Advanced Sensors and Instrumentation

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ASI Program Update

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What is going on right now in the world is nothing short of unusual and unprecedented. The COVID-19 pandemic has forced us to reinvent the way we do things and adapt to a more remote way of running our lives. We have been able to continue moving forward with our research as best as we can, adjusting schedules and moving most of our meetings and webinars to the virtual room. There is still a lot of uncertainty as what the next few months will bring, but we need to continue to move forward and strive to do our best under the circumstances. Please remember to reach out to us with any questions or concerns.

The Advanced Sensor and Instrumentation (ASI) program mission continues to focus on innovative sensors and instrumentation research that directly supports and enables the sustainability of the current nuclear fleet, the development and deployment of next generation reactor designs, and the advancement of fuel cycle technologies.

One of ASI's FY 2020 accomplishments was to develop a program plan that outlined the ASI mission for the next five years. The four main strategic research and development areas that are addressed in the program plan include: 1) Sensor and Instrumentation; 2) Communication; 3) Advanced Control Systems; and 4) Big Data, Machine Learning, and Artificial Intelligence. Additionally, the plan will provide general information on research goals, challenges, approaches, and benefits. A copy of the program plan will be posted on our website soon.

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Some additional accomplishments that were completed in FY 2020 include:

- A NE Sensor Database (https://nes.energy.gov/), which was created to collect, store, and maintain nuclear plant sensor technology information that would be easily accessed and queried on the web by the sensor user community. This sensor database will provide a mechanism to suggest additional nuclear energy sensors and identify sensors' needs and gaps.
- An ASI website is being developed that will house ASI information on competitive awarded and direct funded projects, annual summaries report, annual review webinar presentations, and bi-annual newsletters. Presentations, videos, poster presentations along with links to relevant sites such as funding opportunities will be available as well. The link will be provided to the Instrumentation and Controls (I&C) community soon.
- Five research and development projects led by DOE national laboratories and U.S. universities were awarded funding for FY 2020. These projects will conduct research to address crosscutting nuclear energy challenges that will help to develop advanced sensors and instrumentation, digital monitoring and control, and nuclear plant communication.

As the ASI program continues to move forward into FY 2021, we encourage the I&C community to visit our website for the current funding opportunity announcements - especially for the recent Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA) that can be found at neup.gov.

Sapphire Single-Mode Fiber Development Towards High-temperature Radiation Resilient Sensors

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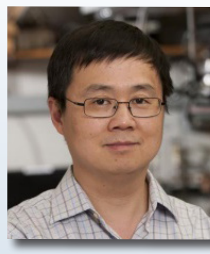

Introduction

Governments across the world face dual pressures to meet increasing electricity demands while decreasing dependency on fossil fuels. In addition to developing renewable energy resources, such as wind, hydro, solar, biodiesel, and ethanol, the United States also needs to develop additional nuclear power generation to meet the continued growth of electricity demand. To ensure public safety and maintain energy security, the new reactors must be significantly safer and more efficient than previous designs. The Gen-IV design initiative is driving the development of the next generation nuclear plants with designs such as the very high-temperature reactor (VHTR), gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), sodium-cooled fast reactor (SFR), and supercritical-water cooled reactor (SCWR) [1]. These reactors will operate at temperatures between 500 and 1200°C. An advantage to high-temperature reactors is that, in addition to electricity production, they provide the required heat to produce hydrogen in large quantities without producing additional CO_2 [2].

In-core fuel and coolant temperature measurements are critical for safe, efficient very high-temperature Gen-IV reactor operation. High accuracy temperature measurements are needed to ensure operation at peak efficiency in high-power density Gen-IV designs. This would also enable the capture of temperature spikes that lead to premature failure of the reactor pressure vessel, fuel modules, containment breach, and possible fission product release. No such low-drift temperature measurement technology exists, which is suitable for the planned very high-temperature (800°C+) Gen-IV reactor designs. Accurate temperature measurements are critical to identify hot spots, control thermal cycles, and perform temperature compensation of other sensors. Thus, Luna Innovations Incorporated (Luna), The Ohio State University (OSU), and the University of Pittsburgh (Pitt) have partnered to advance the development of OSU's patented method for creating an internal cladding in a sapphire optical device [3] toward the production of commercial grade distributed Single-Mode Sapphire Fiber (SMSF) sensors, Figure 1. The United States Department of Energy (DOE) Small Business Innovation Research (SBIR) Phase I award, DE-SC0019834, which funded the work presented here, focused on characterizing the produced SMSF via OSU's method of creating an internal cladding in a sapphire optical device and evaluating the SMSF performance as a temperature sensor separately to 1300°C and to a neutron fluence of 5E+17 n/cm^2

Current state-of-the-art 800°C+ nuclear environment sensors are electrically based and experience significant measurement drift above 1000°C. The SMSF sensor solution presented here has no electrical components within the reactor core, and the integrity of the sapphire crystalline structure that is being interrogated is expected to be stable in excess of 1700°C. The electrical components being completely external to the core provides additional sensor survivability risk management due to the fact that all electrical components can be housed outside of the reactor containment vessel. Additionally, since the sensors are non-conductive, operation in molten-metal cooled systems poses no risk of electronics shorting due to highly conductive molten-metal coolant.

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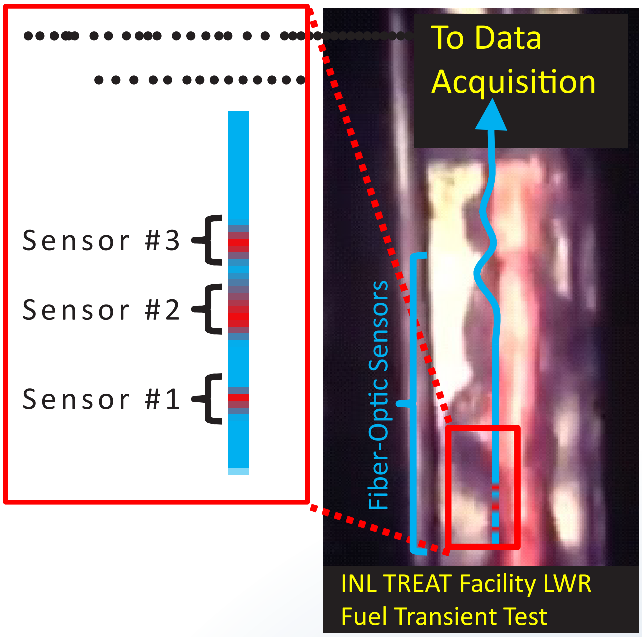

Figure 1. Concept diagram for Sapphire single-mode fiber optic development towards high-temperature radiation-resilient sensors. (Right) a frame from a CEN-224T 450 cal/gm transient test of LWR Fuel in TREAT at INL taken from https://www.youtube.com/watch?v=h0o4P_F4s9s.

Objectives

The overall objective of this effort is to realize a commercial fiber optic sensor technology capable of operating above 1700°C in a high-radiation nuclear environment. The objectives for this program through a Phase II effort are to (1) advance the SMSF technology such that a single fiber sensor containing hundreds of measurement points is cost competitive with traditional high-temperature thermocouples, which only provide a single-point measurement; (2) characterize the fiber modal structure; (3) prove SMSF performance to greater than 1700°C; (4) evaluate sensor performance to a neutron fluence of 2.5E+18 n/cm^2.

Current Status

Luna, OSU, and Pitt successfully completed the "Sapphire Single Mode Fiber Development Towards High Temperature Radiation Resilient Sensors" DOE SBIR Phase I project in the spring of 2020. The Phase I project characterized the SMSF index profile and modal structure and demonstrated independently fs-laser inscribed fiber Bragg grating (FBG) distributed sensor performance to 1300°C and to 5E17 n/cm^2 fluence at the OSU Research Reactor.

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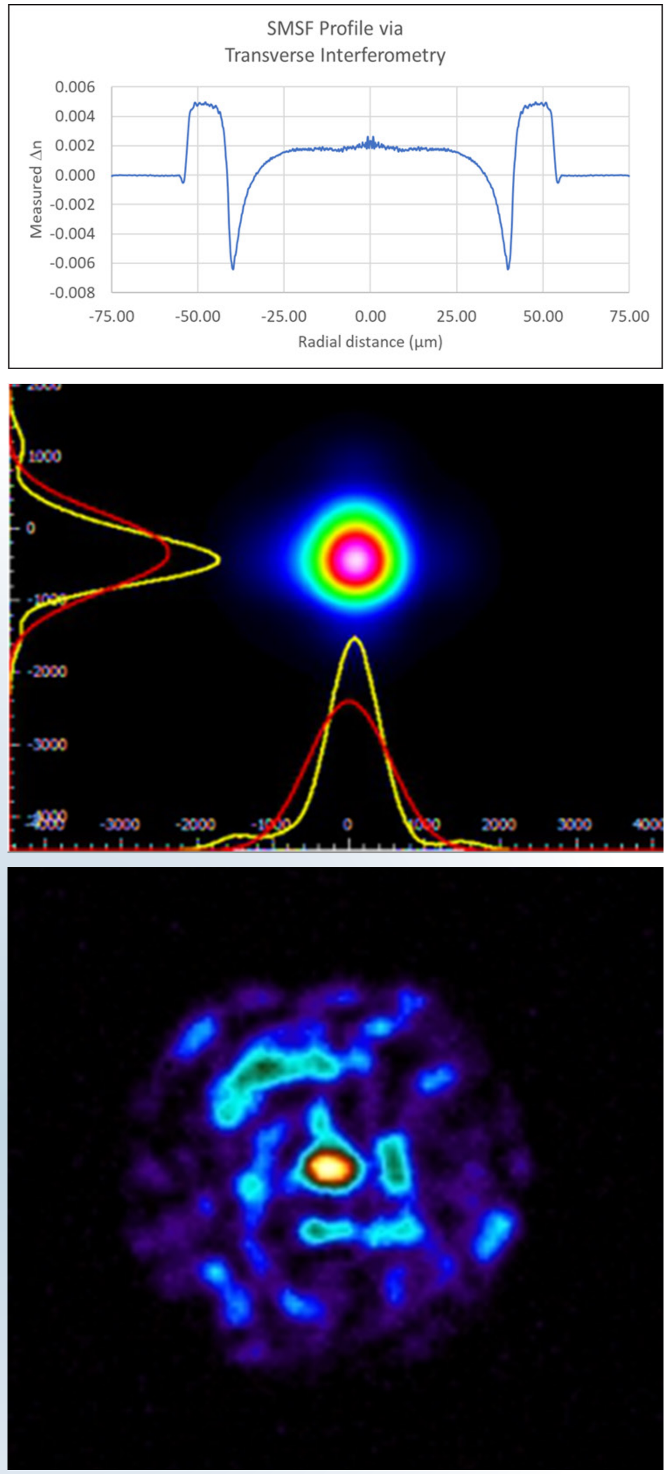

Figure 2. (Top) Interfiber Analysis LLC Transverse Interferometry measurements of SMSF. (Middle) Image of SMSF taken with a ThorLabs BP209-IR Dual Scanning Slit Beam Profiler at OSU. (Bottom) Far field image taken with an IR camera at Pitt.

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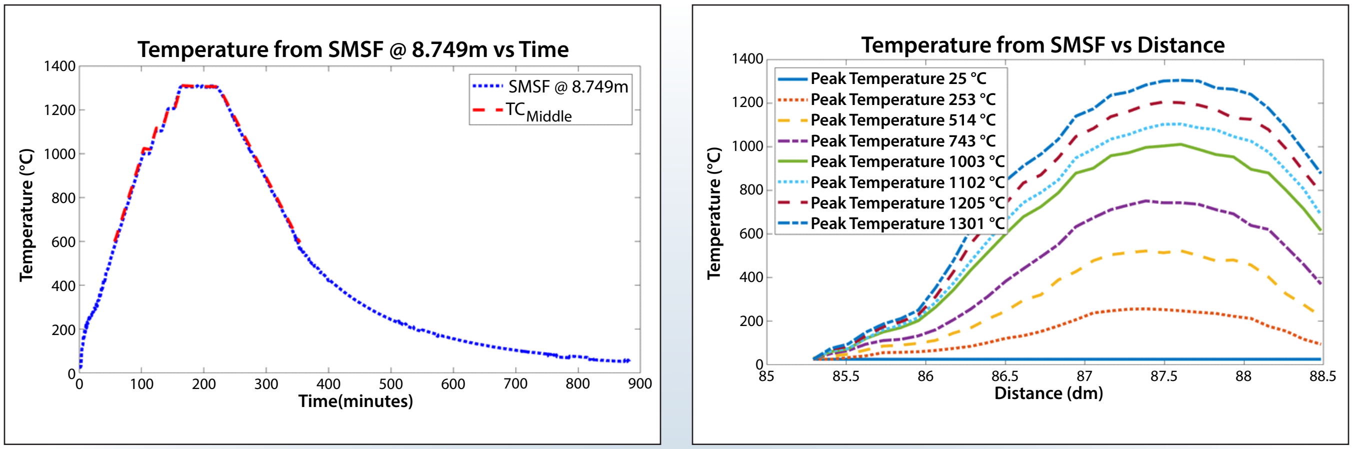

Figure 3. (Left) Temperature determined from spectral shift by a third order fit during descending temperature shift measured by Luna's OBR 4600 versus time at the point of peak furnace temperature is shown in blue. The dotted yellow line is the reading of a type-B thermocouple co-located at this point. (Right) Furnace temperature as a function of distance during several times as determined by the SMSF measurements. There are 30 gauges shown along this length of fiber.

Results

SMSF Waveguide Characterization

The results of index profile measurements of 100 µm SMSF taken by Interfiber Analysis LLC are shown in Figure 2 (top). The graded cladding structure can be seen starting at approximately 25 µm radial distance from the fiber's center, extending outward toward the fiber's surface. The core-cladding index change is approximately 0.008. The structure near the fiber periphery is thought to be due to the non-cylindrical shape of the fiber. Additionally, the magnitude of the core-cladding index change may be affected by the non-cylindrical shape. Both will be investigated for future publication. Figure 2 (Middle and Bottom) show the beam profiles for infrared (IR) laser light transmitted through a section of SMSF measured at OSU and Pitt; both beam profiles show excellent single-mode structure that results from the graded profile shown in Figure 2 (Top).

High-Temperature Testing

We report in this section and the following reactor test section the results for a SMSF with continuous distributed fs-laser inscribed FBGs with 11-mm spacing over a 30-cm region. High-temperature tests were performed at OSU by Luna and OSU researchers in OSU's Micropyretics Heaters International Robust Radiator furnace. After recording optical frequency domain data with a Luna OBR 4600, the spectrum was run through an automated spectral shift analysis program to determine the spectral shift in the fiber with respect to a room-temperature reference. The spectral shift versus thermocouple measurement at the middle of the furnace after 200 minutes (when temperatures had equilibrated at 1300°C) to 354 minutes (600°C) was used with a point added for zero spectral shift correlating to room temperature to determine the best fit calibration coefficients for a third order polynomial correlation function to determine temperature as a function of spectral shift. The data for times 0 to 200 minutes which was not used to determine the model, was used to determine the measurement error. Figure 3 (Top) provides temperature measurements from the SMSF compared to thermocouple (TC) measurements. While the data post-200 minutes is directly correlated with the calibration, the data prior to 200 minutes was not used in determining the calibration coefficients such that, SMSF determined temperatures prior to 20 minutes are independent of the calibration data. The SMSF and co-located type-B thermocouple agree very well, with a full-scale error of approximately 1%. Figure 3 (Bottom) shows the furnace temperature as determined by the SMSF measurements as a function of distance for several points in time as the furnace was heating and cooling. The names in the legend provide the peak furnace temperature determined by the SMSF at the time plotted. There are 30 temperature gauges (FBGs) shown along the length of fiber inside the furnace.

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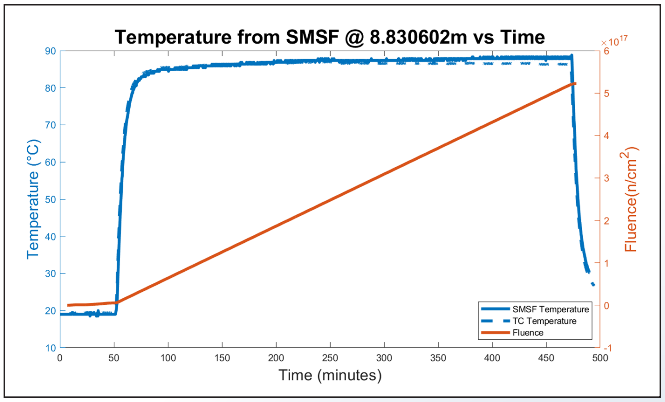

Figure 4. SMSF determined temperature as a function of time irradiated along with collocated thermocouple measurement.

OSU Research Reactor Tests

This test was performed in a similar manner to the temperature test of the previous section. For these lower temperature irradiation measurements, a linear model was used for correlating spectral shift and temperature. During future efforts Luna will work to develop a spectral shift to temperature model for SMSF that minimizes error across the temperature range from 20°C to 1700°C. Figure 4 shows the temperature measurements during irradiation as determined by the SMSF sensor compared to a K-Type thermocouple.

Conclusions

This Phase I research effort validated the single-mode performance of OSUs SMSF and showed excellent sensing performance to 1300°C and to a neutron fluence of 5E17 n/cm^2. The next phase of this program will seek to optimize the performance of SMSF, demonstrate multiple fs-laser written sensing features in SMSF, evaluate SMSF performance to 1700°C+, demonstrate performance to a neutron fluence of 2.5E18 n/cm^2, and develop large-batch production methods to significantly decrease production costs.

References

[1] GEN-IV, "Generation IV Systems," GEN-IV International Forum, https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems, 2019.

[2] INEEL, "Next Generation Nuclear Plant Research and Development Program Plan," INEEL/EXT-05-02581, Idaho National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory, January 2005.

[3] T. E. Blue and B. A. Wilson, "Internal cladding in sapphire optical device and method of making same," United States Patent 10,436,978, October 8, 2019.

Process-Constrained Data Analytics for Sensor Assignment and Calibration

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Introduction

Data analytic methods are being developed to address the problem of how to assign a sensor set in a nuclear facility such that a requisite level of process monitoring capability is realized and that the sensor set is sufficiently rich to determine the status of the individual sensors with respect to need for calibration. There is an awareness in the nuclear industry that data analytics combined with rich sensor sets represent a means to improve operations and reduce costs.

Capability	DD	PB
Immune to operating point change?	N	Y
Diagnosis resolved to specific fault?	N	Y
Rank ordering of likelihood of faults?	N	Y
Applicable to engineering systems?	-	Y
Free of need for library of fault signatures	N	Y
Generates virtual sensors?	N	Y
Adapts upon dropped sensor?	-	Y
Yields component performance index?	N	Y
Supports design of optimal sensor set?	N	Y

Table 1. Advantages of physics-based over data-driven monitoring and diagnostics.

In the utility industry the sensor calibration problem has been approached from an empirical data-driven perspective with several methods having been previously developed. However, the experience of the utilities over the past 10 years with these methods indicates that the absence of physics-based information renders the data-driven approach less reliable. Complicating factors such as the inherent variability of operation (both equipment alignment and operating condition) can confound a pure data-driven approach while there are no rigorous guidelines for determining what constitutes an adequate sensor set. Table 1 summarizes the advantages of a physics-based approach over a data-driven approach.

Algorithm Development

Many of the shortcomings identified can be remedied by including physics in the diagnostic process. This takes the form of a digital twin, which allows specific faults to be identified given an adequate sensor set. A physics-based digital twin is an analytic model constructed from first principles, which may include conservation balances and constitutive relations. It may also incorporate plant historical operating data to augment the analytic relationships and to validate them. A physics-based digital twin has inherent advantages over a data-driven model and is preferred when the additional development effort required is acceptable. These advantages include:

- The ability to estimate unmeasured process variables provides information that can be used to reduce sensor count through the concept of virtual sensors and allows for greater resolution of the state of a system.
- The physics-based twin can be more reliably applied outside the region of nominal calibration.

To differentiate among faults a form of automated reasoning is combined with the digital twin.

Automated reasoning methods provide a formal means for inferring the status of a system given a set of hypothesized relationships among system variables. Each of these relationships is individually held up for inspection as to its validity given measurements of the variables. The relationship between the process variables and fault status is given by the conservation balances for the component as represented by the

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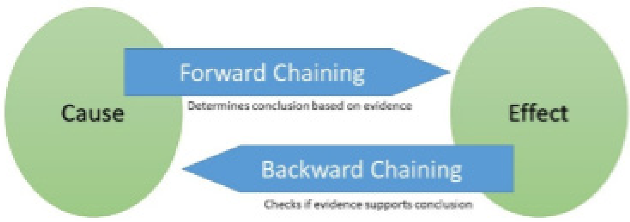

Figure 1. Automated reasoning.

digital twin. The inference regarding system status involves the application of inferential logic illustrated in Figure 1 to determine what the individual truths imply about the overall system.

We are using the above two capabilities to solve for the optimal sensor set to simplify preventative maintenance procedures. This amounts to finding a suitable population of sensors that enable a requisite degree of monitoring capability. Given a list of faults that need to be detected and isolated to a prescribed degree of spatial resolution, the algorithm finds the sensor set that will accomplish this objective at the least cost. It is an inverse problem in the sense that it is the opposite of determining what faults can be diagnosed using an existing sensor set. Instead, determine the sensor set needed to provide a requisite fault diagnosis capability.

Implementation

The digital twin and automated reasoning algorithms are being implemented under the software package PRO-AID (Parameter-Free Reasoning Operator for Automated Identification and Diagnosis) to perform real-time monitoring and diagnostics. The code automatically constructs a digital twin from the fluid system Process and Instrumentation Diagram (P&ID) as provided by the user. The PRO-AID solution to the monitoring and diagnosis problem is unique while its capabilities and ease of use make for the following attractive business case:

- An equipment diagnosis is provided that is consistent with sensor readings and the underlying physics of the faulted plant. A list of candidate faults is not required to be provided a priori.
- Only the plant-specific input contained in the P&ID is required for input, avoiding the need for a subject-matter expert (SME) to construct a detailed model to represent a fluid system.
- PRO-AID operates at the system level rather than at the component level. It can distinguish among process fault-induced perturbations throughout the system to identify the actual faulted component.
- The fault diagnosis is "explainable" and understandable by the system engineer.

The implementation of the optimal sensor set solution involves running PRO-AID repeatedly to minimize a cost function. The set of faults to be diagnosed is drawn up and for each component in the system, eligible locations for sensors are identified. Through repeated runs of PRO-AID, we find that subset of possible system sensors that yield the minimum value of the cost function while successfully diagnosing all the listed faults.

Results

We are working with U.S. utilities to identify systems with reliability issues and related high-value needs for monitoring and diagnostics. Such systems have components that are important to continued plant operation and have high capital costs to replace should degradation leading up to failure not be diagnosed.

A partnering utility identified the combined feedwater pump and motor set as a system of high interest. Data provided by the utility included a system P&ID (Figure 2) and plant operating data for plant startup for pre-monitoring calibration and for normal power operation for use in routine monitoring. Digital twin models were developed for the centrifugal pump and for the synchronous induction motor with the combined system yielding virtual sensors to supplement the

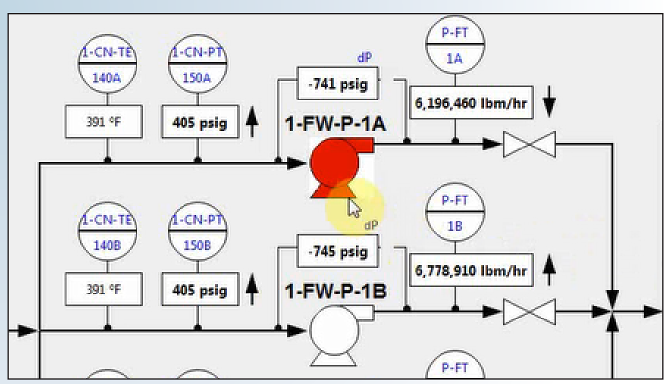

Figure 2. Process and instrument diagram for feedwater pump system.

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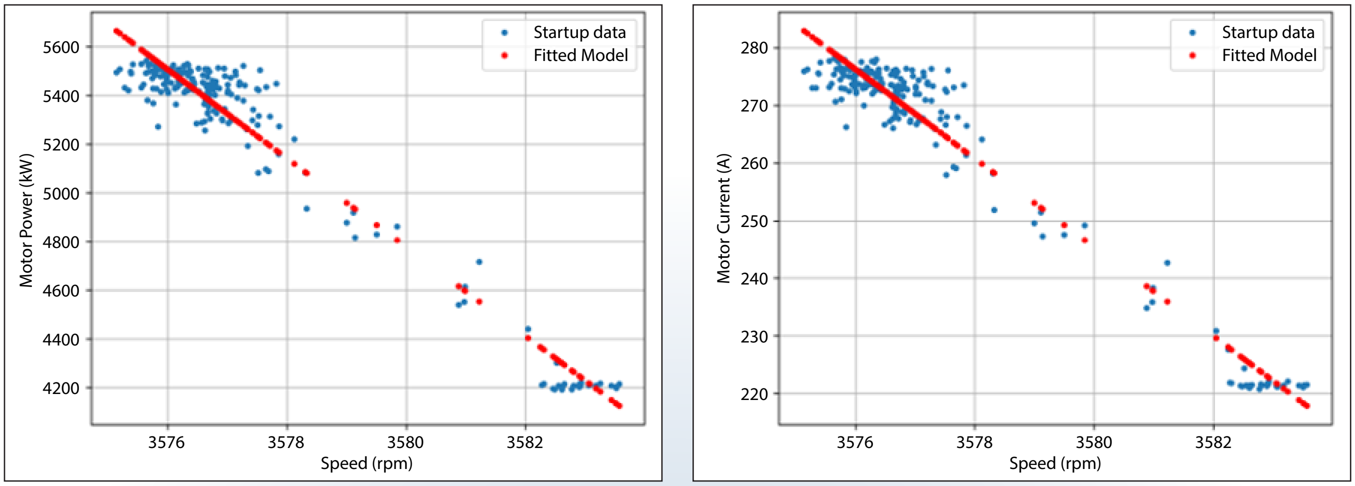

Figure 3. Calibration of motor input power model (left) and motor current model (right).

information available for making a diagnosis. Analysis of the sensor set for the combined pump-motor set showed that any single sensor or component fault could be diagnosed. However, no diagnosis is possible when these two components are taken as standalone components. This attests to the power of considering a system of components rather than the components individually in isolation of each other. The models were calibrated against startup data (Figure 3). To simulate out-of-calibration sensors, bias errors were superposed on normal operating data.

The diagnostic output for the case of pump flowrate and motor power sensor bias errors is shown in Figure 4. The injected bias is 2% of full-power value and is successfully detected based on the unique signature of the deviation of algorithm signals from their values at normal operation.

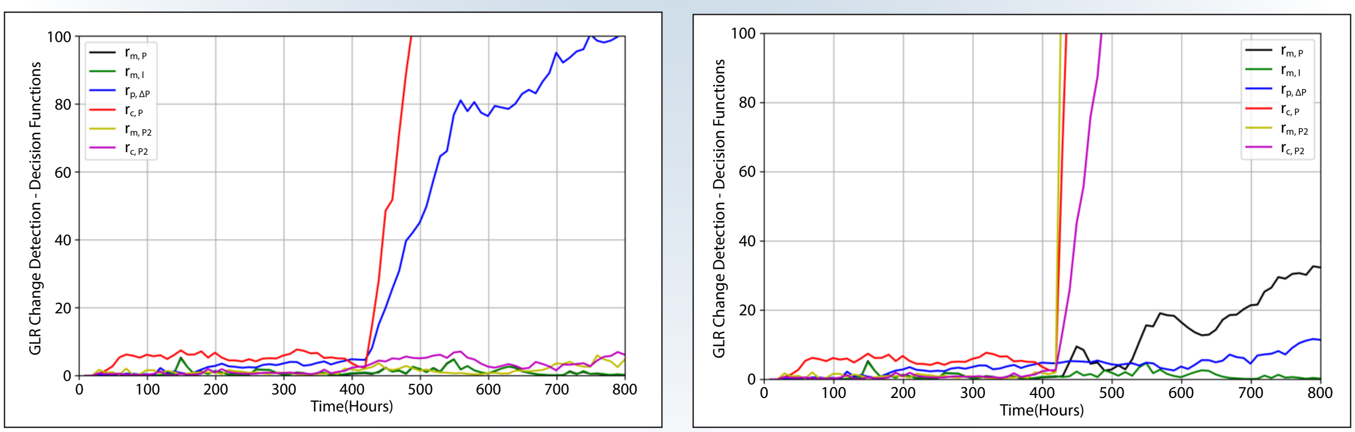

Figure 4. Successfully diagnosed feedwater flowrate (left) and motor power (right) sensor bias errors.

Self-powered Through-wall Data Communication and Sensing Systems for Nuclear Environments

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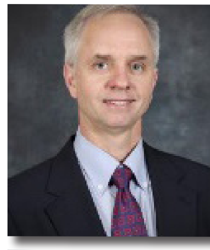

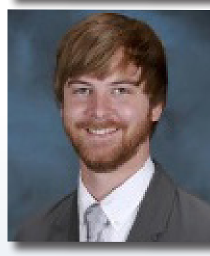

Introduction

In the nuclear power industry, many vital components, such as storage canisters for spent fuel and nuclear reactor pressure vessels (RPV), are entirely enclosed by metal and surrounded by thick concrete walls to avoid the harmful radiation and environment pollutions. For example, after removing dry casks from the reactors and cooling the casks in spent fuel pools, there is a need to store (and transport) the spent nuclear fuel assemblies inside leak-tight canisters of 1/2 in. to 5/8-in-thick stainless steel surrounded by concrete walls, which provide the front line of protection with a service life of 50 years or longer. To ensure the safety and security of the fuel containment, timely monitoring of the temperature, pressure, radiation, humidity, structural health, etc., within the enclosed vessels becomes crucial. Because of the potentially volatile nature of the spent fuel, wiring through the metal walls for power and data transmission is undesirable and infeasible in most nuclear environments. This poses a great challenge to the sensing of and communicating with the internal canister monitoring. This report summarizes the recent progress of the self-powered ultrasound through-wall communication and harsh-environmental sensing system.

Project Overview

In the United States, one-third of the nuclear fuel elements in reactors are typically replaced every 18 months, and 70,000 metric tons of uranium (MTU) are contained in spent fuel in the light of the U.S. Nuclear Regulatory Commission's (NRC's) estimation. However, no available effective sensing and instrumentation system can provide direct measurements of the critical conditions because: (1) there is no sustainable power supply for sensors inside the canisters, (2) data cannot be transferred out of the enclosed steel canister using wires or RF wireless, and (3) the harsh high-temperature (150–175°C on the wall surface) and high-radiation environment inside the enclosed vessel create challenges for electronics and sensors to survive.

This project aims to address these challenging issues by providing a self-powered data communication system for nuclear reactors and fuel cycle facilities using a sustainable power supply from energy harvesting, through-wall ultrasound communication, and harsh environment electronics. The specific objectives include (1) energy harvesting from the gamma rays using the gamma heating and thermo-electrics and from the beta particles using beta voltaic cells; (2) data stream transmission through the metal wall via ultrasound; and (3) demonstration of the complete system.

The entire system is illustrated in Figure 1, which includes: (1) a radiation/thermal energy harvester; (2) an ultrasound wireless communication module; (3) electronics modules for sensing and data transmission; and (4) an electrical circuit for power management. The energy harvester can produce power of tens of mW from the thermal source inside the nuclear canister directly. The harvested power will be stored and used to power sensors and ultrasound data transmitter inside the vessels.

Energy Harvesting from the Nuclear Environment

Energy harvesting and wireless communication provide a promising opportunity to revolutionize nuclear sensors and instrumentations, which could significantly benefit reactor design and fuel cycle facilities due to the elimination of wiring and batteries. More importantly, the energy harvester can still provide self-sustainable power to monitor the nuclear power plant's critical parameters or fuel cycle facilities even when a severe accident or massive loss of grid power occurs.

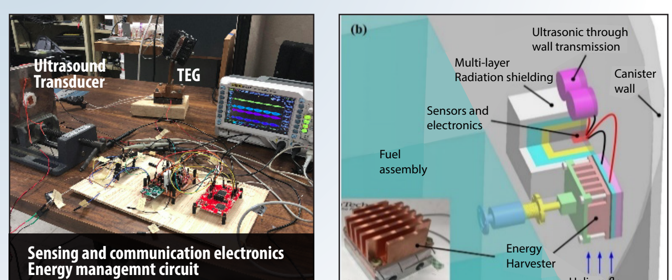

Figure 1. The prototype system of the self-powered ultrasound data communication and sensing (upper-left) and illustration of its installation in the nuclear canisters (lower-right).

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In a canister, spent nuclear fuel emits alpha, beta, neutron, and gamma rays as radioactive decay, which provides abundant harvestable energy sources.

The gamma and neutron rays are the two primary radiation particles within the canister. The decay heat generated within the dry cask storage is highly dependent on the fuel makeup and its operation within the reactor. The initial decay heat in a canister can be as high as 38.44 kW after storage for 5 years in the pool and decreases to 10.67 kW after another 50-years storage according to the simulation results.

The canister's peak temperature can be as high as 620 K, due to the decay heat generated by the gamma and neutron ray deposition. To accelerate the dissipation rate of the decay heat, the canister is backfilled with helium gas. The strong convective heat transfer processes inside and outside the canister create a significant temperature drop near the canister wall, making it ideal for thermoelectric energy harvesting. Calculations show that the temperature drop near the canister wall may be as high as 70 K at initial loading of the canister. The temperature difference decreases to ~13 K after 50 years.

Noticing these, we built an energy harvester that can effectively convert the gamma heating in the tungsten plate and the existed temperature gradient near the canister wall into electricity. The thermoelectric energy harvester's performance was verified under a simulated environment where a hydraulic oil circulation loop was used to simulate the real helium environment in the canister. The results show that the maximum power output of the harvester was up to 60 mW [1], which exceeded the 10 mW of power needed for the electronics.

The management circuits are developed at two stages: the impedance matching stage for maximum power transfer and boost stage for stepping up the voltage from the energy harvester to rated capacitor voltage (3 V). A self-start circuit is designed to automatically start the circuit when the super-capacitor is fully charged. The supercapacitor periodically powers the JFET-based electronics via a boost regulator, which increases the voltage to 12 V (the RF module supply voltage). The JFET electronics operate for 3 seconds and then go to sleep mode to conserve power. A microcontroller controls the work cycle.

Ultrasound Through-wall Data Communications

In this project, the amplitude modulation (AM) of ultrasonic waves inside a metal wall was developed to exchange information via an ultrasonic wave produced by the piezoelectric transducers (PZT). The main advantage is that it is highly reliable in a high-temperature nuclear environment. As a breakthrough, we have experimentally demonstrated the ultrasonic TEXT communication up to 300°C temperature using a one-to-one transducer configuration.

In addition, we have developed a novel method for ultrasonic data communication. Traditional ultrasonic data communication relies on two transducers attached on two sides of the steel wall. One is used as the transmitter, and the other is used as a receiver. In our new method, we have used a laser beam to replace the receiver transducer so that the data communication can be performed using a hybrid approach (laser and ultrasonic). The experiment has been performed, and the results show that the binary data can be transmitted through the wall and recovered after demodulation from the laser received signal.

Figure 2 shows the experiment diagram of the proposed new approach. One PZT transducer is used as a transmitter to transfer the modulated signal through the wall. On the other side of the wall, we use a Polytech 505 laser vibrometer to pick up the vibration signal. The vibration signal is fed into an oscilloscope for data analysis.

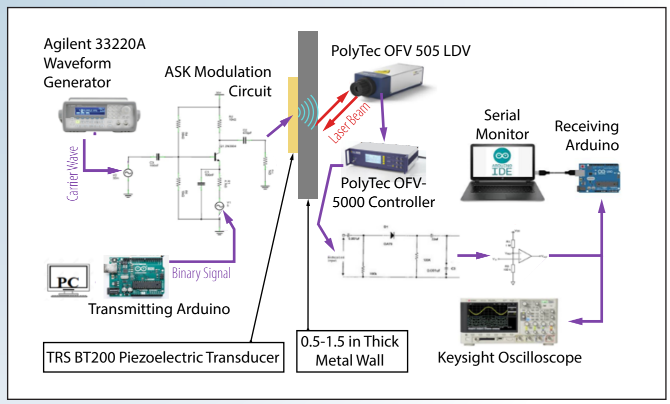

Figure 2. Schematic of ultrasound text transmission.

To transmit the binary data, we used an Arduino to generate "Hello World" and send the signal to a function generator that could perform the modulation. The modulated signal was transmitted to the PZT transducer. The acoustic signal passes through the metal and a laser-based method is used to receive the signal. From the oscilloscope, we were able to see the input and output signal separately. Aluminum metal with a dimension of 6 in × 4.6 in x 0.39 in was used as a wall surrogate.

Temperature and Radiation Hardened Electronics for In Cask Sensor Interfacing and Communications (ORNL)

Electronics and sensors located within the fuel casks will be exposed to very high levels of radiation and elevated temperatures over the anticipated monitoring lifetime. Studies have been initiated to estimate the in cask, position-dependent radiation dose expected over the 50

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year operating life of the monitoring system. In addition, published in-cask temperature modeling data predicts temperatures approaching 300°C at the onset of the cask monitoring. With these requirements in mind, various electronics topologies have been investigated based on different classes of components, including single- and double-sideband analog modulation, on-off keying, and other forms of digital communication. Figure 3 shows the chosen electronics architecture based on multi-sensor direct modulation of a carrier waveform. A prototype sensor interface and modulation circuit was designed, simulated, prototyped, and tested using off-the-shelf components in a laboratory environment [2]. Silicon-based JFETs were chosen as the primary active device technology due to their established radiation hardness.

The impacts of gamma radiation on the performance of the system

To examine the performance of the modules in the nuclear environment, gamma exposure experiments were performed in a radiation test chamber provided by Westinghouse Electric Company in Pittsburgh.

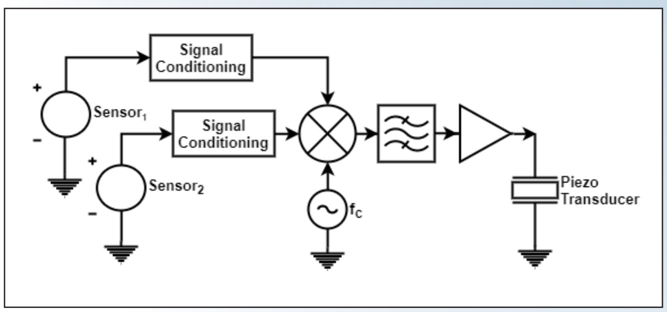

Figure 3. Direct sensor modulation with a carrier waveform of frequency fc.

All the components designed to be exposed to gamma radiation were set up in the radiation chamber with necessary sensors and cables connected to a laptop located outside of the radiation chamber (Figure 4). The performance of the system before and after irradiation was compared. There is no obvious change in the thermoelectric materials (Bi2Te3) and ultrasound transucer (TRS BT200) after 100-Mrad total ionizing dose (TID). A set of PCBs with JFET-based sensor interface electronics were successfully irradiated to 2 Mrad. Testing to a higher gamma radiation dose (100 Mrad) is planned.

Since all the electronics components need to work in the nuclear canister for more than 50 years, radiation shielding and thermal protection are still necessary. High-density tungsten (W) is more environmentally friendly for gamma shielding than lead. A high abundance of Boron makes boron carbide (B4C) suitable for the ideal neutron radiation shielding materials. A multi-layer design, with stainless

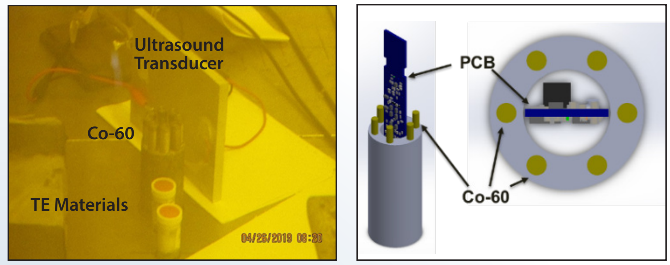

Figure 4. Gamma radiation test in hot cell at Westinghouse.

steel external layer, fiber glass thermal insulation layer, and W-B4C radiation shielding layer may be used to protect the electronics component installed on the canister wall. High-temperature 3D printing technologies, such as selective laser melting (SLM), are good choices to fabricate these multi-layer shielding layers.

Conclusions

This project successfully demonstrated a self-powered solution for sensing inside of nuclear canisters using radiation-hardened energy harvesters, JFET-based sensor interface electronics, and ultrasonic data communications. Two energy harvesters were designed to power the electronics for the wireless through-wall data communication in nuclear environments. Simulation and lab tests were conducted with a representative setup and verified that ~60 mW can be achieved from an MPC-32 canister at 50 years of service life. A circuit was designed and built to store the harvested energy as well as to boost and stabilize the voltage output. The ultrasonic TEXT transmission at temperatures up to 300°C using a one-to-one transducer configuration was experimentally verified. The key components for energy harvesting and ultrasound communication showed little degradation following 100 Mrad TID gamma radiation and the electronics components survived over 2 Mrads. Tests are planned to demonstrate the JFET-based electronics radiation hardness to 100 Mrad TID.

Acknowledgements: The authors would like to thank Yongjia Wu, Kan Sun, Jackson Klein, Hyunjun Jun, Feng Qian, Qiaofeng Li, Suresh Kaluvan, Huijing He, Cheng Zhang, Roger Kisner, Robert Flammang, and Mike Heibel for their contributions.

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Acoustic Sensors for In-Core Measurements

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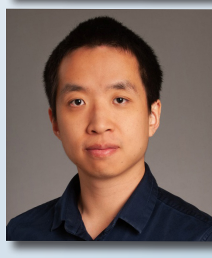

Introduction

Acoustic and ultrasonic transducers can be used as a base technology in numerous sensors measuring a multitude of parameters, such as temperature, gas pressure, vibration, etc. With the ability of some ultrasonic sensors to make spatially distributed and multiplexed measurements, sometimes without direct access to the sample to be measured, development of these sensors is increasingly relevant given the push to develop new reactor concepts.

Ultrasonic Thermometry

The first measurement target for acoustic sensor development is temperature. Ultrasonic thermometry has the potential to improve upon temperature sensors currently used for in-core temperature measurements. Ultrasonic thermometers (UTs) work on the principle that the speed at which sound travels through a material (acoustic velocity) is dependent on the temperature of the material. Temperature may be derived by introducing a short acoustic pulse to the sensor and measuring the time delay of acoustic reflections generated at acoustic discontinuities along the length of the sensor. An example of UT design is shown in Figure 1.

UT temperature measurements may be made near the melting point of the sensor material, allowing monitoring of temperatures potentially in excess of 3000°C. Although still developmental, UTs have been included in several irradiation experiments and have performed well. Figure 2 shows data from a UT and several nearby thermocouples from a recent irradiation experiment at the Advanced Test Reactor.

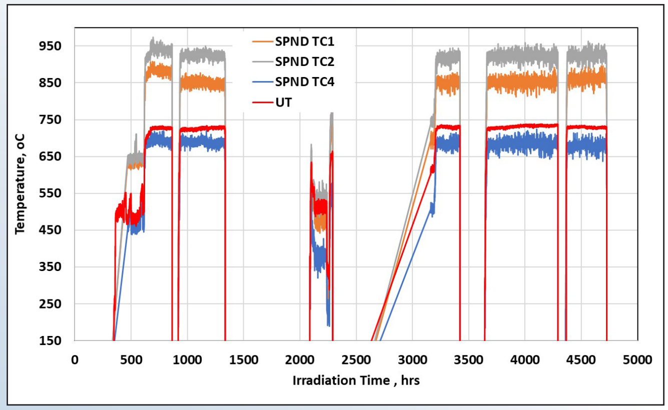

Figure 2. Temperature data from UT and thermocouples from ATR irradiation.

Modelling and Design Optimization

Through collaboration between INL and Boise State University, a fully coupled, multiphysics finite element model for an ultrasonic thermometer is being developed to improve understanding of the device's working principle, enable design optimization, and improve measurement accuracy.

The INL ultrasonic thermometer, as shown in Figure 3(a), consists of a magnetostrictive waveguide, an AC coil generating and detecting the acoustic waves, and a DC coil providing a bias magnetic field to enhance signal amplitude. Since all components are symmetric and concentric, a 2D axisymmetric model incorporating mechanical, magnetic, and electrical dynamics was constructed in COMSOL Multiphysics as shown in Figure 3(b). The magneto-mechanical coupling in the magnetostrictive waveguide is represented by interpolation functions calculated from a nonlinear constitutive model [1] [2]. The electromagnetic coupling in the coils are described by Maxwell's equations.

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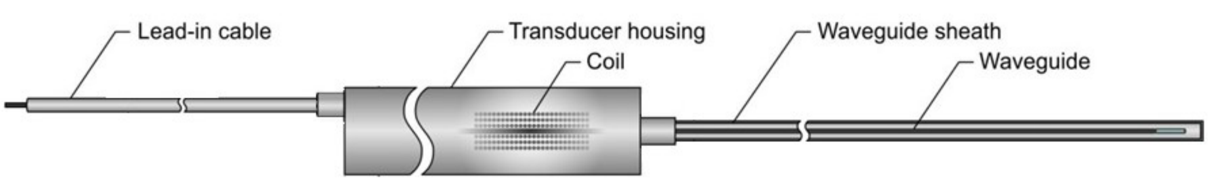

Figure 1. Schematic of typical ultrasonic thermometer.

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Some magnetostrictive materials require a biasing magnetic field to maximize magneto-mechanical coupling. Such a bias magnetic field is generated by applying a constant current to the DC coil. The finite element model developed in this study successfully predicts the optimal current amplitude maximizing the sensitivity of the thermometer. The acoustic wave propagation and the resulting voltage signals across the AC coil are modeled in time domain. Figure 3(c) shows the snapshot of the compressive wave inside of Galfenol waveguide 40 µs after the pulsed excitation. The resulting voltage signals induced by the reflected waves are benchmarked against experimental results in Figure 4. The current model underestimates system damping and waveguide stiffness resulting in a 12.5% error in time-of-flight estimations. To mitigate simulation error, a future model will first include energy loss and measured stiffness of the waveguide.

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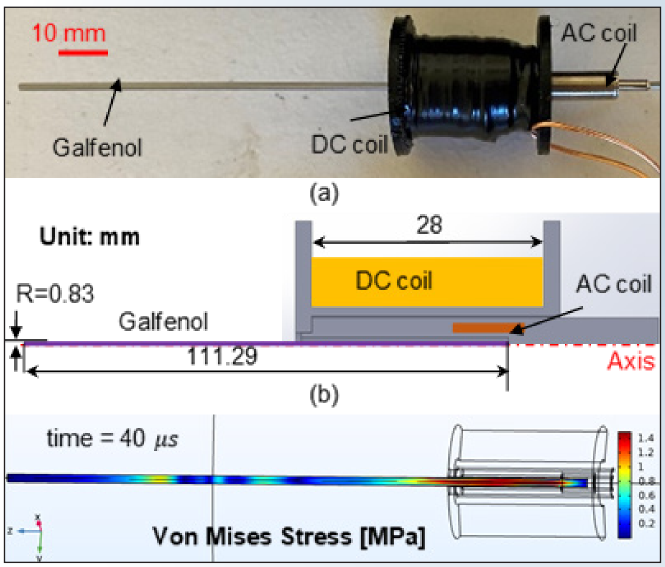


Figure 3. (a) Physical assembly of the pulse-echo mode ultrasonic thermometer with an additional DC bias coil. (b) 2D axisymmetric model layout in COMSOL Multiphysics. (c) Simulated compressive wave propagating in the Galfenol wire (40 µs after excitation).

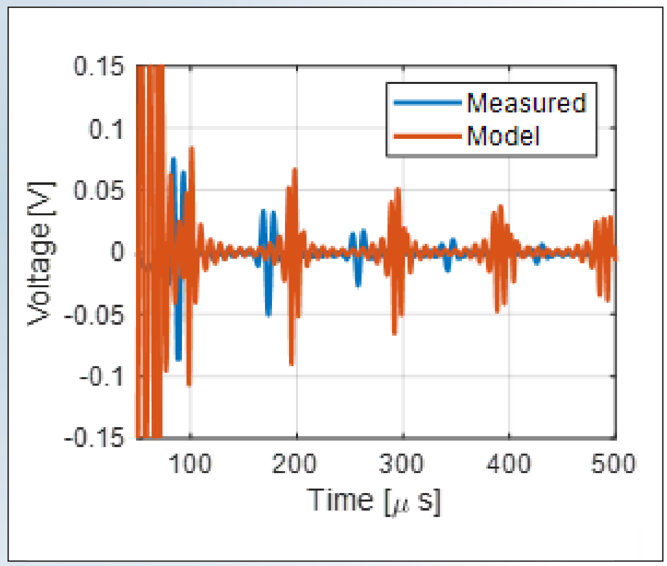
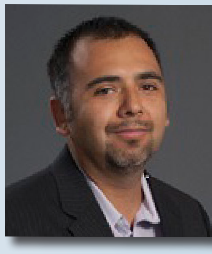


Figure 4. Voltage across the AC coil induced by acoustic echoes at room temperature. (Both experimental measurements and finite element simulation results).

Boise State University collaborates with Idaho National Laboratory to support the development of advanced sensors and instrumentation

Brian Jaques
Boise State University

David Estrada
Boise State University



Introduction

Strategic Investments from the Advanced Sensors and Instrumentation (NEET-ASI) direct-funded research and development programs have led to a close-knit collaboration between Boise State University (BSU) and Idaho National Laboratory (INL). In alignment with the mission of the Department of Energy Office of Nuclear Energy (DOE-NE), the ASI program is a science-based program for in-pile instrumentation development that is structured to leverage the strengths of a multidisciplinary sensor development process through cross-cutting research thrusts using materials science and engineering (MSE), advanced manufacturing (AM), modeling and simulation (M&S), and instrumentation development. It brings together researchers from academia and INL to tackle challenging projects that benefit from a unique combination of expertise and infrastructure, while developing the future nuclear workforce and reducing the time to innovate in the nuclear industry.

The cross-cutting and multifaceted structure of the ASI program promotes innovative solutions to sensor design, development, and deployment via opportunities for faculty, scientists, and the future nuclear workforce to engage, network, and collaborate. The program is comprised of multiple research thrusts based on strong interdisciplinary scientific collaboration designed upon specific instrumentation research and development needs. While each thrust addresses key technological questions, the overarching structure encourages strong engagement between activities to achieve sensor deployment strategies. Research thrusts comprised of several team members (Table 1) were identified and have been working to facilitate prototype sensor design, fabrication, and experimentation. In fiscal year (FY) 2020, the ASI program supported nine research thrusts, ten faculty members, five staff members, 11 graduate research assistants, and 14 undergraduate research assistants at BSU.

RESEARCH THRUST	INL TPOC	BSU				
		TPOC	FACULTY	STAFF	GRA	UGRA
HTIR-TC	Richard Skifton	Lan Li	2	0	2	3
ADVANCED MANUFACTURING	Michael McMurtrey	David Estrada	5	1	3	3
MECHANICAL PROPERTIES	Richard Skifton	David Estrada	3	0	3	3
ACOUSTIC SENSORS	Joshua Daw	Dan (Zhangxian) Deng	1	0	2	0
LINE SOURCE	Austin Fleming	David Estrada	1	0	1	0
RADIATION TOLERANT FIBERS	Austin Fleming	Nirmala Kandadai	3	1	3	4
ELECTROCHEMICAL SENSORS	Hongqiang Hu	Michael Hurley	3	0	2	2
NEUTRON GENERATORS	Troy Unruh	Brian Jaques	1	1	0	1

Table 1. I2 Program researcher involvement by research thrust at Boise State University (TPOC-Technical point of contact, GRA-graduate research assistant, UGRA-undergraduate research assistant.

Continued from previous page

Within the program, the AM research thrust is an excellent example of the impact the ASI program is having on the university, INL, and the state of Idaho. BSU and INL are members of the Center for Advanced Energy Studies (CAES)— a research, education, and innovation consortium that brings together INL and the public research universities of Idaho and Wyoming to conduct cutting-edge research, train and educate the future energy workforce, and partner with industry in Idaho and throughout the region to advance competitiveness. AM is one of seven focus areas outlined in the CAES Strategy and a key strategic strength at Boise State, and the partnership between INL and the university in the ASI program is one example of the collaboration CAES has enabled in this research thrust. Led by Dr. Dave Estrada, the CAES Associate Director for BSU, and Dr. Michael McMurtrey of INL, the project aims to develop advanced manufacturing methods and new capabilities that enable transformative sensor technology for in-pile monitoring and in-situ analysis of fuels and materials. The use of additive- and micro/nano-manufacturing to fabricate next-generation in-pile sensor technologies offers new opportunities for in-pile instrumentation as well as new challenges. Supported by atomic scale simulations and phase fields models, the AM research team is developing novel materials for conformal printing of passive and active sensors capable of measuring temperature, thermal conductivity, strain, and neutron flux inside the reactor core. An example of this is seen in Figure 1 where a capacitive strain gauge (CSG) was conceptualized and realized in a nuclear application. The CSG is used to measure fuel pin swelling and has been conformal printed on the circumference of a typical nuclear fuel pin using AM techniques.

Knowledge gained from the AM research thrust has resulted in four invention disclosures; two were converted to U.S. provisional patents, and one has been awarded a U.S. patent. Results have contributed to four peer-reviewed journal articles, with several others currently in preparation, and the students and lead investigators have presented their results at 17 national and international conferences, including numerous invited talks at prestigious meetings of professional societies. In addition, results have been leveraged in numerous grant applications to federal and state agencies, resulting in new research awards from the state of Idaho, NASA, the Department of Defense, and most recently a Department of Energy Small Business Innovation Research award to develop and commercialize nanoparticle inks for printed thermocouples. A startup company has also formed out of BSU to commercialize a patented platinum-based ink compatible with high temperatures that far exceed the limited operating range of commercially available silver inks. Perhaps the most important result of this collaboration, the lead graduate research assistant – Kiyo Fujimoto – is working full time at INL on this research thrust while completing her dissertation research under the INL Graduate Fellowship program, where she has taken a lead role in expanding INL's additive electronics manufacturing efforts.

Fujimoto's experience is not unique. As a direct result of the investment in students and faculty through the ASI collaboration, multiple students have been awarded prestigious fellowships, scholarships, internships, and recognized among the best performing students at BSU, and in the country. She is one of five students to be awarded INL Graduate Fellowships, which provide recipients with nearly $60,000/year to work at the INL Site with close mentorship of INL researchers during the final 2 years of their Ph.D. research. An additional five students were nationally recognized and awarded prestigious NEUP fellowships of $52,000/year including a summer internship at a national laboratory to pursue Ph.D. research in alignment with the DOE-NE mission; and six undergraduate students have been awarded research scholarships (three of which were NEUP). A number of students have received additional training and mentorship through several research internships at INL, including ten graduate student internships and three undergraduate student internships. As a testament to the opportunities provided to students performing research in the ASI program, two have been awarded the 2020 Innovations in Nuclear Technology R&D awards and two undergraduate students have been recognized as BSU Top Ten Scholars. The Top Ten Scholars program recognizes the top ten performing students at the university for their exceptional academic success, research, scholarly achievements, and impact on the community. The development and success of the future nuclear workforce through unique, real-world opportunities in challenging sensor solutions for the harsh environments required of nuclear reactors is a highlight of the of the collaborations that have emerged from the ASI program.

Another highlight is the significant impact on the sensors' community in the development of cross-cutting, in-pile sensor solutions to the current needs for nuclear innovation. Accordingly, discoveries and research related to the collaborations have resulted in four patent applications, 15 peer-reviewed journal publications, and more than 40 research conference

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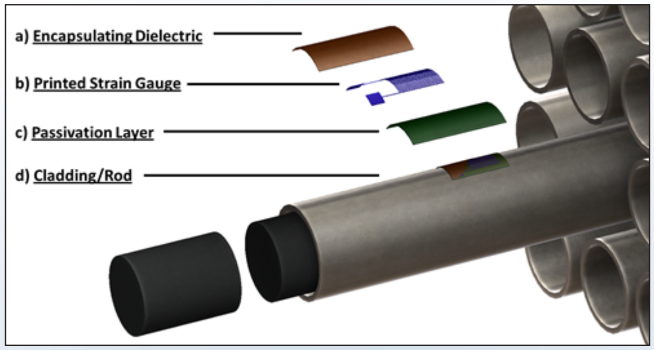

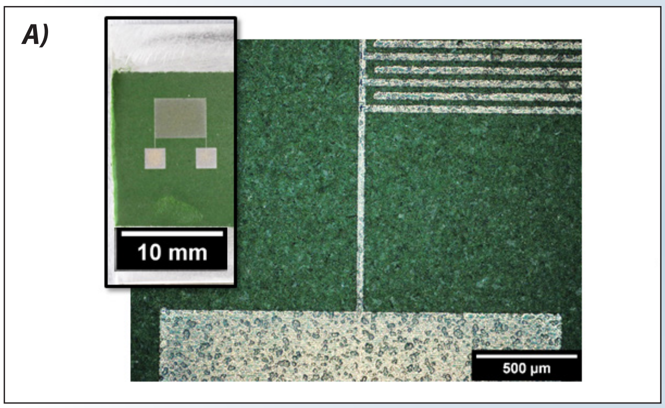

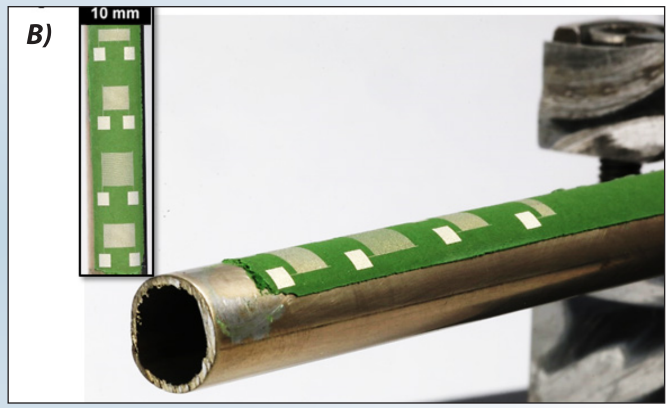

Figure 1. Schematic of AM strain gauge on fuel pin. (A) Close up of the aerosol jet printed capacitive strain gauge (AJP-CSG) and (B) the AJP CSG on a 9.5-mm-diameter fuel pin with an insulation layer.

presentations and seminars, including 15 invited presentations. In addition, the expertise and capabilities enabled from ASI investments have positioned the BSU team of investigators to successfully receive additional research funding from multiple additional federal programs such as: the Nuclear Energy University Program (NEUP), the Department of Energy and NASA Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, the Nuclear Science User Facility (NSUF) Rapid Turnaround Experiments (RTE) and Scientific Infrastructure Support for Consolidated Innovative Nuclear Research Funding Program (CINR), as well as several others. The outcomes of the program align with the vision of the DOE-NE and support the mission of multiple NE programs through cross-cutting research thrusts using MSE, AM, M&S, and instrumentation development to decrease the innovation time in nuclear. The successes of the program are constantly being updated and shared among the nuclear sensors' community through peer-reviewed journal and conference publications, conference presentations, and through the development of joint intellectual property. In addition, the support and opportunities of the NEET-ASI program has led to expansive networking and responses to multi-institution funding opportunities; resulting in several federally funded research projects that compliment and support the mission of the ASI program and, therefore, NEET-ASI and DOE-NE. Finally, the ASI program has led to unprecedented opportunities for the next generation nuclear workforce and will undoubtedly reduce the nuclear workforce gap. For all of this and more, the joint collaboration between BSU and INL would like to thank and acknowledge the continued support and opportunities provided by the Advanced Sensors and Instrumentation program through the Nuclear Energy Enabling Technology program.

Evaluation and Development of Self-Powered Neutron Detectors

Keven Tsai
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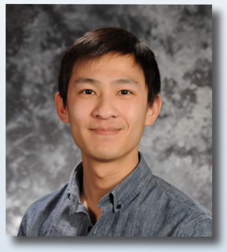

Introduction

In-core detectors are used to directly measure localized live-time neutron flux. The measured data have significant applications towards power distribution monitoring for operations and experiment neutronic-environment monitoring for advanced fuels testing; therefore, in-core detectors are often used in commercial and research reactors and many are commercially available. Self-Powered Neutron Detectors (SPNDs) are a category of in-core neutron detectors that are commonly used given its small physical footprint, low signal noise, wide sensitivity range, and robust construction. Given its versatility and common usage, research on sensitivity modeling and performance evaluation has been performed on many types of SPNDs [1-3]. By the same process, new SPNDs needs to be tested and qualified to ensure proper operation in support of advanced fuels testing. Additionally, since most SPNDs are typically designed and evaluated for light water reactor (LWR) environments, new SPND designs are needed to compensate for changes in neutronics and thermal conditions of advanced reactors that are atypical of LWR conditions. A database of validated SPND designs per application and a robust predictive model for designing new SPNDs are needed to support both efforts of deployment and fuels testing.

Methodology

Separate-effects benchtop testing and irradiation testing at various conditions and neutron energy spectrum are performed to both improve and validate sensitivity models. Presently, preliminary MCNP models are used to predict SPND sensitivity. Given the unique opportunity for in-core sensor testing at the Transient Reactor Test (TREAT) facility, irradiation evaluation of newly fabricated prompt-response gadolinium-SPNDs has been the focus of this research. The research activities are based on a historical TREAT SPND evaluation [4]. The newly fabricated SPNDs demonstrated excellent time response in comparison to the reactor power as shown in Figure 1. Two separate irradiations involving flux and fission wires collocated with SPNDs at different regions of the core has also been performed. Figure 2 shows the inclusion of SPNDs in an experimental vehicle for core-center irradiation testing. The analysis from these irradiations will become the stepping-stone towards qualifying SPNDs in support of advanced fuels testing in TREAT.

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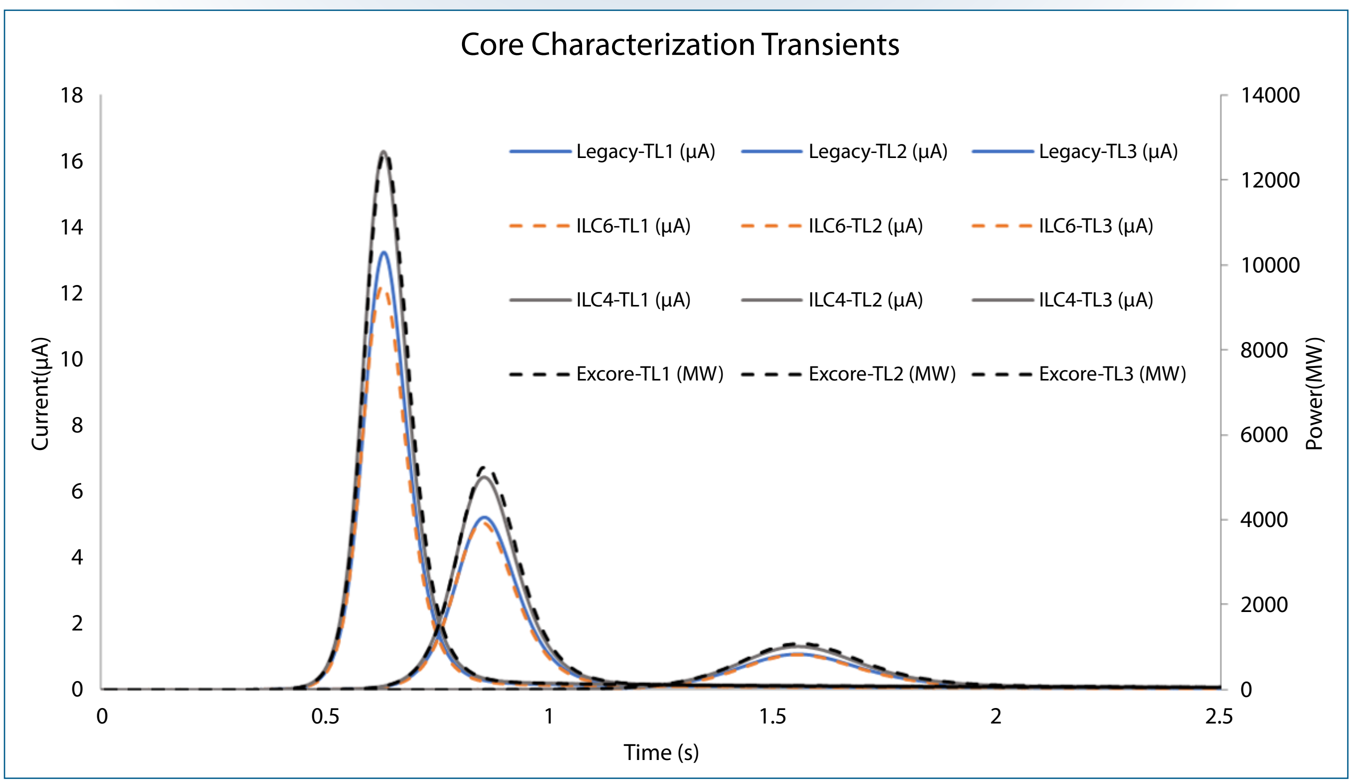

Figure 1. SPND signal trace comparison overlay with reactor power for three different pulse transients of varying peak power.

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Figure 2. Insertion of an experiment vehicle containing three gadolinium-SPNDs into the TREAT reactor.

Path Forward

As a complimentary addition to the evaluation of SPNDs for transient operations in TREAT, efforts are underway towards accomplishing a similar task in the Advanced Test Reactor Critical (ATRC) facility for steady-state operation of SPNDs. SPND operational demonstration and evaluation in ATRC will have three major outcomes: (1) providing a step towards qualifying SPNDs in support of ATRC activities, (2) Identifying the feasibility deploying SPNDs in low-flux steady-state reactors such as microreactors, and (3) evaluation of SPNDs for supporting ATR experiments.

Furthermore, to understand the separate effects of gamma-particle contribution and temperature effects, near term plans are made for gamma irradiation and furnace testing. Gamma-particle contribution and temperature effects have generally been considered small to negligible for most applications, but these contributions and effects are predicted to become more significant in advanced reactor environments and needs to be addressed. These additional testing will ensure accurate operation and reliable deployment in future advanced reactors.

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In-Situ Creep Testing Capability

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Introduction

The development of advanced nuclear reactors significantly relies on the performance of innovative nuclear fuels and structural materials under extreme irradiation environments, and creep is an essential phenomenon in its assessment. Currently, nuclear materials creep is assessed before and after irradiation, in complex and costly post-irradiation examination (PIE) activities. Furthermore, removing the samples in and out of the reactor disrupts most phenomena of interest. Real-time creep measurement during irradiation allows the assessment of two sets of simultaneous phenomena. The first is the applied stress and the displacement damage acting simultaneously under dynamic irradiation conditions, which changes the magnitude and spatial distribution of defect accumulation making the deformation behavior substantially different from that in the case of PIE creep. The second is the thermal condition of the real-time test, which cannot be reproduced during PIE without affecting the material microstructure yet again [1]. An instrumented creep test rig is based on a design developed for irradiation testing at the Halden Boiling Water Reactor (HBWR) in Norway [2,3,4]. Idaho National Laboratory (INL) fabricated and tested an out-of-pile creep test rig in 2019 as part of the Nuclear Energy Enabling Technology (NEET) Advanced Sensor and Instrumentation (ASI) program at the High Temperature Test Laboratory (HTTL).[5] This rig is readily available for deployment and will partially replace the testing capabilities lost along with the termination of HBWR operations.

Methodology

The instrumented creep test rig was initially developed to complete specimen creep testing under Pressurized Water Reactor (PWR) coolant conditions in an Advanced Test Reactor Loop [3]. The creep test rig (Figure 1) is comprised of several elements, including a standard tensile specimen, a linear variable displacement transducer (LVDT) to measure dimensional changes, two types of bellow assemblies, a thermocouple (TC) holder, a support structure to maintain the experiment in an in-pile environment, and National Instruments (NI) data

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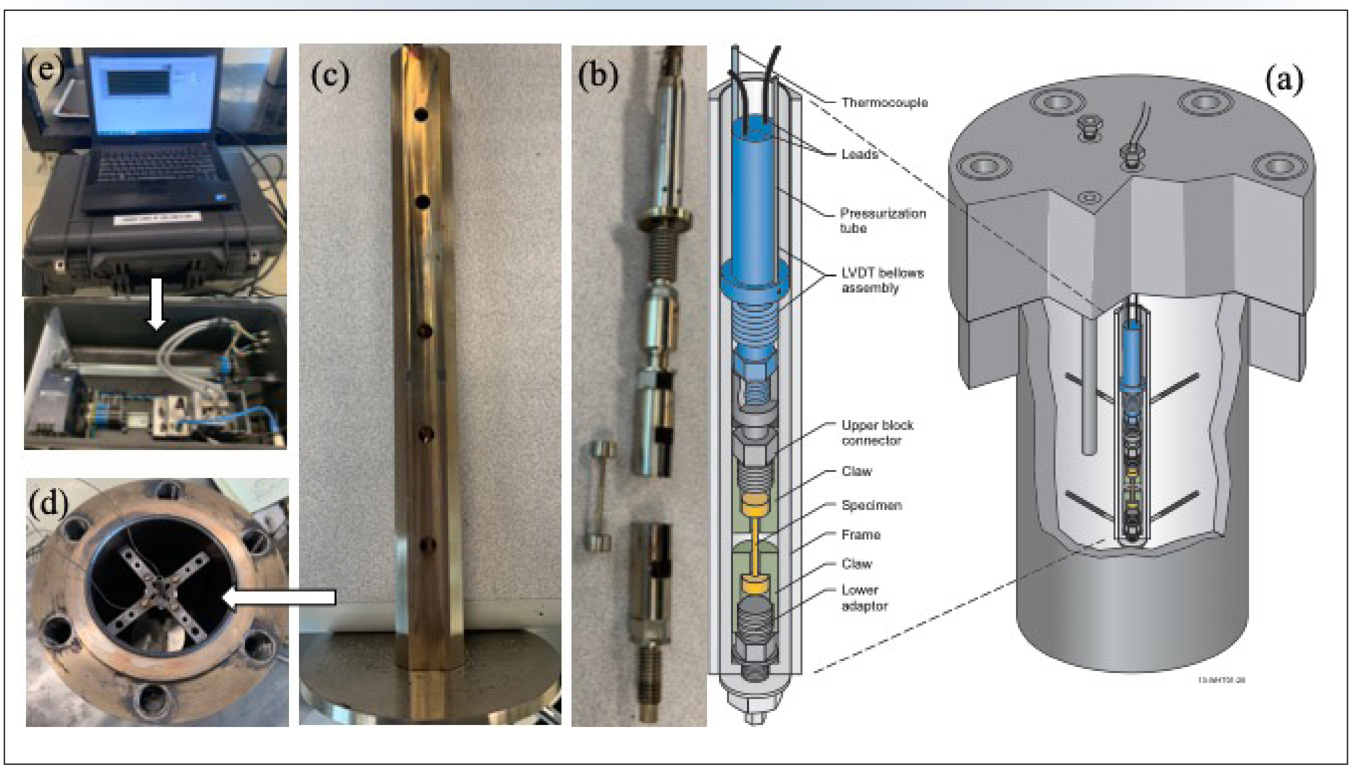

Figure 1 – (a) schematic of the Creep Test Rig inside autoclave, (b) actual parts of the Creep Test Rig with SS 304 sample, (c) Creep Test Rig all together and ready for testing, (d) Creep Test Rig positioned in static autoclave, (e) NI data acquisition system for recording TC and LVDT signals. [3,5].

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acquisition system for recording LVDT and TC signals. The first bellow assembly is designed to create a static load that corresponds to the external pressure of the coolant in the reactor. The second bellow design allows for a variable strain rate during reactor testing. Lastly, the fixture is designed to constrain the LVDT bellow assembly and one end of the specimen so that the bellows contraction will place the specimen in tension. Cables extending from the LVDT and TC relay measurements of elongation and specimen temperature, respectively, and are monitored live during irradiation with the NI data acquisition system [3,4].

The autoclave calibration fixture (Figure 1) was assembled with the retaining nut tightened just enough to stretch the bellows very slightly to meet the travel block for a specific maximum travel for the LVDT signal range. This stretch in the bellows provides the initial position of the LVDT for the autoclave testing, and as the pressure increases the bellow compresses changing the LVDT output voltage. At a certain autoclave pressure, the bellow will stop compressing due to the limiting travel blocks stopping the upper-connector movement that defines the final LVDT output voltage [5]. Although the INL-developed creep testing capability will ultimately be used for a wide range of materials, initial efforts focused on Type 304 stainless steel samples due to well-known thermal creep behavior. Furthermore, future work will consist of using a flowing autoclave to test the vibrations from the flowing water that will show the robustness and reliability of the rig.

Conclusion

Malwina Wilding serves as principal investigator for creep testing capability, calibration testing for creep test rig in static autoclave at PWR prototypic conditions, material research and selection for suitable tensile specimens, verification of signal processing equipment, and calibration testing using samples with known creep behavior. As part of the NEET ASI, an instrumented creep testing capability was developed by the HTTL team to allow specimens to be tested during irradiation in PWR coolant conditions. Results from laboratory evaluations of a prototype creep test rig were incorporated into a final design that will be inserted into the flowing autoclave. In-situ creep tests that can provide real-time data for detecting specimen elongation and controlling loads applied to the specimens have already been completed. In summary, testing of the in-situ creep test rig confirmed the availability for deployment and will partially replace the testing capabilities lost along with the termination of HBWR operations.

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Sensors based on the Linear Variable Differential Transformer (LVDT)

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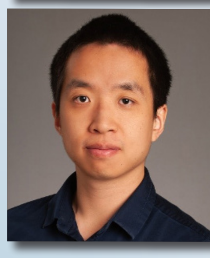

Introduction

Real-time pressure and dimensional changes in fuel and/or fuel cladding during irradiations can be used to understand phenomena, such as fuel and cladding elongation, the buildup of "crud," pressurization from fission gas release, and pellet-clad mechanical interactions. These phenomena can adversely affect fuel performance and/or heat transfer pathways away from the fuel. Therefore, in-situ measurements are critical to advancing the knowledge base related to irradiation effects on advanced fuels and cladding and associated structural materials.

Linear Variable Differential Transformers (LVDT) sensors, known for superior in-pile performance under irradiation, are available to provide micron-scale resolution data enabling the evaluation of fuel performance. Such a high-resolution measurement requires a careful understanding of not only sensor itself, but also the complete implementation strategy, including thermal conditions, hardware selection and design, and data processing. To evaluate sensor performance, reduce sensor size, and optimize sensor configurations, both numerical simulation and detailed experimental studies should be performed. In addition, transient irradiation testing requires fast response performance (~1 ms) from LVDT measurement devices; therefore, this testing needs innovative data acquisition approaches, distinct from traditional systems used at steady state test reactors.

The Idaho National Laboratory (INL) High Temperature Test Laboratory (HTTL) is developing and testing new pressure and displacement sensors based on LVDTs procured from Institute for Energy Technology (IFE). Boise State University is providing computational modeling to support INL's efforts. The University of Pittsburgh is developing a wireless transmission technology for LVDTs. The main objective of these efforts is to provide LVDT-based instruments for materials test reactors (MTRs) (e.g., TREAT facility and Advanced Test Reactor [ATR]). This article will briefly touch on each effort.

Background LVDT Information

LVDTs are simple, reliable sensors that convert the mechanical movement of a specimen into an electrical output. A cross section of a basic LVDT design is shown in Figure 1. As indicated, a magnetically permeable core is attached to a specimen. The core then moves inside a tube in response to any change in specimen length or position. Three coils are wrapped around the tube: a single primary coil and two secondary coils.

To operate the LVDT, an alternating (excitation) current is driven through the primary coil, causing a voltage to be induced in each secondary coil, which is proportional to its mutual inductance with the primary. As the specimen and the attached core move, these mutual inductances change, causing voltages induced in the secondary coils to experience a corresponding change. The secondary coils can be connected in reverse series; an output voltage can be conveniently derived from the difference between the two secondary voltages. Specifically, when the core is in its central position (equidistant between the two secondary coils), equal but opposite voltages are induced in the secondary coils, so the output voltage is zero. When the core is moved to its full-scale mechanical position (in either the positive or negative direction) the coil nearest to the core goes full-scale while the voltage in the other secondary coil goes to zero.

The IFE is one of the pioneers in LVDT development for in-pile testing. In an IFE LVDT design [1, 2, 3], the primary coil is activated by a 400-Hz constant current generator

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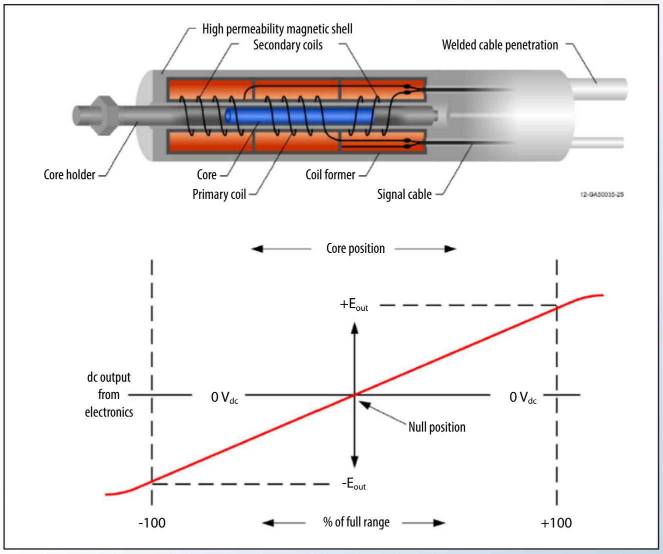

Figure 1. Cross section of basic LVDT design and displacement/ electrical output curve.

and the position of the core can be measured with an accuracy of ±1 μm. Since the IFE began making in-core measurements, more than 2200 LVDTs of different types have been installed in different test rigs in their Halden Boiling Water Reactor (HBWR). Failure rates of less than 10% after 5 years of operation are expected for their LVDTs operating in BWR, PWR, or CANDU conditions.

IFE LVDTs Procured for Study

A diverse assortment of LVDTs and a high-speed driver and processor have been obtained from IFE (see Figure 2). The purpose of this procurement is to use these LVDTs in the development of sensors that will provide critical data for in-pile testing in MTRs. Real-time pressure and dimensional sensing will be the fundamental focus of this work. This work will also focus on reducing the response time for these sensors along with miniaturization of the sensor. A potential benefactor of this work will be the Temperature Heat-Sink Overpower Response (THOR) capsule. THOR is a thick-walled capsule in which rodlet-type fuel specimens are surrounded with liquid metal for intimate thermal transport. Tests that will be conducted in THOR will require high-speed monitoring of the internal fuel pin pressure. This will require a sensor capable of fitting within the boundaries of the fuel pin and will require an LVDT-based pressure sensor with an unprecedented response time. A sensor is being developed based on the IFA miniature LVDT that could benefit tests conducted in the THOR capsule.

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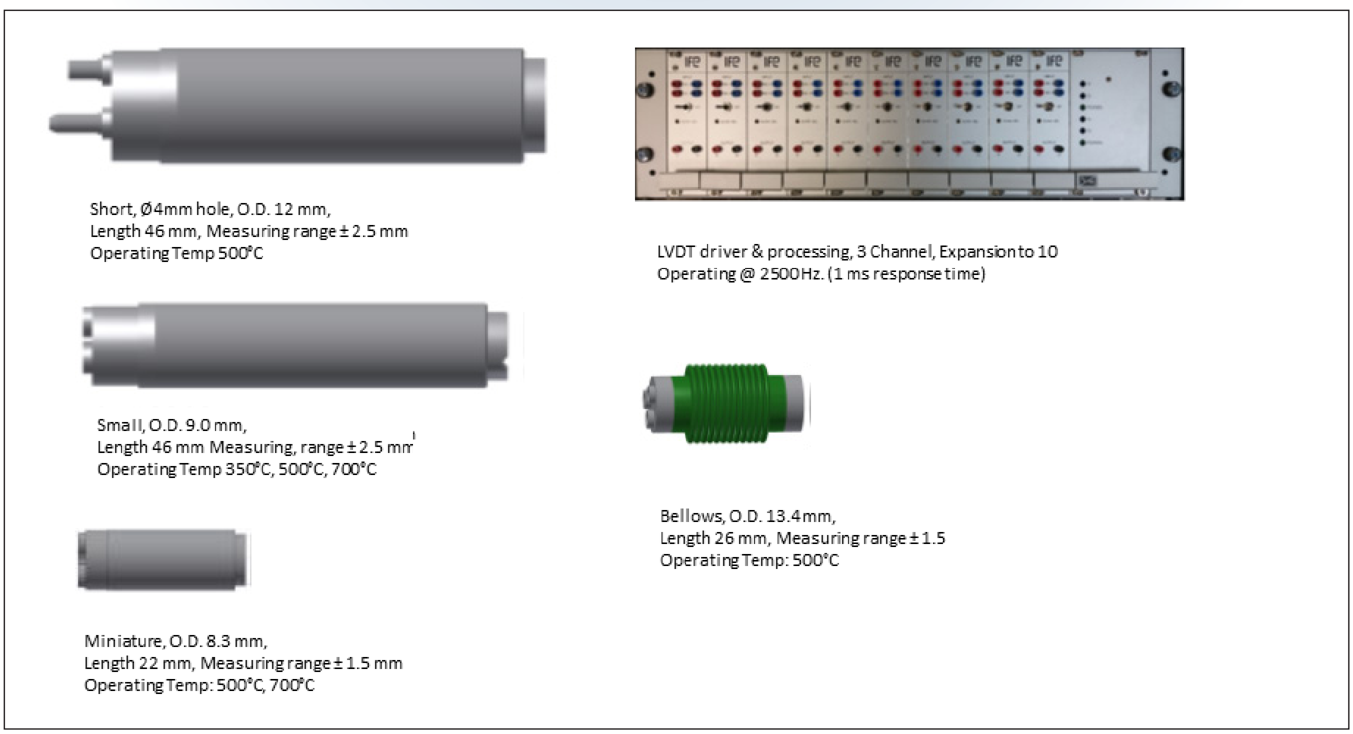

Figure 2. Assortment of LVDTs and high-speed driver and processor procured from IFA.

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Modeling of LVDT

A finite element model in COMSOL Multiphysics for LVDT sensors was developed to investigate the impact of each component's dimensions and material properties. This study then established a finite element model, including a through hole at the LVDT core to allow for instrumentation pass-through, such as a fiber optic cable.

Figure 3(a) shows an X-ray computed tomography (CT) image of the LVDT sensor modeled in this study. Due to its axial symmetry, a 2D axisymmetric model, as shown in Figure 3(b), is constructed in COMSOL Multiphysics. To further improve the computational efficiency, the electromagnetic coupling described by Maxwell's equations is solved in frequency domain by assuming constant magnetic permeability in each component. Figure 3(d) shows the distribution of magnetic flux at steady state when the core is 0.1 mm away from the null position.

The numerically modeled and experimentally measured demodulation voltages are plotted against the core displacement in Figure 4(a). A simulation error of less than 1.6% is achieved. Based on this accurate model, the impact of the through hole size is studied, as shown in Figure 4(b). The sensitivity reduction is less than 5% when the hole radius is smaller than 0.57 mm.

Based on the enhanced understanding of LVDT sensors enabled by this model, future studies will target sensor optimization and miniaturization for nuclear applications.

Wireless LVDT

Work is being performed to develop and demonstrate a wireless sensor LVDT for reactor test vessels (i.e., to have inductively coupled power transmission and wireless data communication through stainless steel walls). The technology

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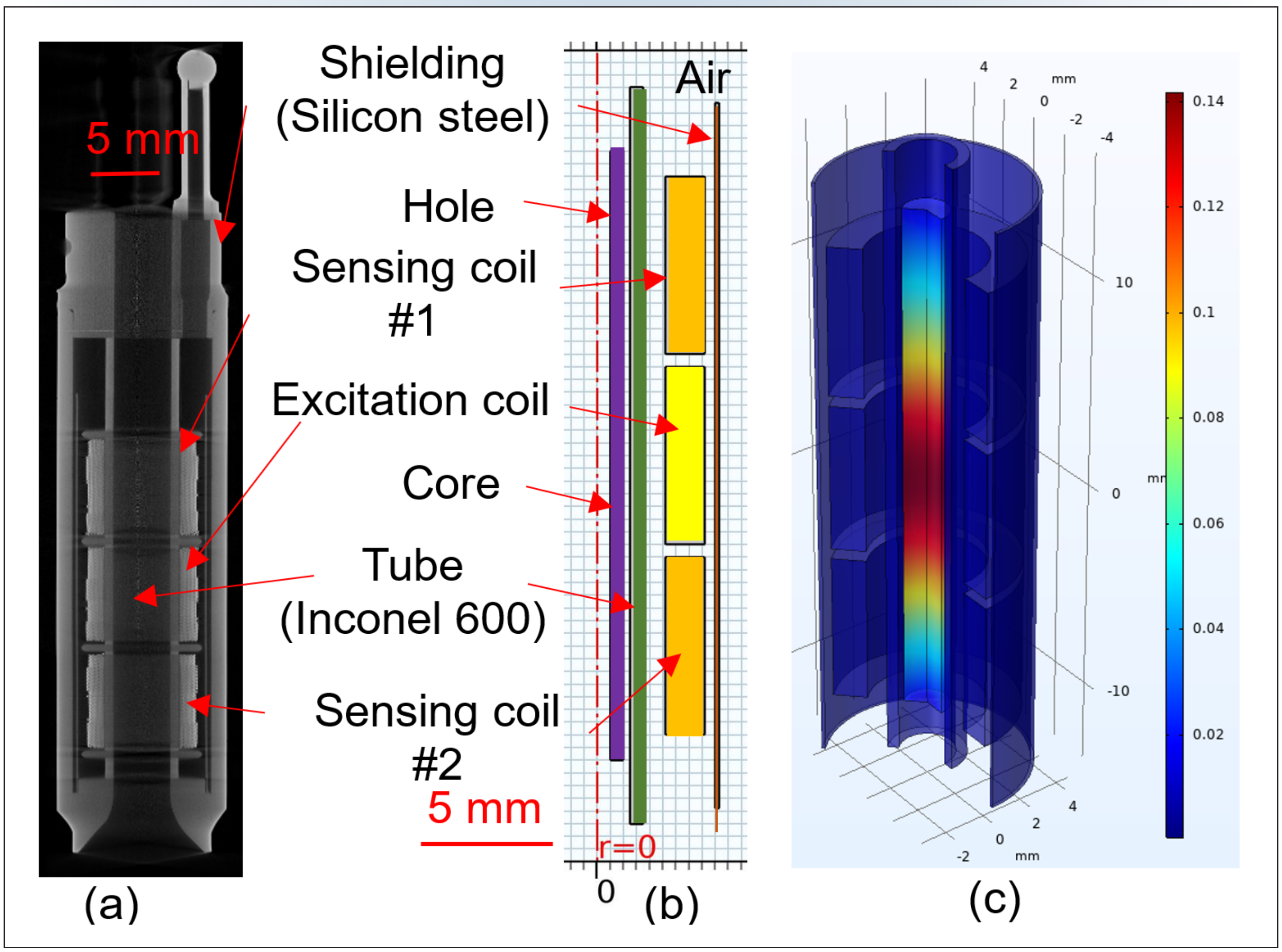

***Figure 3** (a) A CT image showing the cross section of an IFE LVDT sensor. (b) 2D axisymmetric model configuration in COMSOL Multiphysics. (c) Magnitude of magnetic flux density in Tesla when the core is 1 mm away from the null position.*

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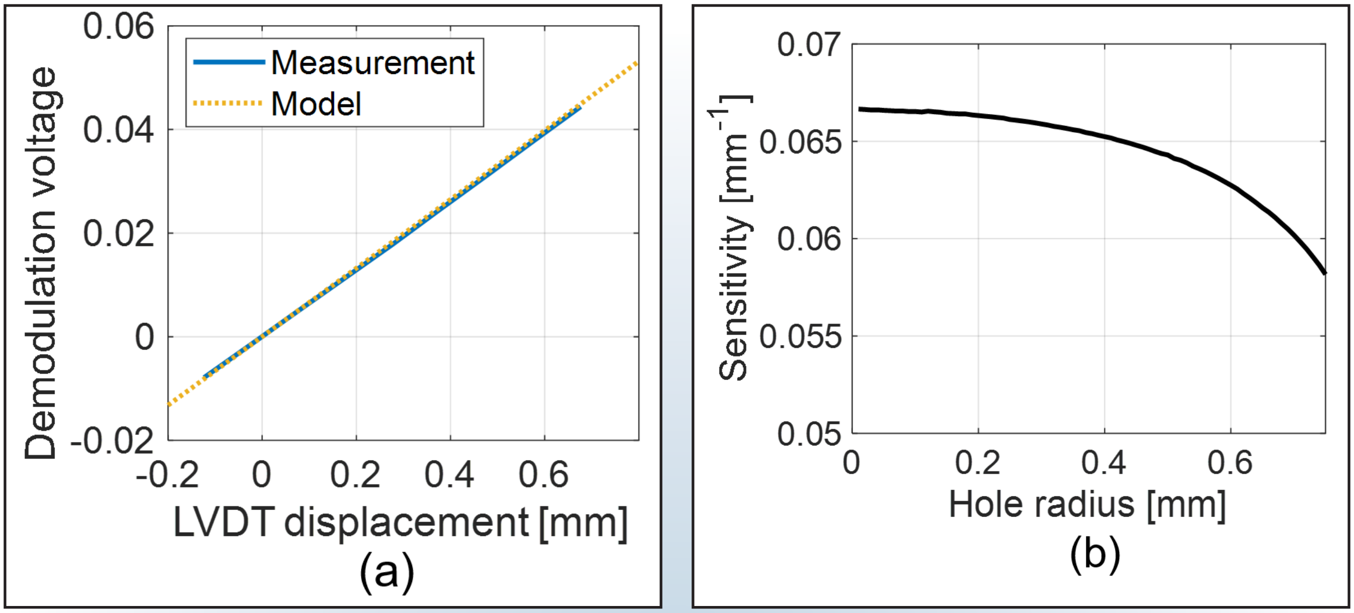

Figure 4 (a) Comparison of modeled and measured sensor performance. (b) LVDT sensitivity versus central hole radius.

will resolve the challenge of electrical feedthoughs and connections penetrating high-temperature high-pressure barriers. The basic LVDT sensor is for displacement measurement, although it can be converted to measure a suite of fuel performance related parameters, such as fuel centerline average temperature, fuel axial swelling/expansion, cladding axial growth, and plenum pressure. An important feature of this innovative concept is that the fluids used inside the test vessel can be sodium, lead/lead bismuth, salt, or helium. The outside environment can be air or another medium in Transient Reactor Test Facility (TREAT). The flexibility of inductive transmission signal and power enables a "universal" or "standard" cartridge design for material and fuel experiments, which can accelerate fuel development effort significantly.

The specific objectives of wireless LVDTs are:

1. Establish the feasibility of LVDT wireless coupling for power and signal transmission
2. Develop the theoretical basis and computational simulation capability to model the system performance
3. Optimize design for a lab prototype experiment and build and test the system in the laboratory
4. Design and development a system for TREAT demonstration

Conclusions

The development of sensors based on the LVDT will be crucial in meeting the future needs of tests conducted in MTRs, specifically TREAT experiments supporting near-term Light Water Reactor (LWR) and liquid metal experiments. Modeling and the development of a wireless LVDT sensor will become an integral step for successful deployment. High LVDT data acquisition speeds will be required.

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Development of Intrinsic Optical Fiber Sensors for In-Pile Measurements

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Introduction

Fiber optic instrumentation is commonly accepted as a standard class of instruments and is highly desirable for their widely touted benefits of small footprint, electromagnetic interference immunity, high-speed, and multi-modal capability. Optical fiber instrumentation can be used in a variety of ways to measure different physical phenomena, such as temperature, strain, pressure, and fluid level. As with any class of instrumentation, a unique set of challenges are encountered with in-pile deployment. Most notably for fiber optics, this includes the radiation-induced attenuation and radiation-induced emission. However, developments in radiation-resistant fiber optics and measurement techniques that minimize the impact of these phenomena have resulted in successful deployments of in-pile fiber optic instrumentation.

Optical fiber sensors and sensing techniques fall into two main categories: intrinsic sensing and extrinsic sensing. Intrinsic sensing uses the fiber itself to make a measurement and extrinsic sensors use something external to the fiber, such as a cavity, to make a measurement. Work that is being conducted on intrinsic optical fiber sensors will benefit extrinsic sensors because extrinsic sensors still use optical fibers to transmit the measurement information, and often times will have to run the cabling through high-temperature or radiation areas.

Sensor Design

Two common types of intrinsic optical fiber sensors are distributed temperature or strain sensors and fiber Bragg gratings (FBGs). Distributed sensors using the Optical Frequency Domain Reflectometry (OFDR) sensing technique are deployed in a cooling channel in the Transient Reactor Test Facility (TREAT). The OFDR technique operates on the principle of injecting light into an optical fiber and measuring the backscattered light (Rayleigh scatter) off of the local density fluctuations along the length of the fiber. As the temperature increases the optical fiber expands and the backscatter profile changes. This change can then be correlated to a change in temperature [1]. This method can also be used to measure strain distributed along the length of the fiber, where strain causes the fiber to expand or contract. An advantage of the OFDR technique is the spatial resolution of the measurements along the length of the fiber. A temperature or strain measurement can be recorded, with a spatial resolution less than a centimeter, along the entire length of the fiber. This allows for a full-temperature profile of an

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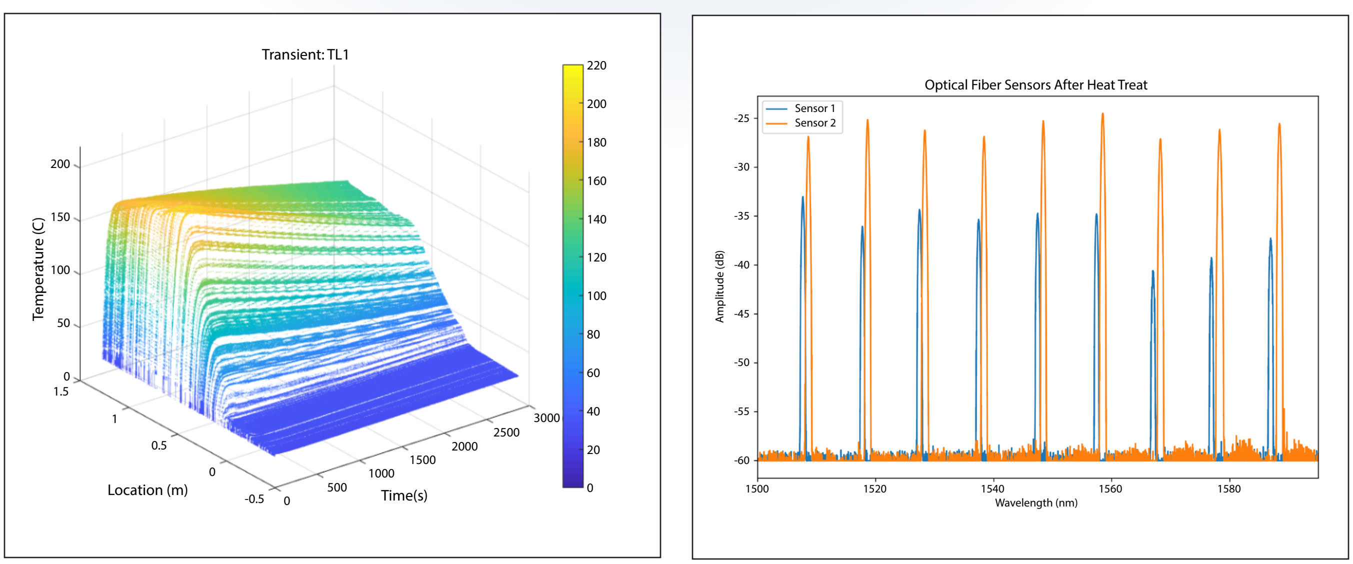

Figure 1. Left: Temperature profile of a TREAT cooling channel during a transient measured by an optical fiber. Right: Reflected spectrum of optical fibers with FBGs.

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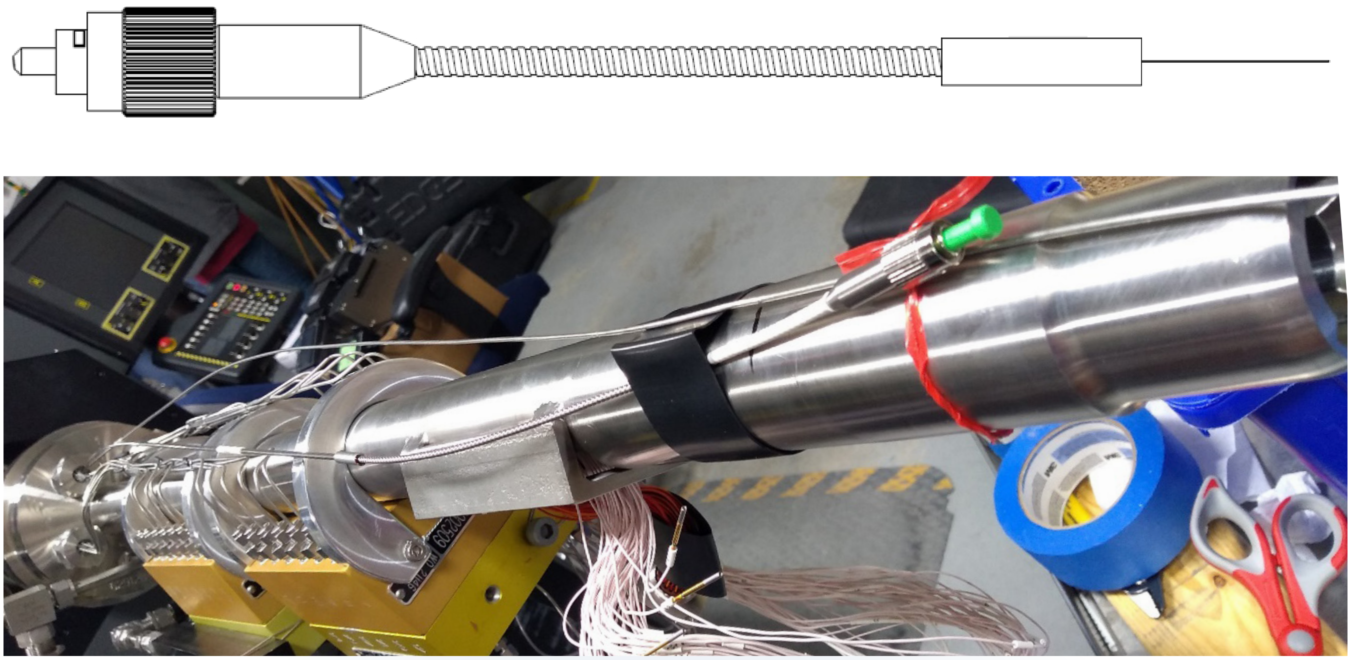

Figure 2. Top: Schematic of optical fiber sensor. Bottom: One of the FBG sensors installed in the HDG-1 experiment.

experiment or specimen to be measured with only one feedthrough and a very small footprint. Figure 1 on the left shows the full-temperature profile of a TREAT cooling channel during and during and after a transient run.

Distributed sensing in optical fibers has temperature limitations. These limits can be raised by modifying the fiber and inscribing FBGs. FBGs are a periodic variation in the fiber core index of refraction that allows specific wavelengths of light to be reflected, while remaining transparent to other wavelengths of light [2]. Temperature is measured by measuring the Bragg wavelength shift that occurs from the thermal expansion of the grating. As the fiber expands, the period of the grating changes and shifts the Bragg wavelength; this shift is measured by measuring the wavelength of light that is reflected to the detector. FBGs allow for a higher thermal stability in the intrinsic optical fiber measurement; however, the spatial resolution is not as high as the distributed measurement. Temperature or strain measurements in an FBG fiber are point measurements made at the location of each FBG, like a multipoint thermocouple. The spatial resolution is limited by the number of FBGs in the fiber and the wavelength range of your optical interrogator. Figure 1 on the right shows the reflected spectrum of two optical fiber sensors with nine FBGs each that are currently installed in the HDG-1 experiment that is awaiting installation in the Advanced Test Reactor. Figure 2 shows a schematic of an optical fiber sensor connection for both types of intrinsic sensors and one of the sensors that is currently installed in the HDG-1 experiment.

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Development of in-pile thermal conductivity measurement instrumentation based on photothermal radiometry

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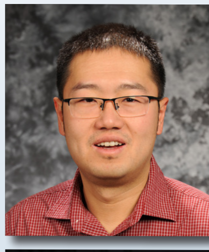

Description of activity

The goal of this project is the development of an optical, fiber-based instrument to measure in-pile thermal conductivity of fuels and materials. This instrument is based on photothermal radiometry and involves locally heating a sample and measuring the temperature gradient by collecting black-body radiation. The sample conductivity is extract by comparing experimental results with a continuum-based model. This contactless, remote measurement approach has numerous advantages over other laser-based measurement techniques. First, it does not need an optically smooth surface, thus no surface preparation is required. Second, measurement accuracy increases with increasing temperature making it ideally suited for high-temperature measurements. Third, this technique does not require access to the backside of the sample. Lastly, this approach can be used to measure friable spent fuel samples with irregular and/or poorly defined boundary conditions.

Impact and value to nuclear applications

Thermal conductivity of nuclear fuels is a critical physical property that is directly related to reactor safety, reliability, and efficiency. Moreover, development of advanced fuels with higher thermal conductivities will enable operating fuels at lower temperatures. Low-temperature operation is desirable because fission gas transport is greatly reduced at lower temperatures. Understanding how thermal conductivity changes with irradiation is key to developing high-conductivity fuels. Thermal transport in oxides and to a lesser extend in metallic fuels is influenced by radiation defects (e.g., point defects, dislocation loops, small defect clusters). Researchers have speculated for years that the in-pile conductivity can be significantly smaller from that measured in a PIE environment. The reason for this is that point defects, which effectively scatter thermal carriers, anneal before PIE measurements can be performed. Having the ability to make accurate, in-pile measurements of fuel conductivity will greatly benefit advanced fuel performance codes and will aid in the development of high-conductivity fuels.

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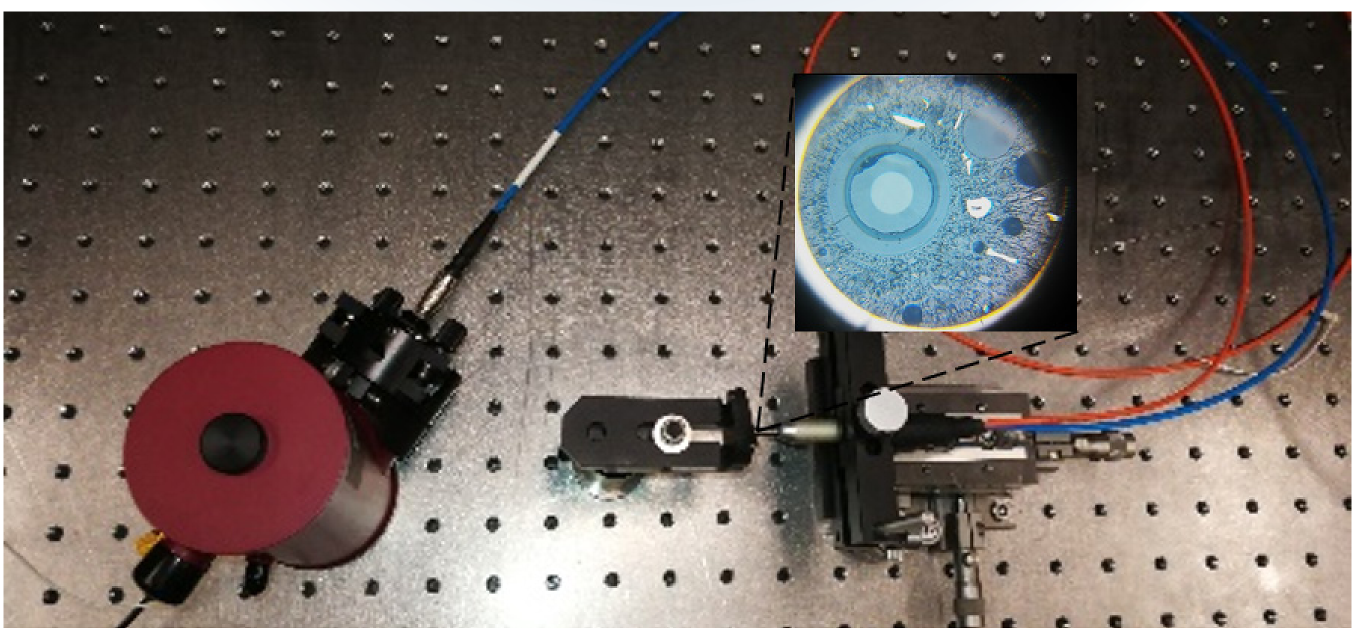

Figure 1. Proof of concept system using a fiber-optic to collect black body irradiation associated with transient laser heating. The inset shows an optical micrograph of the fiber end facing the sample.

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Sample	Measurement results of thermal diffusivity [mm^2/s]	Reference values (LFA) of thermal diffusivity [mm^2/s]	Difference %
Pyrex	0.8	0.69	15.9%
Pyroceram	2.15	2	7.5%
Alumina	12.2	12.5	-2.4%
Poco graphite	60	64.6	7.1%

Table 1. Result summary from the fiber-based system on reference samples in laboratory environments.

Recent results and highlights

A free-space photothermal radiometry system (built in fiscal year [FY] 2019) was used to gather data on several samples having conductivities that span the spectrum from high-conductivity fresh metallic fuels to low-conductivity spent oxide fuels. A continuum-based model was used to define a measurement envelop that produces accurate/reproducible results. This work helped identify and isolate measurement artifacts associated with optical diffraction and transfer function nonlinearities. Current efforts are aimed at the testing and optimization of the optical fiber-based system. Preliminary testing shows promising results. The major highlights are summarized below.

1. A free-space photothermal radiometry system was built up and used to validate the measurement approach. A novel frequency-domain measurement approach that was specifically designed for the fiber-based in-pile measurement instrumentation was tested and the feasibility was validated. Measurement accuracy better than 10% has been achieved on reference samples with thermal conductivities covering a range from fresh metallic fuels to spent oxide fuels. Most importantly, the measurements were successfully conducted on porous materials without surface treatment, which are representative of spent fuels and fuels in service.
2. A fiber-based photothermal radiometry system with two-fiber sensor heads was designed and constructed (Figure 1). Preliminary measurements, shown in Table 1, compare favorably with reference values.
3. High-temperature measurements were conducted with a heating plate. The signal level was increased by two orders of magnitude as expected (Figure. 2), indicating better accuracy at high temperatures. Further system optimization is underway and involves replacing optical and electronic components that are optimized for use at high temperatures. Our analysis shows that the system signal-to-noise ratio is expected to be improved by another factor of 10 after the new components are installed, and the system will exhibit enhanced performance at a higher temperatures (up to 700°C).
4. Finally, a couple of peer-reviewed manuscripts to summarize the system development and optimization are under preparation and expected to be submitted before the end of the fiscal year.

Future plans

In this fiscal year, the current fiber-based system will be used to assess key implementation of the instrumentation questions for the in-pile testing. The feasibility assessment will be summarized in a milestone report due at the end of September 2020. In fiscal year 2021, a real-time thermal conductivity measurement will be conducted on surrogate materials in a laboratory furnace that simulates the high-temperature environment of an operating reactor. Following the high temperature test, a preliminary design of an in-pile instrument suitable for operation in the TREAT reactor will be drafted.

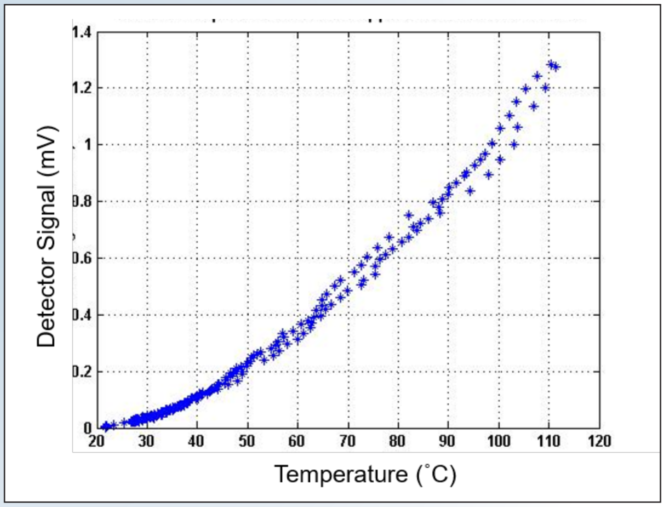

Figure 2. Signal improved by more than 100 times with elevated temperature (from room temperature to 110 ˚C). Good repeatability was observed from heating up and cooling down procedure.