple at the beginning of this irradiation. In addition, the HTIR-TC located at a higher temperature region within the capsule (TC-4-2) yielded a consistent, but higher temperature, signal. However, in October 2008, the Type N thermocouple failed; and its signal ceased. The successful operation of HTIR-TCs in this test has led to requests for INL to supply them to other MTRs. In 2010, three HTIR-TCs were supplied to MIT for an irradiation test in the MIT Nuclear Research Reactor (MITR). In addition, three HITR-TCs were recently fabricated and shipped to IFE/HRP for use in the Halden Boiling Water Reactor (HBWR).



(a)

(b)

Fig. 7. Setup for evaluating transient hot wire needle probe.

B. *Thermal Conductivity*

Currently, changes in fuel or material thermal conductivity due to ATR irradiations are evaluated out-of-pile. However, as discussed in this section, real-time methods for detecting changes in thermal conductivity during irradiation in instrumented lead and loop tests are now available as a result of ATR NSUF instrumentation development efforts.

Historically, in-pile thermal conductivity measurements were made using an approach with one (or more) thermocouples embedded near the center of the fuel rod and one exterior to the fuel (in the coolant or a structure outside the fuel element). As part of a collaborative effort with Utah State University (USU) and the IFE/HRP, INL evaluated the multiple thermocouple steady-state thermal conductivity approach and a transient hot wire method (THWM) with a single probe, containing a line heat source and thermocouple (see Fig. 7), embedded in the fuel as candidate in-pile effective thermal conductivity measurement techniques. Results, as documented in [12], indicate that the THWM needle probe offers an enhanced method for in-pile detection for thermal conductivity.

INL explored the use of a hot wire probe design, that was developed based on ASTM D 5334 −05.18.93. [13] In the THWM approach, thermal conductivity is determined from the temperature rise in the sample when the heat source is energized. In a solid, this method may be applied by embedding the probe in the material whose thermal conductivity is to be measured. From a condition of thermal equilibrium, the probe is energized and heats the sample with constant power. The temperature response of the sample is a function of its thermal properties, and the thermal conductivity is calculated from the temperature rise detected in the sample. Following a brief transient period, a plot of the temperature versus the natural logarithm of time becomes linear, as shown in Fig. 8 (linear region of the time period between times t_1 and t_2 and temperatures T_1 and T_2). The slope of the linear region is used to calculate the test material thermal conductivity.

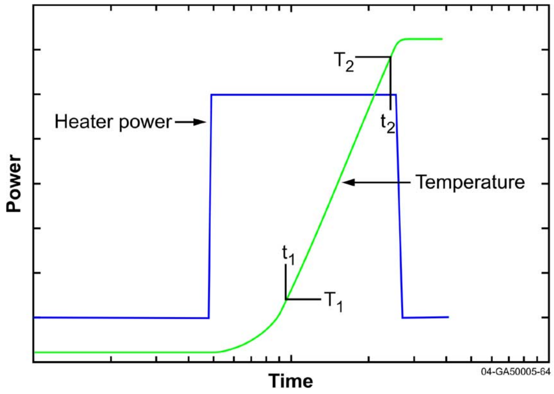


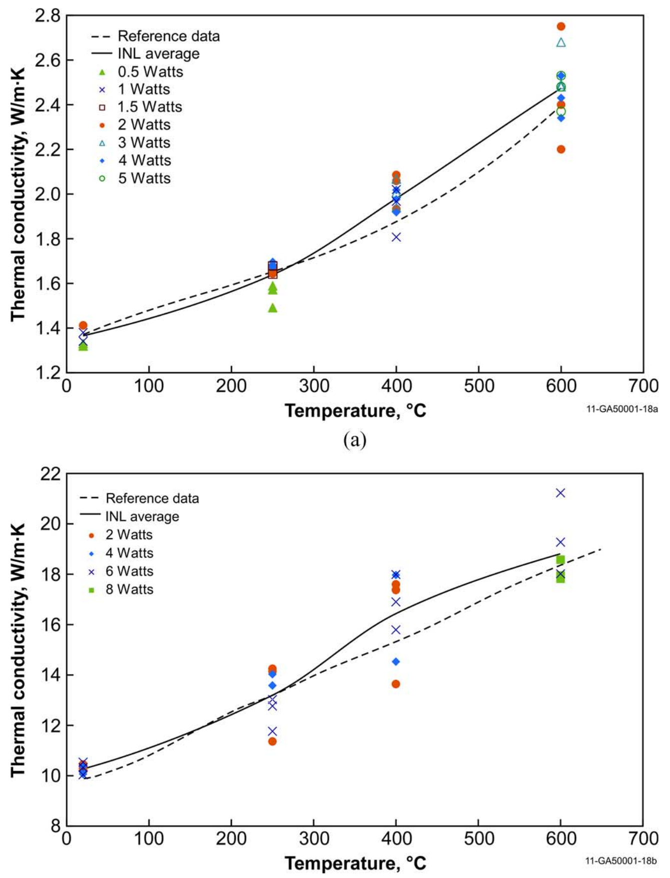
Fig. 8. Semi-log temperature rise plot for transient methods.

Probes were designed and fabricated at INL's HTTL for both room temperature proof-of-concept evaluations and high temperature testing. Using the setup shown in Fig. 7, experimental results show that the THWM needle probes can measure the thermal conductivity of fused silica, the ASTM recommended reference material, within 2% at room temperature, 250°C, 400°C, and 600°C. In these evaluations, the probe design was selected such that materials and geometry were optimized to improve accuracy for the proposed test temperature and surrogate rod material (e.g., selected wire diameters and materials were optimized to reduce losses in different surrogate fuel rods and test setups).

The needle probe was demonstrated to work very well for materials with thermal conductivity ranging from 0.2 to 16 W/m-K with measurement errors of less than 5%, delivering thermal conductivity measurements with a high degree of accuracy and consistency (see Fig. 9). However, test results indicate that special design considerations are needed for high thermal conductivity sample materials and for smaller diameter samples. Methods are being explored that could overcome these challenges; primarily techniques are under evaluation that could reduce signal noise and allow better characterization of the probe response time. However, results from long term evaluations indicate that the current needle probe design is a robust sensor that could survive in the harsh environments associated with in-pile fuel testing. In February 2011, a prototype needle probe was prepared for an upcoming irradiation of hydride fuel in the MITR.

C. *Dimensions*

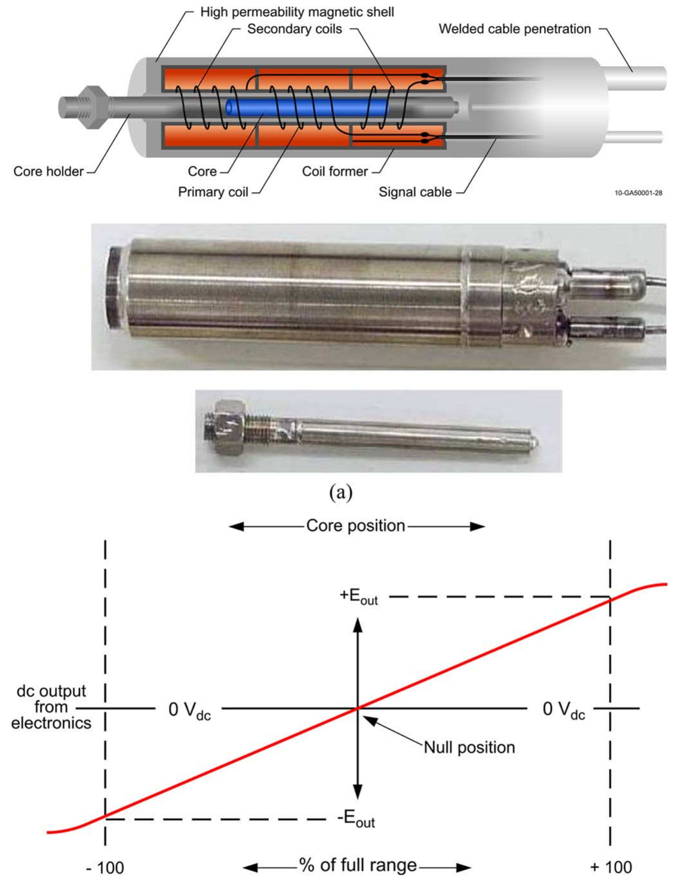
Today, most MTRs rely on Linear Variable Differential Transformers (LVDTs) to detect changes in length during



(a)

(b)

Fig. 9. Comparison of THWM needle probe results obtained at various power levels for (a) fused silica and (b) Inconel 625.



(a)

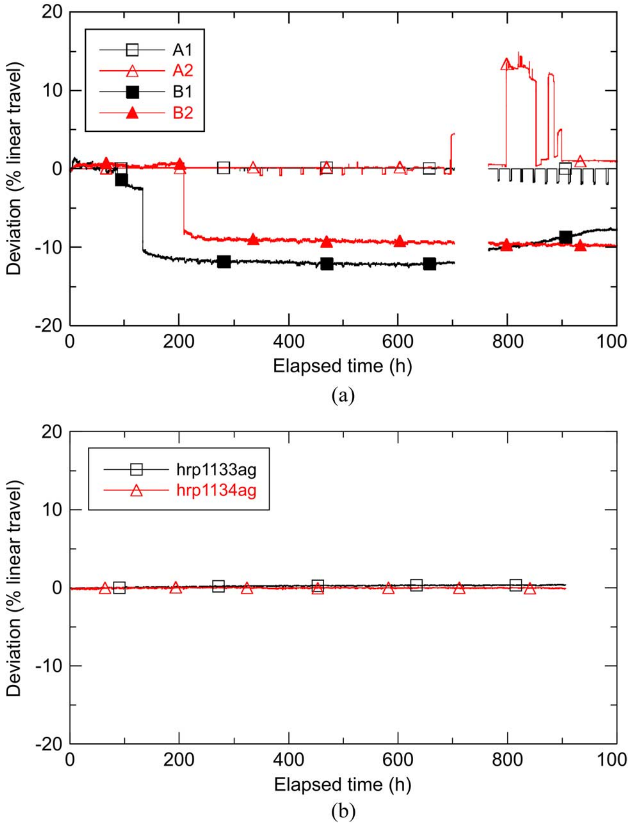
(b)

Fig. 10. LVDT components (a) and operation (b).

irradiation. As shown in Fig. 10(a), LVDTs are electrical transformers with three coils placed end-to-end around a tube. The center coil is the primary, and the two outer coils are the secondaries. A cylindrical magnetically-permeable core, attached to the object whose position is to be measured, slides along the axis of the tube. An alternating current is driven through the primary, causing a voltage to be induced in each secondary which is proportional to its mutual inductance in the primary. As the core moves, these mutual inductances change, causing the voltages induced in the secondaries to change. The coils are connected in reverse series, so that the output voltage is the difference between the two secondary voltages. When the core is in its central position, equidistant between the two secondaries, equal but opposite voltages are induced in these two coils, so the output voltage is zero (see Fig. 9(b)). Many features of LVDTs (e.g., frictionless measurements, long lifetime, high resolution, etc.) make them ideal for in-pile applications.

Most research reactors rely on LVDTs made by the IFE/HRP. In the IFE/HRP LVDTs, the primary coil is activated by a constant current generator (at 400–2500 Hz). The position of the magnetically-permeable core can be measured with an accuracy of $\pm 1 - 10\ \mu\mathrm{m}$ (references vary on this value). Since the IFE/HRP started with in-core measurements, more than 2200 LVDTs of different types have been installed in different test rigs in the HBWR and other test reactors around the world [14]. A failure rate of less than 10% after 5 years of operation is expected for their LVDTs operating in a wide range of test conditions [14]. Hence, operating experience has shown that these sensors are a robust, frictionless instrument for detecting dimensional changes in lower-temperature, irradiation environments. Recently-completed INL efforts have focused on developing a higher temperature sensor for detecting dimensional changes during irradiation testing at the ATR and other MTRs.

Nuclear-grade LVDTs from US and foreign sources were evaluated as candidates for high temperature in-pile sensors. INL efforts, [15] which included calibration evaluations and long duration, high temperature testing (see Fig. 11(a)), clearly indicated the superiority of LVDTs supplied by IFE/HRP. However, evaluations of Curie point effects, due to the nickel contained in the LVDT coil material, indicate the potential for a change in accuracy (under certain operating conditions) near 360°C, the temperature that corresponds to the Curie point for the copper nickel wire used in the LVDT windings. Consequently, temperatures could be an issue depending on the in-core position of the sensor and the corresponding gamma heating levels. For that reason, INL collaborated with IFE/HRP to develop and evaluate developmental LVDTs with an alternate coil material that is not susceptible to the Curie effect. Calibration and long term high temperature testing of the developmental LVDTs performed by INL demonstrates that the new LVDTs can operate in a very stable manner for long



(a)

(b)

Fig. 11. LVDT response during long duration (1000 hour) test at 500°C: (a) LVDTs originally provided by nuclear grade vendors (LVDTs designated with an "A" were provided by IFE/HRP; and (b) developmental LVDTs provided IFE/HRP.

periods (1000 h) at high temperatures (500°C). As shown in Fig. 11(b), the degradation of the original LVDTs provided by IFE/HRP and by another nuclear-grade LVDT manufacturer was not observed in the developmental LVDTs provided by IFE/HRP. Hence, developmental LVDTs are recommended for use in ATR high temperature irradiation tests.

For example, developmental LVDTs will be incorporated into an in-pile creep test rig design. This test rig is scheduled for deployment in an ATR PWR loop in 2012. A prototype creep test rig, shown in Fig. 12, was recently evaluated in an autoclave at INL's HTTL. Initial evaluations with stainless steel tensile specimens in the elastic region yielded data that are consistent with results obtained from a load frame for this material. Testing in the plastic region has also shown very close agreement between LVDT measurements and post-test micrometer measurements for stainless steel and copper tensile specimens. As discussed in [15], specimens with (nominal) gauge diameter of 2 mm and a (nominal) gauge length of 28 mm were intentionally loaded beyond their yield strengths as a result of autoclave pressures and temperatures up to ~16 MPa and ~ 350°C, respectively, in these tests. In all these tests, disparities between LVDT and micrometer measurements with respect to final lengths were found to be very small (<0.9%). These disparities correspond with errors in length of 0.26 mm or less, which is considered to be close agreement given the measurement techniques that were used.

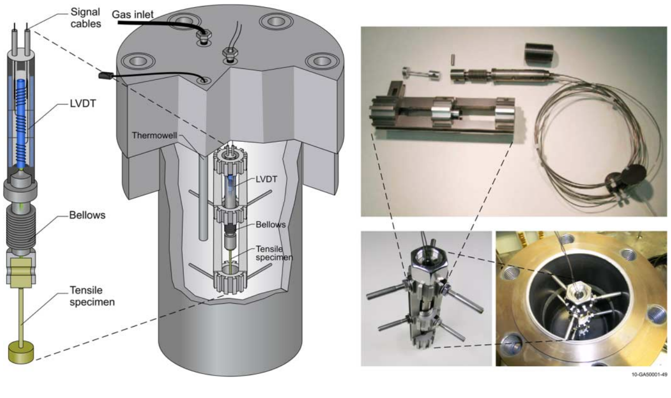


Fig. 12. Creep test rig positioned in autoclave for testing.

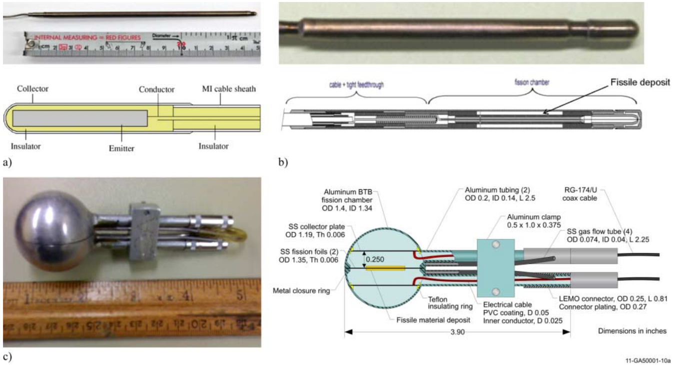


Fig. 13. Representative real-time flux sensors evaluated at ATRC. a) SPNDs; b) CEA Fission Chambers; c) BTB Fission Chambers.

D. Flux

A joint Idaho State University (ISU)/ INL project has been initiated to evaluate new real-time state-of-the-art in-pile flux detection sensors. [16] Initially, the project is comparing the accuracy, response time, and long duration performance of several activation sensors and real-time flux sensors, including CEA-developed miniature fission chambers, specialized self-powered neutron detectors (SPNDs) developed by the Argentinean National Energy Commission (CNEA), specially developed commercial SPNDs, and back-to-back fission (BTB) chambers developed by Argonne National Laboratory (ANL) for the Zero Power Physics Reactor (ZPPR) programs (see Fig. 13). Although SPNDs evaluated in this project are limited to thermal flux detection, the CEA and BTB fission chambers will allow fast and thermal flux detection.

Specialized fixturing was designed, fabricated, and installed for evaluating real-time flux detectors in six of the N-16 positions in the ATRC and integral fluence detectors in the Northwest Large In-Pile Tube (NW LIPT) flux trap (the largest irradiation facility in the ATRC). Flux detector testing started in October 2010. Activation foils were irradiated in various fuel element cooling channels and in the NW LIPT in conjunction with real-time flux detectors (e.g., SPNDs and fission chambers) in the N-16 positions. Additional fixturing is being developed that will allow simultaneous evaluations of two or more sensors in the NW LIPT and further activation foil irradiations in the Southeast In-Pile Tube.

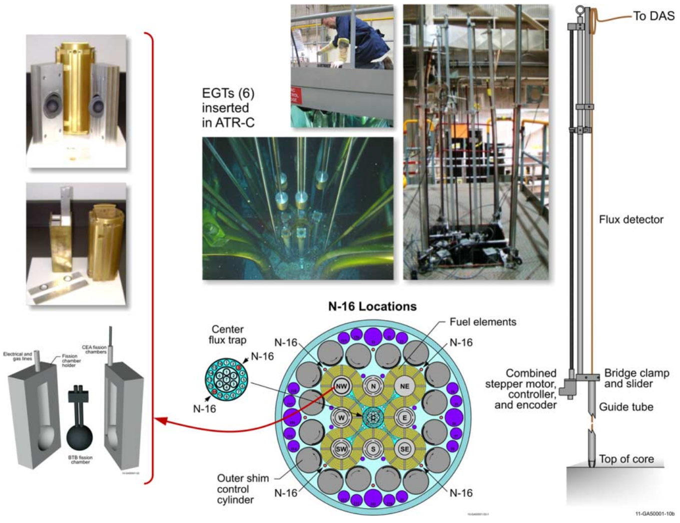


Fig. 14. Specialized fixturing for flux detector evaluation in the NW LIPT (left) and EGTs for evaluations in six N-16 positions (right).

For testing, flux sensors are placed in tinted Lucite tubes to prevent any unwanted leakage of component materials (if they are not leak-tight) and to reduce unwanted noise from having sensor cabling in contact with metal surfaces. As shown in Fig. 14, sensors are inserted into the ATRC N-16 positions using specially-designed Experiment Guide Tubes (EGTs). The EGTs are primarily fabricated from aluminum to minimize their weight. However, selected components, such as the guide tube, are made from stainless steel 304. As illustrated in Fig. 14, the six EGTs mechanically position detectors at a specified vertical location in the four N-16 exterior positions and two Center Flux Trap N-16 positions. The position control and detector response are controlled and measured via LabView to allow all detectors to either individually or simultaneously move and measure the local neutron flux and provide a 3-dimensional measurement of the overall neutron flux. The EGTs are supported above the reactor by attaching to the reactor control bridge.

Tests are performed for three different critical configurations of the outer shim cylinders: balanced; tilted toward the NW flux trap; and tilted away from the NW flux trap. For each configuration, measurements are obtained for at least four intermediate power levels between 1 milliwatt and 600 W. At 600 W, axial flux measurements are obtained by varying detector positions using the EGTs. The response and accuracy of each type of flux detector is compared. In addition, data obtained from real-time flux sensors are compared to results from activation analysis.

Ultimately, results of this effort will be used to select the detector that can provide the best online regional ATRC power measurement. It is anticipated that this may also offer the potential to allow the ATRC to better replicate the ATR by operating in similar lobe power splits, provide 'ATRC flux run' data in minutes versus days and enhance its ability to perform low-level irradiation experiments using the specialized fixturing and software developed in this project. In addition, the data should provide insights about the viability of using these detectors in the ATR. Hence, this effort complements current activities to improve ATR software tools, computational protocols and in-core instrumentation under the ATR Modeling, Simulation and Verification & Validation Upgrade initiative, as well as the work to replace nuclear instrumentation under the ATR Life Extension Project (LEP) and provide support to the ATR NSUF. In addition to real-time flux detectors needed for ATR and ATRC testing, there is significant (e.g., up to 30%) uncertainty associated with real-time flux detector data. Hence, tasks performed in this effort offer significant benefit to MTRs because of the new capability that will be available to 'calibrate' flux detectors for precise flux measurements.

III. CONCLUSIONS

As outlined in this paper, efforts continue at INL to develop and obtain new sensors for measuring key parameters (e.g., temperature, length, diameter, etc.) during irradiation testing at the ATR. Initial efforts are focusing on sensors that can provide data needed for ATR NSUF users and on 'lower risk" technologies that are already deployed at other MTRs. These initial efforts have led to three new or enhanced sensors becoming available to ATR users: the doped Mo/Nb HTIR-TCs, silicon carbide temperature monitors, and enhanced melt wire selection and encapsulation options. During 2012, it is anticipated that efforts to evaluate a creep test rig in an autoclave at the HTTL will yield a fixture ready for deployment in an ATR PWR loop. In addition, laboratory evaluations of an in-pile technique for detecting changes in thermal conductivity are continuing, and an evaluation of conductivity probe performance in an MITR fuel irradiation will be completed in 2012. In 2010, efforts were initiated to evaluate the viability of using miniature fission chambers developed by CEA and other flux detection systems (e.g., SPNDs) at the ATRC. Although not described in this paper, efforts have also been initiated to explore 'advanced' technologies, such as fiber optics and ultrasonic techniques, for in-pile detection of elongation and temperature. Ultimately, it is anticipated that these advanced technologies can be used to gain insights related to changes in fuel microstructure during irradiation testing.

REFERENCES

[1] FY2009 Advanced Test Reactor National Scientific User Facility User's Guide, INL/EXT-07-13577, Idaho National Laboratory, 2008.

[2] J. Rempe, D. Knudson, K. Condie, J. Daw, and S. C. Wilkins, "New sensors for in-pile temperature measurement at the advanced test reactor national scientific user facility," *invited paper, NURETH13 Special Edition, Nucl. Technol.*, vol. 175, pp. 681–691, Sep. 2011.

[3] Standard Guide for Use of Melt Wire Temperature Monitors for Reactor Vessel Surveillance E706 (IIE), ASTM E 1214-06, Feb. 13, 2006.

[4] L. L. Snead, A. M. Williams, and A. L. Qualls, "Revisiting the use of SiC as a post-irradiation temperature monitor," in *Effects of Radiation on Materials*, M. L. Grossbeck, Ed. West Conshohocken, PA: ASTM Int., 2003, ASTM STP 1447.

[5] J. L. Rempe, K. G. Condie, D. L. Knudson, and L. L. Snead, "Comparison measurements of silicon carbide temperature monitors," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 3, pp. 1589–1594, Jun. 2010.

[6] J. L. Rempe, D. L. Knudson, K. G. Condie, and S. C. Wilkins, "Long duration performance of high temperature irradiation resistant thermocouples," in *Proc. Int. Congress Advances in Nuclear Power Plants*, Nice, France, May 13–18, 2007.

[7] J. L. Rempe, D. L. Knudson, K. G. Condie, J. E. Daw, H. Ban, B. S. Fox, and G. E. Kohse, "New sensors for the advanced test reactor national scientific user facility," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 5, pp. 2653–2661, Oct. 2010.

[8] J. L. Rempe, M. K. Meyer, D. L. Knudson, K. G. Condie, J. E. Daw, and S. C. Wilkins, "ATR NSUF Instrumentation Enhancement Efforts," *invited paper, NPIC HMIT Special Edition, Nucl. Technol.*, vol. 173, pp 66-77, Jan. 2011.

[9] D. L. Knudson, J. L. Rempe, K. G. Condie, S. C. Wilkins, J. E. Daw, and J. C. Crepeau, "High temperature irradiation resistant thermocouples—A low cost sensor for in-pile testing at high temperatures," presented at the Int. Congress Advances in Nuclear Power Plants, Anaheim, CA, Jun. 8–12, 2008, Paper 8222.

[10] J. L. Rempe, D. L. Knudson, K. G. Condie, S. C. Wilkins, J. C. Crepeau, and J. E. Daw, "Options extending the applicability of high temperature irradiation resistant thermocouples," *invited paper for NURETH12 Special Edition, Nucl. Technol.*, vol. 167, pp. 169-177, Jul. 2009.

[11] J. E. Daw, J. L. Rempe, D. L. Knudson, S. C. Wilkins, and J. C. Crepeau, "High temperature irradiation-resistant thermocouple performance improvements," in *Proc. Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies Topical Meeting*, Knoxville, TN, Apr. 2009.

[12] J. Daw, J. Rempe, K. Condie, D. Knudson, S. C. Wilkins, B. Fox, and H. Ban, "Hot wire needle probe for in-pile thermal conductivity detection," in *Proc. 7th Int. Topical Meeting Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies*, Las Vegas, NV, Nov. 7–11, 2010.

[13] ASTM D 5334-08, "Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe Procedure," approved 2008.

[14] S. Solstad and R. Van Nieuwenhove, "Instrument capabilities and developments at the Halden reactor project," *Nucl. Technol.*, vol. 173, pp. 78–85, Jan. 2011.

[15] D. Knudson and J. Rempe, "Recommendations for use of LVDTs in ATR High Temperature Irradiation Testing," in *Proc. 7th Int. Topical Meeting Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies*, Las Vegas, NV, Nov. 7–11, 2010.

[16] T. Unruh, J. Rempe, D. Nigg, P. Hart, G. Imel, J. Harris, and E. Bonebrake, "Flux sensor evaluations at the ATR critical facility," in *Proc. 7th Int. Topical Meeting Nuclear Plant Instrumentation, Control, and Human Machine Interface Technologies*, Las Vegas, NV, Nov. 7–11, 2010.