INL/CON-13-28029
PREPRINT

Advanced In-Pile Instrumentation for Materials Testing Reactors

ANIMMA 2013

J. L. Rempe
D. L. Knudson
J. E. Daw
T. C. Unruh
B. M. Chase
K. L. Davis
A. J. Palmer
R. S. Schley

June 2013

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Idaho National Laboratory

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***Abstract*— The US Department of Energy sponsors the Advanced Test Reactor (ATR) National Scientific User Facility (NSUF) program to promote U.S. research in nuclear science and technology. By attracting new research users - universities, laboratories, and industry - the ATR NSUF facilitates basic and applied nuclear research and development, advancing U.S. energy security needs. A key component of the ATR NSUF effort is to design, develop, and deploy new in-pile instrumentation techniques that are capable of providing real-time measurements of key parameters during irradiation. This paper describes the strategy developed by the Idaho National Laboratory (INL) 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. As reported in this paper, INL staff is currently involved in several tasks to deploy real-time length and flux detection sensors, and efforts have been initiated to develop a crack growth test rig. Tasks evaluating 'advanced' technologies, such as fiber-optics based length detection and ultrasonic thermometers are also underway. In addition, specialized sensors for real-time detection of temperature and thermal conductivity are not only being provided to NSUF reactors, but are also being provided to several international test reactors.**

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

I. Introduction

The Advanced Test Reactor (ATR) National Scientific User Facility (NSUF) facilitates basic and applied nuclear research and development, further advancing U.S. energy security needs.[1] A key component of the ATR NSUF is to design, develop, and deploy new in-pile instrumentation techniques for measuring key parameters during irradiation. This paper describes the strategy for identifying instrumentation needed for 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. Typical Irradiation Options

The ATR NSUF now includes several Materials Testing Reactors (MTRs), including the ATR at the Idaho National Laboratory, the Massachusetts Institute of Technology Research Reactor (MITR), the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL), and the PULSAR reactor at North Carolina State University [1]. Each MTR design differs dramatically. However, typical MTR irradiation options are listed below with typical types of instrumentation that can be included in each option.

- *Static Capsules* – These capsules may be used to irradiate samples or engineered components. Static capsule experiments may be sealed or may contain material that can be in contact with MTR primary coolant (such capsules are in an open configuration without being sealed). Instrumentation in such irradiation locations is currently limited to sensors that detect peak temperature or neutron fluence.
- *Instrumented Lead Experiments* - In these locations, 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. In addition to thermocouples for monitoring 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 or by gamma spectrometry of temperature control gases exiting the capsules. Leads extending from sensors in these locations allow real time display of experimental parameters on control consoles.
- *Pressurized Water Loop Experiments* - Many MTRs have flux traps equipped with pressurized water loops for fuels and materials testing. These water loops can be operated at different temperatures, pressures, flow rates, and water chemistry conditions. Often, these loops operate at or above the standard temperature and pressure of commercial pressurized water reactor (PWR) or boiling water reactor (BWR) power conditions. Water loops can be instrumented to measure and control coolant flows, temperatures, pressures, and other parameters.
- *Hydraulic Shuttle Irradiation System (HSIS)* - The ATR HSIS is a hydraulic "rabbit" and enables rapid insertion and removal of experiment specimens while an MTR is operating. Instrumentation in a rabbit, such as the ATR HSIS, is limited to sensors that detect peak temperature or neutron fluence.

The 250 MWth ATR includes all of the above irradiation options and offers a maximum unperturbed thermal neutron flux of 1×10^{15} n/cm^2-s and a maximum fast neutron flux of 5×10^{14} n/cm^2-s. The HFIR and MITR also offer several high flux irradiation test positions. With additional in-pile

Manuscript received May 26, 2013. Work supported by the U.S. Department of Energy, Office of Nuclear Energy, Science, and Technology, under DOE-NE Idaho Operations Office Contract DE AC07 05ID14517.

J. L. Rempe*, D. L. Knudson, J. E. Daw, T. C. Unruh, B. M. Chase, K. L. Davis, A. J. Palmer, and R. S. Schley are with the Idaho National Laboratory, P.O. Box 1625, MS 3840, Idaho Falls, ID, 83415, USA *(phone: 208-526-2897; fax: 208-526-2930; e-mail: Joy.Rempe@inl.gov).

instrumentation to support such testing capabilities, the features offered by ATR NSUF facilities can be even more fully utilized.

B. Sensor Development Effort Status

A key component of the ATR NSUF effort is to design, develop, and deploy new in-pile instrumentation techniques capable of measuring key parameters during irradiation. At the start of this effort, a review was completed to identify instrumentation available to users at international MTRs. Table I presents an updated version of results from this initial review that reflects recent INL activities to develop and deploy new in-pile sensors [2].

TABLE I
INSTRUMENTATION AVAILABLE AT ATR AND OTHER MTRS

Parameter	Location			ATR Technology	Proposed Advanced Technology	
	Static Capsule/Rabbit	**Instr. Lead**	**PWR Loop**		**Available at Other MTRs**	**Developmental**
Temperature	√	√	√	-**Melt wires** (peak temperature)[a,b] -**SiC Temperature Monitors** (peak temperature for range of values)	-Paint spots (peak)	
		√	√	-Thermocouples (Type N, K, C,[c] and **High Temperature Irradiation Resistant Thermocouples (HTIR-TCs)**)		*- Fiber optics* -Noise thermometry *-Ultrasonic thermometers (UTs)*
Thermal Conductivity		√	√	**-Transient Hot Wire Method (THWM) techniques**	-Degradation using signal changes in thermocouples	
Fluence/Flux (neutron)	√	√	√	**-Flux wires and foil dosimeters** [b]		
		√	√		*-Self-Powered Neutron Detectors (SPNDs)* *-Subminiature/ miniature fission chambers*	*-Micro-Pocket Fission Detectors (MPFDs)*
Gamma Heating		√	√		-Calorimeters *-Gamma thermometers* *-Self-Powered Gamma Detectors (SPGDs)*	
Dimensional		√	√	**-Linear Variable Differential Transformers (LVDTs)**	-Diameter gauge -Hyper-frequency resonant cavities	*-Ultrasonic techniques* *-Fiber optics*
Fission Gas (Amount, Composition)		√	√	- Gas Chromatography - Pressure Sensors - On-line Fission Product Monitoring - Sampling	-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			√		-Diameter gauge with neutron detectors and thermocouples	
Crack Growth Rate			√		*-Direct Current Potential Drop (DCPD) Techniques*	

[a] Blue italic text denotes instrumentation being investigated for ATR applications; red bold text denotes new instrumentation deployed at the ATR or for which lab testing has been completed for deployment.
[b] Although melt and flux 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.
[d] Type C thermocouple use requires a "correction factor" to correct for decalibration during irradiation.

Several international programs [3], such as the Institute for Energy Technology at the Halden Reactor Project (IFE/HRP) have maintained their instrumentation development and evaluation research capability to support irradiation testing at the Halden Boiling Water Reactor (HBWR) and other MTRs. The Japan Atomic Energy Agency (JAEA) and Studiecentrum voor Kernenergie • Centre d'Étude de l'énergie Nucléaire (SCK•CEN) also offer a suite of instrumentation to users performing irradiations in their MTRs. The Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA), which supports the existing OSIRIS MTR and the new Jules Horowitz MTR, not only offer users a suite of instrumentation, but are rapidly trying to increase their capabilities. If the US MTRs within the ATR NSUF are to be competitive, enhanced instrumentation must be made available to users.

The instrumentation initially developed by INL was primarily selected based on anticipated user needs and "technology readiness" (to provide users needed instrumentation as soon as possible). For example, many international MTRs have sensors available for real-time detection of parameters such as neutron flux (thermal and fast). As indicated by the blue italic text in Table I, efforts are underway to explore using these technologies at the ATR and other US MTRs. However, adapting instrumentation used at lower power MTRs often requires special considerations because of the harsher irradiation conditions (e.g., higher neutron fluxes, higher temperatures, etc.) and test capsule geometries requested by users at US MTRs, such as ATR.

As indicated by the red bold text in Table I, several new or enhanced sensors are now available to users at ATR and other MTRs as a result of this instrumentation development effort. The ultimate goal of this effort is to provide ATR users sensors for detecting all of the parameters listed in Table I. INL sensor development and evaluation activities rely heavily on collaborations with other research organizations, such as IFE/HRP and CEA, to maximize the benefit from research expenditures. In addition, several collaborations have been initiated with universities possessing specialized capabilities in sensor development and evaluation areas. Section II of this paper highlights progress in sensors for detecting four types of parameters: temperature, thermal conductivity, elongation, and flux. Progress in other areas is reported in [2].

II. Representative Development Efforts

Selected examples of efforts to develop new methods for detecting temperature, thermal conductivity, geometry, crack growth, and flux during ATR irradiations are summarized in this section. In addition, efforts to deploy ultrasonic and fiber optic-based sensors are reported.

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 now available for all irradiation facilities. As discussed in [4,5,6], INL now has an established melt wire library with materials ranging from ~85 to 1455 °C, quartz and metal tube encapsulation methods, and documents describing pre-test evaluations of encapsulated melt wires to evaluate suitability prior to post-irradiation examinations (see Fig. 1). INL also has a verified capability for annealing and measuring electrical resistivity of irradiated SiC temperature monitors[7,8], which can be used for a temperature range of 200 to 800 °C.

For high temperature, long duration irradiations, real-time temperature data can be obtained using doped molybdenum/niobium alloy High Temperature Irradiation Resistant Thermocouples (HTIR-TCs) that were developed for instrumented lead and pressurized water loop applications. Evaluations [9, 10] indicate that these thermocouples resist degradation associated with transmutation in an irradiation test and survive high temperatures up to 1800 ºC. All of these temperature sensors (and other INL-developed sensors) are available to users at ATR NSUF facilities. In addition, other MTRs may obtain such sensors from INL. The INL has also provided four HTIR-TCs to the IFE/HRP for use in the Halden Boiling Water Reactor (HBWR) (see Fig. 3) [11]. As discussed in [12,13], INL is exploring the use of ultrasonic thermometers (UTs) for temperature detection. UTs are advantageous because a single small diameter (down to 1 mm) probe can be used to obtain a temperature profile along the length of specimen(s).

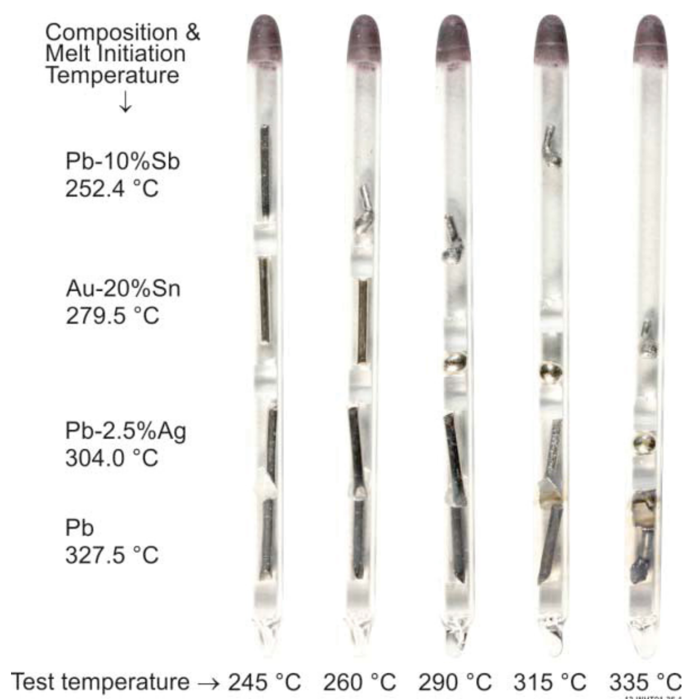

Fig. 1. Quartz tube containing four melt wires in separated compartments (after heating tests to evaluate suitability as a temperature indicator).

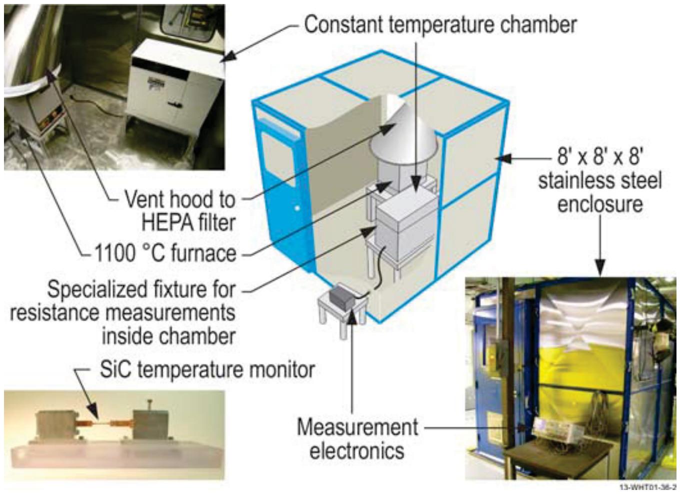

Fig. 2. Setup to anneal and measure electrical resistivity of SiC temperature monitors.

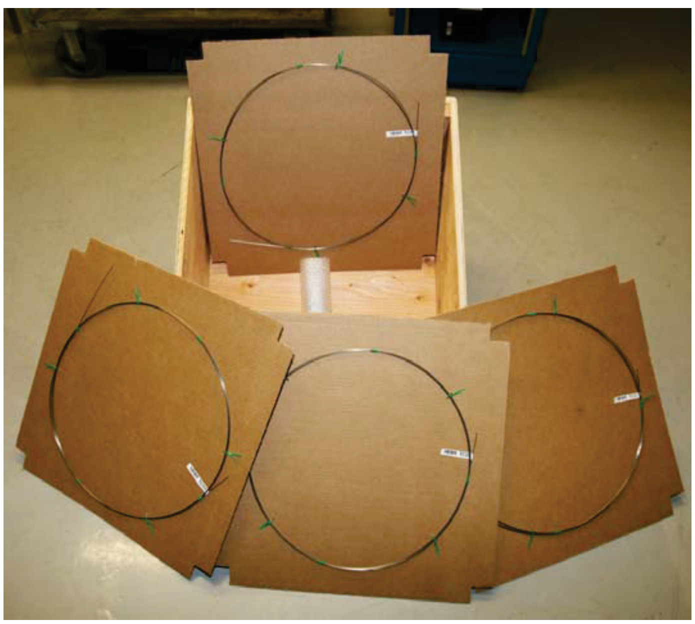

Fig. 3. HTIR-TCs prior to shipment to IFE/HRP.

B. *Thermal Conductivity*

Currently, changes in fuel or material thermal conductivity during irradiation are evaluated in MTRs by considering steady-state changes in heat flux based on centerline temperature measurements or by post-irradiation evaluations [3]. However, as part of a collaborative effort to develop an in-pile thermal conductivity measurement technique, Utah State University (USU) and INL have developed a transient hot wire method needle probe (THWM NP) based on an ASTM D standard [14]. In the THWM NP approach, thermal conductivity is determined from the transient temperature rise in the sample when an internal heat source is energized. From a condition of thermal equilibrium, the probe heater 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 inferred from the temperature rise detected in the sample. Following a brief transient period, a plot of temperature versus the natural logarithm of time becomes linear, as shown in Fig. 4 (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.

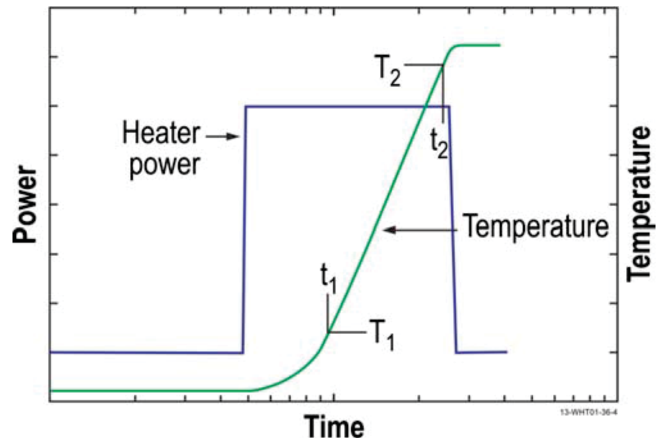

Fig. 4. Semi-log temperature rise plot for transient methods.

THWM NPs containing a line heat source and a thermocouple (see Fig. 4) embedded in a solid insulator, were designed and fabricated by INL for both room temperature proof-of-concept evaluations and high temperature testing. Results [15,16] indicate that the THWM NP offers an enhanced method for in-pile detection for thermal conductivity. Using the setup shown in Fig. 5, THWM NPs measured the thermal conductivity of fused silica, the ASTM recommended reference material, within 2% of accepted values at temperatures of 20 ºC, 250 ºC, 400 ºC, and 600 ºC. 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 [16]. However, test results indicate that special considerations are needed for high thermal conductivity sample materials and for smaller diameter samples. Methods were explored to reduce the challenges associated with such samples, primarily techniques that could reduce signal noise and allow better characterization of the probe response time. In addition, results from long term evaluations indicate that the INL-developed THWM NP for in-pile detection of thermal conductivity is a robust sensor that could survive in the harsh environments associated with in-pile fuel testing. Currently, INL is fabricating THWM NPs, which at this time are solely produced by INL, for evaluations by IFE/HRP and CEA.

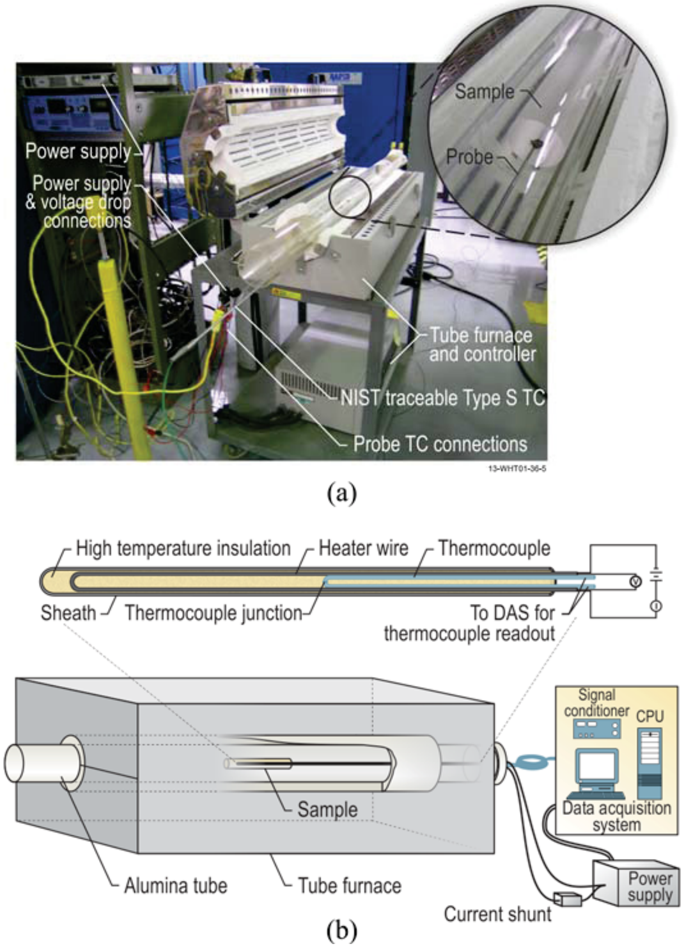

Fig. 5. Setup for evaluating transient hot wire needle probe.

C. *Dimensions*

For decades, the IFE/HRP has successfully developed and deployed LVDT-based test rigs at the Halden Boiling Water Reactor (HBWR) and other MTRs [2]. IFE/HRP test rigs enable on-line measurement of sample elongation and diameter changes for assessing phenomena, such as tensile strength and cladding creep, fuel pellet-cladding mechanical interaction, fuel creep / relaxation, and fuel rod crud deposits. However, none have been deployed at the high flux levels that exist at US MTRs. INL evaluations [17,18,19] suggest that temperatures in higher gamma fields may lead to inaccuracies because of Curie temperature effects associated with the nickel/copper alloy wires used in the IFE/HRP LVDTs.

To address this concern, nuclear-grade LVDTs from US and foreign sources were evaluated as candidates for in-pile deployment. These evaluations, which included calibration assessments and long duration, high temperature testing, clearly indicated the superiority of LVDTs supplied by the IFE/HRP. However, evaluations indicated that Curie temperature effects, due to the nickel contained in the LVDT coil material, have the potential to affect accuracy near 360 °C. Consequently, use of these LVDTs could be an issue depending on the in-core position of the sensor and the corresponding gamma heating levels. For that reason, INL worked with IFE/HRP to develop and evaluate enhanced LVDTs with an alternate coil material that is not susceptible to the Curie effect. Calibration and long term high temperature testing of these enhanced LVDTs, which was performed by INL, demonstrate that the enhanced LVDTs can operate in a very stable manner for long periods (1000 h) at high temperatures (500 °C). Hence, these enhanced LVDTs are being implemented for ATR NSUF high temperature irradiation tests.

An in-situ creep test rig that includes this new LVDT has been designed for testing in ATR PWR loops (see Fig. 6). An initial prototype of this test rig, which applies a load to specimens based on the coolant pressure and temperature in which the test rig is placed, was evaluated in an autoclave, and an optimized version was fabricated for deployment in an ATR coolant loop.

The initial test rig design developed by INL is limited in that it can only apply a load that corresponds to the external pressure of the coolant in the ATR PWR loop. Although it is unlikely that the primary damage experienced by a specimen will be affected by the applied stress during irradiation, the subsequent process of dislocation formation, that is responsible for radiation hardening, yield drop, and plastic flow localization, will be substantially altered by the applied stress. Furthermore, it is speculated that the fatigue lifetime during in-situ cyclic loading experiments may be significantly different from the ones obtained during fatigue experiments on specimens in the post-irradiated condition. Hence, INL is now developing an enhanced in-situ material creep testing system for inclusion in PWR loops that has the ability to apply a variable load to a specimen (see Fig. 7).

This new design is being developed for testing in reactor coolant at PWR conditions and includes provisions for internal pressurization of the bellows via a pressurization tube as shown in Fig. 7. Current efforts are focused on developing processes and parameters for fabricating this test rig. During 2013 its performance will be evaluated in an autoclave. After evaluations are complete, it will also be available for deployment using the same ATR PWR Loop test frame developed for the initial creep test rig design.

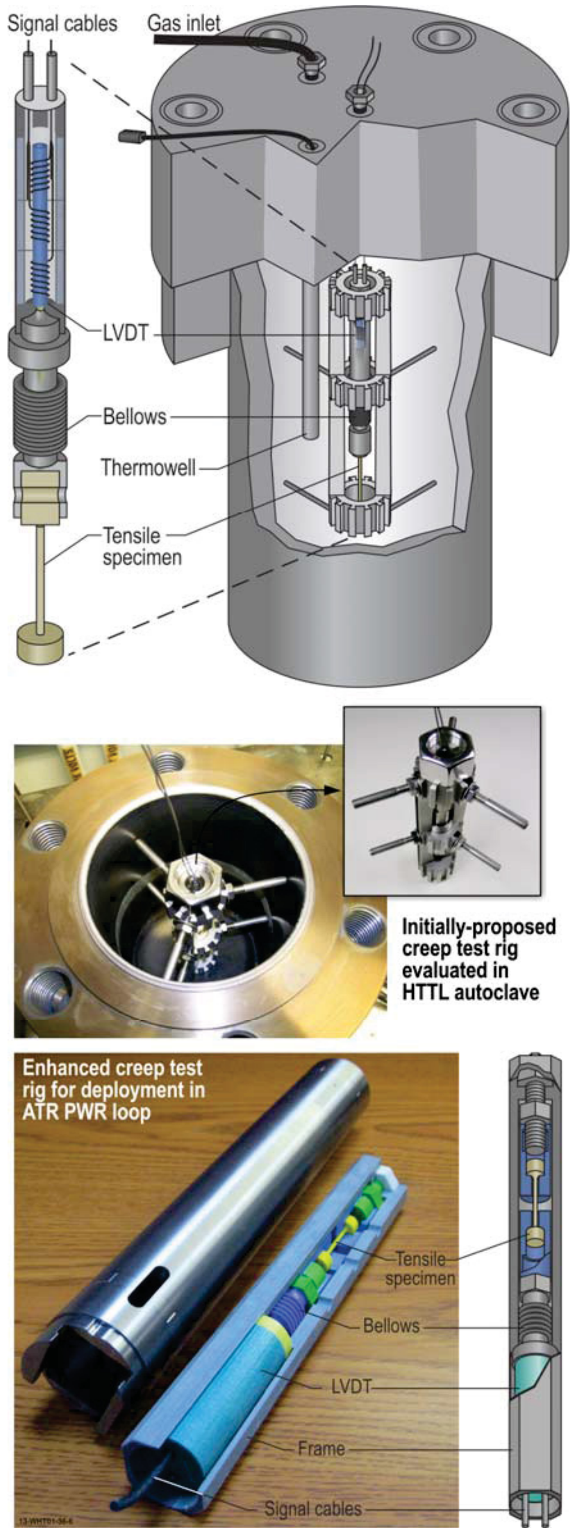

Fig. 6. Creep test rig evaluated with autoclave testing and enhanced design to be deployed in ATR PWR loop.

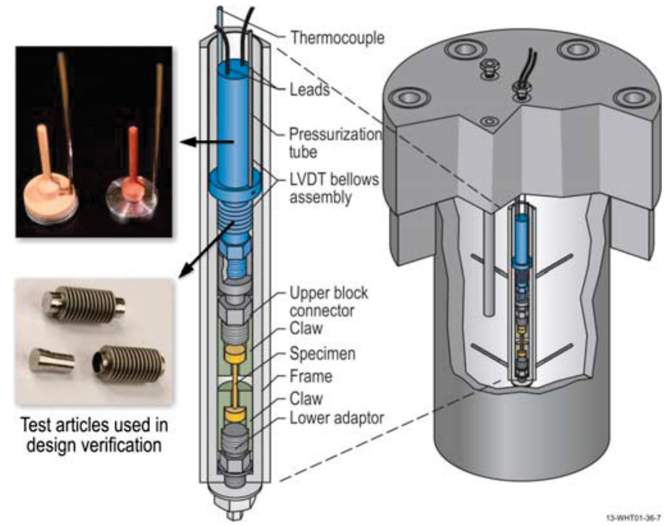

Fig. 7. Variable load creep test rig component fabrication activities to prepare for autoclave testing.

D. Crack Initiation and Growth

Crack initiation and growth of samples irradiated in instrumented lead and PWR loop tests in US MTRs are evaluated out-of-pile. However, the Direct Current Potential Drop (DCPD) method, which is based on sending a precisely controlled electrical current through the specimen and measuring the drop in voltage at several locations on the CT-specimen, offers a method for in-pile measurement of crack growth [3]. Because the measured voltage changes as a function of crack growth, the crack-length can be determined from the measured voltages. Several lower flux MTRs have applied the DCPD method in-pile [3]. For example, the IFE/HRP has applied the DCPD method to measure crack growth as a function of coolant parameters (pH, impurities, boron concentration, etc.). In addition, IFE/HRP can perform such measurements on pre-irradiated fuel removed from commercial reactors. Fig. 8 shows the essential features of the in-pile hardware used at HBWR. A loading mechanism is used to stress the crack in a CT specimen. The mechanism utilizes a miniature high pressure bellows, which expands to apply the force required to propagate the crack. The CT specimens are fabricated with "ears" above the loading holes to provide locations for current and voltage connections.

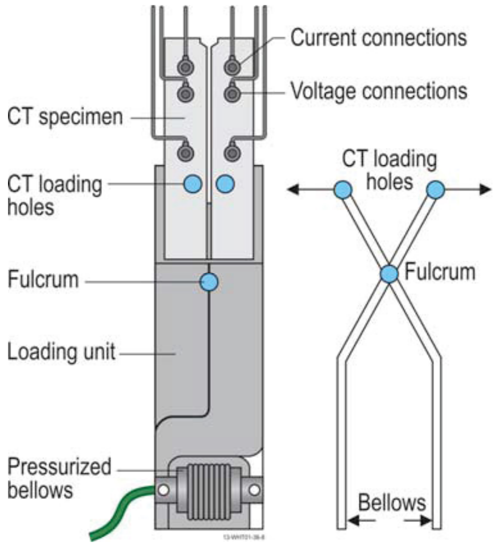

Fig. 8. Essential elements for in-pile implementation of the DCPD method.

Currently, INL and MIT are collaborating on an effort to adapt the DCPD method to high flux US MTRs. As a first step toward implementing this technology, a prototype loading mechanism was constructed at INL based primarily on the HBWR design. Techniques were developed for making laser welds between the miniature bellows and the end fittings used to transfer the loads as shown in Fig. 9. In addition, candidate techniques are being evaluated to optimize processes for connecting the leads to the CT specimens (see Fig. 9). During 2013, laboratory evaluations will be conducted to assess the accuracy of this test rig using autoclaves. Prior to deployment in the ATR, this effort will include an evaluation in the MITR to assess the test rig's performance.

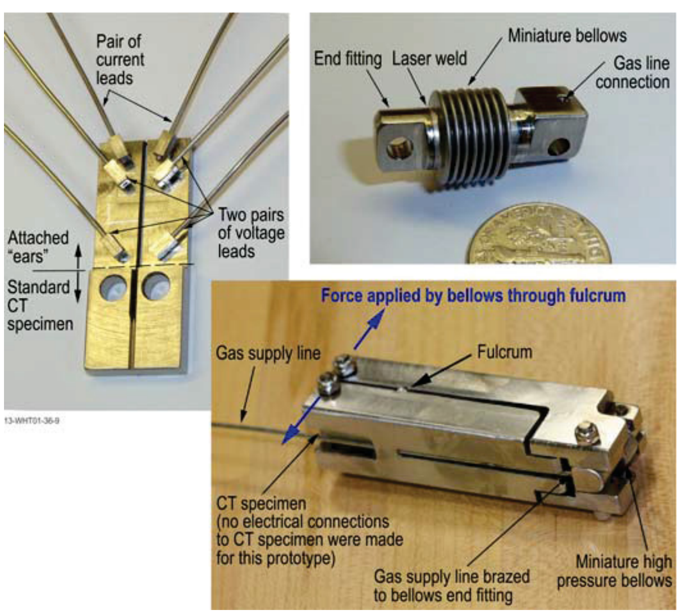

Fig. 9. INL-fabricated hardware for in-pile implementation of the DCPD method.

E. *Flux and Fluence*

INL is involved in several activities to improve flux and fluence monitoring capabilities for US MTRs. With respect to fluence monitoring, INL has access to a range of activation foils and wires, with primary energy response ranging from 1 eV to 6 MeV. In addition, INL developed new methods (see Fig. 10) for encapsulating flux wires in leak-tight vanadium containers with diameters as small as 1 mm.

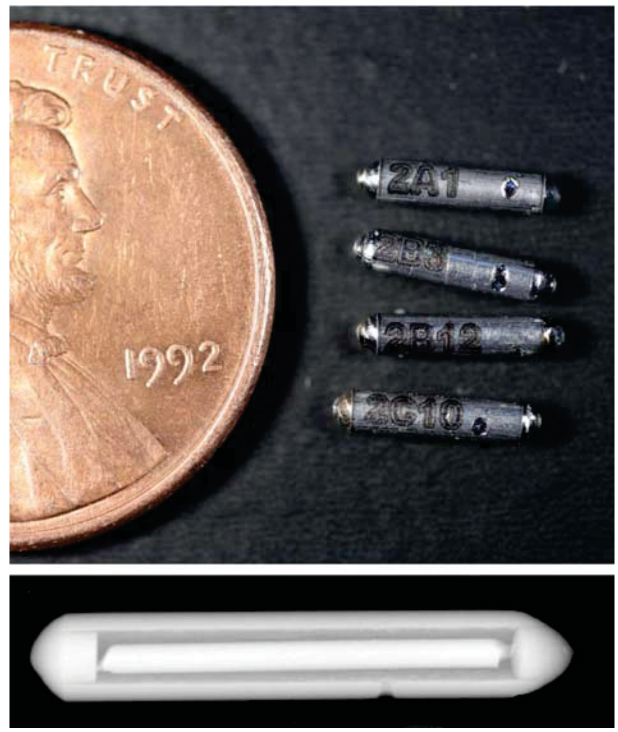

Fig. 10. INL-encapsulated iron flux wires with radiograph.

A joint Idaho State University (ISU)/ INL project is also underway to evaluate new real-time state-of-the-art in-pile flux detection sensors [20]. 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 (BTB) fission chambers developed by Argonne National Laboratory (ANL) for the Zero Power Physics Reactor (ZPPR) programs (see Fig. 11).

Specialized fixturing was designed, fabricated, and installed for evaluating real-time flux detectors in the Advanced Test Reactor Critical (ATRC) facility. Flux detector testing started in October 2010. Activation foils were irradiated in various fuel element cooling channels and in the Northwest Large In-Pile Tube (NW LIPT) in conjunction with real-time flux detectors (e.g., SPNDs and fission chambers) in the six N-16 positions. Additional fixturing has been 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 (see Fig. 12).

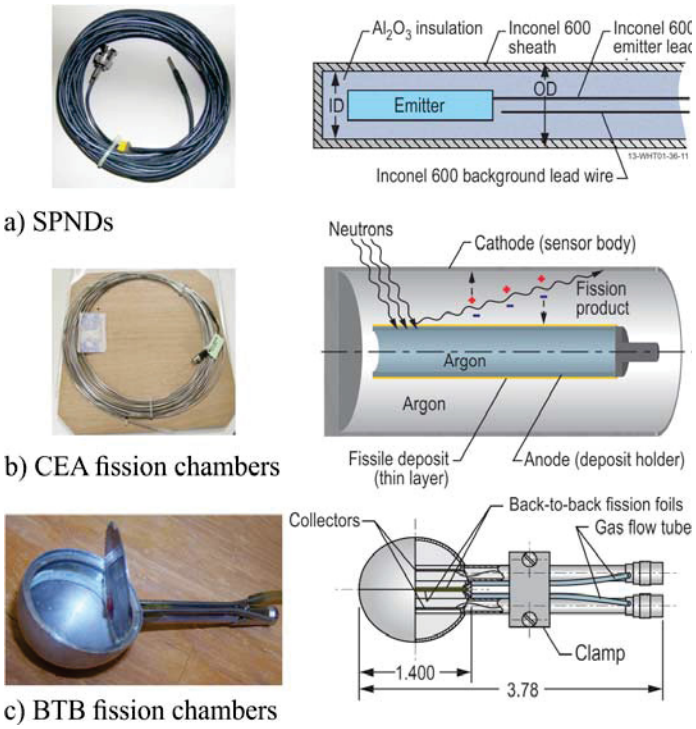

Fig. 11. Representative real-time flux sensors evaluated at ATRC.

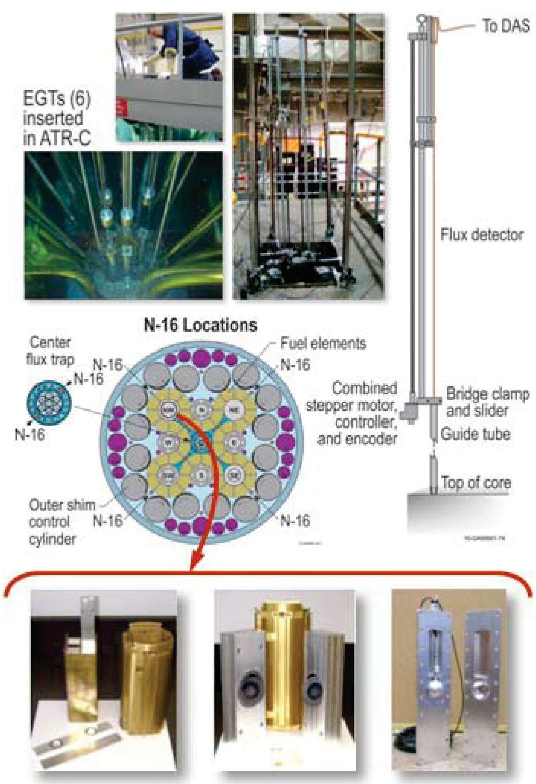

Fig. 12. Specialized fixturing for flux detector evaluation in the NW LIPT (bottom) and EGTs for evaluations in six N-16 positions (top).

Reactor testing in the ATRC requires several of the flux sensors to be shielded from the reactor cooling water. The SPNDs and CEA fission chambers are housed 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. 12, 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. 12, 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. During 2012, specialized fixturing was fabricated that allows a BTB fission chamber to be inserted into the ATRC NW LIPT alongside other real-time flux detectors, such as SPNDs or the CEA fission chambers, to compare responses in nearly identical flux conditions. The water-tight test fixture that will be used to insert these BTB fission chambers into this ATRC location is shown in Fig. 12. Another detector holder was also fabricated that positions three fission chambers across the NW LIPT for assessment of the flux gradient across the flux trap.

Evaluations of these real time flux sensors are expected to be performed in 2013. The tests will utilize three different critical configurations of the ATRC reactor with different power splits across the core. The response and accuracy of each type of flux detector will be compared. In addition, data obtained from real-time flux sensors will be compared to results from previous tests using activation analysis methods. 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.

INL is also collaborating on a joint INL, Kansas State University (KSU), and CEA collaborative task to develop a Micro-Pocket Fission Detector (MPFD). Miniature fission chambers and thermocouples have been used in-pile at research and test reactors throughout the world; however, none have been deployed in a single compact package to survive the harsh conditions that exist in high performance MTRs.

Fission chambers (see Fig. 11b) are typically constructed with two coaxial cylindrical electrodes, one of which has a fissile material deposit that is sensitive to neutron interactions. The gap between the electrodes is filled with a gas, typically argon; and a voltage potential is applied between the electrodes. After a neutron interacts with the fissile material, fission products are ejected into the gas, and a large number of charge pairs are created in the device. These charges are separated and collected at their respective electrode which leads to a current pulse being generated.

MPFDs utilize the same concept, but parallel plate electrodes are included rather than coaxial cylinders (see Fig. 13). Hence, the MPFD has a very small (1 mm diameter) detection area. MPFDs are also unique because of their ability to measure three reactor parameters at very nearly the same location in the reactor core with a single compact detector. MPFDs utilize two miniature parallel plate ionization chambers that contain a deposit of U-235 for thermal flux detection, a deposit of Th-232 for fast neutron detection, and a thermocouple directly above the fission chambers. In addition, MPFDs are constructed from materials that are resistant to radiation and high temperature damage. These qualities make the MPFD an attractive sensor for U.S. MTR users requiring real-time data from experiments.

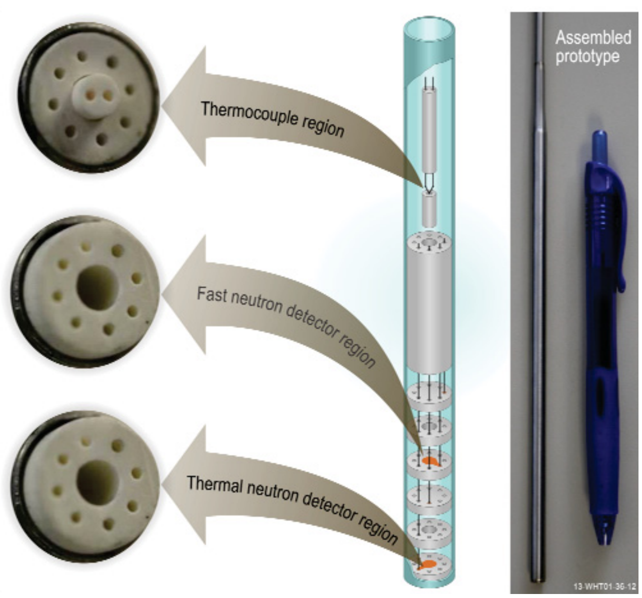

Fig. 13. MPFD (exploded view of components and assembled prototype).

In addition, the MPFD design is set apart from other fission chamber designs because their signal only requires that part of the available fission product energy deposition be captured in the detector. This is opposed to classical fission chambers that require all of the energy be captured for their signal response. This departure from conventional fission chamber design and operating characteristics allows the MPFDs to have a much smaller chamber size with a much lower fill gas pressure. The design has excellent discrimination characteristics because the energy deposited by the fission products is much greater than other types of background radiation interactions in the detector. As another added benefit, the small size allows them to have a faster response time, and thus have the potential to achieve higher count rates than conventional fission chamber designs.

The MPFD development effort consists of two research tasks. The objective for the first task is to develop an enhanced MPFD design and fabricate a prototype in a laboratory setting to ensure that it is leak-tight and that it can withstand high temperature and pressure conditions. Fig. 13 shows components of an initial low-temperature prototype being fabricated. The objective for the second task is to construct an enhanced MPFD prototype with fissile deposits and evaluate its signal in reactor facilities. It is planned that MFPD development and evaluation tasks will be completed by 2014. During 2013, high temperature evaluations and neutron flux evaluations of MPFD prototypes will be performed at INL and KSU. In 2014, simple response testing will be performed at the INL Health Physics Instrument Laboratory (HPIL) neutron and gamma panoramic irradiators and at KSU using their TRIGA Mark II research reactor. Pending funding availability, more complex evaluations will be completed utilizing the specialized ATRC fixturing installed shown in Fig. 12.

E. *Viability Evaluations of Advanced Technologies*

As indicated in Table I, INL initiated several investigations of sensors that rely on advanced technologies, such as ultrasonic and fiber optics based techniques. Prior to deploying such sensors, their survivability in high flux neutron environments must be evaluated. This section reports on INL progress on two of these survivability evaluations: an effort to compare the irradiation performance of ultrasonic transducers and a proposed effort to compare the irradiation performance of fiber optics. Results from these evaluations have the potential to enable the use of a host of new sensors to support irradiation testing in high flux US MTRs.

1) *Ultrasonic Transducer Irradiation*

The objective of this task is to address in-pile implementation issues that apply to all ultrasonic-based sensors. The long and successful history of out-of-pile ultrasonic measurements suggest that ultrasonic-based sensors could be used in-pile for materials and fuels characterization, enabling deployment of ultrasonic sensors for in-pile measurement of fuel and material morphology changes, fission gas composition and pressure measurements, fuel and material geometry changes, and temperature [12,21].

The development of ultrasonic tools to perform a variety of in-pile measurements requires a fundamental understanding of the behavior of ultrasonic transducer materials in high-radiation environments. While a number of irradiation studies of ultrasonic transducers have been described in the literature, prior tests were at lower flux/fluences than typically desired by ATR NSUF users. To address this need, the ATR NSUF announced in 2012 that funding would be provided to support an ultrasonic transducer irradiation proposed by PSU in collaboration with researchers from INL, Argonne National Laboratory, and Pacific Northwest National Laboratory. The irradiation will be performed at the MITR in an irradiation position with a peak thermal flux of $3x10^{13}$ n/cm^2-s and a peak fast flux (E > 1 MeV) of $4x10^{13}$ n/cm^2-s. Temperature control will be afforded by a helium/neon gas gap with adjustable gas composition, and a test temperature target of approximately 350 °C. It is planned that the test will exceed fast neutron fluences of prior piezoelectric transducer irradiations (e.g., > $1x10^{21}$ n/cm^2). In order to observe rapid changes at relatively low fluences, it is proposed to start the test with the reactor coming to power slowly.

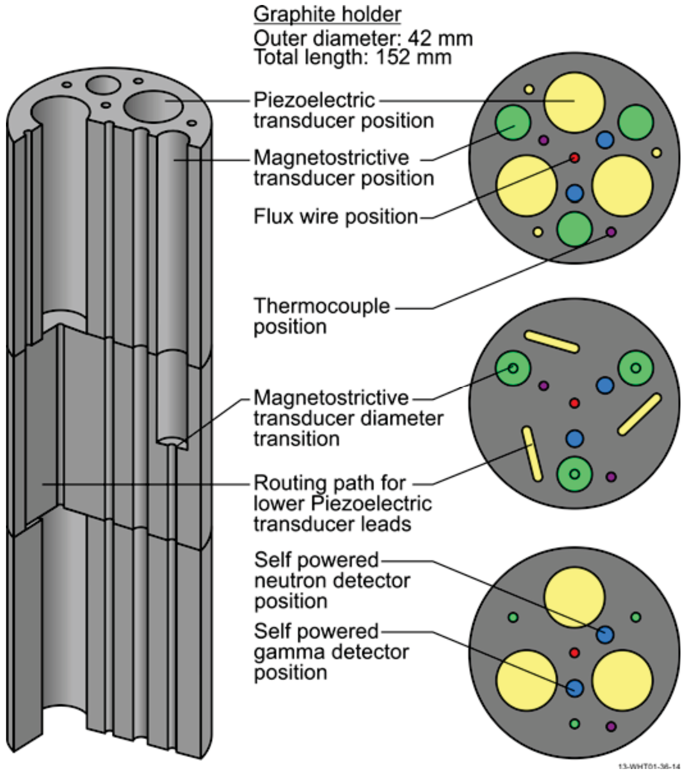

Fig. 14. Initial MPFD components (a) alumina insulators and (b) assembled prototype.

As shown in Fig. 14, the planned capsule design uses structural graphite as a holder material. Based on estimated space requirements for each transducer, it is anticipated that the test will include six piezoelectric samples and three magnetostrictive samples. Instrumentation will be included in this test to allow accurate monitoring of temperature, gamma heating, and both fast and thermal neutron flux. Reference [12] provides additional details about the test conditions, the ultrasonic transducers that will be included, and the planned post-irradiation examinations.

2) Fiber Optics Irradiation

Similar to ultrasonic-based sensors, out-of-pile applications demonstrate that fiber-optic based instrumentation has much to offer with respect to sensor size, accuracy, and resolution. However, prior to deployment, it is important to quantify any degradation that may occur in long duration high temperature irradiation testing in high flux US MTRs. Copper and gold coated fibers are available which can endure long term temperatures in the 600 to 700 °C range. Fiber optic sensing applications in temperatures over 1000 °C have been reported [22], but longevity may only be a few hours. This temperature limitation may preclude the use of optical fibers from in-situ direct fuel measurements. However, temperature capabilities of fiber optic sensors would be sufficient for measurements near the fuel cladding or in cases where the fiber could be used to direct light to or collect light from the fuel surface.

Radiation effects on optical fibers and the probe components are an important issue for the long term survivability of fiber based sensors. A summary of the fiber issues and related research has been reported previously [23]. Irradiation testing of the optical fiber and components is paramount to quantitatively determining the effects on the sensor accuracy and lifetime. A collaborative Ohio State University and INL effort has led to development of a proposal for a fiber optic radiation test. Similar to the currently funded ATR NSUF ultrasonic transducer irradiation test, this instrumented lead test would allow real-time measurement of radiation induced attenuation in several types of optical fibers. If funded, the proposed test would help answer long standing questions on the longevity of optical fiber based sensors in high flux US MTRs.

III. Conclusions

As outlined in this paper, INL is continuing to develop and deploy new sensors for measuring key parameters (e.g., temperature, length, diameter, etc.) during irradiation testing. Initial efforts focus on sensors that can provide data needed for users at US MTRs, such as the ATR, and on "lower risk" technologies that are already deployed at other MTRs. These initial efforts have led to several new or enhanced temperature sensors becoming available to MTR users: the doped-Mo/Nb-alloy HTIR-TCs, silicon carbide temperature monitors, and enhanced melt wire selection and encapsulation options. In addition, a creep test rig is now ready for deployment in a PWR loop; new options are available for flux wires at US MTRs; and the INL-developed thermal conductivity probe is being fabricated for use in foreign fuel evaluations. As described in this paper, several other efforts have been initiated to explore a range of sensors for use in higher flux US MTRs. These efforts not only include enhanced versions of existing sensors that can withstand the higher flux and temperature irradiation conditions requested by users at US MTRs, but also 'advanced' technologies, such as fiber optics and ultrasonic techniques, that will allow high resolution and high accuracy measurements of irradiation test parameters.

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ACKNOWLEDGEMENT

Work supported by the US Department of Energy, Office of Nuclear Energy, Science, and Technology, under DOE-NE Idaho Operations Office Contract DE AC07 05ID14517.