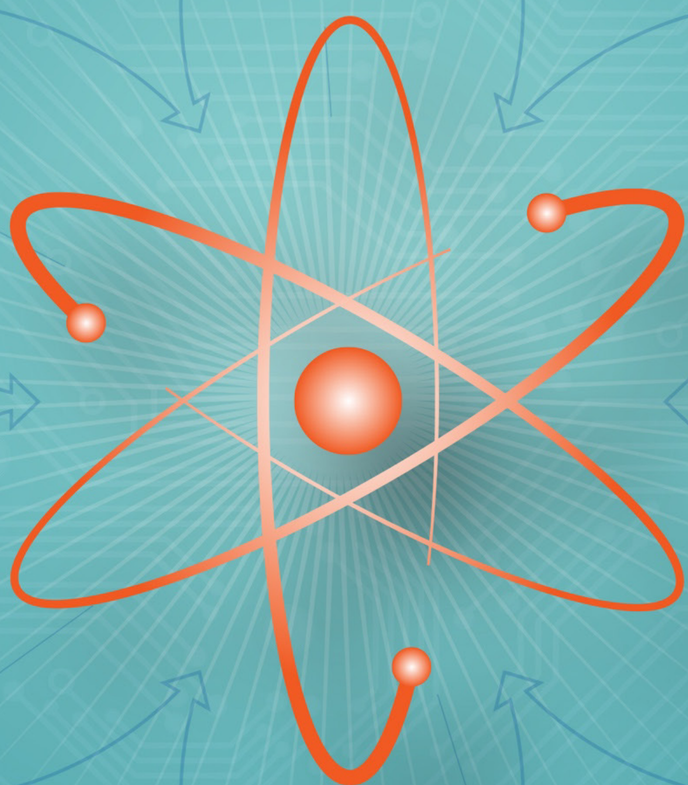
U.S. DEPARTMENT OF
ENERGY

ADVANCED SENSORS AND INSTRUMENTATION

2023 SUMMARY OF ACCOMPLISHMENTS



ABSTRACT

The Advanced Sensors and Instrumentation (ASI) program is the element of the Nuclear Energy Enabling Technologies (NEET) initiative dedicated to Instrumentation and Control (I&C) technology. This document collects in the form of summaries the research accomplishments presented at the program 2023 Annual Review meeting, which was held virtually between October 30 and November 2, 2023.

TABLE OF CONTENTS

INTRODUCTION

In 2011, the Department of Energy's Office of Nuclear Energy (DOE-NE) initiated the Nuclear Energy Enabling Technologies (NEET) initiative to conduct research, development, and demonstration (RD&D) in crosscutting technologies that directly support current reactors and enable the development of new and advanced reactor designs and fuel cycle technologies. The Advanced Sensors and Instrumentation (ASI) program is the element of NEET dedicated to Instrumentation and Control (I&C) technology.

The NEET ASI Program has the following roles:

- Coordinate crosscutting research among NE programs to avoid duplication; focus R&D in support of advances in reactor and fuel cycle system designs and performance.
- Advance technology readiness levels (TRL) across the four ASI research areas to support maturation of R&D from first concepts to commercialization.

The ASI Program has spurred innovation in the measurement science field by funding research to advance the nuclear industry's monitoring and control capability. These capabilities are crucial in developing research solutions that enable reduced costs, improved efficiencies, and increased safety for both current and advanced reactors operations. They also serve a vital role in Materials Test Reactors (MTR) to measure environmental conditions of irradiation experiments and to monitor aspects of advanced fuel and materials behavior.

RESEARCH ACCOMPLISHMENTS

This section collects in the form of summaries the research accomplishments presented at the ASI program 2023 Annual Review meeting, which was held virtually between October 30 and November 2, 2023. The content is organized following the four meeting sessions, as follows:

- Sensors for Advanced Reactors
- Sensors for Irradiation Experiments
- Sensor Integration

Sensors for Advanced Reactors

Neutron Flux Sensors

PI: Kevin Tsai – Idaho National Laboratory
Collaborators: Geran Call and Michael Reichenberger – Idaho National Laboratory
Loïc Barbot and Grégoire de Izarra – French Alternative Energies and Atomic Energy Commission
Matthew Van Zile, Kevin Herminghuysen, Susan White, Andrew Kauffman – The Ohio State University

Project Description: The goal of the INL neutron flux work package is to evaluate and develop in-core neutron flux sensors for high-temperature applications in support of upcoming advanced reactor demonstrations. The specific sensor technology of focus are the self-powered neutron detectors (SPND) and fission chambers. The activities of fiscal year 2023 are performance benchmarking of commercial high-temperature fission chambers and demonstrating of temperature compensation techniques of SPNDs at temperatures up to 850°C.

Impact and Value to Nuclear Applications: Performance evaluation of high-temperature fission chambers and demonstration of temperature compensation techniques of SPNDs are both targeted for sensor applications in advanced reactor demonstrations with operational temperature exceeding 600°C. Evaluation of high-temperature fission chambers identifies operational characteristics such as temperature effects, operational limits, and failure modes. Demonstration of temperature compensation techniques for SPNDs provides methods to subtract the temperature effects on SPNDs for more reliable measurements.

Recent Results and Highlights: Fission chambers were irradiated in the Ohio State University Research Reactor (OSURR) up to 850°C with varying reactor power.

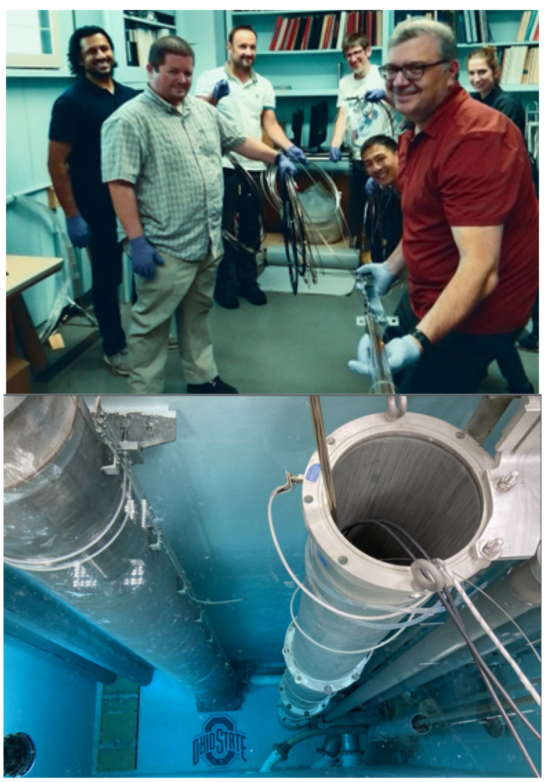


Figure 1. (top) Experiment team holding the experiment (bottom) OSURR 9.5-inch dry tube with experiment.

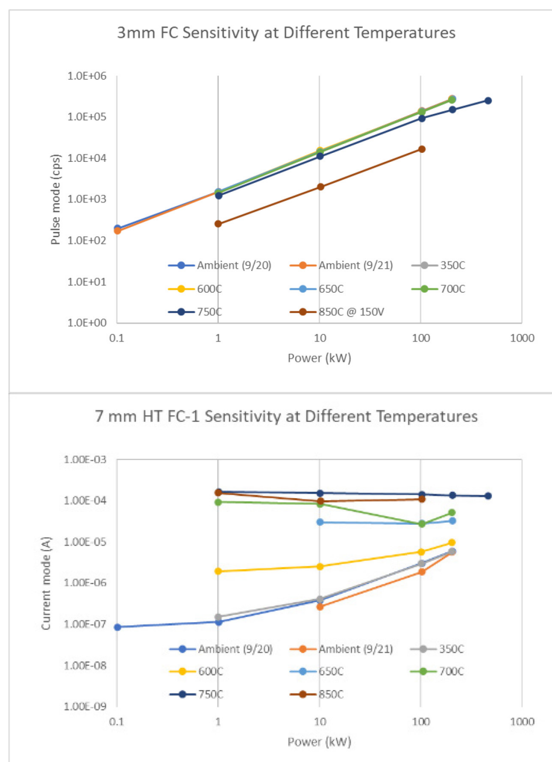


Figure 2. Sensitivity curve at different temperatures for the (top) 3mm fission chamber (bottom) 7mm high-temperature fission chamber.

Reactor Power Synthesis with Simulated SPND Responses & SPND Analysis of WIRE-21

PIs: Anthony Birri and Padhraic Mulligan – Oak Ridge National Laboratory
Collaborators: Daniel C. Sweeney, Callie C. Goetz, N. Dianne Bull Ezell, Kara M. Godsey, Christian M. Petrie– Oak Ridge National Laboratory

Project Description: The goals of this research are to analyze experimental data produced by self-powered neutron detectors (SPNDs) irradiated in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, as well as to develop power synthesis models to assess the ability to infer power distributions with SPND arrays. The developed power synthesis models (informed by MCNP and Geant4) focus specifically on next-generation light-water reactors that are under development or in current utilization. The models allow for a study of impacts of sensor uncertainty, how sensor arrangement affects synthesis accuracy, and how well power perturbations can be resolved.

Impact and Value to Nuclear Applications: SPNDs are neutron flux detectors that can provide crucial data for reactor operations in real time and while in situ. SPNDs have been implemented for decades, and more recent advances have led to their optimization and reduction in sensor uncertainty; furthermore, careful tuning of materials and dimensions can result in identification of an SPND design appropriate for a variety of advanced reactor designs. SPNDs are crucial for power distribution synthesis, as they are one of the only radiation detector technologies that can be deployed practically, in situ, in an array. As such, they uniquely enable detection of power tilt from xenon build-in, burn-up impacts, and the effects of control rod manipulation on the 3D distribution of power. The SPNDs included in the WIRE-21 experiment are the first SPND measurement of neutron flux in HFIR.

Recent Results and Highlights: Data analysis of SPNDs in HFIR showed peak flux shift over the course of a cycle due to control plate movement, which validated neutronics models of the reactor. The SPNDs also showed a response to changing temperature in the experiment, indicating a decrease in signal with increasing temperature. Recent results from power synthesis simulations have allowed for the determination of how the synthesized power distribution error scales as a function of SPND uncertainty. Furthermore, a high-fidelity model of the Texas A&M TRIGA reactor was generated, and accurate perturbation detection was demonstrated, which indicates the model can serve as a test bed for further perturbation analysis.

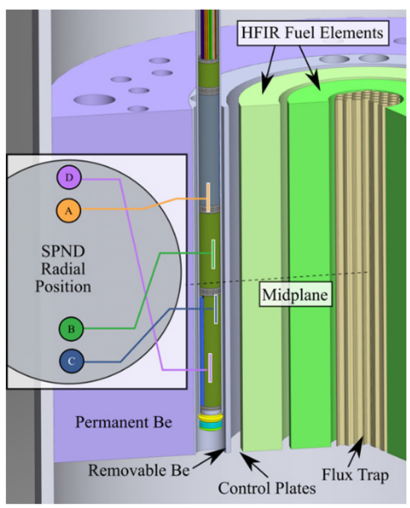


Figure 1. WIRE-21 SPND locations in the HFIR removable beryllium reflector.

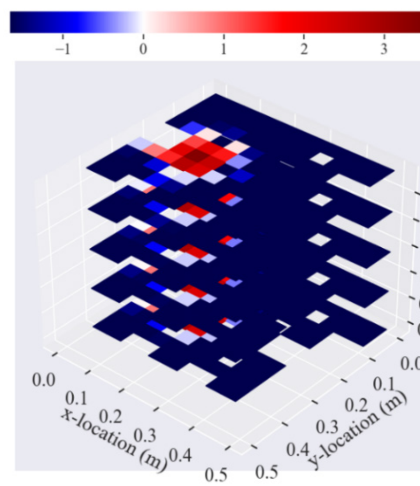


Figure 2. Perturbation detection in the TAMU TRIGA with power synthesis.

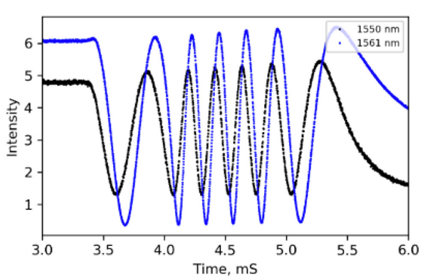
Optical Fibers – INL

PI: Austin Fleming – Idaho National Laboratory

Project Description: Although fiber optic sensors have been widely adopted as standard instrumentation in many industries, certain challenges presented by reactor environments have caused the nuclear industry to be slow in adopting this technology. This project aims to directly address these challenges so that fiber optic sensors can have the same innovative impact on the nuclear industry as they have had in other fields. Regarding the development of fiber optic sensors and sensor technologies, this project prioritizes near-term applications (i.e., customers with immediate needs), straightforward paths to development (mostly engineering, with little to no R&D), and impact to the nuclear industry. Fiber optic work in fiscal year (FY) 2023 progressed several fiber optic sensor activities related to the INL developed pressure sensor, in-pile imaging, and fiber optic temperature sensors.

Impact and Value to Nuclear Applications: Fiber optic sensors offer many notable benefits that are of interest to the nuclear industry: small footprints, high sensitivity, immunity to electromagnetic noise, high speeds, and multiplexed sensing. The fiber optic sensors being investigated will be used for temperature/pressure monitoring as well as in-core imaging. To account for degraded optical fiber performance in high-temperature irradiation environments, active compensation techniques are needed to minimize sensor drift and improve sensor longevity in material test reactors and advanced reactors. Furthermore, development of high-pressure, high-temperature optical fiber feedthroughs will be necessary to install fibers in high-interest locations (e.g., fuel pins) or to enable coolant monitoring for thermal hydraulic characterization.

Recent Results and Highlights: A high-speed data acquisition system was developed for the fiber optic pressure sensor to meet the transient testing needs for nuclear fuels. The design of this measurement system and a sample of some of the data collected is provided below. Additionally, this fiscal year the INL developed active compensation sensor was irradiated in the MIT reactor collecting data on the radiation induced compaction and index of refraction changes. Significant advancements were made in the optimization of in-pile imaging system using ray tracing and experimentally testing fiber buddle connections. The results from the ray tracing and experimental testing were compared with good agreement.



Sample data collected from the high speed fiber optic pressure sensor data acquisition system

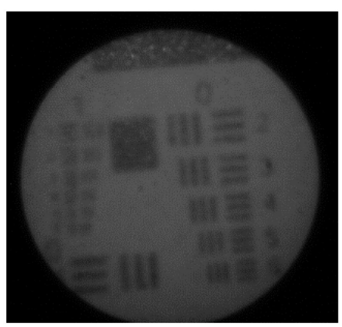
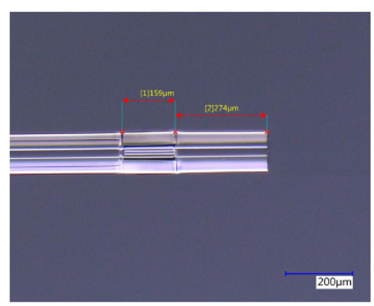


Image collected from coherent fiber bundle with testing the efficiency and resolution associated with a connection



Experimental results from testing the sensor performance at elevated temperatures

Analysis of Extreme Radiation Dose Effects on Fiber Optic Sensors

PI: Christian M. Petrie – Oak Ridge National Laboratory
Collaborator: Daniel C. Sweeney – Oak Ridge National Laboratory

Project Description: This project leverages a recent instrumented irradiation experiment performed in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory, funded by the Nuclear Science User Facilities Program. Many fiber optic sensors were tested with and without inscribed fiber Bragg gratings (FBGs), both Type I and Type II, with varying chemical dopants (F and Ge), under the highest fast neutron flux ever reported. The results were analyzed to determine the effects of signal attenuation and drift of fiber optic temperature sensors and their dependences on chemical dopants and grating types.

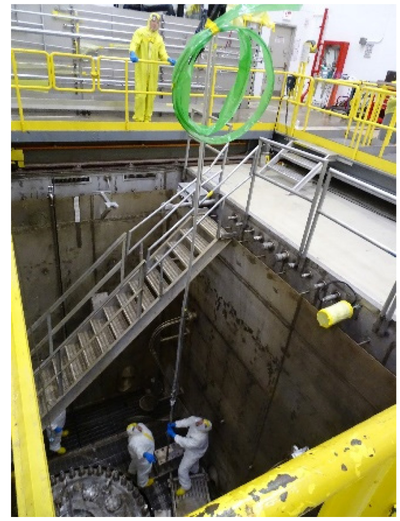


Figure 1. Experiment being loaded into HFIR.

Impact and Value to Nuclear Applications: Optical fiber-based sensors have a wide range of potential applications in advanced nuclear reactors and in irradiation experiments performed in materials test reactors. For example, fiber-based sensors have been demonstrated to measure temperature, strain, pressure, vibration, liquid level, fluid flow rate, and gamma heating rates, and many of these sensors are capable of spatially distributed measurements at high temperatures. This work fills important data gaps regarding radiation-induced signal attenuation and drift, which are the primary challenges to extending these measurements to in-core nuclear applications.

Recent Results and Highlights: Ge-doped fibers showed prohibitively large signal attenuation, whereas F-doped fibers showed backscattered light intensities that were *higher* after accumulating ~10^{21} n_{fast}/cm^2 than they were prior to irradiation.[1] Type II FBGs were shown to be more radiation-tolerant than Type I FBGs and their survivability depended on the core doping (F-doping improved survivability). Surprisingly, the signal drift in all fibers far exceeded that predicted by state-of-the-art models for radiation-induced compaction and its effect on optical properties. We believe this to be an effect of radiation on the fiber coating and plan to investigate this phenomenon in more detail in fiscal year 2024.

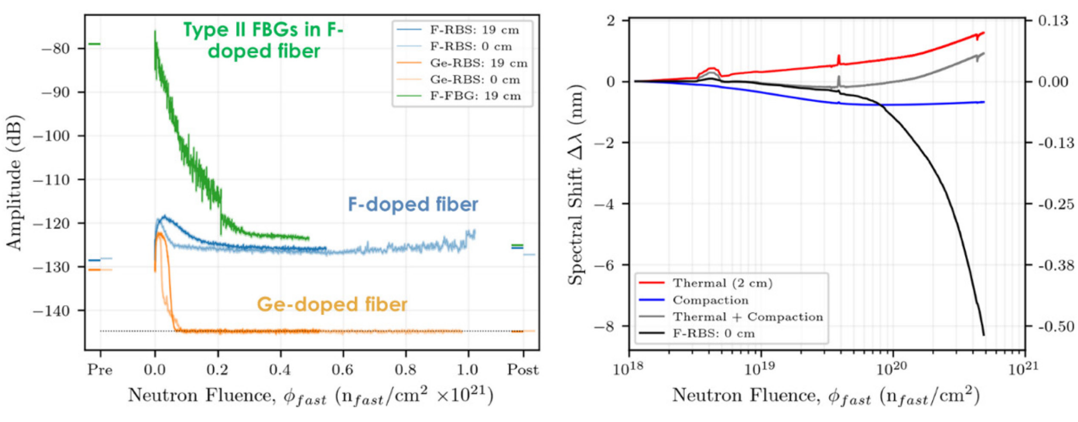


Figure 2. Reflected signal amplitudes (left) and drift (right). Reprinted from Petrie and Sweeney[1] with permission from Elsevier.

[1] Petrie, C. M. and Sweeney, D. C. 2023. "Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage," *J. Non-Cryst. Solids,* **615**, 122441.

Structural Health Monitoring and Acoustic Sensors

PI: Joshua Daw, Bibo Zhong – Idaho National Laboratory
Collaborator: Dan Deng – Boise State University

Project Description: The goal of this research is to complete Idaho National Laboratory (INL)'s development of an ultrasonic thermometer (UT), and to assess the current state of sensors based on acoustic technologies usable for structural health monitoring (SHM) and pressure measurements for advanced reactor applications.

Impact and Value to Nuclear Applications: Acoustic and ultrasonic transducers serve as the base technology in numerous sensors for measuring a multitude of parameters, or for directly interrogating structures so as to monitor their degradation states. Accurate online monitoring of test parameters (e.g., temperature and strain) will greatly reduce the time and cost associated with developing, demonstrating, and licensing new nuclear technologies. In this regard, the UT (a temperature sensor based on an acoustic waveguide) is being developed for in-core, multi-point temperature monitoring at extreme temperatures. SHM via ultrasonic methods is a well-developed technology not yet widely applied to commercial reactors. Online monitoring of reactor components could potentially enhance both the safety and reliability of next-generation nuclear technologies. The sensors and transducers typically used for this type of monitoring are known to have limited radiation tolerance.

Results and Highlights: Multiple UT design enhancements were tested, including high-frequency, high-temperature coils using 3D-printed coil formers. The newer designs showed improved performance over prior UT designs. Several commercial acoustic emission, vibration, and pressure sensors were evaluated to benchmark the performance of the sensors and testing facilities, and to identify needed design changes for optimizing performance in high-radiation environments. These results will drive the development of new sensors based on technologies with higher inherent radiation tolerances. Physics-based models were developed by Boise State University to aid in accelerating the design and diagnostics of UTs, as well as newer sensors based on the base magnetostrictive technology used in UTs.

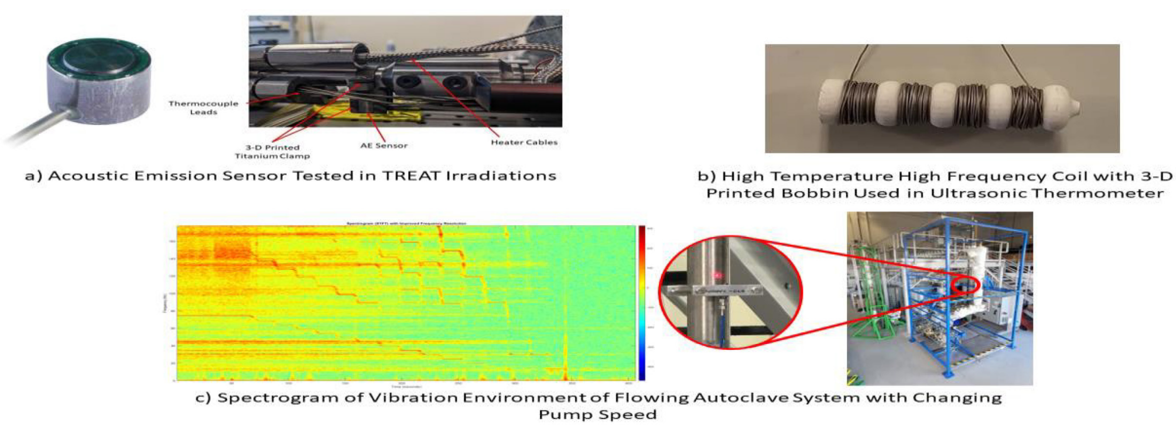


Figure 1. Assorted sensors tested during fiscal year 2023.

Influence of Joule Heating on the Stability of High Temperature Irradiation Resistant Thermocouples

PI: Richard Skifton – Idaho National Laboratory
Collaborators: Scott Riley, Brandon King, Allyssa Bateman, Brian Jaques – Boise State University

Development of in-core instrumentation is driven by the pursuit of safer and more economic energy production from both existing nuclear reactors and Generation IV reactor designs. Idaho National Laboratory (INL) has developed high temperature irradiation resistant thermocouples (HTIR-TCs) for temperature sensing inside Generation IV nuclear reactors. These thermocouples are composed of phosphorus-doped niobium (Nb-P) and lanthana-doped molybdenum (Mo-LaO) thermoelements, an alumina (Al2O3) insulation, and a niobium sheath. HTIR-TCs require an initial heat treatment exceeding the maximum service temperature to stabilize the generated electromotive force (EMF) signal; however, the mechanism behind this stabilization is not well understood. This work evaluates the impact of Joule heating on the thermoelements' microstructures, chemical stability, and mechanical properties to determine the mechanisms by which the EMF signal stabilization occurs. Accordingly, during the Joule heat treatment, a secondary Nb3P phase coarsened along the length of the Nb-P thermoelement, along with a chemical interaction region at the Al2O3/niobium interface. Joule heating induced stability within the generated EMF signal of HTIR-TCs through the formation of secondary phases within the Nb-P and the interaction of the alumina insulation with the thermoelements.

To evaluate the influence of Joule heating on the stability of the generated EMF signal of the HTIR-TCs, thermocouples heat treated using 1.25, 2, and 2.25 A for 30 minutes were subsequently held within a resistive heating furnace for 50 hours at both 1250 and 1450 °C while the EMF signal was collected, as seen in Figure 1. The stability observed in both the 2 and 2.25 A Joule heated HTIR-TCs is attributed to the formation of an interaction region between the thermoelements and the alumina insulation. By forming the interaction region about the outer perimeter of the thermoelements it acts to impede further diffusion of alumina into the thermoelements which stabilizes the generated EMF signal. The EMF magnitude and stability was most prevalent in the joule heating 2.25A case.

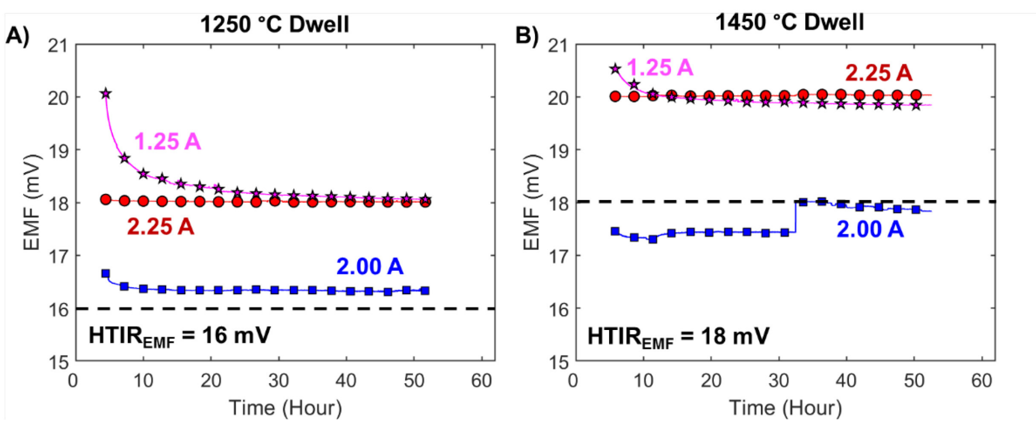


Figure 1. EMF signal generated for Joule heated HTIR-TCs as compared with the standard EMF signal generated for a HTIR-TC heat treated for 6 hours between 1450 and 1650 °C. The EMF magnitude and stability is more prevalent in the 2.25A joule heated case.

Reduction of Random Uncertainty in Differential Temperature Measurements, Using Common-Leg Thermocouples

PI: Richard Skifton – Idaho National Laboratory

Measuring the temperature of nuclear fuel is a complex endeavor that requires many phenomena such as thermos- and nuclear interactions to be considered. However, first and foremost, nuclear fuel must be able to physically accommodate a sensor without disrupting the desired outcome. This drives sensors such as thermocouples (TCs) to be made smaller and more compact, and for more sensors to be built into a single probe. A common practice is to create a common leg TC as one sensor.

The temperature sensed by a TC is governed by what metals were used as thermoelements and the overall shape of the thermal gradient those distinct metals were inserted into. This can be seen as

$$V = \int_0^L S_{A_1} \frac{dT}{dx} dx + \int_L^0 S_{A_2} \frac{dT}{dx} dx \tag{1}$$

where S is the material specific Seebeck coefficient, i and j are the individual thermoelements contained in the TC circuit, dT/dx is the local temperature profile and L is the overall length of the thermoelement. For common-leg (CL) TCs, Eq. 1 is applied and simplified by comparing two TC junctions that are sharing the material properties of one of the thermoelements, A_1, and then comparing the two different voltage outputs of the common leg TCs, A_1A_2 and A_1A_3, as follows,

$$\Delta V_{CL} = V_{A_1A_2} - V_{A_1A_3} \tag{2}$$

Type A uncertainty quantification involves an ideal case of two TCs that share a common leg between them. Various techniques can be employed to reduce the standard error to a minimum. For random correlated error from a common-leg TC, the random uncertainty includes the covariance term where the total uncertainty at the 95% level is therefore:

$$U_{CL} = 2\sqrt{{b_{AB}}^2 + {b_{AD}}^2 - 2\rho_{ABAD}\sigma_{AB}\sigma_{AD}} \tag{3}$$

where the higher the correlation the lesser the uncertainty in ΔV of Eq. 2. For separate leg TCs, the covariance term is not present, driving the uncertainty in equation 2 to be higher than that of the common leg TCs.

With the covariance term being negative, as seen in Eq. 3, use of a common-leg TC can reduce the overall random uncertainty per:

$$U_{CL} = \frac{U_{SL}}{R} \tag{4}$$

where R is a unitless number. Different TC materials may greatly affect R, but it is estimated that R is bounded by 1, up to a finite value of around 3–5.

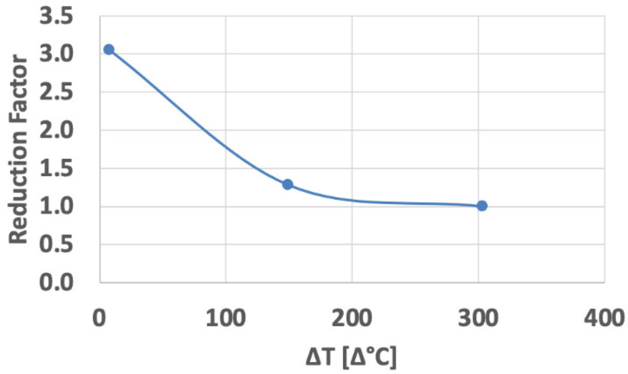


Figure 1. Reduction factor when using common-leg TCs vs. two individual TCs to measure ΔT. The chart shows that, with expanding ΔT, diminishing returns are gained from using common-leg TCs.

Front End Digitizer (FREND): FY23 Activities and Achievements Summary

PI: K.C. Goetz - Oak Ridge National Laboratory
Collaborators: Daniel C. Sweeney, F. Kyle Reed, N. Dianne Ezell – Oak Ridge National Laboratory

Introduction: High-radiation and high-temperature environments pose notoriously detrimental conditions for electronics. Nevertheless, sensors are critically important for safe operation and validity of the scientific experiments conducted within the nuclear reactors. The front-end digitizer (FREND) (Figure 1) seeks to improve the fidelity of nuclear sensor data by placing a radiation-resistant analog front end within a high-radiation area, followed by immediate signal encoding and transmission outside of the high-radiation area to an instrument room via optical fiber. Early signal preamplification and encoding increase sensor signal integrity, while optical transmission renders the system blind to electromagnetic noise introduced with lengthy cabling. FREND is designed to support the digitization and transmission of signals from nuclear sensors relevant to reactor functionality. The present prototype supports up to seven sensors, which can be multiplexed for transmission over a single fiber-optic cable.

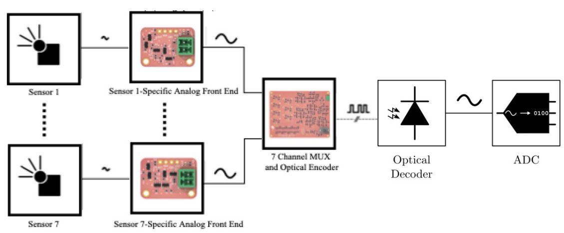


Figure 1. Block diagram of the FREND system.

FY 2023 Activities: During FY23, seven FREND systems were irradiated, three in a neutron field and four in a mixed neutron–gamma field. The first irradiation used a ^{252}Cf fast neutron source at Oak Ridge National Laboratory's Radiochemical Engineering Development Center (REDC) and provided a minimum survivability measurement to 10^{13} n/cm^2. The second irradiation of FREND was performed in-pool at North Carolina State University's PULSTAR reactor to ~10^{16} n/cm^2. A summary of the two irradiations is provided in Table 1.

In both irradiations minimal changes to the FREND circuit were observed prior to 1013 n/cm2. However, during the PULSTAR irradiation, the FREND system stopped reliably performing at fluences of ~1014 n/cm2. Notably, some of the FREND subcircuits, such as the clocks, on both boards remained functional beyond 1015 n/cm2. The survival of the clocks suggests that implementing radiation-drift compensation circuitry in the digital subcircuits may improve the system's overall radiation tolerance. As the selected junction-gate field effect transistors (JFETs) have demonstrated high tolerance with little noticeable effects to ionizing radiation, it is suspected that the observed failures in the circuitry were caused by neutron degradation of the JFETs. Neutron displacements and transmutations of the semiconductor and doping materials would vary the JFET characteristics, such as the threshold voltage, channel mobility, and transconductance. These characteristic variations in the JFETs manifested in the observed drifts in DC offset, oscillation frequency, duty cycle, and signal amplitudes of the FREND system.

Table 1. Irradiation summary, including the irradiation location, the maximum fluence a given board was exposed to, and the fluence at which the system stopped reliably reporting the input sensor data.

Board number	Irradiation facility	Cause of death	Max fluence (n/cm^2)	Death fluence (n/cm^2)
1	^{252}Cf	NA	2.5×10^{13}	NA
2	^{252}Cf	NA	2.5×10^{13}	NA
3	^{252}Cf	NA	2.5×10^{13}	NA
5	PULSTAR	Water damage	1.3×10^{13}	NA
6	PULSTAR	Water damage	1.3×10^{13}	NA
8	PULSTAR	Radiation	1×10^{16}	2×10^{14}
9	PULSTAR	Radiation	1×10^{16}	1.8×10^{14}

An important observation from the analysis is the lack of single event effects (SEEs) in the two high-flux irradiations. This is due to the lack of charge trapping centers in JFETs due to their design lacking a gate-insulation. However, modern Si and SiC JFETs struggle with neutron-induced single event burnouts. This result is a vital takeaway from this experiment because it highlights the vastly different effects radiation in a nuclear environment has on electronics compared to the traditionally studied space applications. The observations regarding the circuit performance allow for more neutron-robust circuits to be designed. Future enhancements should include using larger rail voltages, adjusting JFET biasing, and introducing logic threshold asymmetry. However, the greatest increase to system performance would be achieved by combining these principles with a wide-bandgap transistor-based application-specific integrated circuit.

Versatile Acoustic and Optical Sensing Platforms for Passive Structural Systems Monitoring

PI: Gary Pickrell, Anbo Wang – Virginia Tech

Project Description: The objective of the research is to develop a non-contact "burst detection" system to monitor the structural health of the fuel cladding under high fluence and elevated temperatures. Fuel cladding displacement and radial strain measurements will be performed in real time via an optical fiber based interferometric sensing system. The performance of a prototype sensing system will be demonstrated in a simulated laboratory environment to prepare for in-pile deployment and testing.

Impact and Value to Nuclear Applications: Fuel cladding integrity is a primary focus of safety testing and remains a significant research priority for the Advanced Fuels Campaign. Performance of accident-tolerant fuel (ATF) candidates must be evaluated under simulated loss-of coolant accident (LOCA) conditions to support licensing of these materials. Licensing to extend the peak rod average burnup requires an understanding of high-burnup fuel fragmentation, relocation, and dispersal (FFRD) in the event of cladding failure under LOCA conditions. A non-contact displacement and radial strain monitoring system of standard fuel cladding specimens will enable the nuclear community to better assess ATF candidates and FFRD under LOCA conditions.

Recent Results and Highlights: To meet the project objectives, sensor operating requirements and specifications were determined via collaboration with INL. Theoretical analyses and modeling was performed to optimize the configuration and response of a unique "dual-probe" Fabry Perot sensor. Sensor algorithms were developed and implemented with a "dual-probe" sensor to successfully demonstrate feasibility of the approach via bench-top testing. Laboratory scale test facilities were constructed to simulate the swelling and bursting of the fuel cladding to enable performance testing of sensor prototypes. A "laboratory standard" sensing probe was designed and fabricated; displacement measurements were acquired, in real-time, upon induced swelling and bursting of a pressurized stainless-steel tube. A "multi-probe" sensor was designed for "real-time" non-contact radial strain measurements. An intellectual property disclosure was filed for the dual probe sensor design with Virginia Tech Intellectual Properties (VTIP).

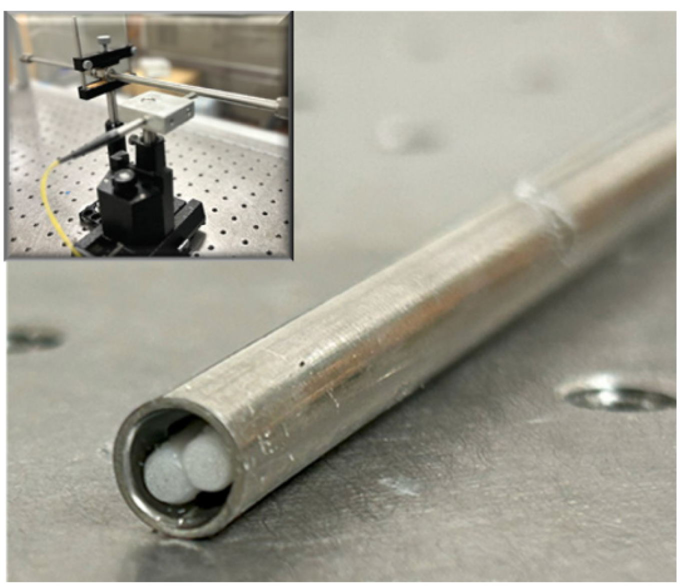


Figure 1. "Laboratory standard" dual fiber optic sensing probe for real-time displacement and strain measurements. Implementation of sensing probe for non-contact monitoring of pipe ballooning shown in the insert.

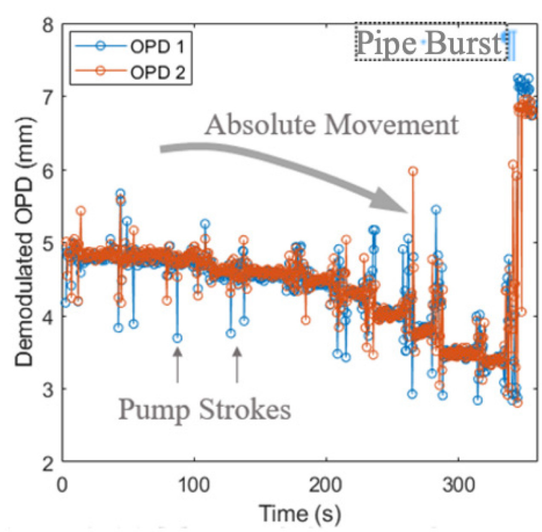


Figure 2. Pipe displacement measurements obtain from the "laboratory standard" dual sensing probe upon ballooning and a burst event.

Irradiation of Optical Components of In-situ Laser Spectroscopic Sensors

PI: Igor Jovanovic – University of Michigan
Collaborators: Milos Burger – University of Michigan, Piyush Sabharwall – Idaho National Laboratory, Paul Marotta – Micro Nuclear LLC,
Sungyeol Choi – Seoul National University – INERI program
Lei Cao – Ohio State University Nuclear Reactor Laboratory – NSUF support

In the past year, we completed the analysis of all linear and nonlinear measurements performed during this program, published results in journals, and presented at multiple conferences. We highlight one novel result published this year (Fig. 1, [1]). Using our custom-constructed mobile Z-scan setup, we have shown that, in addition to previously reported nonlinear negative absorption, a measurable amount of negative nonlinear refraction can be induced by neutron irradiation (Fig. 1). The combined effect of irradiation is the increase in transmission and defocusing of light incident onto irradiated samples at sufficiently high intensities, such as those encountered in laser-induced breakdown spectroscopy-based instrumentation.

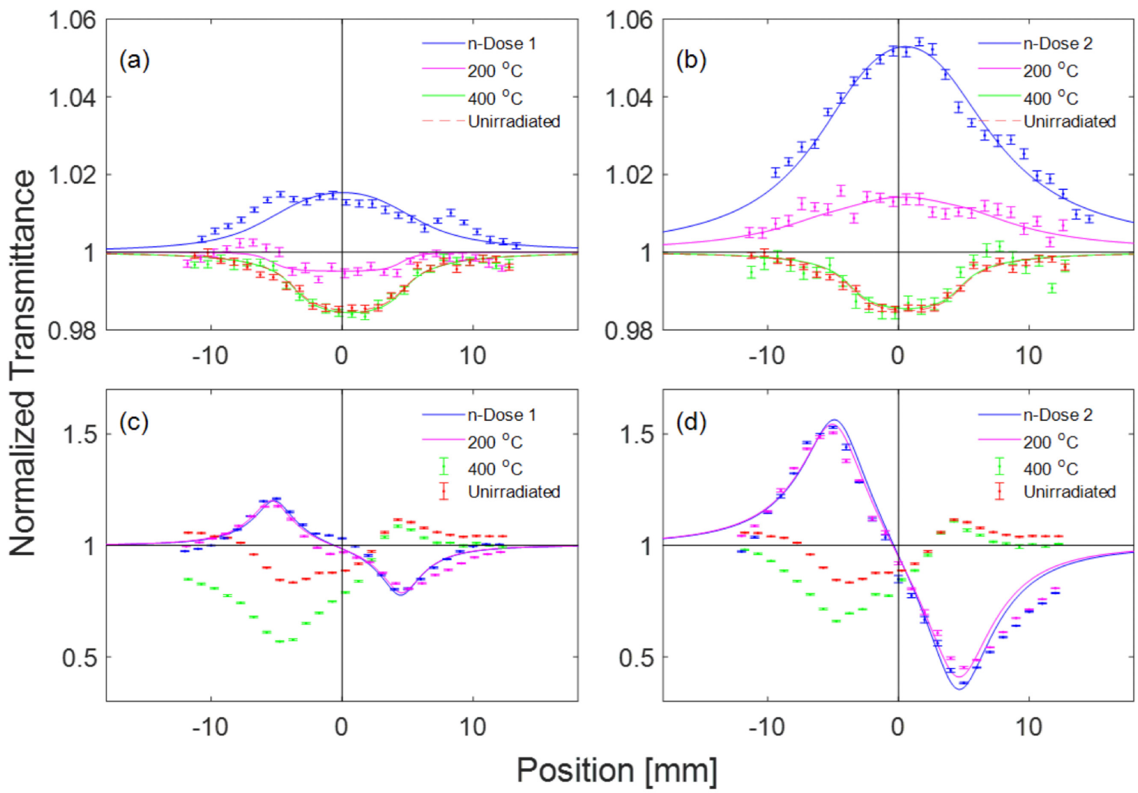


Figure 1. Z-scan measurement results in radiation-resistant BK7G18 glass [1]: top – nonlinear absorption; bottom – nonlinear refraction. Measurements were performed with two neutron doses, and samples were annealed at two temperatures.

1. Morgan, B. W., et al. 2023. "Radiation-Induced Negative Nonlinearities in Fused Silica, Sapphire, and Borosilicate Glass." *Journal of Nuclear Materials,* 582, 154486.

High Fluence Active Irradiation and Combined Effects Testing of Sapphire Optical Fiber Distributed Temperature Sensors

PI: Kelly McCary – Idaho National Laboratory
Collaborators: Joshua Daw – Idaho National Laboratory; Christian Petrie – Oak Ridge National Laboratory; Thomas Blue – Ohio State University

Project Description and Impact: Recently, silica-based optical fiber sensors have seen rapid development and acceptance for use in irradiation experiments. However, these sensors remain limited in terms of the maximum temperatures and fluences under which they can operate. The goal of this research is to investigate the in-pile performance of sapphire optical fiber temperature sensors, develop clad sapphire optical fibers for in-pile instrumentation, and evaluate the distributed sensing performance of these sensors via optical backscatter reflectometry under combined radiation and temperature effects, as well as high neutron fluence. This work is advancing nuclear technology by characterizing and demonstrating a new sensor technology for potentially taking measurements with high spatial and temperature resolution at higher temperatures than prior optical sensors. This technology can also be applied to measurements other than temperature. The research will deliver modern optical fiber sensing techniques usable in multiple extreme environment applications. In the area of nuclear fuel/material testing, these fibers will enable access to operational data with excellent time and space resolution during irradiation testing.

Recent Results and Highlights: Previous progress on this work included out-of-pile furnace testing and the conducting of irradiations (at the Ohio State University Research Reactor [OSURR]) to both clad the sapphire and irradiate at temperatures of up to 1600°C. The FY-23 work has focused on the completion of a long-term irradiation test at the Massachusetts Institute of Technology Research Reactor (MITR). This long-term irradiation at MITR consisted of five sapphire optical sensors, as well as two silica sensors for use in making baseline comparisons. The irradiation lasted for two cycles at MITR, at temperatures of around 680°C for a total fluence of approximately 1.6×10^{21} n/cm^2. The results indicated that the temperature of the irradiation is significant to the attenuation in the sapphire fiber. This work indicates that sapphire optical fiber has the potential to provide distributed measurements at temperatures up to 1700°C for low fluence applications.

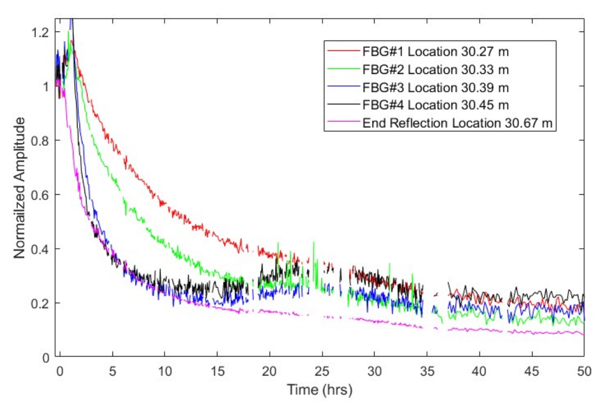


Figure 1. 125 um Sapphire optical fiber normalized backscatter amplitude over the first 50 hours of irradiation at MITR.

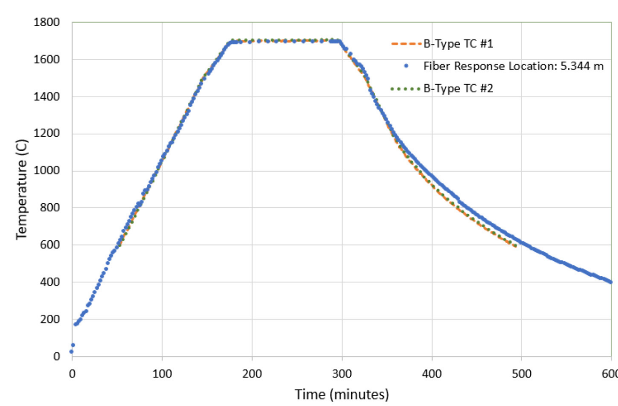


Figure 2. 125 um Sapphire optical OFDR temperature measurement up to 1700°C.

Development of Microwave Resonant Cavity Transducer for Flow Sensing in Advanced Reactor High Temperature Fluids

PI: Alexander Heifetz – Argonne National Laboratory

We are investigating a microwave resonant cavity transducer for flow sensing in the vessel of a high temperature fluid advanced reactor (AR), such as a molten salt cooled reactor (MSCR) or a sodium fast reactor (SFR). This transducer is a hollow metallic cylindrical cavity, with one of the flat walls of the cylinder flexible enough to undergo microscopic deflection due to dynamic fluid pressure. Membrane deflection leads to a shift in the microwave resonant frequency, which can be detected with a spectrum analyzer.

We have performed a preliminary proof-of-principle test of flow sensing in high temperature liquid sodium in environment. For this test, we have developed a cylindrical resonator, which was machined from stainless steel 316 and electroplated with silver on the interior surfaces. Outer diameter of the cylindrical cavity is approximately 3cm, and the thin wall is approximately 200μm thick. We have also developed an insertion probe consisting of a 50cm WR-42 brass waveguide enclosed in a protective SS316 tube. The cavity was excited through a WR-42 waveguide through a subwavelength hole on the side of the wall of the cylinder in the TE_{011} mode with resonant frequency $f \approx 17.8$GHz.

The liquid sodium setup consists of a cylindrical vessel with a center feed line, where a transducer inserted through the top cap of the vessel measures velocity of the impinging liquid jet. The sodium flow sensing study was performed in a liquid sodium vessel at 340^{o}C temperature and ambient pressure. The flow rate was changed by varying sodium pump power, and a frequency shift of several hundred kHz was observed. The transducer was removed after 70 days of testing. No visual damage was observed, and the electromagnetic response remained the same.

As a calibration experiment, we assembled a water vessel with a center feed, and with dimensions similar to those of the liquid sodium setup. Frequency shift of the cavity spectral response was obtained at room temperature and ambient pressure by gradually increasing water flow rate from 0 to 25GPM (gallons per minute). Corresponding monotonic increase of resonant frequency by several hundred kHz was observed. Water flow sensing was performed before and after liquid sodium test. The responses in both cases are similar and agree with COMSOL computer simulations.

From the measurements, we observed significant scatter in high temperature liquid sodium at low flow velocity values. Our hypothesis is that this is caused by temperature drift in the liquid, which results in thermal expansion of the cavity and a drift in the resonator frequency. In this report, we investigate temperature dependence of the resonant frequency through development of analytic models and preliminary analysis of experimental data. In addition, we develop a procedure for compensation for temperature drift during flow sensing.

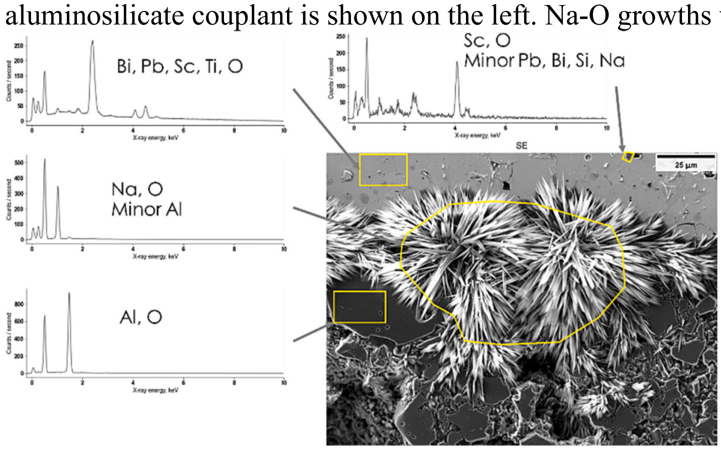
Irradiation of Sensors and Adhesive Couplants for Application in LWR Primary Loop Piping and Components

PI: James Wall – Electric Power Research Institute
Collaborators: Luke Breon and Maria Guimaraes – Electric Power Research Institute,
Pradeep Ramuhalli – Oak Ridge National Laboratory, Joshua Daw – Idaho National Laboratory

Project Description: Austenitic-stainless-steel primary coolant loop components in light-water reactors are susceptible to stress corrosion cracking (SCC). This susceptibility can be highest near piping and component welds, due to welding-induced sensitization, which is the local depletion of chromium as a result of chromium carbide formation at the grain boundaries. The nuclear industry is seeking a method of utilizing semi-permanently installed ultrasonic transducers to monitor primary loop cracks online in lieu of fully manual ultrasonic examinations, thereby reducing costs as well as dose to personnel. In this NSUF 1.1 project, piezoelectric ultrasonic transducers affixed to aluminum substrates using various high-temperature adhesive couplants were irradiated at the North Carolina State University (NCSU) PULSTAR reactor to quantify the effects of neutron irradiation on ultrasonic signal quality and the microstructure of the sensor assemblies. Post irradiation examination (PIE) studies performed at NCSU and the Oak Ridge National Laboratory LAMDA laboratory include positron annihilation spectroscopy and SEM imaging, EBSD and x-ray spectroscopy.

Impact and Value to Nuclear Applications: In commercial nuclear power plants, SCC of primary loop piping and components can result in extended outages and unplanned inspection/repair activities, leading to increased maintenance costs and significant dose to personnel. EPRI seeks to develop sensor systems that enable online monitoring of stress corrosion cracks in primary loop piping and component welds in order to determine whether the cracks are dormant or actively growing, and, if growing, to estimate their growth rates. A critical component of this effort is this NSUF 1.1 study on irradiation and PIE of ultrasonic sensors and adhesive couplants to determine whether they can be utilized long term to monitor primary loop piping and components, particularly those close to the core, such as the hot and cold leg nozzle dissimilar metal welds.

Recent Results and Highlights: Two types of piezoelectric sensors and four types of adhesive couplants were identified for the irradiation campaign via an elevated temperature benchmarking study performed at EPRI. Eight sensor assemblies were mounted in a custom-designed capsule and irradiated to a fluence of ~5 × 1016 n/cm2 (E > 1 MeV) in the PULSTAR reactor. Ultrasonic waveforms were collected in situ during the irradiation. Positron annihilation lifetime spectroscopy and doppler broadening spectroscopy were performed at NCSU. Electron microscopy and x-ray microanalysis performed at the ORNL LAMDA laboratory is partially complete, Fig. 1. A no cost extension has been granted to finish the PIE at ORNL in FY 2024. The final NSUF report will be published at the end of 2024. A summary of the experiments and PIE results obtained to date has been published: J. J. Wall et al., Nuclear Engineering and Design, **414**, 112594 (2023). An example of a SEM micrograph and x-ray analysis of the interface between a bismuth titanate sensor and aluminum substrate adhered using aluminosilicate couplant is shown on the left. Na-O growths were identified at the couplant/sensor interface.



Sensors for Irradiation Experiments

Linear Variable Differential Transformers

Principal Investor: Kurt Davis – Idaho National Laboratory
Collaborators: Malwina Wilding, Austin Fleming, Chase Case – Idaho National Laboratory
Michael Marciante – Newtek Sensors Solutions

Project Description: In Fiscal Year 2023, our research was dedicated to the development and rigorous testing of a commercial prototype LVDT (Linear Variable Differential Transformer). This specific LVDT was created by a reputable U.S. supplier, Newtek Sensor Solutions, whose selection was based on recommendations from our comprehensive supply chain study. This pivotal cross-cutting development initiative aims to ensure that stakeholders have access to the most advanced LVDT-based technologies for deployment in forthcoming irradiation tests.

Impact and Value to Nuclear Applications: The Institute for Energy Technology (IFE) stands as the global singular source for LVDTs used for in-pile testing, placing the international testing community in a vulnerable position in the event of a limited LVDT supply. Recognizing this critical need, our current research endeavors to enhance our comprehension of LVDT performance in future irradiation tests, while also diversifying the base of LVDT suppliers.

Recent Results and Highlights: Our evaluation of the prototype LVDT from Newtek Sensor Solutions has revealed promising potential as a viable alternative to the IFE-manufactured LVDT. Testing occurred in the out-of-pile INL LVDT test and calibration rig at 20, 100, 200, 300, and 400°C. Performance was impeccable with a linearity at or below 4% for most tests. We observed high sensitivity (0.126 (V/V)/mm) and project sub-micron resolution for all future applications. Finally, identified design enhancements hold the promise of elevating this LVDT to a performance level comparable to the IFE LVDT.

Idaho National Laboratory

NEWTEK Sensor Solutions
Providing Custom Sensor Solutions

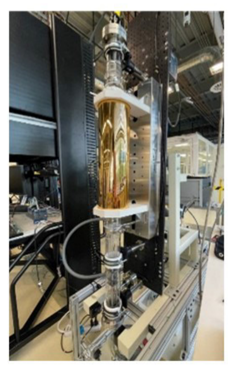


Figure 1. Prototype LVDT provided by Newtek Sensor Solutions and the INL LVDT calibration and test rig with the LVDT mounted in translation rails.

Passive Temperature Monitors

PI: Malwina Wilding, Kiyo Fujimoto – Idaho National Laboratory
Collaborators: David Estrada, Josh Eixenberger – Boise State University

Project Description: Passive temperature monitors are needed for when real-time sensors are impractical or uneconomical to install in an irradiation test. Although passive peak temperature monitors have been used in irradiation testing experiments for many decades now, limited innovation has been applied to these technologies. This activity focuses on using advanced manufactured melt wires and Silicon Carbide (SiC) temperature monitors (TMs). Melt wires involve placing material wires of a known composition and melting temperature in an irradiation test. This method requires post-irradiation examination of the material wire to determine whether melting occurred; this in-turn indicates whether the corresponding melting temperature was reached or perhaps even exceeded. Sensor development via advanced manufacturing methods enables the production of robust miniaturized sensors for nuclear applications and expands the current capabilities of passive melt wires. Researchers observed that SiC's neutron-irradiation-induced lattice expansion anneals out when the post-irradiation annealing temperature exceeded the peak irradiation temperature. To further advance this capability an optical dilatometer had been purchased and was verified with irradiated SiC TMs (disks and rods) for post-irradiation evaluations of irradiation temperatures.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measuring irradiation temperature during post-irradiation examination, which require no feedthroughs/leads, as is the case were using more highly complex real-time temperature sensors. These monitors were chosen for deployment because of their proven track record of being used by stakeholders but require continued development and characterization to ensure successful integration with program schedules and objectives.

Recent Results and Highlights: FY-23 work for printed melt wires investigated a proof-of-concept printed in-plane capacitors (interdigitated electrodes) with an electrical readout package that was encapsulated in an advanced manufactured ceramic capsule. The final melt wire array consisted of indium (100%) with a melting point of 157°C, tin (100%) with a melting point of 230°C, and zinc (100%) with a melting point of 420°C. A prototype melt capacitor wire was fully fabricated that delivered a data set that correlates electrical readout performance with visual inspections of printed sensors that have been thermally cycled. FY23 work for SiC monitors conducted further verification testing of the optical dilatometry method by using eight 3-mm SiC irradiated disks provided by NSUF's N-SERT experiment. This will conclude continuous optical dilatometry to be a valid method for measuring peak irradiation temperatures of passive SiC TMs of various shapes and sizes (12.5 mm long sticks, 3 mm and 5 mm disks). The optical dilatometer utilizes an automated process, requires only a small amount of time to run, and is easy to use, thus saving valuable labor time in comparison to the traditional resistivity measurement method.

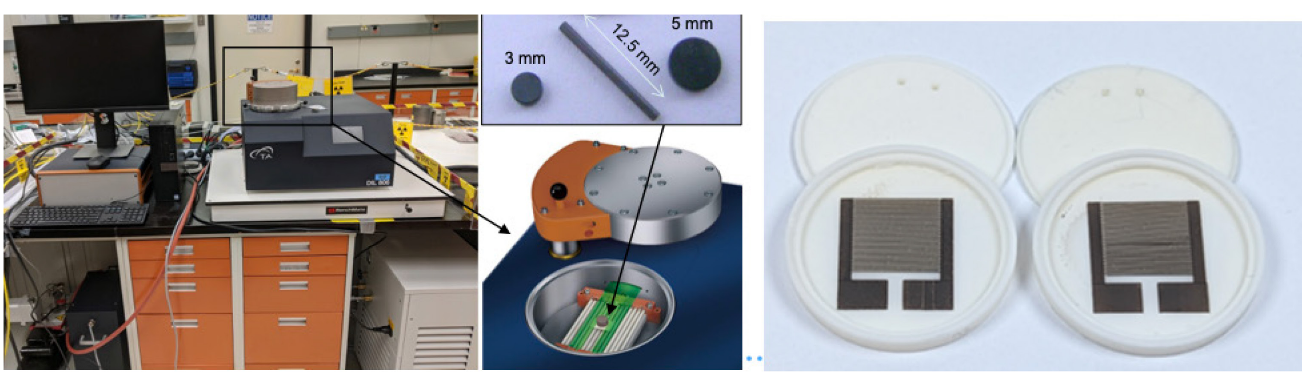


Figure 1. Left: Optical dilatometer for processing SiC TMs. Right: Prototype melt capacitor wire capsule

Advanced Sensors and Instrumentation Program: Materials Properties

PI: Michael McMurtrey – Idaho National Laboratory
Collaborators: Tim Phero, Amey Khanolkar – Idaho National Laboratory

Project Description: Real-time characterization of structural materials during irradiation experiments is typically accomplished by measuring deformation via linear variable differential transformers (LVDTs). However, LVDTs are large and invasive in terms of design integration, and are not always practical or feasible for in-pile experiments. LVDT-based systems are typically designed for a single specimen or component (e.g., fuel pins) and are challenging to apply to multi-specimen tests. To expand the capability of conducting in-core testing of materials' mechanical properties, it is necessary to understand and develop systems based on strain gauges that can reliably operate in radiation environments. Printed strain gauges, with additional development, are capable of being applied in various orientations and on complex geometries. This work seeks to better understand and qualify commercially available high-temperature strain gauges, and to develop printed strain gauges for reactor experiments.

Impact and Value to Nuclear Applications: The real-time understanding of strain and deformation of materials provides prognostic health monitoring of components of current operational reactors and valuable data that shortens the timeline for the development of new nuclear-relevant materials in test reactor experiments.

Recent Results and Highlights: Work this year (FY-23) focused on the development and testing of additively manufactured strain gauges for operation at elevated temperatures (up to 500 °C). Barium Strontium Titanate (BST) was selected as the material for the insulation layer due to its high temperature stability and dielectric properties. BST ink and printing techniques were developed and printed films tested up to 500 °C, looking at material structural stability (cracking, failed adhesion to substrate), as well as changes in the dielectric properties. Micro-scale cracks were observed after temperature cycling up to 500 °C, which can impact the sensitivity and functionality of the strain gauge. The effective dielectric constant of BST was found to be stable while held at the elevated temperature. In addition to this work, efforts continued to develop methods for evaluating the quality and resilience of the printed strain gauge to reduce the risk of instrumentation failure during tests. Laser spallation testing showed that the BST films of different thicknesses led to different failure morphologies, with thinner prints (< 8 μm thickness) demonstrating the best adhesion between the BST film and substrate.

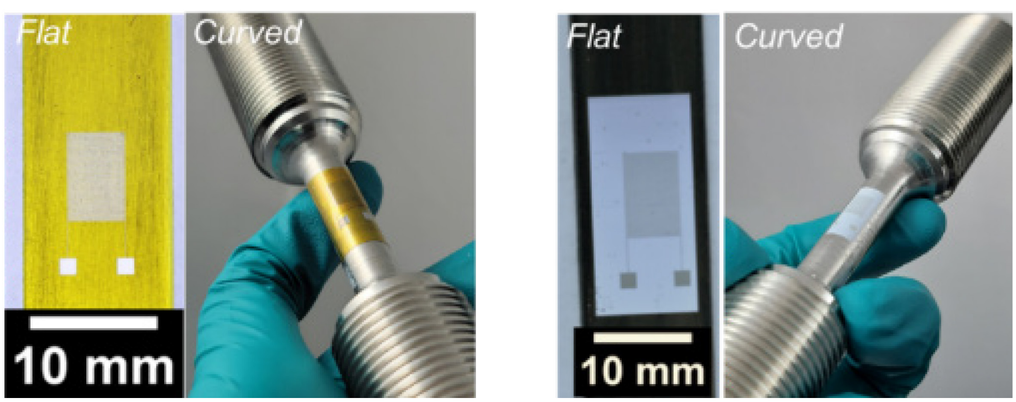


Figure 1. Strain gauges printed on flat and cylindrical specimens with (left) polyimide and (right) BST (using aerosol jet printing) insulation layers. The polyimide was used previously for lower temperature (<300 °C) strain gauges. The BST was developed for use with high temperature strain gauges.

Irradiation Testing of Sensors

PI: Troy Unruh – Idaho National Laboratory
Collaborators: Austin Fleming, Devin Imholte, Joe Palmer – Idaho National Laboratory

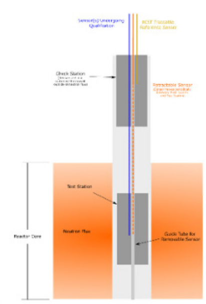
Project Description: Advanced instrumentation enables testing of nuclear fuels and materials in support of the United States advanced nuclear technology industry. In fiscal year (FY) 2023 this project kicked off the design and development of a device used to qualify the performance of temperature sensors for irradiation environments. In addition to this new activity, the irradiation of sensors in test reactors continued under this work package. An irradiation was carried out at the Ohio State Research Reactor to test the high temperature performance of neutron sensors.

Impact and Value to Nuclear Applications: The early part of sensor development can be done outside of the reactor environment, but full technical readiness requires experience gained from in-core performance testing. Materials or fuels researchers usually only have one shot to conduct their irradiation experiments; therefore, it is vital to demonstrate newly developed instruments in operational conditions, prior to incorporating them into long-term, high-value experiments.

Recent Results and Highlights: A successful high temperature irradiation test of neutron sensors was carried out in the OSURR. This irradiation tested sensors up to 850 C, well beyond the operating range of traditional neutron sensors. Commercial partners and international collaborators from France provided sensors to benchmark their performance under these extreme conditions. The sensors undergoing tests included self powered neutron detectors (SPNDs) and a variety of small fission chambers.

(above) Irradiation position in OSURR, (right) irradiation device used for neutron sensor testing

An irradiation device has been designed for in-pile use to qualify the performance of temperature sensors. This device has been designed for use at multiple facilities to maximize the utility in many different irradiation conditions. It has been built for modularity This device utilizes a previously developed retractable sensors design which transverses sensors in and out of the reactor core to provide accurate comparison between sensors that are constantly under irradiation to "fresh" sensors. These fresh sensors are located above the irradiation from the reactor and undergo a closure calibration at the conclusion of the experiment. This provides a NIST-traceable performance metric for the in-pile sensors undergoing qualification. Most importantly the irradiation device is capable of irradiation a statistically significant number of sensors, therefore able to provide rigorous uncertainty metrics for a sensor design under those conditions. This unprecedented sensor performance will provide reactor designers referenceable and defendable data for the most rigorous applications.



(left) Prototype of temperature sensor qualification device (right) overview of operations of the device

Gamma Thermometer Irradiation in the HFIR Spent Fuel Pool

PI: Anthony Birri – Oak Ridge National Laboratory
Collaborators: Daniel C. Sweeney, Nicholas Russell, Christian M. Petrie – Oak Ridge National Laboratory

Project Description: The goal of this research is to develop, model, and demonstrate an optical fiber–based gamma thermometer (OFBGT) in an intense gamma-ray field. The irradiations are to occur within spent fuel elements from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) to evaluate the effects of intense gamma heating without a significant neutron flux. Testing within multiple spent fuel elements with different gamma-ray source strengths will provide multiple data points to simulate different nuclear heating rates in a commercial reactor. In addition, the axial variations in gamma heating will be quantified by taking advantage of the distributed nature of the fiber optic measurements to compare with model predictions. This work aligns with the OFBGT irradiations conducted by The Ohio State University and Texas A&M University as well as power inferencing method development occurring at ORNL.

Impact and Value to Nuclear Applications: An OFBGT can provide a distribution of gamma dose or heating rates along its axial length; this is based on a distributed measurement of temperature differences across an insulating gas gap using multiple optical fibers. This capability gives an OFBGT an advantage over a thermocouple-based gamma thermometer (TCBGT), which acts as a point sensor. Therefore, OFBGTs could serve as a replacement to TCBGTs—which are traditionally used to calibrate local power range monitors (LPRMs) in boiling water reactors—by providing up to hundreds or thousands of data points along their axial length. This capability significantly reduces the footprint and cabling requirements compared to an array of TCBGTs. Furthermore, data analytic techniques are being developed at ORNL to potentially use gamma thermometer data to directly infer reactor power distributions, potentially eliminating the need for LPRMs.

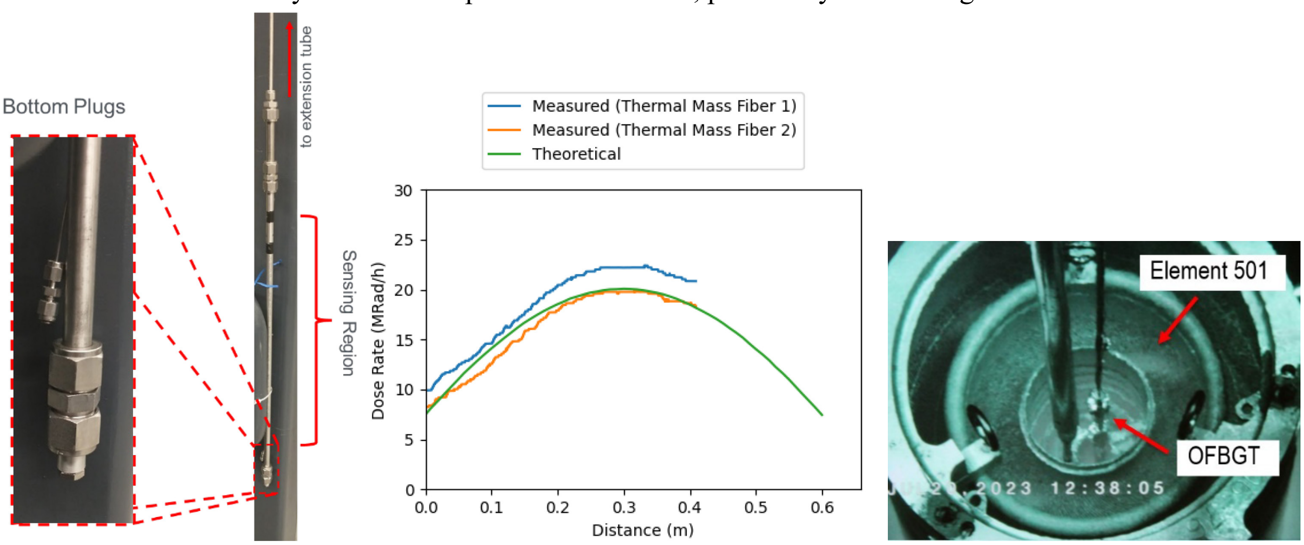


Figure 1. OFBGT Configuration. Figure 2: Testing in Spent Fuel. Figure 3. Data from 501 Element.

Recent Results and Highlights: The OFBGT was deployed in the HFIR spent fuel pool and tested in spent fuel element from cycle 501. The OFBGT showed reasonable agreement with the theoretical gamma ray dose rate profile in the spent fuel element. In general, the findings of report no. ORNL/TM-2023/2984 suggest that the OFBGT is a feasible technology for measuring extremely high gamma ray dose rate spatial distributions, such as spent fuel gamma ray profile characterization.

Nuclear Energy Sensor Database

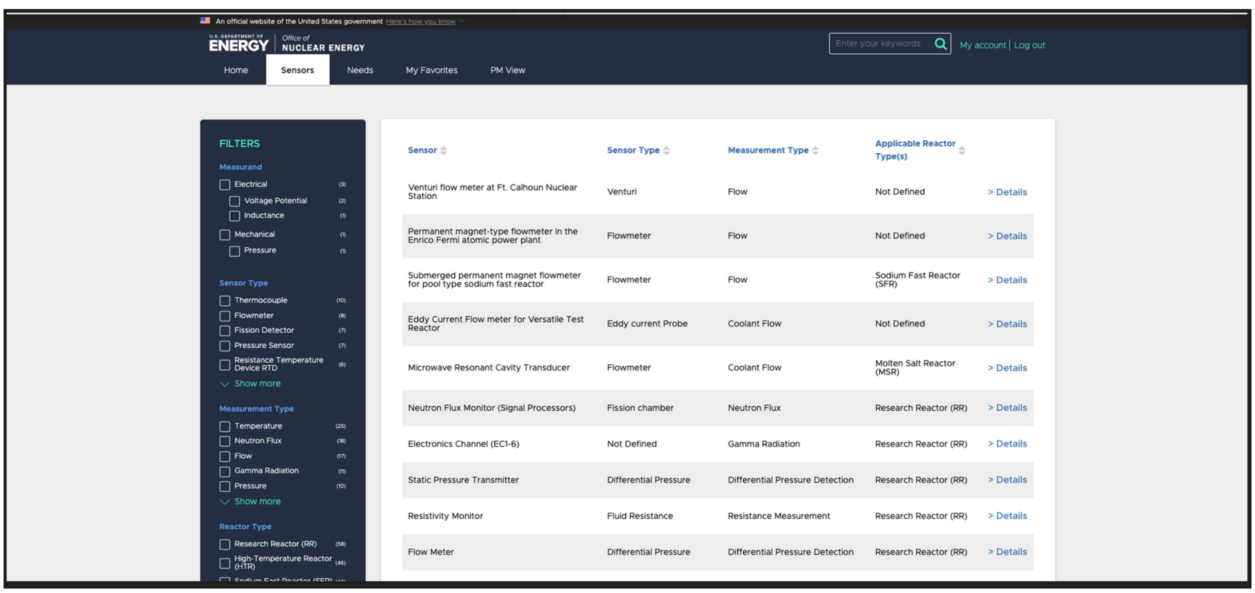
PI: Shan Osborn – Pacific Northwest National Laboratory

Project Description: Previously developed sensor technology assessments for advanced nuclear reactor systems have helped identify technology gaps and prioritize R&D efforts. However, improved access to and visualization of the information was needed to aid in these decisions. To address this need, the Nuclear Energy Sensors website database (i.e., https://nes.energy.gov) was created to help nuclear facilities, universities, and industry staff members find sensor information used in the nuclear energy field.

Impact and Value to Nuclear Applications: The Nuclear Energy Sensors website database (https://nes.energy.gov) is a resource for nuclear facilities, universities, and industry staff members to find sensor information used in the nuclear energy field. This website is intended to be used as a "one stop shop" to search for information related to nuclear energy sensors and prioritized needs and gaps. In addition to this content, the website also provides a method for users to suggest new sensors or other enhancements for inclusion in the database.

Recent Results and Highlights: The initial version of the site went live in early FY21 with 71 and since has grown to 165 sensors identified from the "Assessment of Sensor Technologies for Advanced Reactors" document, which is publicly available at https://info.ornl.gov/sites/publications/files/Pub68822.pdf.

Since the initial site launch, PNNL has worked with INL, the nuclear industry, and other entities to gather and grow additional sensor information. In FY21, 24 sensors were added to the system Nuclear Energy Sensor database; in FY22, 96 sensors were added; in FY 23 there are now a total of 165 sensors. The primary focus in FY23 has been to redesign to support the hierarchical drilldown of sensors, add Radiological measurand categories functionality, collect and curate sensors to include in the database, improve data quality of existing sensors by consolidating duplicate information, and software updates to address bugs fixes and improve usability, styling, and security patches.



Progress summary for the NSUF project “Deployment and in-reactor test of an instrument for real-time monitoring thermal conductivity evolution of nuclear fuels”

PI: Zilong Hua, Caleb Picklesimer, Austin Fleming, David Hurley – Idaho National Laboratory, Weiyue Zhou, Michael Short – Massachusetts Institute of Technology, and David Carpenter – Massachusetts Institute of Technology Research Reactor

As one of the most critical physical properties of nuclear fuels, thermal conductivity directly ties into reactor safety and efficiency. It is well known that microstructural defects generated by and evolved in extreme in-reactor environments significantly impact thermal conductivity of nuclear fuels, but the detailed scattering mechanisms between all sorts of defects and the thermal carriers remain a knowledge gap. Current efforts rely on post-irradiation examination (PIE) testing on thermal conductivity and microstructure characterization. However, point defects as the primary type of phonon scatters anneal at high temperature in the time between reactor shut down and PIE can be performed. This project aims to deploy a photothermal radiometry (PTR)-based instrument to the Massachusetts Institute of Technology Research Reactor (MITR) in order to perform real-time in-reactor thermal conductivity measurements.

This 2-year project includes two rounds of insertion experiments in MITR. In each round of insertion experiments, proposed work includes instrument adaption and optimization, data collection, and PIE. By the end of the project, a user protocol for regular use of this instrument to perform routine thermal conductivity measurement in reactor will be developed. In the first round, we successfully deployed the instrument to MITR core position and collected thermal diffusivity data from the reference material Al_2O_3. Meanwhile, no signal was collected from other positions including the testing fiber, partially due to a lower-than-expected probe temperature. After the in-reactor experiment, we first improved the thermal analysis model precision by using the actual temperature profile measured from reactor to fine tune the model. Then, to increase the temperature maximum, we optimized the instrument design by adding a Ti insulation capsule to reduce the gas conduction and convection and graphite inserts as additional internal heaters. The predicted temperature maximum of the updated model has increased from 450 ºC to 950 ºC, giving us a significantly larger temperature range for data collection. Although delayed by reactor maintenance, PIE testing has started. Optical transmission testing indicates the fiber was/would be more likely damaged during the insertion and retraction of the instrument, and near or in the core position of the reactor. It provides valuable information to improve the survivability of the instrument for the second round of irradiation, which is currently rescheduled to January 2024.

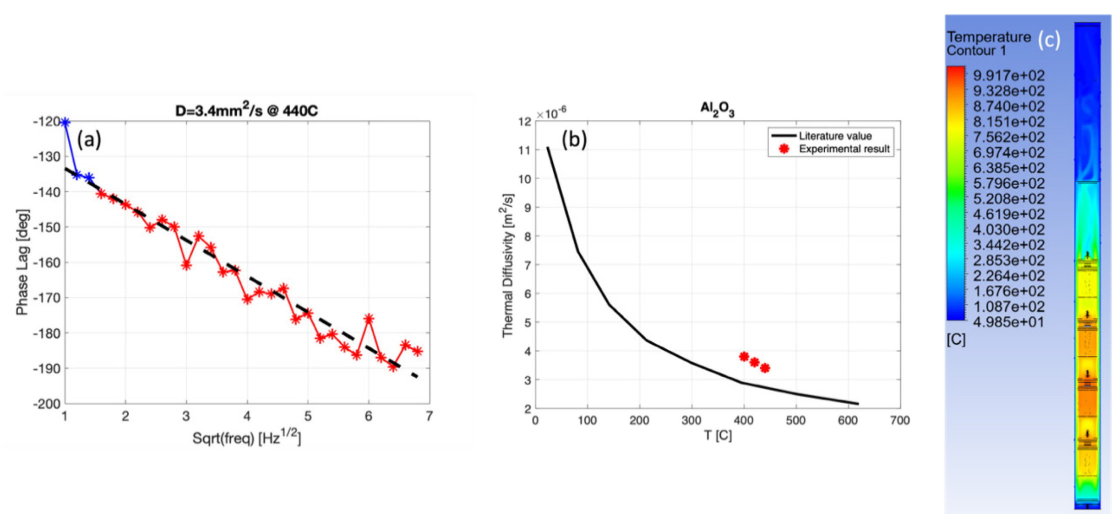


Figure 1. (a) raw data of thermal diffusivity measurement on Al_2O_3, with the dash line representing the best-fit; (b) thermal diffusivity of Al_2O_3 was collected from the in-reactor environment in the temperature range of 400-440℃; (c) with the improved instrument design, thermal analysis model gives an increase temperature maximum of ~950℃.

An Innovative Monitoring Technology for the Reactor Vessel of Micro-HTGR

PI: Lesley Wright – Texas A&M University
Collaborators: Rodolfo Vaghetto – Texas A&M University,
Elia Merzari – Pennsylvania State University,
Lander Ibarra, Roberto Ponciroli – Argonne National Laboratory,
Erik Nygaard – BWX Technologies, Inc. (BWXT)

Project Description: The project supports the mission of ASI by leveraging recent advances in both machine-learning (ML) based field reconstruction techniques and diagnostic software to augment traditional sensor capabilities. We will develop & demonstrate integrated sensor technology for real-time monitoring of thermal-mechanical stresses of reactor vessel for micro-high temperature gas reactors (mHTGRs). The technology will be based on the use of a sparse network of outer wall temperature measurements and other plant operating conditions. Convolutional Neural Network (CNN) approaches will be utilized to optimize the number and location of the measurement points. By leveraging the algorithms available for degradation diagnostics of the well-established PRO-AID software, the proposed technology will provide (i) real-time, reliable, and cost-effective monitoring methodology; (ii) quantification of the lifetime and integrity of the pressure vessel, and (iii) improved economics of micro-reactor systems.

Impact and Value to Nuclear Applications: The primary deliverable of this project is a novel, non-intrusive sensing technology for real-time monitoring of the thermal-mechanical stresses in the reactor vessel of a mHTGR. This project will lead to safer and more economical operation of mHTGRs through the development of a novel combined software/hardware sensing technology capable of monitoring the health of reactor components. This will be accomplished by the creation of a credible pathway for an innovative measurement system for a key component of gas-cooled micro-reactors (i.e., the pressure vessel). The collaborative project will develop a tool to facilitate the fault diagnostics with a measurement procedure than is less invasive than the current state-of-the- art sensor placement strategies

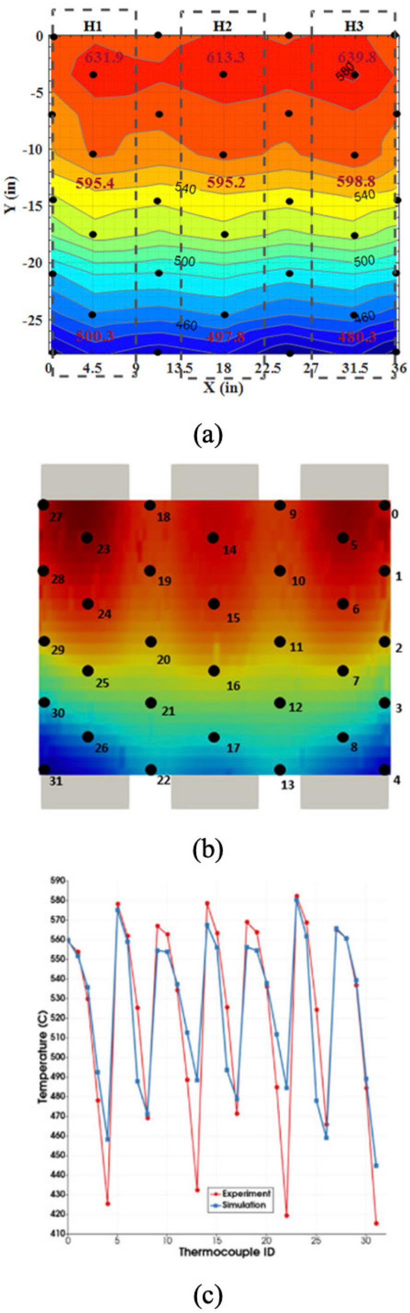


Figure 1. Validation of the Experimental Setup and Numerical Simulations for the Reactor Vessel Model

Recent Results and Highlights: This is a three-year project that began in FY23. During this first year of the project, initial validation of the experimental facilities and numerical simulations was completed. Figure 1 shows sample temperature distributions on a vessel model. The experimental measurements were obtained with thermocouples in the Thermal-Hydraulic Research Laboratory at Texas A&M University (Fig. 1(a)). A digital twin of the TAMU facility was created by Penn State University. The researchers at PSU are using the MOOSE software framework developed at INL. To match the experimental conditions, they have successfully modelled the radiative heat transfer between the heaters and the vessel wall utilizing MOOSE's ray tracing and heat conduction models. Figure 1(b) shows a sample temperature distribution on the vessel wall, and Fig. 1(c) provides a direct comparison between the experimental measurements and the numerical simulations. In addition to validation of the experimental measurements and numerical predications, a modified CNN was conceptualized for future demonstration of the integrated real-time monitoring and diagnostics. With baseline experimental and numerical results, the training, testing, and refinement of the network will continue into FY24.

SENSORS INTEGRATION

Advanced Controls

PI: Richard Vilim – Argonne National Laboratory

Project Description: This project investigated the potential benefits of using an engineering digital twin (DT) to achieve greater autonomy for monitoring and control functions in advanced reactors. The project picked up from the previous year to focus on a high-value control task at an operating facility, the Mechanisms Engineering Test Loop (METL) liquid sodium facility at Argonne National Laboratory. The sodium purification system was selected for demonstration as it requires significant human in-the-loop interaction to accomplish its design function. We set out to show for this representative system how operation can be automated while preserving oversight of the operator to ensure that the system design functions are met.

Impact And Value to Nuclear Applications: The economics of nuclear power can benefit by transitioning those maintenance and operations tasks that have traditionally involved significant human-in-the-loop interaction to implementations where the machine performs the task, and the human takes on the role of oversight. The potential opportunity is greatest for advanced reactors where the concepts of operation are still under development. Automating the monitoring and control of systems and then moving oversight from the plant floor to a remote monitoring and diagnostic center allows a single individual to oversee multiple systems and brings with it greater efficiencies and reduced potential for human error.

Recent Results and Highlights: The use of a digital twin for health monitoring was demonstrated for the sodium purification system of the METL facility. A monitoring and diagnostic center was created and located in a building separate from the facility to demonstrate the concept of remote monitoring. The results of the diagnostic algorithm in operation are displayed on a video wall 18x5 feet in dimension. Real time diagnostics are supported by a communication link between the facility and the remote video wall. Several equipment faults were injected into METL with a correct diagnosis then appearing on the video wall.

The use of a digital twin for automated control of the sodium purification system was also demonstrated, albeit through a digital twin-based computer simulation. It showed how the use of a DT can facilitate the control of an engineered system and how in can provide for seamless transition across operating points and between operating modes. Operation that might otherwise be performed manually was performed by computer algorithm.

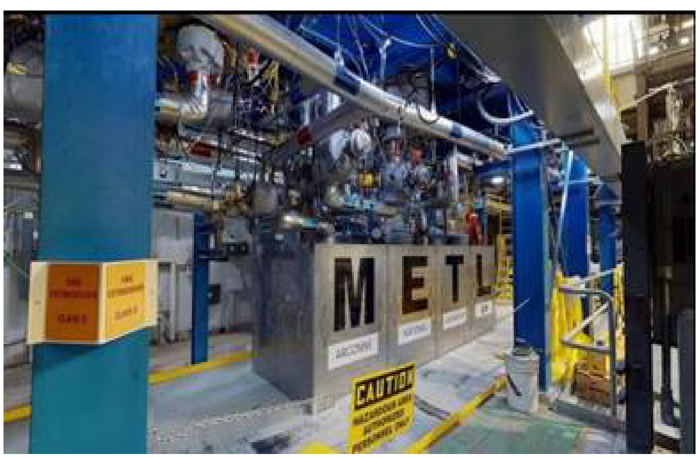


Figure 1. Mechanisms Engineering Test Loop. Liquid Sodium Facility

Figure 2. Video Wall in Monitoring and Diagnostic Center

Advanced Controls / Digital Twin

PI: Ahmad Al Rashdan, Jake Farber – Idaho National Laboratory

Advanced nuclear reactors are essential to meet the changing energy requirements throughout both the United States and the rest of world. In addition to other features, they are designed to enable remote monitoring and deployment in remote locations, which will require a new control paradigm in which their operations are eventually fully (or near-fully) autonomous. To realize autonomously operating reactors, the U.S. Department of Energy's Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation (NEET ASI) program conducts research and development into the enabling methods and tools needed, including digital twins, machine learning, and risk modeling, in addition to various types of control methods. These technologies are the key foundations needed to achieve fully autonomous systems.

To develop and evaluate the technologies necessary for achieving autonomous operations, it is critical to identify a software tool capable of integrating all the required elements. In surveying the available solutions, no software platforms were identified that could accomplish what was needed without introducing drawbacks. This challenge was the motivation for the current effort: to develop a software platform that can seamlessly integrate autonomous-control-enabling technologies and algorithms, allowing for faster, more efficient research and development and transfer of ideas. The resulting platform, known as the Control and Optimization Modular Modeling Application for Nuclear Deployment (COMMAND), is Python-based, and leverages open-source tools to provide flexibility and facilitate building upon prior research. It is designed to enable advanced reactor developers to deploy and test advanced control methods coupled with their own models, solutions, and hardware.

Given the substantial undertaking of developing such a platform, the current effort focused on laying down scalable, flexible software foundations and infrastructure, then demonstrating the platform via a use case. These foundations included developing generic modules, which contain the base variable and system blocks (the information and functional building blocks, respectively) that can be used to design a simulation, the scheduling tools needed to run and synchronize the various blocks, and the data storage blocks needed to exchange information between the various blocks; as well as enabling-technology-specific modules. This platform was evaluated via a use case, which was to simulate and control a process for the Microreactor Automated Control System (MACS) test bed. While MACS is not directly coupled to any specific microreactor physics, it was initially developed in concert with the Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor, and so the MARVEL physics are used here. As part of this use case, several enabling-technology-specific blocks within COMMAND were created, including proportional integral derivative (PID) control, a Reactor Excursion and Leak Analysis Program (RELAP5-3D) integration block, and anomaly detection capabilities.

The COMMAND software platform was successfully demonstrated to achieve the scalability and flexibility objectives of this effort and will be leveraged by the program's research efforts to advance state of the art control methodologies towards autonomous operations of advanced reactors. As new use cases are created and implemented, it is anticipated that COMMAND will continue to grow and evolve to meet new requirements.

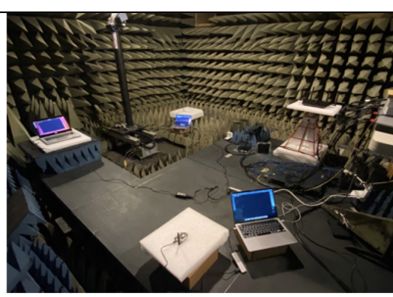
Technical Basis for a Multi-band Heterogeneous Wireless Network for Nuclear Applications

PI: Vivek Agarwal – Idaho National Laboratory
Collaborators: Imtiaz Nasim – Idaho National Laboratory,
Sneha Kasera, Mingyue Ji, and Syed Ayaz Mahmud – University of Utah

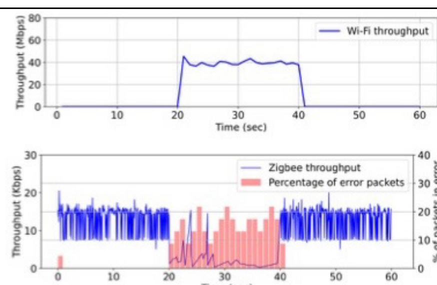
Project Description: This research provides a technical basis for understanding the coexistence of wireless technologies, specifically 2.4 GHz Industrial Scientific and Medical (ISM) operating in an unlicensed spectrum, through an experimental evaluation. This research investigates interactions between Wi-Fi, Bluetooth low energy (BLE), and ZigBee encompassing variables such as transmission power level, distance between the devices, data rates, and the utilization of co-channel or adjacent channels.

Impact and Value to Nuclear Applications: To attain automation across different applications in existing nuclear fleet and in advanced reactor technologies, stakeholders are beginning to leverage advancements in wireless communication technologies. A "one-size-fits-all" solution cannot be applied since wireless technologies are selected according to application needs, quality of service requirements, and economic restrictions. To balance the trade-off between technical and economic requirements, a multi-band heterogeneous wireless network architecture is needed. A multi-band heterogeneous wireless architecture is required for streamlining the data to control systems, to digital twin, to optimize maintenance strategies, and to remote possible operation and monitoring.

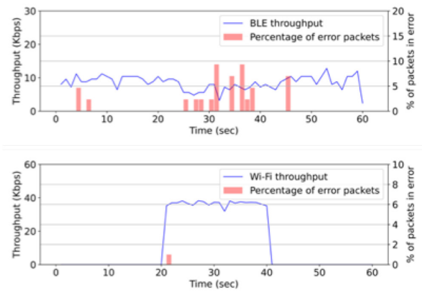
Recent Results and Highlights: This research extensively examines the coexistence of three wireless technologies, Wi-Fi, ZigBee, and BLE, operating within the 2.4 GHz ISM band in a controlled anechoic chamber, as shown in Figure 1(a). The evaluation of performance metrics (specifically throughput and packet error rate [PER]) for each of these technologies indicates that the operation of both ZigBee and BLE is noticeably compromised when coexisting with Wi-Fi within the same frequency spectrum (Figure 1(b)-(c)). ZigBee registered a high throughput drop of 65.5% and PER between 4.3 and 27.1%, while BLE showed a throughput drop of 41.29% and PER between 2 and 9% in the presence of Wi-Fi. Alternatively, the presence of ZigBee and BLE has a negligible impact on the performance of Wi-Fi and on each other performance (Figure 1(d)). The future work will conduct more test scenarios under different environments and provide a solution for the coexistence of all three technologies in the same vicinity.



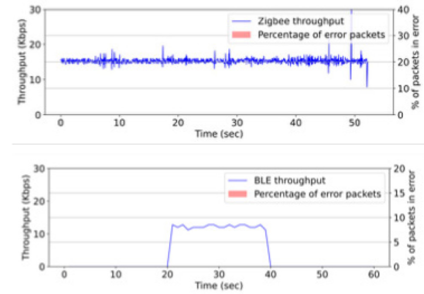
(a)



(b)



(c)



(d)

Figure 1. (a) Experimental evaluation of coexistence of Wi-Fi, BLE, and ZigBee in anechoic chamber. (b) – (d) Performance metric when Wi-Fi and ZigBee, Wi-Fi and BLE, and ZigBee and BLE coexistent respectively.

Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid

PI: Roberto Ponciroli – Argonne National Laboratory
Collaborators: Akshay J. Dave, Tat Nghia Nguyen, Haoyu Wang, Richard B. Vilim – Argonne National Laboratory, Brendan Kochunas – University of Michigan, Anthonie Cilliers – Kairos Power LLC

Project Description: The objective of this research is to improve the economic competitiveness of advanced reactors through the optimization of the plant performance. To strengthen the position of nuclear units in deregulated electricity markets, the coupling of advanced reactors with thermal energy storage technologies is being investigated. An architecture comprised of an automated reasoning system that closely interacts with a multi-layer control system is necessary to address the complexity of coordinating two thermally-coupled units. Three steps were identified to design and demonstrate this architecture:

- Design of an integrated energy system (IES) that ensures reliable power production as well as flexible operation capabilities.
- Development of a control system architecture capable of automating control sequences, monitoring the component conditions and supporting the operators in decision-making tasks.
- Assessment of the savings through a cost-benefit analysis.

Impact and Value to Nuclear Applications: This work leverages, expands, and integrates existing schemes for diagnostics, control, and decision-making tasks. The goal of the developed architecture is to ensure the continuity of service by meeting the demand at any time without violating constraints and reducing the Operation and Maintenance costs.

Recent Results and Highlights: Last year efforts were focused on four major areas:

- Implementation of the Integrated Markov Decision Problem (MDP) Analysis Approach. Markov models for projecting ahead fault probabilities of Intermediate Circuit components were developed. These models were then coupled with PRO-AID diagnostics model.
- Collection of the costs and durations of the corrective actions to address the selected failures.
- Development of an innovative Generation Risk Assessment (GRA) methodology to accurately estimate the impact that multiple faults have on the power production capabilities of the whole system.
- Definition of a test-case scenario to demonstrate the capabilities of the designed architecture. Simulation of the system response after the implementation of the suggested actions and maintenance interventions by adopting the SAM high-fidelity model.

Next steps will be focused on the finalization of the decision-making module by implementing the transition to different Operation Modes as a possible outcome of the decision process.

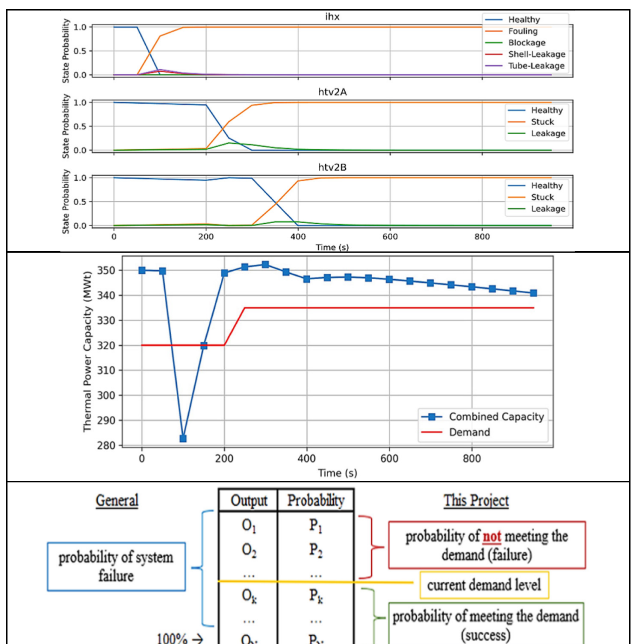


Figure 1. From top to bottom, probabilities of the different faults, expected power production capabilities of the Intermediate Circuit, comparison of demand level with current power production capabilities.

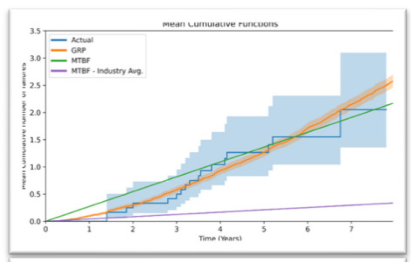
Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance

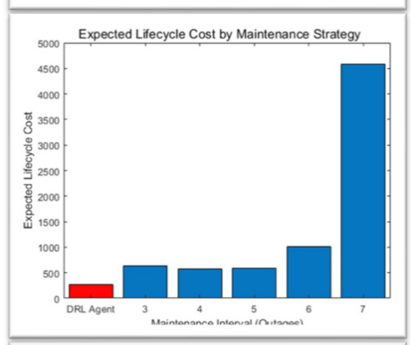
PI: Daniel G. Cole – University of Pittsburgh
Collaborators: Heng Ban – University of Pittsburgh; Vivek Agarwal – Idaho National Laboratory

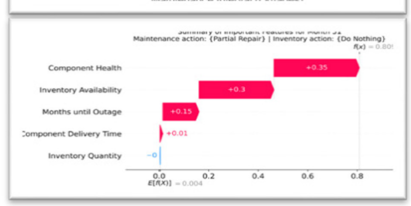
Project Description: The goal of this research project is to develop and demonstrate advanced online monitoring to better manage nuclear plant assets, operation, and maintenance. We are developing a framework to model the interaction between component reliability and condition monitoring, supply chain and resources availability, financial and business decision making, and asset management. This Bayesian network model integrates the following: big data analytics, condition monitoring, and models of the supply chain and business process applications. The output of this model will be an estimate of financial risk. Such a tool could be used by utilities for planning short and long-term asset management and for decision-making about plant operation.

Impact and Value to Nuclear Applications: For advanced nuclear reactors to be cost effective, we must take advance instrumentation and big data analytics to operate plants more efficiently, streamline maintenance, and have minimal staffing levels. We must develop and demonstrate advanced online monitoring and use such tools to support and improve decision making. If this research is successful, the nuclear industry will benefit by being able to improve cost-benefit analysis, conduct predictive analytics of operational and maintenance data, implement risk-informed condition monitoring technologies, and integrate economics, big data, and predictive maintenance to enable better asset management.

Recent Results and Highlights: We conducted an analysis of DRL (deep-reinforcement learning) methods that could be used for decision-making in nuclear O&M. These provided excellent decision-making ability that could support nuclear operators in optimizing maintenance actions. Through baseline performance comparisons, we showed that DRL was a good alternative to time-based maintenance strategies, offering significant robustness in the face of uncertain observations. The DRL agent made near-optimal decisions in the presence of high amounts of noise and outperformed time-based maintenance strategies. These results provided significant assurance that cost reductions could be achieved by using DRL for condition- and risk-based decision-making. We demonstrated how explainable AI methods could be used to improve the operator trustworthiness of the system. SHAP values showed which features of the model had the most impact on the chosen actions, which was helpful in trusting an output. The integration of DRL methods into nuclear O&M decision-making processes proved to be promising. The robustness of DRL in the presence of observation uncertainty, combined with its improved performance over traditional time-based maintenance strategies, highlighted its potential for cost-effective and risk-informed decision-making. Furthermore, the application of explainable AI methods, such as SHAP values, enhanced the transparency and trustworthiness of the system, making it a viable tool for nuclear operators.







Gallium Nitride-based 100-Mrad Electronics Technology for Advanced Nuclear

Reactor Wireless Communications: FY23 Summary Report

PI: F. Kyle Reed, M. Nance Ericson, N. Dianne Bull Ezell – Oak Ridge National Laboratory; Siddharth Rajan, Raymond Cao – Ohio State University

Collaborators: Brett Witherspoon, Tyler McCormick, Lloyd Clonts, Kevin Deng, Emma Brown – Oak Ridge National Laboratory; Chandan Joshi, Hyunsoo Lee, Adithya Balaji, John Cobbinah – Ohio State University

Introduction: Recent advances in nuclear power generation technologies show great promise for efficient and safe generation of carbon-free power. However, full realization of this power generation paradigm will require further maturation of radiation- and temperature-tolerant electronics technologies. While industry has adequately addressed harsh environment electronics needs for low earth orbit satellites, the much more extreme conditions associated with electronics placed near or in a reactor core remain largely unaddressed. This project investigates the use of gallium nitride (GaN), a wide bandgap circuit technology capable of operating in harsh environments, to address the unique needs of sensor interface electronics and communications in reactor environments. This report summarizes the first year's project activities related to developing and optimizing devices and circuits for this GaN high electron mobility transistor (HEMT) process.

Summary of Accomplishments: Activities in FY23 have focused on fabrication and irradiation of GaN HEMT devices, wireless architecture simulation, and GaN integrated circuit design and layout. To date, over 20 dies have been successfully fabricated at the Ohio State University (OSU). Four dies consisting of an assortment enhancement-mode (E-mode) and depletion-mode (D-mode) devices were irradiated to ~1016 n/cm2 at the OSU Nuclear Research Reactor (NRL). A total of 16 devices (7 E-mode and 9 D-mode) were measured in situ during irradiation to characterize their performance and develop simulation models under mixed neutron and gamma radiation. The change in drain current with gate voltage of 1 V and drain voltage of 3 V is shown in Fig. 1. Early analysis of the data suggests that threshold and gain change due to neutron displacements, gamma heating, and charge trapping in the passivation layers.

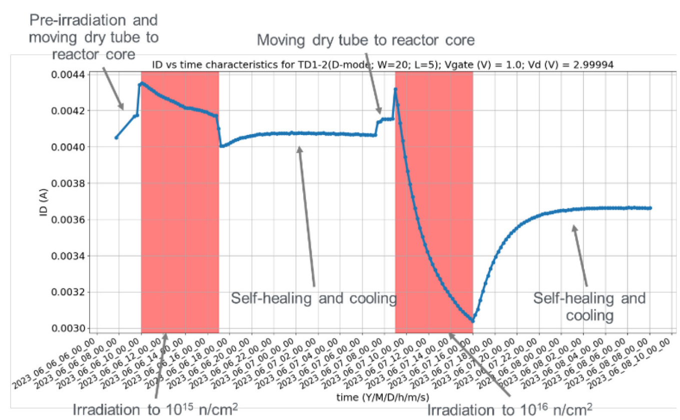


Figure 1. Drain current of a D-mode HEMT biased with $V_{GS} = 1\ V$ and $V_{DS} = 3\ V$ during irradiation to 10^{15} and 10^{16} n/cm².

Wireless communications architectures, which could be implemented in the OSU GaN process, were investigated at Oak Ridge National Laboratory (ORNL) emphasizing transmitter simplicity and receiver complexity. A wireless communications testbed was constructed using three software defined radios (SDRs) to investigate frequency shift keying (FSK) modulation with pulse-width modulation (PWM) binary encoding due to the simplicity required for the transmission circuitry. The rad-hard GaN-based sensor transmitter electronics were emulated using two independent SDRs, and the signal was received by another SDR. The receiver complexity in this scheme is greater as the receiver will be be placed in a radiation benign environment. The experimental testbed demonstrated that sensor signals could be recovered to within 1-2% of their original value. Due to software delays, the error appeared greater for rapid changes. However, this is believed to be an artifact of software emulation and would not be expected in a hardware implemented system.

In FY23, the ORNL-OSU team was the first to irradiate GaN HEMTs to ~1016 n/cm2 and has made significant strides in GaN fabrication process development, GaN HEMT fabrication, and wireless architecture design. The successes in FY23 will continue with an early FY24 heated irradiation of the GaN devices at the OSU-NRL.

Understanding irradiation behaviors of ultrawide bandgap Ga_2O_3 high temperature sensor materials for advanced nuclear reactor systems

PI: Ge Yang – North Carolina State University
Co-PI(s)/Collaborators: Cheng Sun – Idaho National Laboratory, Ayman Hawari – North Carolina State University, Yaqiao Wu – Boise State University

Project Description: The objective of the project is to understand fundamental irradiation behaviors of emerging ultrawide bandgap Ga_2O_3 high temperature sensor materials through a series of well-designed irradiation experiments and post-irradiation examination tests. Due to its unique physical properties, especially intrinsic high radiation resistance and excellent temperature tolerance, Ga_2O_3 has been considered as a promising candidate material for several key nuclear sensing and radiation hardened electronics applications for nuclear instrumentation of next-generation nuclear reactor systems and fuel cycle technologies. The proposed research focuses on two key parts to achieve the project objective: (1) performing systematic neutron irradiation and positron annihilation lifetime spectroscopy (PALS) and Doppler broadening spectroscopy (DBS) analysis at NCSU's PULSTAR Nuclear Reactor; and (2) conducting targeted post irradiation examination at CAES to measure the changes of microstructures, compositions and functional properties of Ga_2O_3 sensor materials.

Impact and Value to Nuclear Applications: The proposed work aims to achieve a deep understanding of irradiation behaviors of Ga2O3 sensor materials through well designed irradiation experiments and post irradiation examination. Such fundamental knowledge is urgently needed to fill the current knowledge gap of Ga2O3 sensor materials. The success of the project will generate crucial scientific and technical insights into the deployment of the innovative Ga_2O_3 sensors in advanced nuclear energy systems.

Recent Results and Highlights: The project has been going well, and the planned research activities are on track. Two presentations have been given at the American Nuclear Society (ANS) Annual Conference and Winter Meeting respectively. At this time, we have finished all the room temperature irradiation experiments. The room-temperature irradiated Ga_2O_3 samples have been taken out of the NCSU PULSTAR reactor and put into the storage area for cooling down. As planned, we have multiple sets of samples irradiated under the same conditions. Some of them have been packaged according to the shipping requirements and then sent to CAES for post irradiation examination. Some of them have been kept at NCSU for complementary characterization and analysis, e.g., PALS measurements. The figure below shows the preliminary microstructure characterization results of Ga_2O_3.

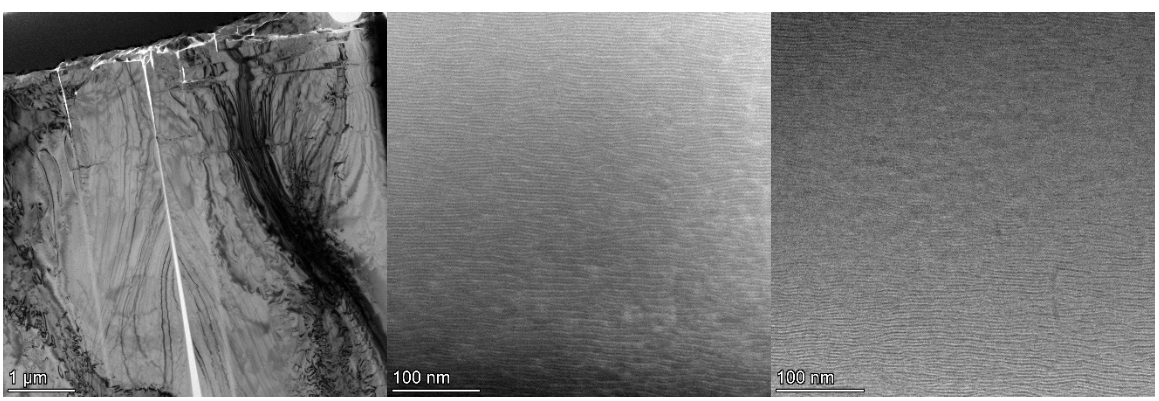


Figure 1. Transmission electron microscopy images of Ga_2O_3. (left) Bright-field, (middle) HAADF, (right) STEM-BF.

COMPLETED PROJECTS AND FUNDING PROFILE

The ASI program activities are implemented through two primary funding methods:

- Directed research activities implemented at DOE National Laboratories;
- Research Projects competitively awarded as part of the DOE Consolidated Innovative Nuclear Research (CINR) funding opportunity.

In fiscal year (FY) 2011, before the ASI program was initiated, three 3-year projects totaling $1,366,886, were selected under the mission supporting, a transformative (Blue Sky), portion of the Nuclear Energy University Programs (NEUP) under the ASI topic. These projects were completed in 2014:

- A High Temperature-tolerant and Radiation-resistant In-core Neutron Sensor for Advanced Reactors, The Ohio State University, $455,629 (09/29/2011–09/30/2014)
- High Temperature Transducers for Online Monitoring of Microstructure Evolution, Pennsylvania State University, $455,628 (10/12/2011–12/31/2014)
- NEUP: One-Dimensional Nanostructures for Neutron Detection, North Carolina State University, $455,629 (09/29/2011–09/30/2014)

In FY 2012, directed research activities totaling $7,622,000, were initiated to address a range of common and crosscutting needs identified by the DOE-NE R&D programs. These projects were concluded in FY 2014 when the NEET ASI program transitioned to a fully competitive solicitation and selection process:

- NEET In-Pile Ultrasonic Sensor Enablement, Idaho National Laboratory, $1,000,000 (03/01/2012–09/30/2014)
- Micro Pocket Fission Detectors, Idaho National Laboratory, $1,015,000 (03/01/2012–09/30/2014)
- High-Temperature Fission Chamber, Oak Ridge National Laboratory, $574,000 (03/01/2012–03/30/2014)
- Recalibration Methodology for Transmitters and Instrumentation, Pacific Northwest National Laboratory, $529,000 (03/01/2012–04/30/2014)
- Digital Technology Qualification, Oak Ridge National Laboratory, $1,269,000 (03/01/2012–06/30/2015)
- Embedded Instrumentation and Controls for Extreme Environments, Oak Ridge National Laboratory, $770,000 (03/01/2012–03/30/2014)
- Sensor Degradation Control Systems, Argonne National Laboratory, $360,000 (03/01/2012–02/28/2014)
- Design for Fault Tolerance and Resilience, Argonne National Laboratory, $900,000 (03/01/2012–03/30/2014)
- Power Harvesting Technologies for Sensor Networks, Oak Ridge National Laboratory, $380,000 (03/01/2012–06/30/2014)
- Development of Human Factors Guidance for Human-System Interface Technology Selection and Implementation for advanced NPP Control Rooms and Fuel Cycle Installations, Idaho National Laboratory, $825,000 (03/01/2012–02/28/2014)

In FY 2013, three projects totaling $1,199,664, were awarded competitively to design custom radiation-tolerant electronics systems and methods to quantify software dependability. These projects were completed in 2015:

- Radiation-Hardened Circuitry using Mask-Programmable Analog Arrays, Oak Ridge National Laboratory, $400,000 (10/01/2013–09/30/2015)

- Radiation Hardened Electronics Destined for Severe Nuclear Reactor Environments, Arizona State University, $399,674 (12/16/2013–12/15/2015)
- A Method for Quantifying the Dependability Attributes of Software-Based Safety Critical Instrumentation and Control Systems in Nuclear Power Plants, The Ohio State University, $399,990 (12/26/2013–12/25/2015)

In FY 2014, six projects totaling $5,963,480, were awarded competitively and completed in 2017:

- Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks, Boise State University, $980,804 (01/01/2015–12/31/2017)
- Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation, Pacific Northwest National Laboratory, $1,000,000 (10/01/2014–09/30/2017)
- Operator Support Technologies for Fault Tolerance and Resilience, Argonne National Laboratory, $995,000 (10/01/2014–09/30/2017)
- Embedded I&C for Extreme Environments, Oak Ridge National Laboratory, $1,000,000 (10/01/2014–09/30/2017)
- Enhanced Micro Pocket Fission Detector for High Temperature Reactors, Idaho National Laboratory, $1,000,000 (10/01/2014–09/30/2017)
- High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle Systems, University of Pittsburgh, $987,676 (10/01/2014–09/30/2017)

In FY 2015, two projects totaling $1,979,000, were awarded competitively and completed in 2018, 2019:

- Nuclear Qualification Demonstration of a Cost Effective Common Cause Failure Mitigation in Embedded Digital Devices, Electric Power Research Institute, $991,000 (10/01/2015–06/30/2019)
- Development of Model Based Assessment Process for Qualification of Embedded Digital Devices in NPP Applications, University of Tennessee, $988,000 (10/01/2015–09/30/2018)

In FY 2016, three projects totaling $2,789,228, were awarded competitively and completed in 2019, 2020:

- Self-powered Wireless Through-wall Data Communication for Nuclear Environments, Virginia Tech, $1,000,000 (10/01/2016–09/30/2020)
- Transmission of information by Acoustic Communication along Metal Pathways in Nuclear Facilities, Argonne National Laboratory, $1,000,000 (10/01/2016–09/30/2019)
- Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply, Westinghouse Electric Company LLC, $789,228 (10/01/2016–07/31/2020)

In FY 2017, five projects totaling $4,889,688, were awarded competitively and completed in 2021, 2022:

- 3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures, Vanderbilt University, $1,000,000 (10/01/2017–09/30/2021)
- Integrated Silicon/Chalcogenide Glass Hybrid Plasmonic Sensor for Monitoring of Temperature in Nuclear Facilities, Boise State University, $890,000 (10/01/2017–9/30/2021)
- Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring, Virginia Tech, $1,000,000 (10/01/2017–09/30/2021)

- Ultrasonic Sensors for TREAT Fuel Condition Measurement and Monitoring, Pacific Northwest National Laboratory, $1,000,000 (10/02/2017–09/30/2021)

- High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems, $999,688 (10/01/2017–09/30/2022)

The ASI program funded directed research activities for a total of $5,000,000. These activities were implemented at Idaho National Laboratory in collaboration with Boise State University (BSU) and focused on the development and demonstration of sensors to deploy in Material Test Reactors irradiation experiments, in particular the Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT). The activities were framed as the In-Pile Instrumentation (I2) initiative.

In FY 2018, three projects totaling $2,987,730, were awarded competitively and completed in 2022:

- Development of Optical Fiber Based Gamma Thermometer, The Ohio State University, $987,730 (10/01/2018–09/30/2022)
- Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants, Idaho National Laboratory, $1,000,000 (10/01/2018–09/30/2022)
- Process-Constrained Data Analytics for Sensor Assignment and Calibration, Argonne National Laboratory, $1,000,000 (10/01/2018–09/30/2022)

The ASI program provided $1,500,000 to fund directed research activities at the Oak Ridge National Laboratory under the 2-year project 'Direct Digital Printing of Sensors for Nuclear Energy Applications'. The project aimed at developing advanced manufacturing techniques to fabricate networks of cost effective, wirelessly connected sensors for nuclear power plant components. Additionally, direct funded research in the area of sensors and instrumentation continued at the Idaho National Laboratory under the I2 initiative for a total of $5,300,000.

In FY 2019, five projects totaling $4,500,000, were awarded competitively and completed in 2023:

- Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control, Pacific Northwest National Laboratory, $1,000,000 (10/01/2019–09/30/2022)
- Design of Risk Informed Autonomous Operation for Advanced Reactor, Massachusetts Institute of Technology, $1,000,000 (10/01/2019–09/30/2022)
- Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics, Argonne National Laboratory, $1,000,000 (10/01/2019–09/30/2022)
- Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance, University of Pittsburgh, $1,000,000 (10/01/2019–09/30/2022)
- Context-Aware Safety Information Display for Nuclear Field Workers, Arizona State University, $500,000 (10/01/2019–09/30/2022)

The ASI program provided $5,500,000 to continue direct research in the area of sensors and instrumentation at the Idaho National Laboratory under the I2 initiative.

In FY 2020, two projects totaling $2,000,000 were awarded competitively and are expected to complete in 2024:

- Development of Sensor Performance Model of Microwave Cavity Flow Meter for Advanced Reactor High Temperature Fluids, Argonne National Laboratory, $1,000,000 (10/01/2020–09/30/2023)

- Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid, Argonne National Laboratory, $1,000,000 (10/1/2020–09/30/2023)

The scope of the ASI program directed funded activities was extended to encompass all program objectives and implemented across the Idaho National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory for a total of $4,800,000. Directed funded projects were organized in technical areas as follows:

- Nuclear Instrumentation;
- Sensor Fabrication by Advanced Manufacturing;
- Measurement Systems for Nuclear Materials Properties Characterization;
- Instrumentation Deployment;
- Develop Methods and Tools using Nuclear Science User Facilities Data to Support Risk-informed Predictive Maintenance.

In FY 2021, one project totaling $999,000 was awarded and expected to complete in 2024:

- Gallium Nitride-based 100-Mrad Electronics Technology for Advanced Nuclear Reactor Wireless Communications, Oak Ridge National Laboratory, $999,000 (10/01/2021–09/30/2024)

The ASI program provided $4,785,379 to fund directed research activities at the Idaho National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory. Directed funded projects were organized in technical areas as follows:

- Sensors for advanced reactors;
- Advanced materials and manufacturing methods for sensors applications;
- Instrumentation for irradiation experiments;
- Digital technology.

In FY 2022, one project totaling $800,000, was awarded competitively and expected to complete in 2025:

- An Innovative Monitoring Technology for the Reactor Vessel of Micro-HTGR, Texas A&M, $800,000 (10/1/2022-09/30/2025)

The ASI program provided $5,452,000 to fund directed research activities at Idaho National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory. Directed funded projects were organized in technical areas as follows:

- Sensors for Irradiation Experiments
- Sensors for Advanced Reactors
- Sensor Integration

In FY 2023, two projects totaling $2,000,000 were awarded competitively and are expected to complete in 2026:

- Integrated Stand-Off Optical Sensors for Molten Salt Reactor Monitoring, University of Pittsburgh, $1,000,000 (10/1/2023 – 09/30/2026)
- Optical Sensors for Impurity Measurement in Liquid Metal-cooled Fast Reactors, University of Michigan, $1,000,000 (10/1/2023 – 09/30/2026)

The ASI program provided $4,899,600 to fund directed research activities at Argonne National Laboratory, Idaho National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory. Directed funded projects were organized in technical areas as follows:

- Sensors for Advanced Reactors
- Sensors for Irradiation Experiments
- Sensors Integration

Additional research activities funded by ASI are implemented as part of the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR). More details on the projects and research activities listed above can be found in documents available on the DOE/NE Website: https://www.energy.gov/ne/advanced-sensors-and-instrumentation-asi-program-documents-resources or on the ASI Website: https://asi.inl.gov/#/.