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Advanced Sensors and Instrumentation 2022 Summary of Accomplishments

March 2023

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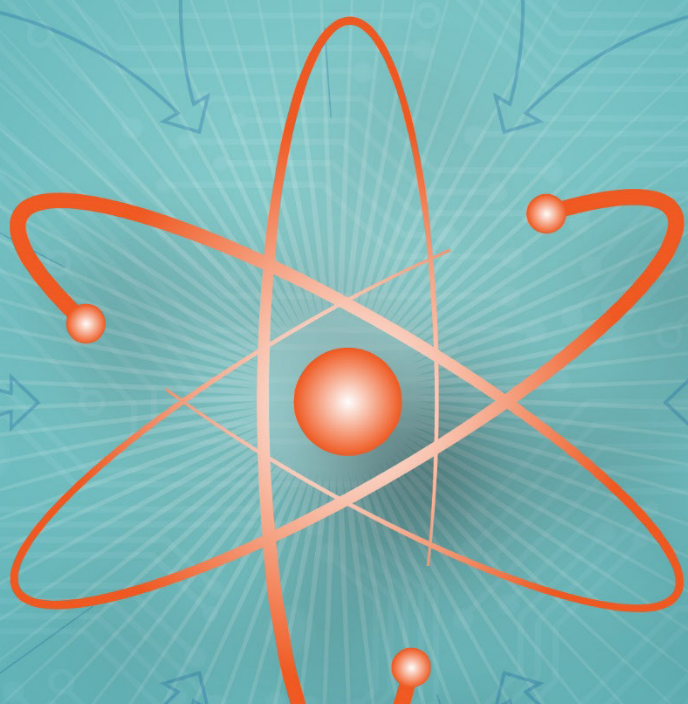
U.S. DEPARTMENT OF ENERGY

ADVANCED SENSORS AND INSTRUMENTATION

2022 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 2022 Annual Review meeting, which was held virtually between October 24 and October 27, 2022.

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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 2022 Annual Review meeting, which was held virtually between October 24 and October 27, 2022. The content is organized following the four meeting sessions, as follows:

- Sensors for Irradiation Experiments
- Sensors for Advanced Reactors
- Sensor Integration
- Small Business Innovation Research (SBIR) / Industry FOA

Sensors for Irradiation Experiments

Nuclear Energy Sensors Database

PI: Tim Downing – Pacific Northwest National Laboratory
Collaborator: Andrew Casella – 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: This website is intended as a "one stop shop" in regard to searching for information related to nuclear energy sensors and prioritized needs and gaps. In addition to providing this content, the website also supports a user forum so subject matter experts can build an online community and provide additional suggestions on new sensors or site enhancements.

Recent Results and Highlights: The initial version of the site went live in early FY21 with 71 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 additional sensor information. While the amount of information on each type of sensor depends on the level of data provided, PNNL has successfully uploaded to the database all the data it has been supplied with. In FY21, 24 sensors were added to the system; in FY22, 96 sensors were added. Although the primary focus in FY22 has been to gather new sensor information, software updates were also conducted to address bugs and improve usability, styling, and security patches.

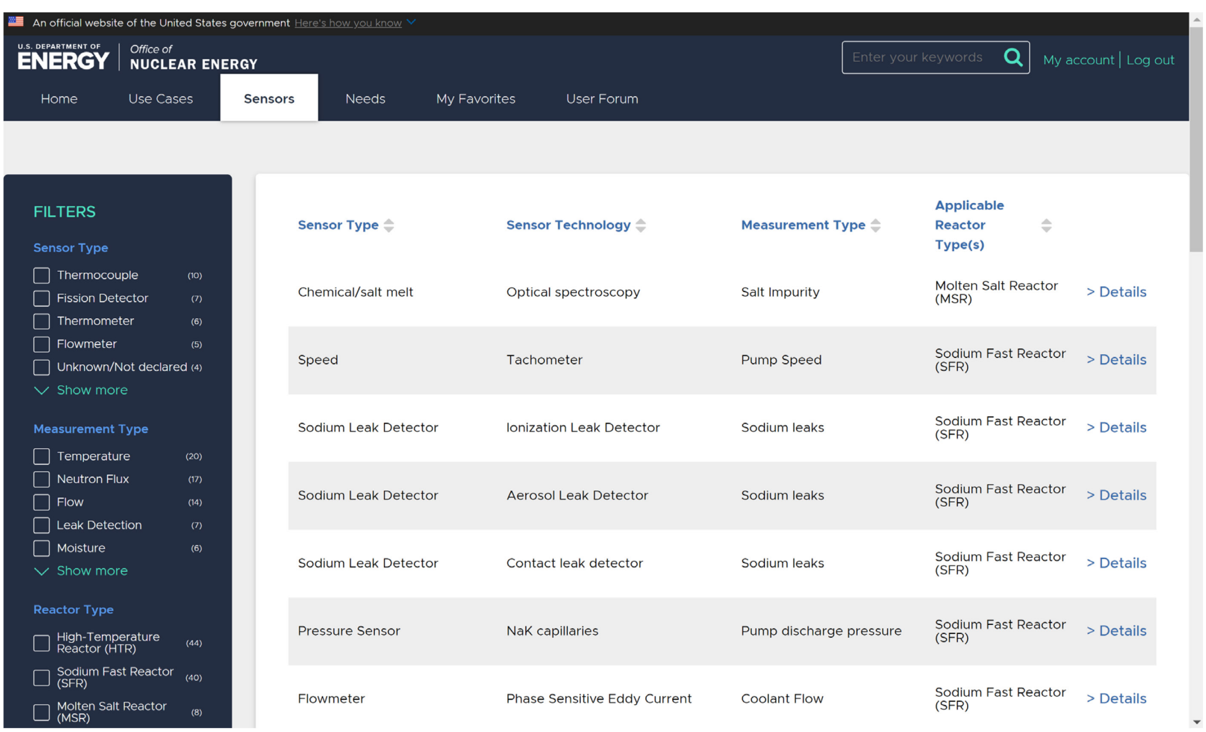


Figure 1. Nuclear Energy Sensors Database.

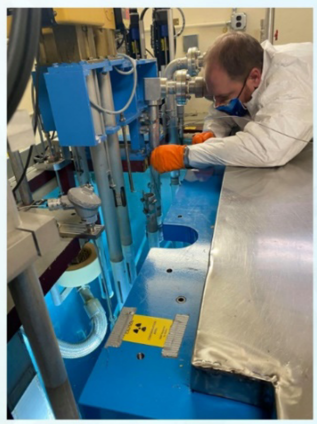
Irradiation Testing of Sensors

PI: Joe Palmer – Idaho National Laboratory
Collaborators: Kevin Tsai, Troy Unruh – Idaho National Laboratory

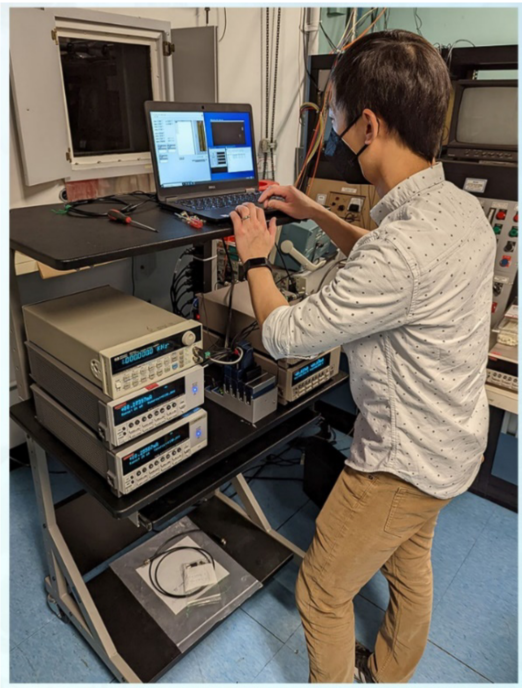
Project Description: Advanced instrumentation enables the testing of nuclear fuels/materials in support of the U.S. advanced nuclear technology industry. In fiscal year (FY) 2022, this project focused on the irradiation testing of neutron flux sensors at elevated temperatures.

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

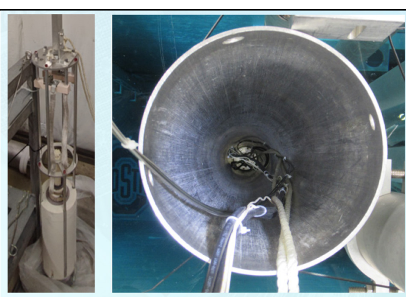
Recent Results and Highlights: An important objective for FY-22 was to begin the characterization of fission chambers and Rh-based self-powered neutron detectors (SPNDs) at temperatures relevant to advanced reactors (i.e., 500–900°C). This testing was conducted in three different reactors: NRAD, MITR, and OSURR. The initial testing (at NRAD) indicated significant temperature dependence in the SPND signals; however, it was difficult to separate the inherent temperature dependence from electromagnetic interference (from the heating element). Because of its greater flux intensity, MITR can generate temperatures in excess of 800°C without supplementary electric heating, thus the second test was a better tool for characterizing Rh SPNDs at elevated temperatures. The results of this testing showed significant but manageable temperature dependence. The final test at OSURR focused on testing fission chambers at temperatures near 350°C. Some degradation of the fission chamber signals was observed after irradiation at this temperature.



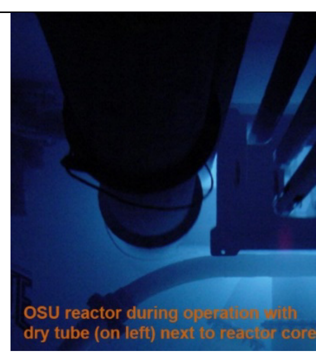
Installing sensors in NRAD



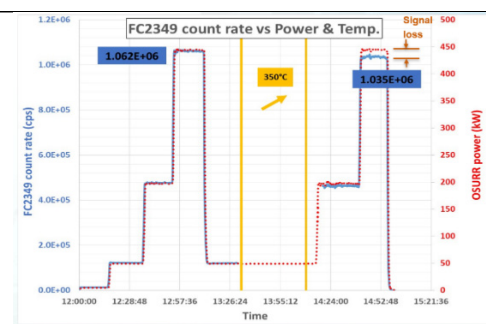
Gathering data at MITR



OSURR heated test rig on left - Installed in dry tube on right



OSU reactor during operation with dry tube (on left) next to reactor core



Data from CEA thermal fission chamber during OSURR irradiation

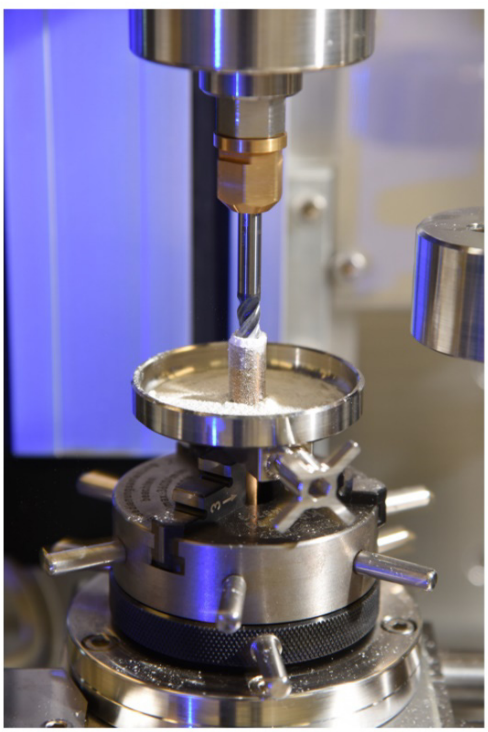
Complete Re-instrumentation Facility Procurements and Fabricate an Instrumented Rodlet Prototype

PI: Joe Palmer – Idaho National Laboratory
Collaborators: Randel Paulsen, Kory Manning – Idaho National Laboratory

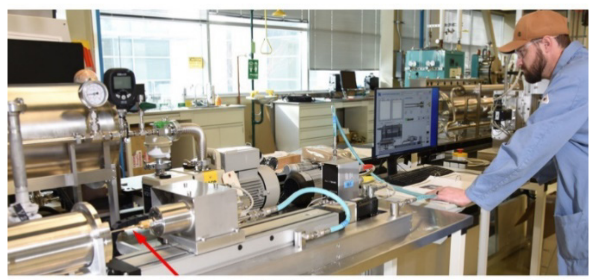
Project Description: Complete the procurement of three equipment modules from the Norwegian Institute for Energy Technology (IFE) Halden Reactor Project and use this equipment to fabricate a prototypical instrumented rodlet.

Impact and Value to Nuclear Applications: For decades, Norway's Halden Boiling Water Reactor (HBWR) was a key resource for assessing nuclear fuel and material behaviors to address performance issues and answer regulatory questions. The HBWR was shut down in 2018. To avoid losing the unique experimental techniques developed at Halden, Idaho National Laboratory (INL) is procuring equipment modules designed to instrument irradiated sections of light-water reactor (LWR) fuel rods prior to reinserting them into a test reactor. This approach has proven uniquely successful—and therefore invaluable—to enabling in-pile measurements on irradiated nuclear fuels. This project increases the capability to deploy and demonstrate advanced in-core instrumentation, and contributes to the broader effort to transfer Halden-developed technology and expertise to Department of Energy facilities. This approach to fuel testing is key to advancing and qualifying new LWR technologies.

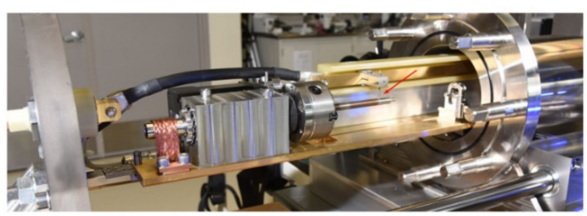
Recent Results and Highlights: The figures below show the major processes required to produce an instrumented rodlet. After finishing the rodlet, a helium leak test was performed to demonstrate the integrity of the welds.



Defueling module removing surrogate pellet material from rodlet mockup



Preparing to start cryo-drilling of a surrogate fuel rodlet



Lining up tungsten electrode prior to welding

Finished rodlet with instrumentation installed

Gamma Thermometer Irradiation in the HFIR Spent Fuel Pool

PI: Christian C. Petrie – Oak Ridge National Laboratory
Collaborator: Anthony Birri – Oak Ridge National Laboratory

Project Description: The goal of this research is to develop, model, and demonstrate an optical fiber-based gamma thermometer (OFBGT) for use in intense gamma-ray fields. The irradiations are to occur within spent fuel elements from the High Flux Isotope Reactor (HFIR), enabling evaluation of the effects of intense gamma heating without a significant neutron flux. Testing multiple spent fuel elements under different gamma-ray source strengths will provide multiple data points for simulating 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 in comparing against model predictions. This work aligns with the OFBGT irradiations conducted by OSU and TAMU, as well as with the power inferencing method being developed at ORNL.

Impact and Value to Nuclear Applications: Using multiple optical fibers, an OFBGT can provide a distribution of gamma dose or heating rates along its axial length, based on a distributed measurement of temperature differences across an insulating gas gap. This capability affords the OFBGT an advantage over thermocouple-based gamma thermometers (TCBGTs), which act as point sensors. Thus, OFBGTs could serve to replace TCBGTs, which are traditionally used to calibrate local power range monitors (LPRMs) in BWRs, by providing up to hundreds or even thousands of data points along their axial lengths. This would significantly reduce the footprint and cabling requirements in comparison to employing an array of TCBGTs. Furthermore, ORNL is developing data analytic techniques for potentially using gamma thermometer data to directly infer reactor power distributions, thus potentially bypassing the need for LPRMs entirely.

Recent Results and Highlights: The OFBGT to be deployed in the HFIR spent fuel pool has been fully fabricated at ORNL and has undergone preliminary testing in open-air heating experiments. Analytic and numerical thermal models have been generated for comparison against open-air experimental results and to predict performance in the HFIR spent fuel pool. In general, the open-air results indicate the OFBGT is performing as expected. Project participants are working with HFIR staff to approve all safety documentation and to schedule the spent fuel pool irradiation.

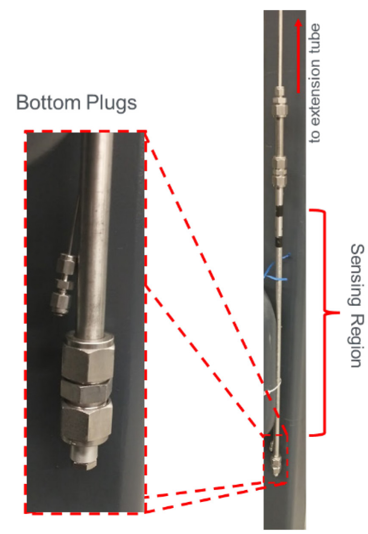


Figure 1. OFBGT Configuration.

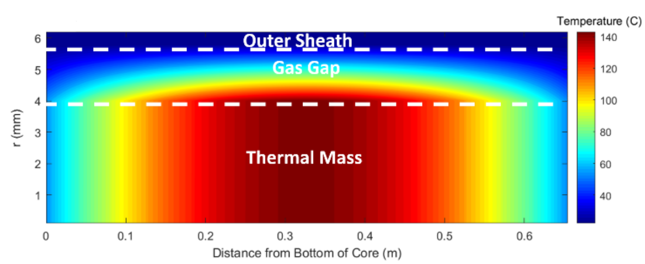


Figure 2. Thermal Modeling of the OFBGT.

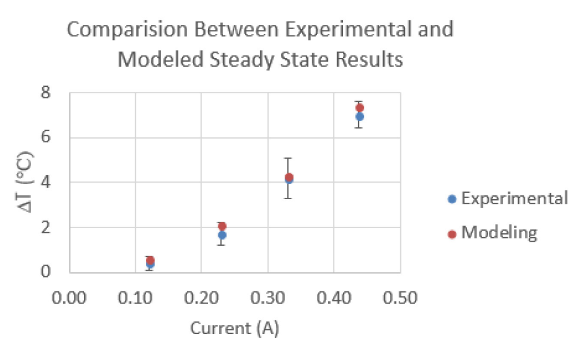


Figure 3. Open-Air Testing Results.

Passive Peak Temperature Monitors: Silicon Carbide

PI: Malwina Wilding – Idaho National Laboratory
Collaborator: Kurt Davis – Idaho National Laboratory

Project Description: Since the early 1960s, SiC has been used as a post-irradiation temperature monitor. Researchers observed that SiC’s neutron-irradiation-induced lattice expansion annealed out when the post-irradiation annealing temperature exceeded the peak irradiation temperature. Passive temperature monitors are needed for when real-time sensors are impractical or uneconomical to install in an irradiation test. Furthermore, though passive temperature monitors have been used for many decades in irradiation testing experiments, further innovations made to these technologies will advance the state of the art by leveraging new equipment and methods that were initiated back in FY-20. To further advance this capability an optical dilatometer had been purchased and was benchmarked against traditional resistivity methods for post-irradiation evaluations of silicon carbide temperature monitors.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measuring irradiation temperature during post-irradiation examination, and 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. Further development of passive monitors for application to higher temperatures and different geometries is needed.

Recent Results and Highlights: The main objective of the FY-22 work was to conduct a benchmark analysis of the optical dilatometry method by using two SiC temperature monitors provided by NSUF’s BSU 8242 experiment, and two other SiC temperature monitors provided by NSUF’s GE Hitachi experiment. The KGT 3336 SiC (GE Hitachi) monitor was split into two pieces during the decontamination process, making the dilatometry method the only way to analyze both those pieces. The optical dilatometry method measured the peak irradiation temperature of BSU 8242 KGT 3597 to be 330°C, while the resistivity method measured the peak irradiation temperature of BSU 8242 KGT 3591 to be 320°C +/ 20°C. The optical dilatometry method measured the peak irradiation temperatures of the pieces of GE Hitachi KGT 3336 to be 260°C (for the larger piece) and 220°C (for the smaller piece), while the resistivity method measured the peak irradiation temperature of GE Hitachi KGT 3341 to be 300°C, with an accuracy range of -50°C to + 20°C. Both methods of SiC temperature monitor analysis produced very similar peak irradiation temperatures for each pair of SiC passive monitors from the two experiments, BSU 8242 and GE Hitachi. This shows continuous optical dilatometry to be a valid method for measuring the peak irradiation temperatures of passive SiC temperature monitors. 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.

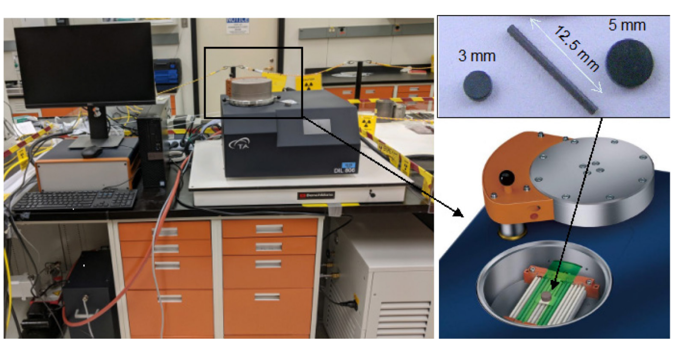


Figure 1. Optical dilatometry method for processing silicon carbide temperature monitors.

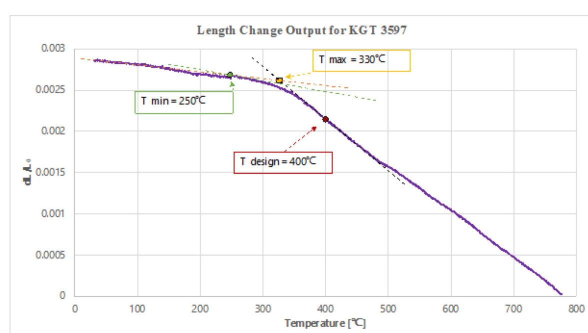


Figure 2. Irradiation temperatures determined based on the delta change in length and the design temperature of the KGT 3597 (BSU-8242) monitor.

Passive Peak Temperature Monitors – Melt Wires

PIs: Kiyo Fujimoto and Lance Hone – Idaho National Laboratory
Collaborators: Malwina Wilding, and Kurt Davis – Idaho National Laboratory

Project Description: Although passive peak temperature monitors have been used in irradiation testing experiments for many decades now, limited innovation has been applied to these technologies. One method of determining peak temperature involves placing material wires of a known composition and melting temperature in an irradiation test. This method requires post-irradiation examination of the 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.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measuring irradiation temperature during post-irradiation examination, and 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. Furthermore, advanced manufacturing techniques will aid in expanding the range of melt wire capabilities.

Recent Results and Highlights: The main objective of the FY-22 work was to optimize the selection of materials—initially investigated in FY-21—for creating the encapsulated printed melt wire package. The focus was on the combability of materials that can generate higher resolutions than traditional quartz encapsulated melt wires. This led to the addition of a ceramic sublayer to increase the image resolution of the x-ray computer tomography. This sublayer also acts as a heat insulator to prevent printed melt wires from prematurely melting during the sealing of the encapsulation discs under inert gas. The final melt wire array consisted of indium (100%) with a melting point of 157°C, indium-silver (96:4) with a melting point of 221°C, and tin (100%) with a melting point of 230°C.

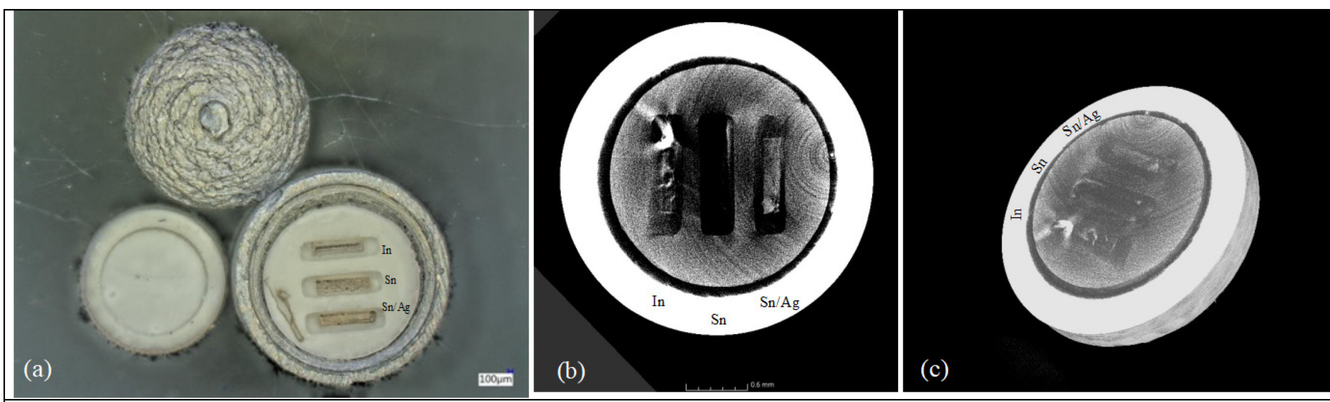


Figure 1. Printed Melt Wire Package: (a) before sealing, (b) after sealing XCT top view image, and (c) XCT 3D image.

Linear Variable Differential Transformers

PI: Kurt Davis – Idaho National Laboratory
Collaborators: Malwina Wilding, Austin Fleming, Kory Manning – Idaho National Laboratory;
Brian Jaques, Zhangxian Deng, Alex Draper, Joshua Poorbaugh – Boise State University;
Heng Ban, William Spirnock – University of Pittsburg; Steinar Solstad – Institute for Energy Technology

Project Description: FY-22 research focused on two major areas. The first was modeling and simulation with linked testing to advance linear variable differential transformer (LVDT) technology for use by stakeholders requiring LVDTs in upcoming irradiation tests. The second area focused on testing an LVDT purchased from a U.S. supplier recommended by the supply chain study. These cross-cutting development activities will ensure that stakeholders have the current state-of-the-art, LVDT-based technologies for deployment in future irradiation tests.

Impact and Value to Nuclear Applications: The Institute for Energy Technology (IFE) is the world's sole provider of LVDTs for in-pile testing, thus putting the international testing community at risk of being unable to collect valuable data should the LVDT supply become limited. Because of this, the present research aims to provide a better understanding of LVDT behavior in future irradiation tests, and to broaden the LVDT supply base.

Recent Results and Highlights: Evaluation of the RDP LIN 56 sensor revealed it to potentially be—under select criteria—a viable substitute for the IFE LVDT. Testing of the TREAT-integrated LVDT rig demonstrated the need for accurate material property data, and it was also demonstrated that LVDTs used in irradiation experiments are capable of being operated wirelessly.

Idaho National Laboratory | BOISE STATE UNIVERSITY | University of Pittsburgh

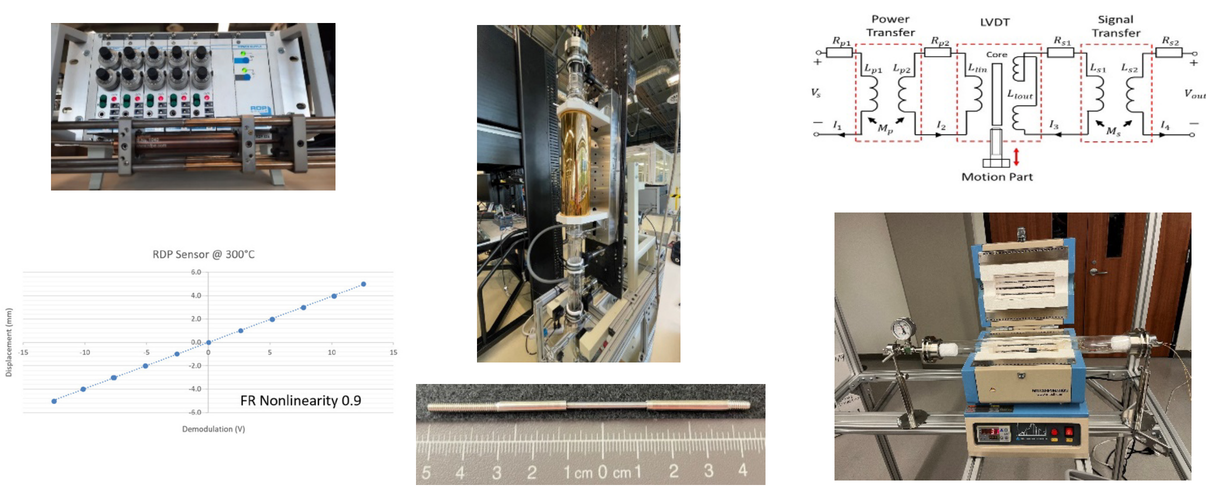


Figure 1. Depiction of tests conducted by Idaho National Laboratory, Boise State University, and the University of Pittsburgh.

Advanced Sensors and Instrumentation Program: Mechanical Properties Characterization

PI: Michael McMurtrey – Idaho National Laboratory
Collaborators: Tim Phero, Kiyo Fujimoto, Amey Khanolkar, James Smith – 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 goal of the Mechanical Properties Characterization project is to develop advanced sensors and instrumentation (e.g., printed strain gauges) for monitoring the mechanical properties and structural health of materials and specimens in test reactor experiments. These sensors enable data acquisition for improved in-pile material testing and for validating modeling and simulation efforts in order to support the development, testing, and qualification of new nuclear materials.

Recent Results and Highlights: For FY-22, commercially available strain gauges were explored, the use of which aided in providing benchmark strain data for embedded sensors in a prototypic heat-pipe-cooled microreactor core, and in validating printed strain gauges in tensile testing experiments. Additive manufacturing was used to fabricate low-profile interdigitated capacitive strain gauges that offer reproducible and predicable strain sensing performance, and that have been tested at up to 300°C. The reliability and quality of printed sensors is a primary concern for sensor deployment in actual test reactor experiments. A non-contact, laser-induced spallation technique was used to quantify the adhesion of silver prints on an aluminum alloy substrate (see Figure 1 below). This laser-based method was compared to a standardized pull-off adhesion test that had provided baseline measurements of adhesion strength. Sintering conditions were shown to play an important role in the film-substrate adhesion strength, as were the cohesion and ductility of the film itself. This technique is being developed as a means of validating printed sensor quality.

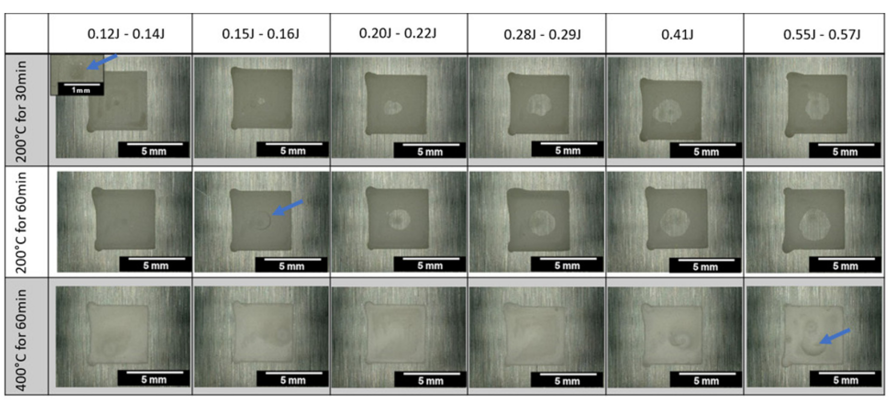


Figure 1. Determining the threshold laser pulse energy needed to induce failure under three different sintering conditions (i.e., 200°C for 30 min., 200°C for 60 min., and 400°C for 60 min.) at energies between 0.12 J and 0.57 J.

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
Michael Short – Massachusetts Institute of Technology
David Carpenter – Massachusetts Institute of Technology Research Reactor

Thermal conductivity is one of the most critical physical properties of nuclear fuels, as it directly ties into reactor safety and efficiency. Microstructural defects that are generated by and evolved in extreme in-reactor environments would significantly impact thermal conductivity, 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. However, point defects, a 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 will be developed. In the first year, we focused on the first round of irradiation experiments, resulting in three major accomplishments. First, the in-reactor testing instrument was designed, assembled, and transferred to MITR. The initial design was created in accordance with the geometry and thermal/neutronic analysis requirements of the MITR core position, and finalized after the thermal and neutronic analysis. Four fiber probes were made and tested with reference samples preloaded. Second, more high-temperature, in situ thermal conductivity testing was performed in the vacuum system and positive results were obtained. The temperature range was expanded to 730°C (i.e., close to the scheduled upper-bound temperature in MITR of 700–750ºC). During the process, the data collection and analysis codes were also optimized. The foolproof data collection code was created for regular, continuous in-reactor measurements. Third, with help from MIT and MITR personnel, key Idaho National Laboratory (INL) personnel travelled to MITR to complete the measurement system and make it ready for deployment. Though the final insertion was delayed due to a ventilation system unexpectedly being down, all the system's optical and electrical connections have been completed. After the instrument is deployed into position, the testing can start.

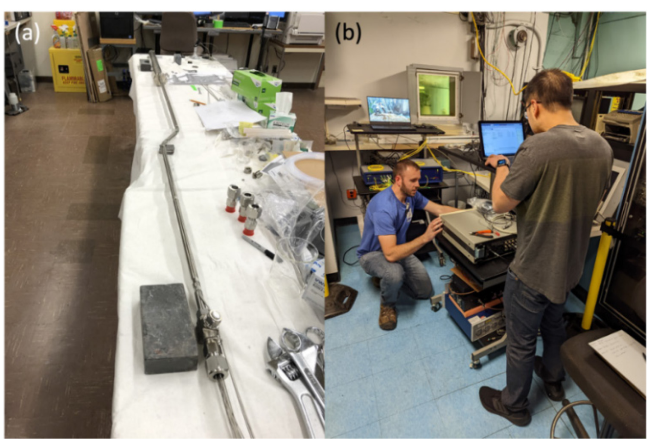


Figure 1. (a) The measurement instrument at the MITR laboratory; (b) INL personnel Caleb Picklesimer and Zilong Hua completing the final optical and electrical connection for the instrument insertion.

Sensors for Advanced Reactors

Development of an Optical-Fiber-Based Gamma Thermometer

PI: Thomas Blue – The Ohio State University
Collaborators: Pavel Tsvetkov – Texas A&M University; Diego Mandelli – Idaho National Laboratory

Project Description: The objective of this project is to develop an optical-fiber-based gamma thermometer (OFBGT) and the associated analytical techniques needed for its use. An OFBGT measures ΔT along the axial length of the sensor, then uses that measurement to infer the core power distribution. Inferencing of the core power is achieved using MCNP-generated data in tandem with the data analytics method developed via this project. We have demonstrated this measurement technique in both the Ohio State University Research Reactor (OSURR) and the Texas A&M TRIGA reactor (TAMURR). Design of the sensor began with a silica-fiber-based OFBGT for university research reactors (URRs), then proceeded to the development of a higher temperature, higher power version for use in current and next-generation reactors.

Impact and Value to Nuclear Applications: A system of OFBGTs in a nuclear reactor would allow for a permanently installed method of calibrating power monitors, thus replacing the traversing in-core probes (TIPs) currently utilized in boiling-water reactors. An OFBGT can extend the entire length of an instrument tube and acquire a distributed gamma-ray absorbed dose rate along its length. TIPs, or even thermocouple-based gamma thermometers, act as point sensors and do not possess such a capability. Therefore, OFBGTs are particularly useful for generating big data, and they enable a higher resolution 3D distribution measurement of core power than can be obtained with ion chambers.

Recent Results and Highlights: This year, we analyzed TAMURR and reanalyzed OSURR in regard to the data generated from reactor testing of silica-fiber OFBGTs. We also retested the sensor in the OSURR and concluded that a fiber was likely sticking in the OFBGT outer sheath (OS). Figure 1 shows the OSURR post-test data analysis results collected after this fiber became free. Multiple experimental and/or modeling errors may partly account for the discrepancies between the measured and calculated $\boldsymbol{q'}$ profiles; however, the biggest cause is probably delayed and activation gamma-ray heating. A special high-temperature-capable OFBGT was designed to reduce the likelihood of fibers sticking in the OS. This improved sensor was fabricated and tested to high temperatures in bench-top experiments, confirming the need for further design modifications to reduce the impact of radiative heat transport in regard to sensor applications in high-temperature, high-power reactors.

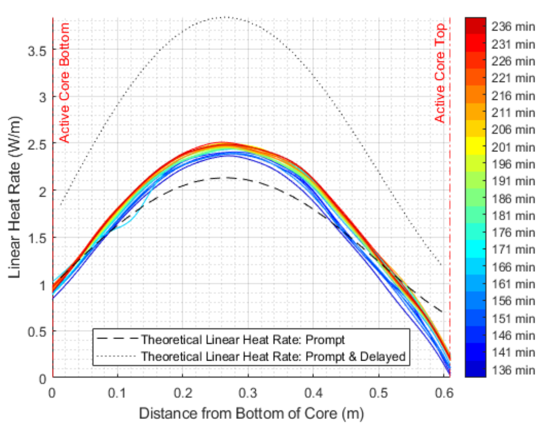


Figure 1. OFBGT-measured linear heat rate in the OSURR WIF.

Figure 2. Improved OFBGT with a slightly thicker (double wall) outer sheath to house the fiber.

High-Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems

PI: Xiaoning Jiang – North Carolina State University
Collaborators: Mohamed Bourham, Mo-Yuen Chow – North Carolina State University

Project Description: Advanced sensors and instrumentation are critical for the monitoring of nuclear power plants (NPPs). This project aims to develop high-temperature embedded/integrated sensors (HiTEIS) and laser ultrasound transducers for remote monitoring of reactors and fuel cycle systems. Specifically, HiTEIS and the associated communication system for monitoring temperature, vibration, stress, liquid levels, and structural integrity will be designed, fabricated, and characterized, followed by the HiTEIS technology verification in reactor and fuel cycle environments.

Impact and Value to Nuclear Applications: Development of HiTEIS will enable non-invasive sensing of the operation status of NPPs. Remote communication will aid in monitoring NPP systems more frequently and reliably, and will minimize the need for human operators to place themselves in the vicinity of high-temperature and radiation hazards.

Recent Results and Highlights: A heated cylindrical steel vessel was used as the mockup structure for a HiTEIS vibration sensor. The vibration sensor, a bulk single-crystal aluminum nitride (AlN), was mounted within a small machined groove on the vessel and then fixed with HT epoxy. The usable frequency range was found to be approximately 150–350 Hz, and a HT test was carried out from 50 to 200°C. A commercial sensor was used to measure the acceleration induced on the structure. The sensor response was found to be lower than in previous vibration tests. Figure 1 shows the sensor response at 100°C, with an induced structural vibration of 275 Hz. Carbon nanoparticles were shown to increase the photoacoustic efficiency of the liquid metal transducer. The optimal laser fluence appeared to be 8 mJ/cm^2 (see Figure 2). The transducer responded well under HT conditions (Figure 3), showing improved durability as well as the ability to both last for multiple tests and weeks and to recover its ultrasound strength as the transducer cools.

Images/graphs/charts:

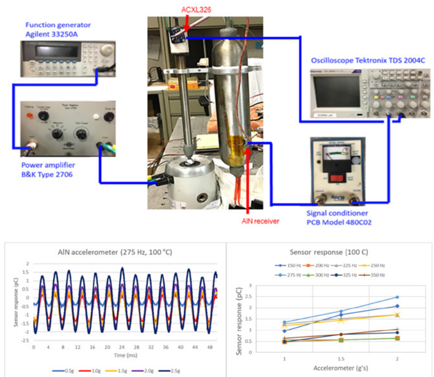


Figure 1. Mockup structure experiment with a vibration-sensing AlN. High-temperature vibration testing was carried out from 50 to 200°C. Fluid used in the vessel limited the maximum temperature range. The vessel was not pressurized.

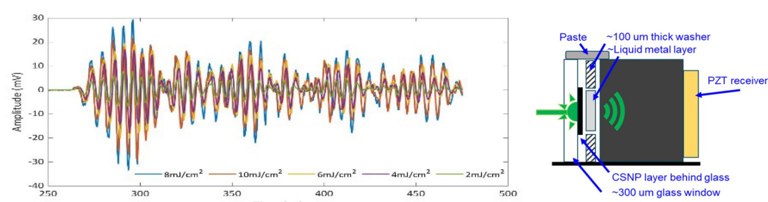


Figure 2. Left: LM-CSNP fluence test results. Right: transducer diagram.

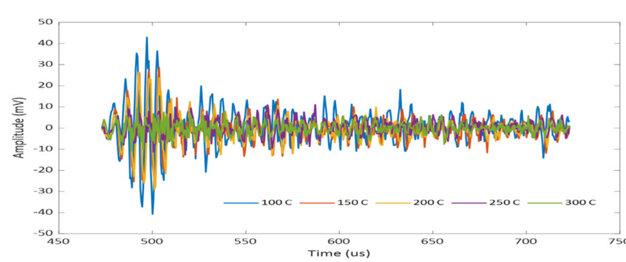


Figure 3. Results for a LM-CSNP heat test that started at 300°C and ended at 100°C. PZT sensor limited max temperature range.

Microwave-Cavity-based Flow Meter for Advanced Reactor High-Temperature Fluids

PI: Alexander Heifetz – Argonne National Laboratory
Collaborators: Sasan Bakhtiari – Argonne National Laboratory;
Miltos Alamaniotis – University of Texas San Antonio; Anthonie Cilliers – Kairos Power

Project Description: We are investigating a microwave-cavity-based transducer for high-temperature fluid flow sensing. This sensor, a hollow metallic cavity fabricatable from stainless steel, is expected to be resilient to the high-radiation, high-temperature, and corrosive environments of sodium fast reactors (SFRs) and molten-salt-cooled reactors (MSCRs). A viable geometry for this sensor is that of a small cylindrical resonator. A schematic drawing of this flow sensor is shown in Figure 1. The principle of sensing entails making one wall of the cavity flexible enough for dynamic pressure, which is proportional to fluid velocity, to cause membrane deflection. A cavity is characterized by its resonant frequencies, which occur due to the constructive interferences of the microwave field inside the cavity. Membrane deflection causes a change in cavity volume, and thus a shift in resonant frequency. The signal readout from the microwave frequency shift in a hollow cavity offers advantages in terms of high-temperature/high-radiation environment applications, because no electronic components are placed inside the transducer. Energy coupling to and from the sensor is achieved through a microwave waveguide, which will be an integral part of the insertion probe. A waveguide is a rigid, narrow, hollow metallic tube that is resilient to high-temperature and high-radiation environments. In principle, waveguides can be designed to be compatible with the thermocouple capillaries of an instrument tree.

Impact and Value to Nuclear Applications: High-temperature fluid reactors (e.g., SFRs and MSCRs) are a promising advanced reactor option, thanks to their highly efficient thermal energy conversion cycle. Streamlining the commercialization of advanced reactors involves the development of new coolant sensing technologies for enhancing performance efficiency. Measurement of high-temperature fluid process variables—particularly the flow inside the pressure vessel—is made challenging by the harsh environments of advanced reactors, which involve radiation, high temperatures, and contact with highly corrosive coolant fluid. Since microwave cavity sensing is based on fluid-structure interactions rather than fluid electrical conductivity, the proposed sensor is equally applicable to liquid sodium and molten-salt flow sensing.

Recent Results and Highlights: We identified an existing liquid sodium experimental setup for demonstrating flow sensing in environments similar to that of an advanced reactor. This setup consists of a cylindrical vessel and center feed line, with a transducer inserted through the lid in order to measure the velocity of the impinging liquid jet. As a calibration proof-of-principal experiment, we assembled a water flow loop that features a vessel with center feed and has the same dimensions as the liquid sodium setup. For reference measurements, a commercial flow meter was installed in the loop. We developed a cylindrical resonant cavity for the K-band (18 GHz to 26.5 Gz) and machined it from brass. The cavity was excited through WR-42 waveguide via a subwavelength hole on the side of the cylinder wall. We also developed an insertion probe consisting of a 50 cm brass waveguide enclosed in a protective SS 316 tube. The cylindrical cavity was excited in the TE_{011} mode with resonant frequency $f \approx 17.8$ GHz. The frequency shift of cavity spectral response was obtained by gradually increasing the water flow rate from 0 to 22 GPM. As a result, the monotonic increase of resonant frequency correspondingly shifted by several MHz. The approximate figure of merit for the sensitivity to flow rate is 100 KHz/GPM.

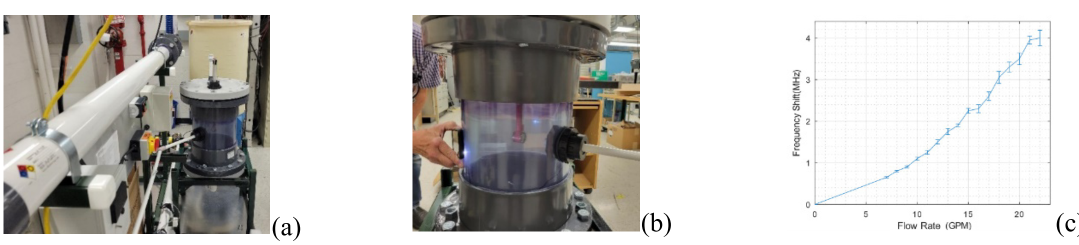


Figure 1. (a–b) Water loop and vessel for flow sensing in an impinging jet geometry. (c) Preliminary results of flow sensing.

Multimodal Sensors for Advanced Reactor Monitoring and Control

PI: Mike Larche – Pacific Northwest National Laboratory
Collaborator: Haifeng Zhang – University of North Texas

Project Description: The environments generated by advanced reactors (e.g., molten-salt reactors) present numerous challenges for in situ sensing. Such challenges include elevated temperatures, radiation, and infrequent outages. New sensors capable of operating under these harsh conditions are needed to monitor critical parameters such as temperature, flow, pressure, fission gas composition, etc. The multimodal sensors project has developed an integrated sensor concept that enables simultaneous measurement of temperature, pressure, and gas composition via a single sensor platform, thereby reducing the number of reactor vessel penetrations needed to monitor these key parameters. This sensor concept is based on usage of surface acoustic wave (SAW) devices, and it leverages multiple acoustic measurements via a single port for measuring the desired parameters.

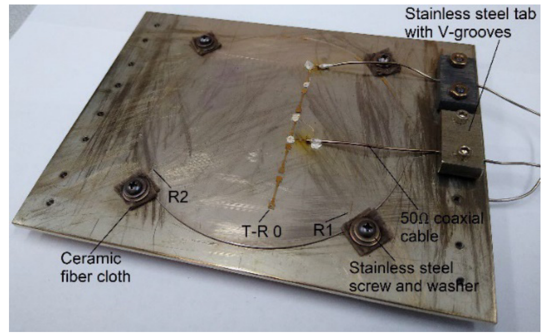


Figure 1. Fabricated SAW temperature sensor with interdigital transducer electrode.

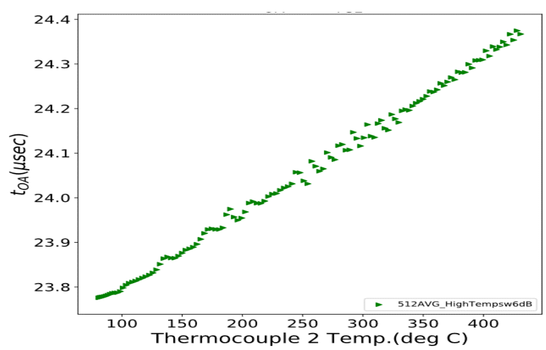


Figure 2. SAW temperature sensor data collection at room temperature to 420℃.

Impact and Value to Nuclear Applications: An integrated multimodal sensor platform will reduce the number of reactor pressure vessel penetrations needed. Furthermore, appropriate selection of materials consistent with harsh, high-temperature environments will help fill the gaps identified in currently available sensors for reactor monitoring and control. For extended periods of continuous operation of advanced reactors, online monitoring using robust sensors is needed.

Recent Results and Highlights: Fabrication and testing of a combined temperature/pressure sensor have been completed (see Figure 1). Elevated temperature measurements were acquired at up to 420°C (see Figure 2). Combined temperature/pressure measurements and isolated CO_2 measurements with temperature compensation were acquired (see Figure 3).

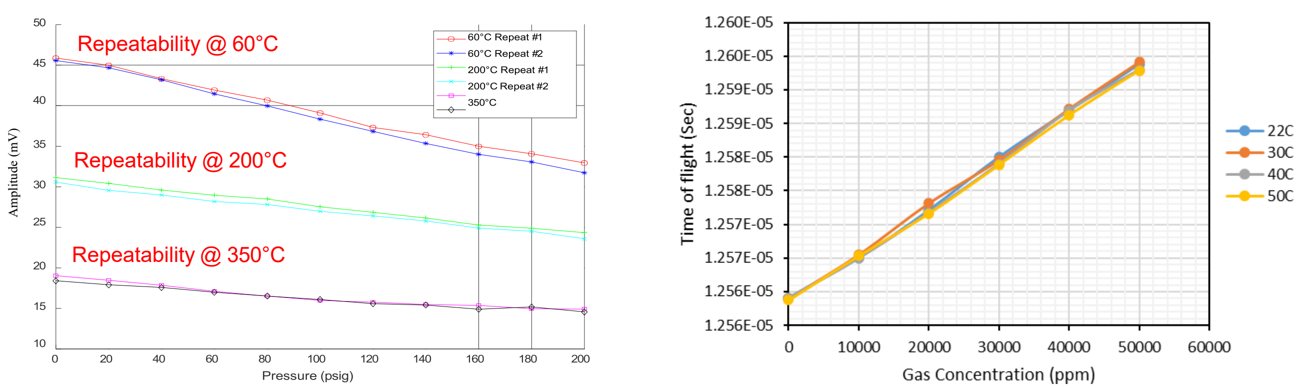


Figure 3. Left: Elevated temperature/pressure repeatability test. Right: Temperature-compensated CO_2 measurements at up to 50k ppm.

Acoustic Sensors

PI: Joshua Daw – Idaho National Laboratory
Collaborators: Pradeep Ramuhalli – Oak Ridge National Laboratory;
Ryan Meyer, Morris Good – Pacific Northwest National Laboratory; Dan Deng – Boise State University

Project Description: The goal of this research is to further Idaho National Laboratory (INL)'s development of an ultrasonic thermometer (UT), assess the current state of structural health monitoring (SHM) for advanced reactor applications, and assess the readiness level of sensors developed under the Advanced Sensors and Instrumentation (ASI) program for inclusion in a potential experiment at Argonne National Laboratory’s sodium test loop facility, the Mechanisms Engineering Test Loop (METL).

Impact and Value to Nuclear Applications: Acoustic and ultrasonic transducers can 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. The ability of some ultrasonic sensors to take spatially distributed and multiplexed measurements—sometimes without direct access to the sample being measured—is highly valuable. 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. 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. However, online monitoring of reactor components could potentially improve both the safety and reliability of next-generation nuclear technologies.

Recent Results and Highlights: A focus of this year’s research was updating the mechanical design of the UT, improving its performance, and making fabrication easier. Several new design options were developed and tested, and these will be incorporated into a functioning prototype for FY-23 testing. Several advanced reactor concept developers were contacted and interviewed with the goal of identifying SHM needs. Simultaneously, a review of current SHM technologies was conducted to identify needed technological advances. Finally, nine ASI-developed sensors were identified as being sufficiently developed for inclusion in the test at METL.

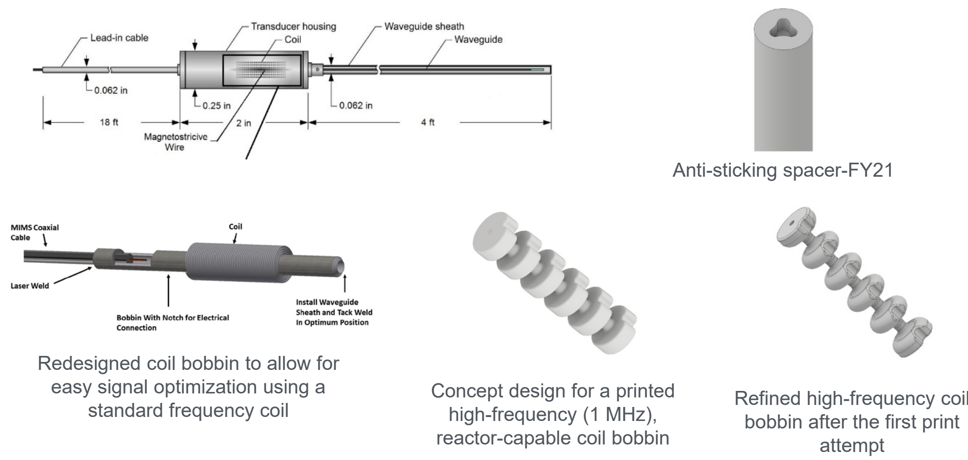


Figure 1. New UT design options.

Neutron Flux Sensors

PI: Kevin Tsai – Idaho National Laboratory
Collaborators: Joe Palmer, Michael Reichenberger, Troy Unruh – Idaho National Laboratory;
Loic Barbot – French Alternative Energies and Atomic Energy Commission

Project Description: The neutron flux work package implements R&D activities to develop and evaluate neutron flux sensors in order to address critical technology gaps in monitoring and controlling existing and advanced reactors and supporting fuel cycle development. The primary objectives in fiscal year 2022 (FY-22) have been to address the gaps in performing neutron flux measurements in high-temperature environments and to demonstrate neutron spectral measurements representative of current advanced reactor designs. Activities performed in FY-22 therefore fall under two categories: (1) the development of a temperature compensation technique for rhodium-based self-powered neutron detectors (Rh-SPNDs) operating in temperatures of up to 800°C, and (2) the demonstration and evaluation of developmental and commercial fission chambers, utilizing different fissile deposits for performing neutron spectrum measurements.

Impact and Value to Nuclear Applications: Development of a temperature compensation technique for Rh-SPNDs will provide a method for extending SPND operational limits to high-temperature environments—something crucial for providing in-core flux measurements in advanced reactors. Demonstration and evaluation of developmental commercial fission chambers for neutron spectrum measurements will provide fuel cycle and advanced reactor developers necessary information on the sensor's operational limits, enabling these sensors to be adopted with minimal risk and eliciting feedback for future evaluations.

Recent Results and Highlights: SPNDs and fission chambers were irradiated in two reactors: the Massachusetts Institute of Technology Research Reactor (MITR) and the Ohio State University Research Reactor (OSURR). The high-temperature (600–800°C) experiment performed at MITR resolved the electric heater phenomena previously identified in FY-21, and yielded operational modes characterized by changes in SPND insulation resistance properties. The heated experiment (20–350°C) performed at the OSURR demonstrated the advantages and limitations of commercial fission chambers in terms of operation and the provision of neutron spectrum measurements.

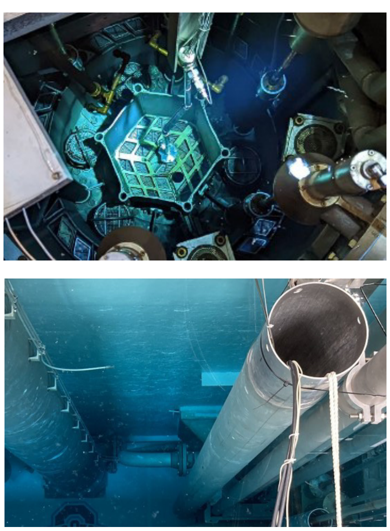


Figure 1. Experiments performed at (top) MITR and (bottom) OSURR.

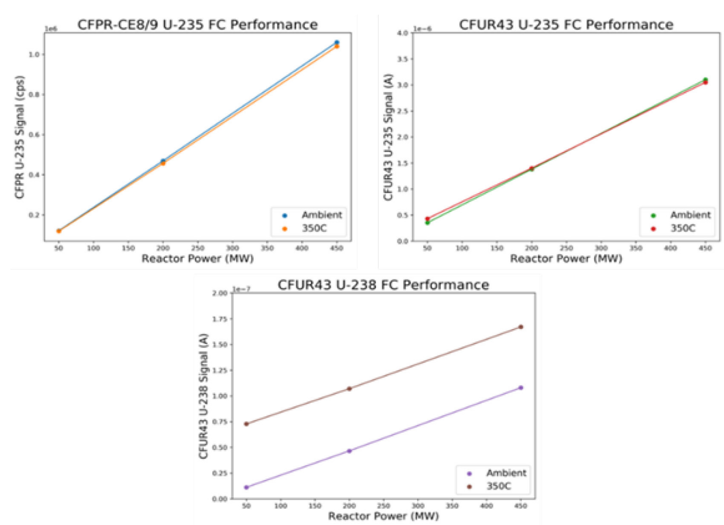


Figure 2. Performance of all three fission chambers irradiated at OSURR.

Optical Fibers

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) 2022 focused on maturing the fiber optic pressure sensor that first went into development back in FY-20. Work was also conducted to develop techniques to compensate for radiation-induced drift in fiber optic sensors, and to implement fiber optic imaging bundles for in-pile conditions in gas environments. Aspects of enabling R&D continued as part of the deployment of optical fiber sensors/systems, with a focus on establishing techniques for fabricating sensors capable of withstanding high temperatures.

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: Fiber optic sensing technology for in-pile applications was advanced on several fronts throughout FY-22. Significant progress was made in developing techniques to actively compensate for radiation-induced drift in fiber optic sensors. This work was archived in several journal articles and laboratory reports. In addition, the fiber optic pressure sensor was tested in an in-pile environment for the first time. The temperature dependence for this sensor was determined both experimentally and analytically, with the results being documented in a laboratory report.

Figure 1. Fiber optic pressure sensor during the assembly of the fueled experiment.

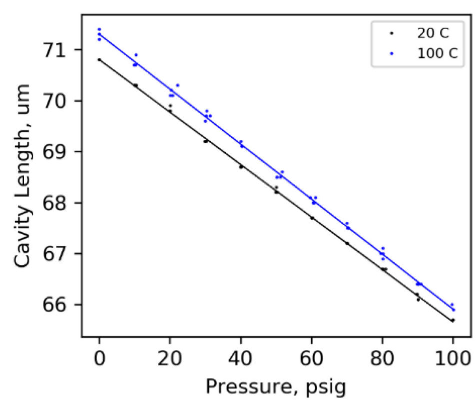


Figure 2. Experimental results from testing the sensor performance at elevated temperatures.

Irradiation of Optical Components in 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 – The Ohio State University Nuclear Reactor Laboratory, NSUF support

Over the past year, we completed gamma and neutron irradiations of all samples at the Ohio State University, and also performed one high-gamma-rate irradiation at the Pennsylvania State University via support from a synergistic program. Our custom post-irradiation examination setup operated reliably, collecting novel data on both linear and nonlinear absorption. Of the major findings achieved throughout the past year, we will now highlight two sets of results that were published in peer-reviewed journals.

1. **Nonlinear optical effects of irradiation** (Figure 1). Using the mobile Z-scan setup, we were able to show for the first time that gamma and neutron irradiation can induce nonlinear absorption and the nonlinear refractive index, constituting a reversal of the usual material properties. As a result, more intense laser light is transmitted with higher efficiency and undergoes defocusing. These effects have been confirmed in quartz glass, sapphire, and BK7G18 glass, and are attributed to the saturated absorption effect that is known to occur in semiconductors and certain micro/nanostructured materials.

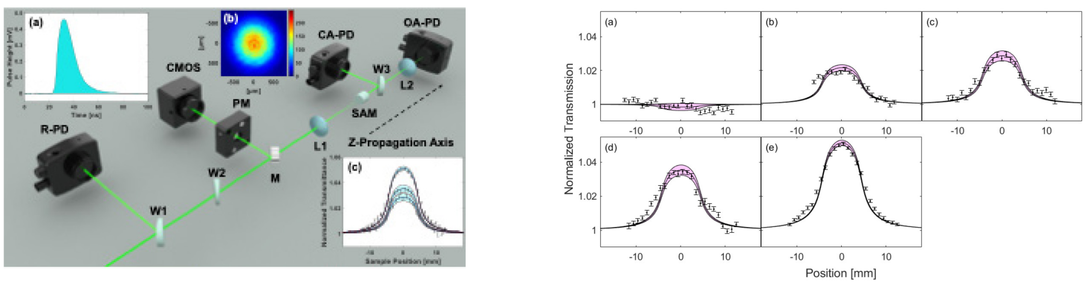


Figure 1. Left: Z-scan setup. Right: nonlinear absorption in quartz with increasing gamma irradiation.

2. **Spectral features of irradiated sapphire under concurrent thermal annealing** (Figure 2). In the linear absorption measurements, we showed that neutron-irradiated sapphire under concurrent-irradiation thermal annealing exhibits reduced 205, 260, 355, and 450 nm attenuation peaks—consistent similar to the case of post-irradiation thermal annealing—but also a significantly enhanced 300 nm attenuation peak. There may be a temperature dependence that favors either the generation of F2 centers from an increased mobility combination of F centers, or the conversion of F+2 centers into F2 centers via electron attenuation from F center donors, thus accounting for the reduced peaks at 205 and 260 nm, as well as the residual peak at 300 nm.

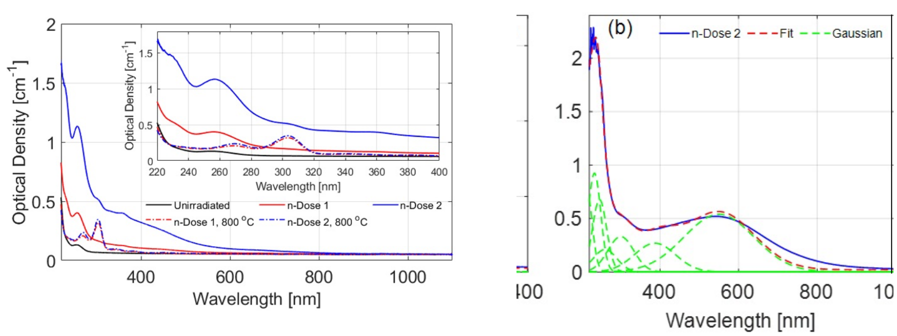


Figure 2. Left: measured sapphire absorption under various annealing conditions.
Right: spectral fit to known absorption features in sapphire.

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: 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.

Impact and Value to Nuclear Applications: 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-22 work has focused on performing a long-term irradiation test at the Massachusetts Institute of Technology Research Reactor (MITR) to demonstrate the performance of sapphire fibers at high fluences. This long-term irradiation at MITR is currently ongoing and consists of five sapphire optical sensors, as well as two silica sensors for use in making baseline comparisons. The irradiation will last for two cycles at MITR, at temperatures of around 680°C.

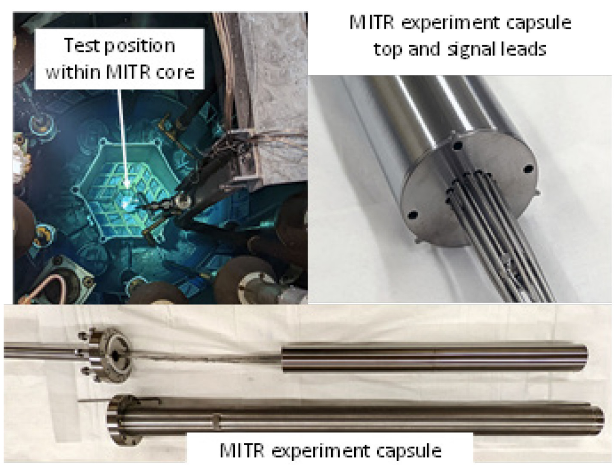


Figure 1. MITR irradiation experiment assembly.

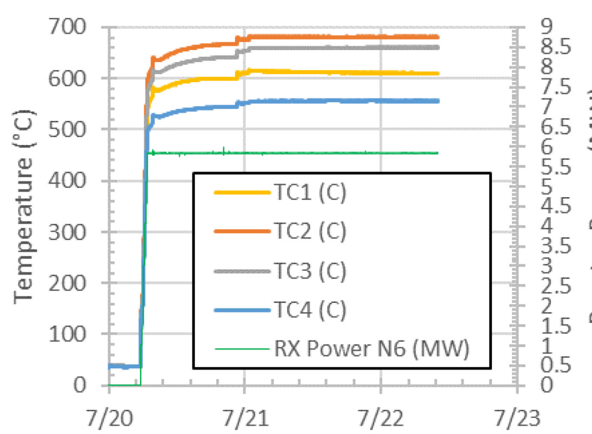


Figure 2. MITR startup power and experiment temperatures.

Surface Acoustic Wave Resonators for Nuclear Reactor Sensors

PI: Prof. Marat Khafizov – The Ohio State University
Collaborator: Ryan Chesser – The Ohio State University

Project Description: This research focuses on characterizing the impact of temperature and nuclear reactor power on lithium niobate ($LiNbO_3$) and aluminum nitride (AlN) surface acoustic wave (SAW) resonators. Experiments are being conducted at The Ohio State University Nuclear Reactor Laboratory (OSU-NRL), which contains the OSU Research Reactor (OSURR), a 500 kW pool-type reactor whose irradiation positions deliver neutron fluence over a range of 10^{12}–10^{13} n/cm^{2}s at full power.

Two forms of AlN are utilized: a single-crystal substrate and a thin-film AlN deposited on sapphire. The resonant frequencies of these devices shift in response to the temperature and neutron fluence. The experiments employ frequency domain reflectometry, which is performed by the network analyzer. The observed changes have mostly been attributed to neutron and gamma damage. Gamma heating has been temporarily observed, but is mostly compensated for by the furnace controller. Previous experiments have served to quantify the gamma heating effect.

The sensors stabilized at a new resonant frequency roughly an hour after the step fluence change. When the neutron fluence is stopped, the resonant frequency returns to its initial value. This same behavior is observed for temperature changes. Figure 1 shows the stable frequency shifts under different temperatures and neutron fluences. The resonant frequency at 0 kW (prior to reactor startup) is used to determine the temperature characterization.

The resonant frequency of both devices indicated a linear relationship with temperature and neutron fluence. A more significant temperature response was observed in $LiNbO_3$ with a TCF of 9.8e-3 [%/°C] and a NFCF of 1.3e-4 [%/kW]. AlN exhibited a TCF of 4.0e-3 [%/°C] and a NFCF of 1.5e-5 [%/kW] for the single-crystal substrate, while the thin-film AlN deposited on sapphire yielded a TCF of 6.5e-3 [%/°C] and a NFCF of 2.3e-4 [%/kW], which ended up being the most significant neutron response. Electromechanical coupling increased with temperature and fluence, and this was attributed to increased elastic constants. The time-dependent frequency shift describes the interaction mechanism and indicates a one-body exponential saturation mechanism for temperature changes and a two-body recombination mechanism for fluence changes. Applying the proposed kinetic models enables determination of the defect absorption rate for a one-body mechanism and a vacancy-interstitial recombination rate for a two-body mechanism. At 300°C, fitting the results produced a recombination rate of 4.5e5 min^{-1} for AlN(sc).

SAW sensors can monitor environments involving high temperatures, high neutron fluences, and other types of extreme conditions. The sensor response is dominated by a shifting elastic constant. Response kinetics determine the shape of the response curve and help describe the mechanism of the observed frequency shift. $LiNbO_3$ provides a clearer signal, thanks to better electromechanical coupling, but its operational temperature is limited by oxygen decomposition. On the other hand, AlN is a suitable candidate for high temperatures, as AlN sensors can function at up to the Curie point temperature (1200°C), generating signals and responses that are both stable and repeatable.

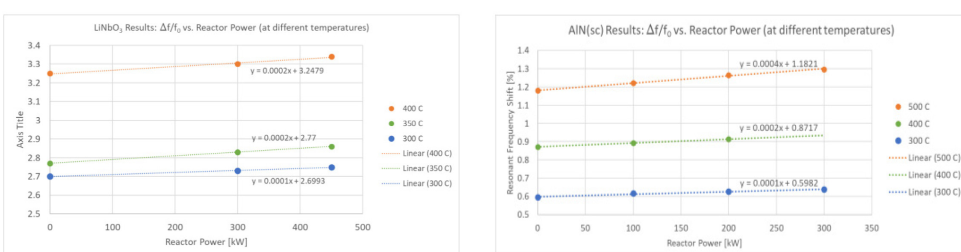


Figure 1. Left: Resonant frequency of the lithium niobate ($LiNbO_3$) sensor during temperature and reactor power transients. Right: Resonant frequency of the single-crystal aluminum nitride (AlN) sensor.

High-Temperature Irradiation-Resistant Thermocouple Drift Model Application to Commercial Thermocouples

PI: Richard Skifton – Idaho National Laboratory

The high-temperature irradiation-resistant thermocouple (HTIR-TC) is the world's leading nuclear thermocouple (TC). It can measure temperatures upward of 1600°C and withstand neutron fluence in the ballpark of 10^{21} nvt. Recently, the HTIR-TC was qualified through the Nuclear Energy Enabling Technology (NEET) Advanced Sensors and Instrumentation (ASI) program. This qualification process also defined an empirical drift model that simulates HTIR-TC performance in any practical application.

Application of the HTIR-TC drift model to other commercial TCs is pertinent, as it can predict temperature and transmutation effects on common metals used in other commercial TCs. For example, use of Type N or K TCs in advanced reactor core designs may help enhance the drivability of the reactor power. Use of Type N and K TCs will be implemented when temperatures are not expected to exceed 1100°C; otherwise, these TCs may drift significantly. The HTIR-TC drift model can predict the performance of any TC in the reactor core.

The drift model was applied to commercially available TCs. A comparison of Type C (representative of common refractory metal TCs), K, N, and HTIR TCs is shown in Table 1. The temperature was modeled at a set value of 1083°C, at a total irradiation of 1.8×10^{21} N/cm^2. The amounts of drift due to irradiation and high temperatures are both provided in their own separate columns.

The Type C TC shows the most drift (i.e., around -19%) under irradiation, as the neutron absorption cross sections are large for its metal composition. The Type N and K TCs are both good performers, as the overall drift caused by irradiation and high temperatures is only around -1% or less. The HTIR-TC shows the best performance in irradiated environments, with negligible drift due to high temperatures, and a drift of -.5% due to irradiation.

The HTIR-TC drift model was successfully applied to commercially available TCs. The drift model shows that other commercially available TCs are viable for irradiation tests, with minor limitations. The HTIR-TC is the best performer, especially for long-term temperatures exceeding 1100°C—or 1290°C in the case of short bursts or a single usage. Other refractory metal TCs should not be considered when measuring high temperatures in-core for extended periods of time.

Table 1. Comparison of Type C (a representative of common refractory metal TCs), K, N, and HTIR TCs operating at 1083°C, at a total irradiation of 1.8×10^{21} N/cm^2.

Thermocouple	Temperature Range (°C)	Irradiation Drift (%)	High Temperature Drift (%)
C	0-2315°C	-18.99	-0.22
K	-270-1260°C	-0.02	0.12
N	-270-1260°C	-0.45	-0.66
HTIR-TC	0-1700°C	-0.46	Negligible

Intrinsic Junction Thermocouples for Surface Temperature Measurements

PI: Richard Skifton – Idaho National Laboratory

The intrinsic junction thermocouple (TC) is best utilized for fast-response surface temperature measurements. The material comprising the TC's intrinsic junctions will continue to function as long as the material remains conductive. However, various factors will affect the TC performance, and these things should be considered when using intrinsic junction TCs; namely, the substrate/surface material, TC build, wire diameter, wire spacing, wire placement, fluid medium, temperature gradient, and temperature transient time.

Intrinsic junction TCs have proven to be the best choice for surface cladding temperature measurements. Critical heat flux (CHF) models show a 300% improvement over sheathed and ungrounded Type K TCs. As a result, the following conclusions have been drawn:

1. The TC thermoelements best suited for measuring the surface temperatures of cladding (i.e., Zirc-4) are Type K or N TCs. When paired with a Zirc-4 substrate, these TCs offer the most rapid response to fast thermal transients.
2. The TC attachment should be perpendicular to the substrate, with 1 or 2 wire diameters between TC thermoelement pairs. The wire diameter is generally recommended to be 0.010 in. (0.254 mm), which should be small enough to benefit the intrinsic junction TCs, but large enough to create rigidity and foster a strong connection with the surface being investigated.
3. Intrinsic junction TCs are the ideal way to measure surface temperatures. However, for accurate surface temperature measurements, one must correctly adjust for the TC fin effects (i.e., the wicking of heat away from the surface). This can be done by using the known, predictable phase transformations of water under pool boiling. A linear m factor is applied to line up the temperature measurement with the CHF and the transition to film boiling. This process must be done on a case-by-case basis but is the best way of correcting for variations in the thermal transients seen in surface temperature measurements.

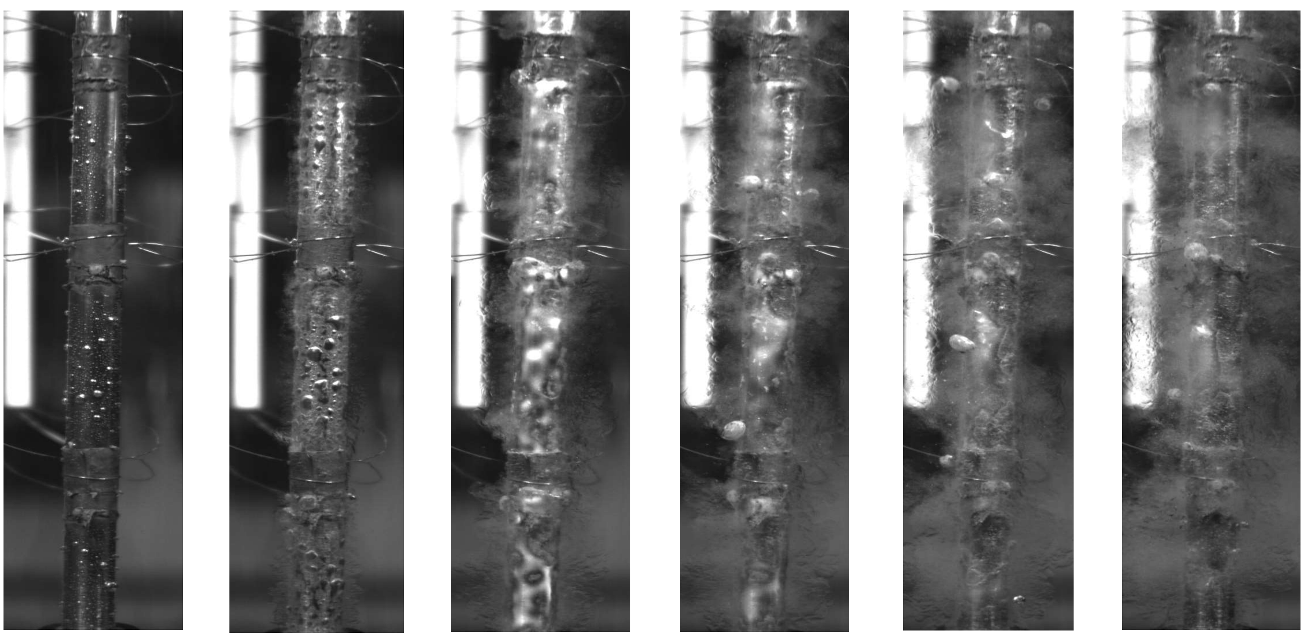


Figure 1. Intrinsic junction TCs during a thermal transient generated by Idaho National Laboratory's pulsed power system.

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 intergranular stress corrosion cracking. 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 via 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.

Impact and Value to Nuclear Applications: In commercial nuclear power plants, stress corrosion cracking of primary loop piping and components can result in extended outages and 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 the NSUF 1.1 study on irradiation and post-irradiation examination (PIE) of ultrasonic sensors and adhesive couplants to determine whether they can be utilized long term in primary loop piping and components.

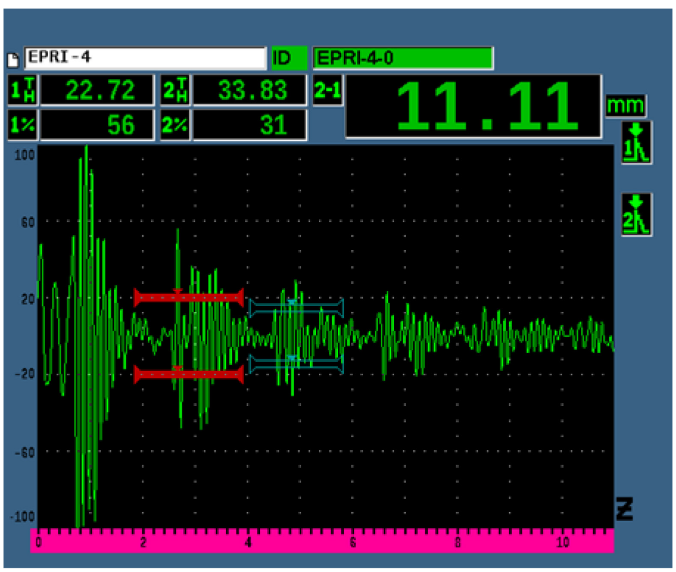


Figure 1. Example of an ultrasonic waveform taken from one of the sample assemblies, showing ultrasonic intensity (y-axis) as a function of propagation distance (x-axis) in the aluminum substrate. Note the multiple reflections from the substrate back wall.

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 ~5×10^{16} n/cm^2 (E > 1 MeV) in the PULSTAR reactor. Ultrasonic waveforms were collected in situ during the irradiation (see Figure 1). Currently, PIE (electron microscopy and x-ray microanalysis) are being performed at the ORNL LAMDA laboratory.

Sensor Integration

Process-Constrained Data Analytics for Sensor Assignment and Calibration

PI: Richard Vilim – Argonne National Laboratory
Collaborators: Brendan Kochunas – University of Michigan; Tim Kibler – Xcel Energy

Project Description: The objective of this project is to develop and implement data analytic methods to address the problem of how to assign a sensor set in a nuclear facility such that (1) the requisite level of process monitoring is realized, and in turn (2) the sensor set is sufficiently rich to enable analytics to determine whether individual sensors require calibration. The need for this capability in applications pertaining to operations and maintenance (O&M) cost reduction was identified via discussions with utility executives and technical staff at industry workshops and meetings.

Impact And Value to Nuclear Applications: Presently, sensor calibration is performed at the end of each cycle, regardless of whether the given sensor needs calibration. Calibration of sensors that do not require it is an inefficiency that unnecessarily increases utility O&M costs. By selecting a sensor set that affords the desired monitoring capabilities, a utility performing end-of-cycle sensor calibrations can confine such calibration to only those instruments that require it.

Recent Results and Highlights: Blind fault tests using archived data were performed for a feedwater pump system at a currently operating nuclear power plant. Data on plant operation events were provided by utility collaborators without disclosing either the presence or identities of faults. So-called "blind" diagnostic analyses were conducted, in which the utility withheld this information until after a diagnosis was made. The blind study uncovered five different equipment and sensor faults. The two equipment fault events were correctly diagnosed, and the results served to demonstrate the high detection sensitivity of the physics-based approach. The three sensor fault scenarios were also correctly diagnosed, demonstrating the approach's ability to detect and uniquely identify sensor faults.

A second application, this time involving the high-pressure feedwater system (see figure) of a pressurized-water reactor, showed that health monitoring capabilities can be improved using a sensor set containing 20% fewer sensors. Maintenance of this system can amount to millions of dollars per year if equipment health issues go undiagnosed and lead to losses of function. We showed that, compared to the installed sensor set, a more strategic assignment of sensors will furnish better health monitoring capabilities while also reducing the number of sensors needed. Where the problem defies solution via manual inspection, as is the case here, the solution can be determined using an algorithm. The solution was obtained in 4 hours using 30 computational cores.

The algorithm that was developed for performing physics-informed diagnoses of equipment faults in this project was integrated with anomaly detection methods that currently exist at commercial nuclear plants. This work was undertaken after we received feedback from nuclear utilities that an integrated capability yielding a single diagnosis—rather than two diagnostic capabilities running simultaneously—would be of greater value. The benefits of this integrated capability were demonstrated in the feedwater pump application described above.

The PI was approached by two energy service providers about commercializing the software developed by this project. Several demonstrations of the software were subsequently performed, and a beta executable was provided to allow the companies to perform an in-house assessment of this capability.

Design of Risk-Informed Autonomous Operation for Advanced Reactors

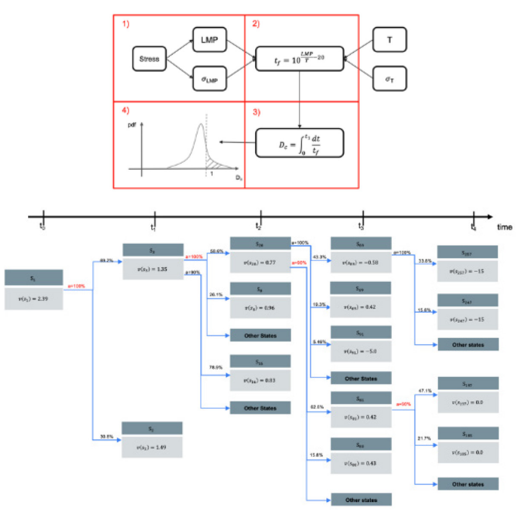
PI: Michael Golay – Massachusetts Institute of Technology
Co-PIs: Hyun Gook Kang – Rensselaer Polytechnic Institute; Birdy Phathanapirom – Oak Ridge National Lab
Collaborators: Xingang Zhao – Oak Ridge National Laboratory; Junyung Kim and Kyle Warns – Rensselaer Polytechnic Institute; Xinyan Wang – Massachusetts Institute of Technology

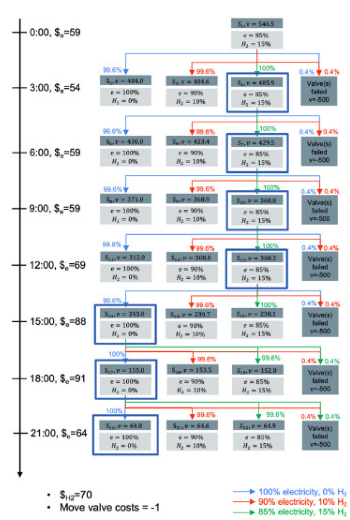
Project Description: This project aims to develop and demonstrate artificial reasoning systems that provide operator decision support—aided by autonomous control technology—for advanced nuclear reactors. The entire autonomous system covers a broad range of operation stages (e.g., health status monitoring, fault diagnostics, prognostics, and operator decision support), and the main goal of this project is to demonstrate methods of creating autonomous decision support systems and the basis for further investments and the advancement.

Impact and Value to Nuclear Applications: Autonomous control systems (ACSs) can greatly improve the reliability of nuclear power plants, since human errors are the dominant contributor to nuclear-related failures. However, the basis for ACS implementations must be improved to make potential adopters sufficiently confident of their feasibility and reliability. The work being performed is expected to improve the knowledge base and specific lore to a convincing level of assurance—and through such progress, strengthen its foundation.

Recent Results and Highlights: The progress made in fiscal year (FY) 2022 includes successful development of a components prognostics model and a decision-making approach that affords operator decision support.

1. The prognostics model is for generic steam generator (SGs) in sodium-cooled fast reactors (SFRs). Creep is the dominant degradation mode in SFR SGs, due to their high-temperature, high-pressure environments and sodium coolant properties. Thus, the prognostics model is based on the Larson-Miller parameter (LMP), an empirically determined parameter for calculating the time-to-failure due to creep damage at a given temperature and stress level (top-left figure).
2. A Markov decision process (MDP)-based decision-making approach was applied to optimize the control logic for a SFR case. The SFR model was simulated using the Modelica language, and component degradations were handled using standalone degradation models (e.g., LMP for SGs). The MDP agent successfully identified the optimal scenario for maximizing electricity generation while maintaining component integrity (bottom-left Figure 1).
3. We also applied the MDP to a SFR H_2+electricity cogeneration plant case in which operators actuate dispatch valves to control the steam distribution between H_2 production and electricity generation. The decision-making agent balances the products' monetary benefits with the expected valve degradation (right Figure 2).





Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

PI: David Grabaskas – Argonne National Laboratory
Collaborators: Carol Smidts – Ohio State University; Pascal Brocheny – Framatome

Project Description: The objective of this project is to improve the economic competitiveness of advanced reactors via the optimization of cost and plant performance by coupling intelligent online monitoring with asset management decision making. To achieve this goal, two key development steps are necessary:

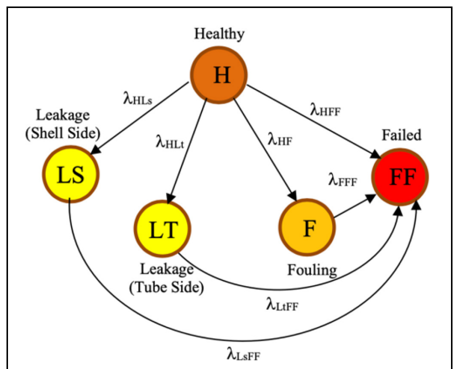
1. During the reactor design phase, it is necessary to develop a sensor network that can properly monitor and diagnose important faults and component degradation throughout the lifetime of the plant. To reduce costs, a methodology was developed for optimizing diagnostic capabilities while minimizing sensor quantities and system penetrations.
2. Once reactor operation begins, the asset management approach must seamlessly integrate online monitoring information and the plant's risk profile in order to develop an optimized plant operation and maintenance plan. This is accomplished by developing a method of performing cost-benefit decision making in multivariate space.

Impact and Value to Nuclear Applications: The project tasks aim to reduce advanced reactor costs, both during construction (via optimization of the sensor network design) and operation (through intelligent cost-benefit decision making in regard to asset management).

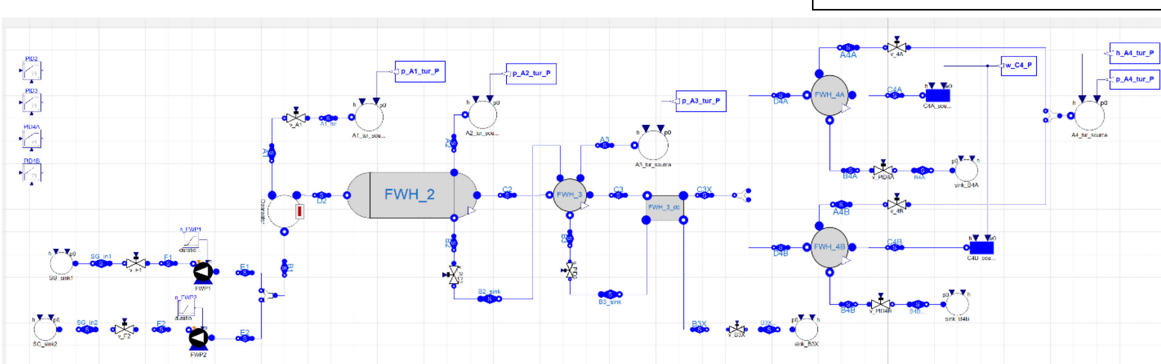
Recent Results and Highlights: FY22 efforts focused on the development and demonstration of an integrated Markov decision process (MDP) approach to asset management decision making—an approach that directly incorporates online component monitoring, Markov component models, and both plant probabilistic risk assessment (PRA) and generation risk assessment (GRA) in order to provide recommended operational strategies.

Application of this approach was demonstrated by assessing the operation of the feedwater system in General Atomics' Modular High-Temperature Gas-cooled Reactor (MHTGR) design. A simulator utilized for the operating facility replicated various operational scenarios involving degraded and/or failed components at different points in an operating cycle.

The final step of the project aims to outline a pathway to commercialization of the approach, based on a time-to-market analysis conducted in collaboration with Framatome.



Feedwater Heater Markov Model



FY22 Front-End Digitizer (FREND) Activities and Achievements Summary

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

Introduction: High-radiation and high-temperature environments represent notoriously detrimental conditions for electronics. Nevertheless, sensors are of critical importance for ensuring the validity and safe operation of scientific experiments conducted in nuclear reactors. The front-end digitizer (FREND) (see Figure 1) aims to improve the fidelity of nuclear sensor data by placing a radiation-resistant analog front end (AFE) within a given high-radiation area, followed by immediate signal encoding and transmission to outside that area (i.e., to an instrument room) via optical fiber. Early signal preamplification and encoding maintain the signal integrity, while optical transmission renders the system blind to electromagnetic noise over the cable runs. FREND is designed to support the transmission of signals from nuclear sensors that are relevant to reactor functionality, with the current prototype supporting up to four sensors which can be multiplexed for transmission over a single fiber-optic cable.

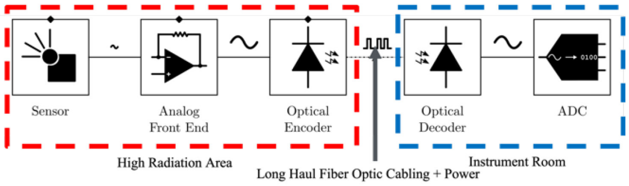


Figure 1. Block diagram of the FREND system.

FY22 Activities: During fiscal year (FY) 2022, we designed, simulated, fabricated, and tested a benchtop prototype of FREND. The circuitry in FREND that must be able to operate in high-radiation environments was designed using discrete junction-gate field-effect transistors, which show high radiation tolerance.

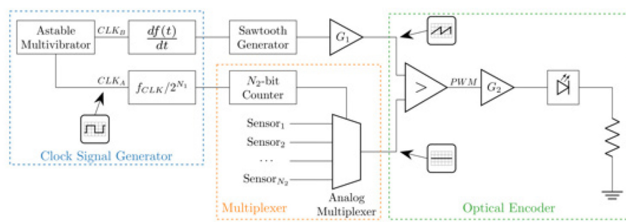


Figure 2. Circuit diagram of FREND. The AFE is highlighted in orange; the optical encoder is highlighted in green. Both contain a clock (blue).

The AFE (see Figure 2) can multiplex and optically transmit signals from up to four sensors. These signals are encoded using pulse-width modulation (PWM), then transmitted to a receiver via optical fiber. Encoding of the signals via PWM serves to mitigate any issues related to radiation-induced attenuation in the fiber optic cable. Finally, the receiver system extracts the individual sensor signals.

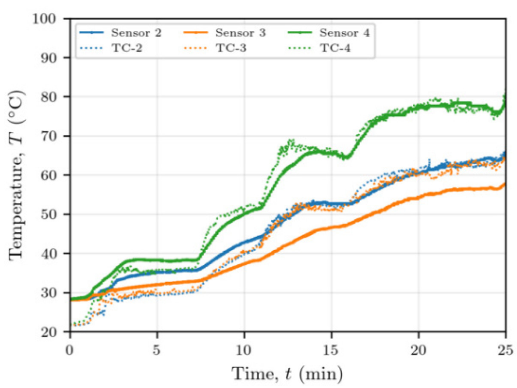


Figure 3. Demonstration data acquisition from thermistors by using the FREND system, as compared to using co-located thermocouples. Note that the Kapton tape attaching sensor 3 to the hot plate loosened during the experiment, causing the sensor to lose direct contact with the hot plate and thus report a lower temperature.

The outputs and relevant internal test points of both the AFE and encoder were tested by using thermistors as simple surrogates. The transfer function of the FREND system was characterized to map the sensor inputs to the duty cycle outputs, and was validated using thermistors to measure temperature variations on a hot plate (Figure 3). To date, we have successfully completed our preliminary benchtop testing and have demonstrated FREND's capability to multiplex, encode, optically transmit, and demodulate data from three temperature sensors.

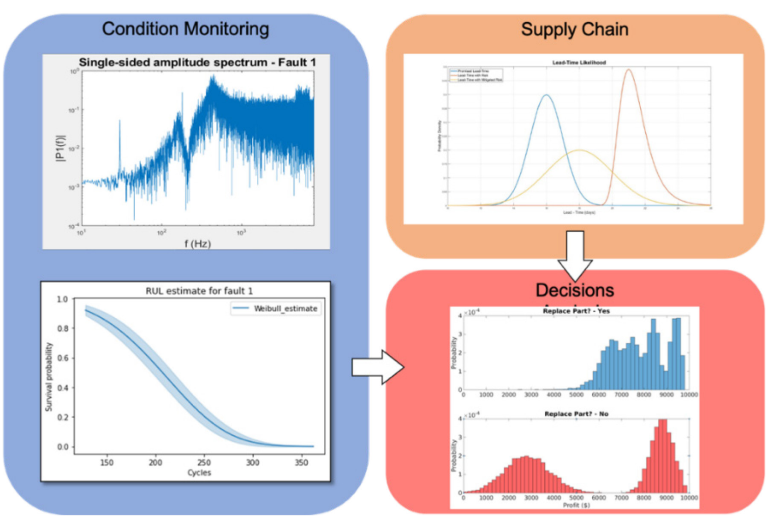
Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance

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

Project Description: This research project aims to develop and demonstrate advanced online monitoring for better management of nuclear power plant (NPP) assets and the operation/maintenance thereof. We are developing a framework that models the interaction between component reliability and condition monitoring, supply chain and resource availability, financial and business decision-making activities, 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 to plan short- and long-term asset management and to make informed decisions on plant operations.

Impact and Value to Nuclear Applications: For advanced nuclear reactors to be cost effective, we must take advanced instrumentation and big data analytics to operate plants more efficiently, streamline maintenance, and implement minimal staffing levels. We must develop and demonstrate advanced online monitoring and use such tools to support and improve decision-making processes at NPPs. If this research is successful, the nuclear industry will benefit from cost-benefit analyses improvements, predictive analytics of operational and maintenance data, risk-informed condition monitoring technologies, and the integration of economics, big data, and predictive maintenance to enhance asset management practices.

Recent Results and Highlights: For condition monitoring, we created policies to automate root cause analyses, and developed advanced machine-learning methods to improve machine health forecasts. For a centrifugal pump, we developed a condition monitoring framework that includes uncertainty as a vital component for estimation. We developed and tested two methods of extracting contact force information for reactor vessel internals, finding that both methods struggled to approximate the condition of the reactor's radial key. For supply chain modeling, we constructed a Bayesian network from a pressurized-water reactor bill of materials that was used to determine supplier reliability. Using this, we developed scenarios to showcase mitigation strategies and ways of improving supplier reliability, depending on the selection strategies. By estimating supplier reliability and quantifying lead-time risks, we reduced the uncertainty for decision makers involved in NPP construction. Deep reinforcement learning algorithms were used to train several types of intelligent agents to predict optimal inspection and maintenance strategies. The DRL agents were able to reduce the lifecycle cost uncertainty and average expected lifecycle costs by 50% in comparison with time-based maintenance strategies. Furthermore, we have completed a decision-making environment that includes reliability, degradation, maintenance, and costs. Testing by DRL agents has identified approximate optimal policies, but work to improve performance remains ongoing.



Context-Aware Safety Information Display for Nuclear Field Workers

PIs: George Edward Gibson, Jr. – Arizona State University; Pingbo Tang – Carnegie Mellon University; Alper Yilmaz – The Ohio State University; Ronald Boring – Idaho National Laboratory; Collaborator: Thomas Myers – Duke Energy

Description of Project: The project team developed an Intelligent Context-Aware Safety Information Display (ICAD) to support nuclear power plant (NPP) field workers in achieving safe, efficient execution of a series of field operational tasks in uncertain and changing NPP workspaces. Over the past 3 years, the project team has completed the development and integration of five techniques into a prototype ICAD Augmented Reality (ICAD-AR) system and then demonstrated that system's real-time execution in a mechanical room. In addition, the project team analyzed the usage of this prototype in other types of workspaces, based on 3D image data and digital design models collected from two additional workspaces: one from a water treatment plant and one from a flow loop training facility owned by Duke Energy. The integrated techniques include (1) sensor log analysis for predicting control actions in given sensor reading contexts; (2) natural language processing (NLP) algorithms that support the generation and updating of nuclear fieldwork process models, based on text analyses of work package descriptions and operation manuals; (3) computer vision (CV) algorithms for automatic localization and navigation of workers; (4) object detection algorithms for identifying task-related objects and sensors that need to be checked for safety; and (5) AR as a platform for integrating text, sensor, and video analytic techniques into a safety information display.

Figure 1. Field: AR information display example.

Impact and Value to Nuclear Applications: This project generated knowledge and technical approaches for building a context-aware intelligent AR device to help realize safe, productive maintenance workflows at NPPs. Safe and efficient operation of NPPs can have positive social, economic, and technical impacts on the nuclear industry at large. This project will help effectively balance time, costs, and safety during NPP operation.

Recent Results and Highlights: During the past 3 years, the project team (1) identified three types of information (i.e., workspace dynamics, workflow prognostics, and hazards) critical for supporting safe and efficient NPP field operations; (2) deployed the developed ICAD-AR display to an iPad Pro tablet (11 in., 3rd generation) and HoloLens 2 AR glasses; and (3) validated the integrated AR solution in two different flow loop workspaces.

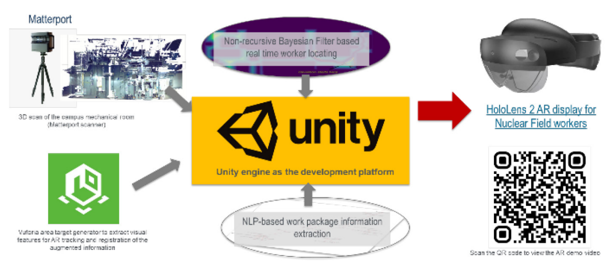


Figure 2. Intelligent Context-Aware Safety Information Display Framework.

Gallium-Nitride-Based 100-Mrad Electronics Technology for Advanced Nuclear Reactor Wireless Communications

PI: Kyle Reed – Oak Ridge National Laboratory

Introduction: Recent advances in nuclear power generation technologies have shown great promise for enabling safe, efficient generation of carbon-free power in the near future. However, full realization of this power generation paradigm requires 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 that must be withstood by 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, in order to address the unique needs of sensor interface electronics and communications in reactor environments. This report summarizes the project's first-year activities that relate to developing and optimizing devices and circuits for this GaN high electron mobility transistor (HEMT) process.

Summary of Accomplishments: The activities in FY22 have focused on fabrication and modeling of GaN HEMT devices, wireless architecture design and simulation, and GaN integrated circuit design/layout. To date, four dies have been successfully processed at the Ohio State University (OSU). Supply-chain-related delays in acquiring the P-wafers were resolved, and fabrication of devices and integrated circuits is now proceeding as planned. The latest GaN die layout is shown in Fig. 1. Measured I-V characteristic data from the fabricated radio frequency (RF) and logic GaN devices were used to developed models based on the Levenberg-Marquardt algorithm. These Verilog-A models were simulated in both Cadence Virtuoso and QucsStudio, and accurately represented the respective device's I-V characteristic performance over a variety of device lengths/widths. These models will be refined in FY23 to include parasitic capacitances and improve the I-V curve matching accuracy.

Wireless communications architectures were investigated at Oak Ridge National Laboratory (ORNL), with an emphasis on transmitter simplicity and receiver complexity. Analog and digital communications were also investigated—the latter providing many advantages over the former. To digitize the signal, temporal encoding methods (e.g., pulse-width encoding [modulation] and pulse density encoding) were considered against conventional binary representations of data. On-off keying, frequency-shift keying, and chirp keying were considered as modulation schemes to transmit the binary represented data. The encoding and modulation architectures were simulated successfully in Python and SPICE, using two software-defined radios (SDRs). As the process advances, the complexity of the communications architecture will increase.

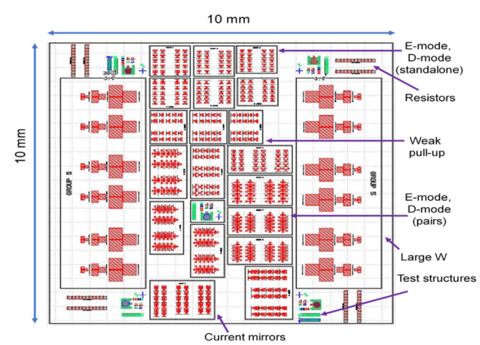


Figure 1. GaN HEMT die layout, with E- and D-Mode devices, test structures, current mirrors, and other analog circuits.

Based on the device models, preliminary transmitter circuit blocks were designed and simulated in QucsStudio. Analog-based blocks for implementing oscillators (LC/RC-phase oscillators, and a ring inverter), modulation (comparator), and mixing (Gilbert cell) showed promising simulation results. The fundamental digital logic cells (NOT, NAND, NOR, AND, and OR) were successfully simulated. These circuit simulations will be improved by modeling the parasitic capacitance of those devices that will impact oscillator frequencies, digital timing, and RF losses. Layouts of the simulated circuits were performed in Magic (an open-source layout tool). A technology file was developed that included the associated layer definitions and design rules. Device layouts have been performed to include some common techniques (e.g., annular gate or enclosed layout tool [ELT]) for increasing radiation and harsh-environment tolerance in comparison to conventional linear layout structures.

In FY22, the ORNL-OSU team made significant strides in developing the GaN and GaN HEMT fabrication processes, the wireless architecture design, and the preliminary analog and digital circuit designs and layouts. The successes in FY22 will smoothly transition into an early FY23 irradiation of the GaN devices.

Understanding the Irradiation Behavior of Ultrawide-Bandgap Ga_2O_3 High-Temperature Sensor Materials for Advanced Nuclear Reactor Systems

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

Project Description: The emerging ultrawide-bandgap semiconductor Ga_2O_3 has seen key sensing applications in advanced reactor systems and strategic fuel cycles, due to its intrinsic high radiation resistance and excellent temperature tolerance. With support from DOE-NE, innovative radiation hard sensors are being developed to explore their potential applications in the monitoring of actinides in sodium-, lead-, lead-bismuth-eutectic-, or molten-salt-cooled reactors, as well as in pyro-chemical fuel processing streams. Furthermore, Ga_2O_3 is currently considered the most promising material for reactor electronics, thanks to the fact that its intrinsic robustness to radiation and temperature makes it especially attractive for reactor applications, including robotic inspection systems used near reactor cores or in accident responses. For many nuclear applications requiring high radiation resistance and temperature tolerance, the ultrawide bandgap (4.8 eV) of Ga_2O_3 makes it a better choice than other wide-bandgap materials (e.g., SiC and GaN).

Impact and Value to Nuclear Applications: Despite the effort being made to develop Ga_2O_3 sensor materials and devices, a proper understanding of irradiation's effects on Ga_2O_3 is clearly lacking. Such knowledge is urgently needed to promote the development and deployment of Ga_2O_3 sensors in advanced nuclear reactors and related fuel cycles. In this project, we propose to conduct a series of irradiation experiments on Ga_2O_3 at targeted temperatures, and to perform systematic post-irradiation examination to understand the irradiation behavior of Ga_2O_3 in high-temperature and strong radiation environments, thus providing decisive information on their potential use in reactor instrumentation and fuel cycle applications. Success of the project will lead to crucial insights regarding the deployment of these innovative Ga_2O_3 sensors in advanced nuclear energy systems.

Recent Results and Highlights: In Year 1, we made good progress toward achieving the goals of this project. The negotiations between NSUF and its partner facilities were completed in the spring of 2022, a series of Ga_2O_3 materials were prepared in order to meet the requirements of the irradiation experiments, and combined chemical procedures were used to carefully clean all the samples during this period. Meanwhile, we bean positron measurements and scanning transmission electron microscopy measurements at NCSU and CAES. The initial positron measurements showed high repeatability across all the samples. The temperature-dependent positron measurements were also conducted (see Figure 1). The scanning transmission electron microscopy measurements gave detailed crystal lattice and dislocation information. We also finished the design and fabrication of targeted sample holders for reactor irradiation experiments. It should be highlighted that the Ga_2O_3 materials have already been loaded into the PULSTAR nuclear reactor to begin the irradiation experiments. In situ electrical measurements are being prepared as well. Overall, the project is progressing well.

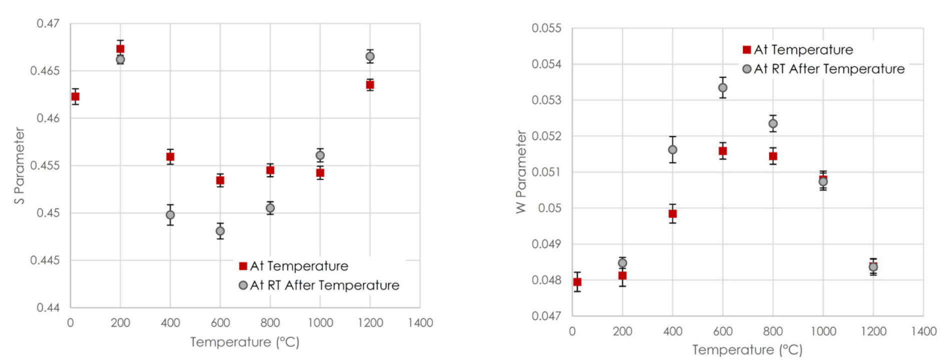


Figure 1. S and W parameters of the Ga_2O_3 sample, as a function of temperature.

Approach to the Integration of Control Methods and Digital Twins for Advanced Nuclear Reactors

PI: Ahmad Al Rashdan – Idaho National Laboratory
Collaborators: Jacob Farber, Maria Coelho, Craig Primer, Vaibhav Yadav – Idaho National Laboratory

Advanced nuclear reactors offer a new set of features for use in energy generation, thanks to their ability to adapt to variable energy demands, operate autonomously, and be deployed in rural locations and monitored remotely. They are compact in size, afford low power ratings, and rely on novel technologies to achieve safer operations. The success of these reactors necessitates intelligent forms of control that can track changing power demands, make autonomous decisions, and reduce the need for human involvement.

This effort reviewed the use of control methods and digital twins, summarizing the current status of both in relation to various industries, including the nuclear industry. The resulting findings were then used to convert the special characteristics of advanced reactors into a set of unique aspects (Table 1), some of which can be addressed via existing solutions. Others reflect technology gaps that must be closed by meeting a set of control requirements.

In addition, this effort explored how some control requirements can be met by using digital twins, which are seen as a key enabler for deploying control methods for advanced nuclear reactors, given their current state of design and development. Digital twins provide otherwise unavailable information for designing and operating controllers, and can compensate for insufficient operating history. In the reactor design stage, they can also be used to help identify the ideal placement of sensors, and to virtualize sensors during operations.

With the key critical requirements identified, a control approach was introduced to demonstrate how the requirements could be met in a manner that enables fully autonomous advanced nuclear reactor control. Also demonstrated within this overarching approach to control is the role of certain key enabling technologies critical to advanced nuclear reactors. Ultimately, this effort can serve as a roadmap for enabling autonomous advanced reactor operations.

Table 1. Summary of identified unique aspects, gaps, and requirements for the control of advanced nuclear reactors.

Title	Unique Aspect	Control Gap	Control Requirement
Regulatory Requirements	AI/ML control may be unable to meet some regulatory requirements.	AI/ML control requires development of a special form of model that meets regulatory requirements.	Include an interface control layer between the plant and any AI/ML decision-making processes in order to ensure that the approach meets regulatory requirements.
Operating Environment	The instrumentation will endure harsh environments for extended periods, increasing the probability of failures.	The high autonomy requirement necessitates methods that foster better plant awareness and compensate for sensor failure.	Identify and compensate for sensor, communication, and electronic failures by using advanced control methods and digital twins to prevent the control function from being compromised due to such failures, and optimize the placement of sensors in order to reduce the impact of sensor-related failures.
High Consequence	The operational consequences of failures are of critical importance to the deployment of advanced reactors.	The broader plant conditions and challenges must be understood in making risk-informed decisions on the best courses of action.	Incorporate risk elements to prevent unnecessary loss of power generation in the presence of known variables and unknown disturbances.
Highly Coupled	Compact and autonomous reactors will produce strongly coupled systems, making isolated control less useful.	MIMO control must be able to handle a high level of non-linearity and interface with continuous and discrete states.	Integrate highly coupled control loops and state awareness methods to ensure safe, optimal performance of the process variables.
Evolving Knowledge	Novel concepts of physics and operation that are used may not be fully understood or validated.	Control method performance depends on the accuracy associated with the system model.	Incorporate robustness into the control loop design to empirically and gradually model the process and adjust the control method as new knowledge is gained, thus ensuring safe and optimal performance amidst uncertainty and changing plant conditions.
Lack of Operating History	There is no useful operating history for feeding into the design and development of the control method.	Adaptive and auto-tunable control methods are needed.	Use software models to identify and react to or track physical phenomena that were unanticipated due to a lack of operating history.

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

PI: Roberto Ponciroli – Argonne National Laboratory
Collaborators: Akshay 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 via optimization of plant performance. To help nuclear units survive in deregulated electricity markets, integration of advanced reactor concepts with energy storage technologies is considered. The operational complexity of coordinating these two thermally coupled systems can be addressed by adopting an architecture comprised of an automated reasoning system that closely interacts with a multi-layer control system. Achieving this goal necessitates three development steps:

- Design of an integrated energy system (IES) that ensures reliable power production and flexible operation capabilities.
- Development of a control system architecture capable of automating control sequences, monitoring component conditions, and supporting operator decision-making activities.
- Assessment of the anticipated savings based on a cost-benefit analysis.

Impact and Value to Nuclear Applications: This work leverages, expands, and integrates existing schemes for diagnostics, control, and decision making into a multi-layer architecture that ensures semi-autonomous operation capabilities and reduced O&M costs.

Recent Results and Highlights: Last year's efforts focused on the following four major areas: Improvements to the SAM high-fidelity simulator. The model was completed by adding multiple lines to ensure continued plant operations in the event of faults, developing suitable components for representing tanks and valves, and ensuring the possibility of simulating component-level faults.

- Design of the CONTROL module. After identifying the process variables to be constrained, the supervisory control layer for feeding setpoints to the PID regulators was implemented.
- Adaptation of available diagnostic capabilities. To assess the proposed architecture, the intermediate circuit was selected for monitoring. PRO-AID models for tanks and valves were developed, and a model for the entire intermediate circuit was built.
- Simulation of controlled transients in different operational modes, and the injection of faults affecting tanks, valves, and the IHX. The outcomes were displayed by a dedicated GUI.

The next steps will focus on designing the decision-making module and coupling it with the existing control/diagnostics modules.

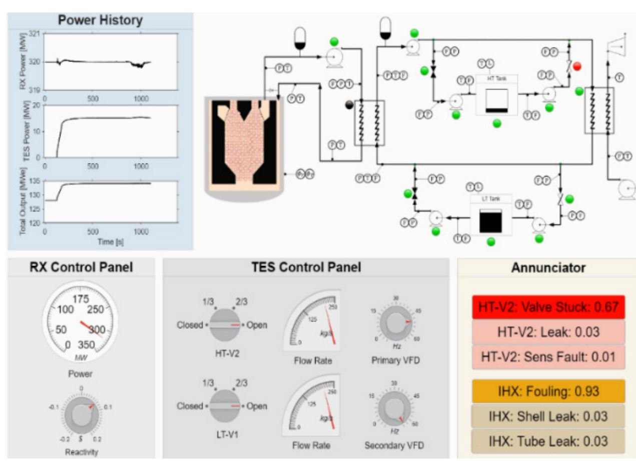


Figure 1. GUI of the proposed architecture, showing the system response and diagnostic/control outputs during operation.

Analytics-at-Scale of Sensor Data for Digital Monitoring in Nuclear Plants

PI: Vivek Agarwal – Idaho National Laboratory
Collaborators: Cody Walker, Nancy Lybeck – Idaho National Laboratory;
Pradeep Ramuhalli – Oak Ridge National Laboratory; Mike Taylor – Electric Power Research Institute;
Charlotte Geiger – Exelon Generating Company

Project Description: This project seeks to develop and demonstrate a transformative and generalizable advanced online monitoring system to enable predictive maintenance (PdM) for critical balance-of-plant equipment in nuclear power plants (NPPs). This goal can be accomplished by focusing on four areas: (1) developmentof a techno-economic methodology for wireless sensors used in equipment monitoring, (2) application of data-based models to diagnose/prognose faults by using heterogenous data, (3) development of a visualization algorithm to present useful and actionable information to the relevant parties, and (4) validation of the developed approaches by using independent data from an operating plant.

Impact and Value to Nuclear Applications: The project demonstrated how to achieve cost reductions related to the nuclear industry's current maintenance practices. Recent research has focused on developing an end-to-end summary (see Figure 1) of how NPPs can acquire, analyze, store, and visualize data to reduce operation and maintenance costs. The developed end-state vision provides a holistic view that enables the nuclear industry to strategize their investments and resource planning as they transition from a preventive maintenance (PM) to a PdM strategy in a cost-effective manner.

Recent Results and Highlights: Recent results have described the necessary features of cloud computing services for use in aiding the development of diagnostic, prognostic, and visualization tools. The research also examined the economic benefits of utilizing cloud services for a centralized monitoring and diagnostic center, and determined that the economic assessment will require the incorporation of costs associated with networking and security, storage and databases, and artificial intelligence deployment. The economic analysis described an approach for including capital and operating expenditures associated with the end-to-end implementation of technologies necessary to transition from a PM to a PdM strategy. The research team also studied the utilization of metrics such as the internal rate of return and the net present value in order to estimate the profitability of potential investments.

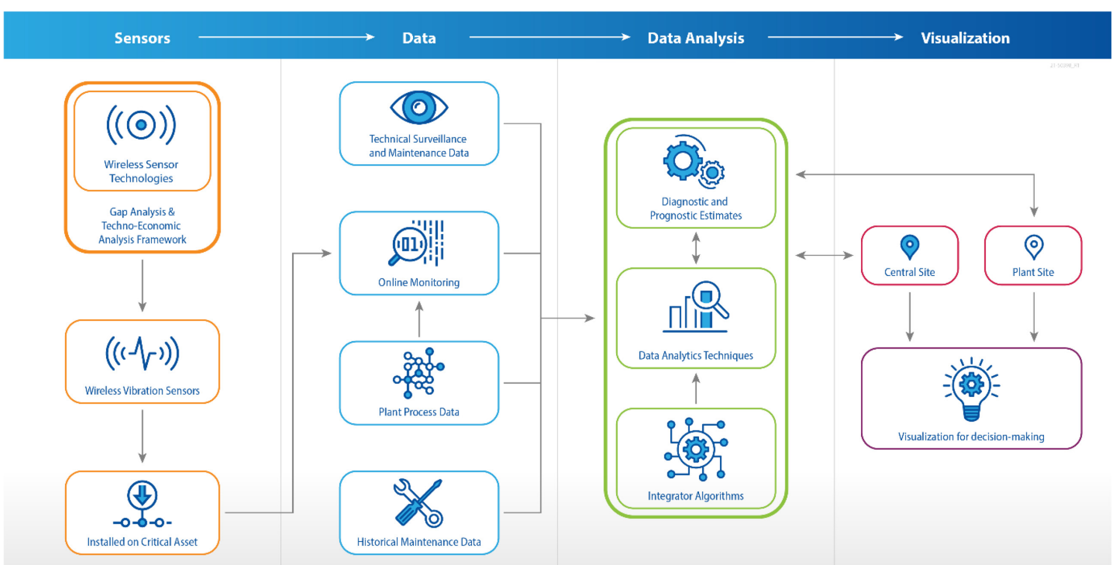


Figure 1. End-to-end vision for achieving digital monitoring in nuclear power plants.

Small Business Innovation Research & Industry FOA

Metamaterial Void Sensor for Fast Transient Testing

PI: Mark W Roberson, Ph.D. – Goldfinch Sensor Technologies and Analytics, LLC
Collaborators: Juliana Pacheco Duarte – Virginia Tech

Project Description: Detecting and quantifying voids (bubbles) that can form on reactor rods during reactor transients is necessary for producing safer fuel rods. As part of Phase II of the Small Business Innovation Research (SBIR) program, the Goldfinch Sensor Technologies and Analytics LLC (GSTA) team developed a void sensor for in-core use. Following the validation phase that is currently underway, GSTA would like to deploy the sensor for use at Idaho National Laboratory (INL). In this regard, GSTA is collaborating with INL to place sensor radio frequency (RF) elements in the Transient Reactor Test (TREAT) reactor core for high-temperature and neutron exposure testing in 2023.

Impact and Value to Nuclear Applications: Researchers use near-DC-capacitive plates to detect voids due to a change in the dielectric constant. Sensing at multiple locations requires multiple feedthroughs, limiting the number of locations that can be sensed. In the GSTA method of sensing, only two ports are required for sensing 10 or more locations with high time resolution, thereby greatly reducing the connectors. The sensor shows promise for bubble spectroscopy, as it can differentiate among different bubble size distributions. GSTA's technology works at both high pressures and temperatures, making it applicable for in-core instrumentation and thus supporting the nuclear energy industry as a whole. The stakeholders of this technology are test groups requiring time-resolved sensing of voids along rods.

Results: GSTA and Virginia Tech executed a SBIR Phase II project that explored the use of a novel metamaterial RF structure to detect voids (bubbles) that form during rodlet testing. The project included extensive modeling and simulation, laboratory testing, and device fabrication. It started out at Technology Readiness Level (TRL) 4 and finished up at TRL 6 after testing sensor elements in the INL TREAT facility for neutronic irradiation. Due to COVID-19 and INL scheduling issues, the project was extended by 18 months, and will now end on December 28, 2022. Outside of nuclear energy, potential applications for this technology are found within the biomedical, oil and gas, and agricultural industries.

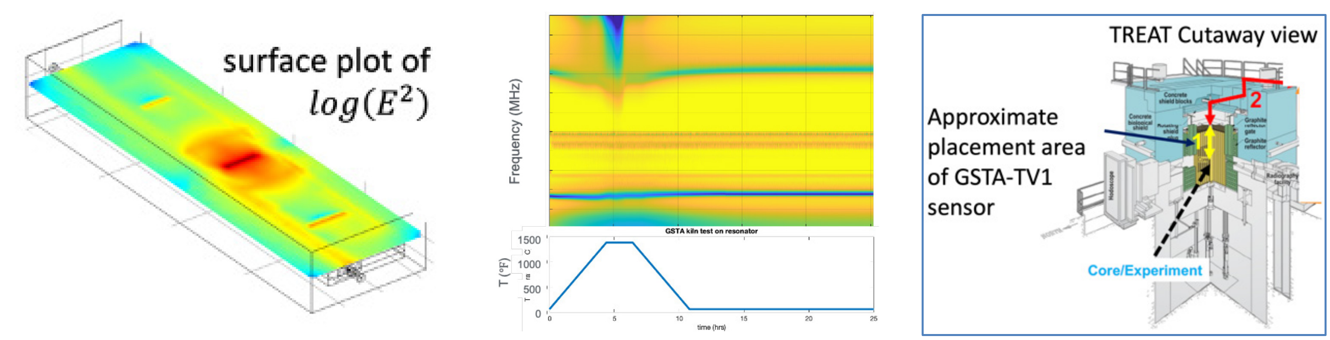


Figure 1. Left: RF modeling of sensor performance in single-void sensing. Middle: Test data at 1400°F. Right: Planned sensor placement for TREAT interstitial testing.

High-Penetration Wireless Networking for Nuclear Power Plant Sensing

PI: Randall King, CTO – Operant Networks Incorporated
Collaborators: Constellation Energy; Idaho National Laboratory; University of California at Los Angeles

Project Description: Predictive maintenance sensors are needed to extend nuclear plant lifetimes, but extreme construction standards make these efforts challenging. For such sensors, wiring was found to be the largest cost barrier, thus making wireless connectivity of interest. Operant's networking software uniquely enables extreme range wireless technology (LoRa) in an end-to-end cybersecure mesh topology. This mesh can extend the range of low-cost commercial LoRaWAN sensors while also enhancing their cybersecurity and resilience (see Figure 1). This project will also investigate whether these new capabilities enable wireless connectivity even when using previously off-limits critical digital assets.

Impact and Value to Nuclear Applications: Two major impacts are envisioned: (1) life extension of existing nuclear plants through reduced maintenance costs, and (2) enhanced sensor connectivity and security capabilities for next-generation nuclear facilities.

Recent Results and Highlights: The first quarter of the 2-year schedule for this project involved five major tracks. Our initial progress regarding each track is detailed below.

Track 1 - Integrate HW/SW: We purchased the gateway hardware and radios required for the initial development, and deployed them to our distributed team so that the development could begin.

Track 2 - Improve Transport SW: We held initial meetings with our key transport partners, Pollere and UCLA, to define first-year goals. Ongoing meetings are scheduled, and active development will begin.

Track 3 - Demonstrate Lab Performance: We have met with INL and defined our first steps. Ongoing meetings are scheduled, and the initial planning has been successfully agreed upon.

Track 4 - Field Trial: No progress to date, though Constellation's role in the partnership remains clearly identified.

Track 5 - Investigate CDA Regulation: The committee members from both INL and Operant have been identified; however, the members from Constellation have yet to be determined.

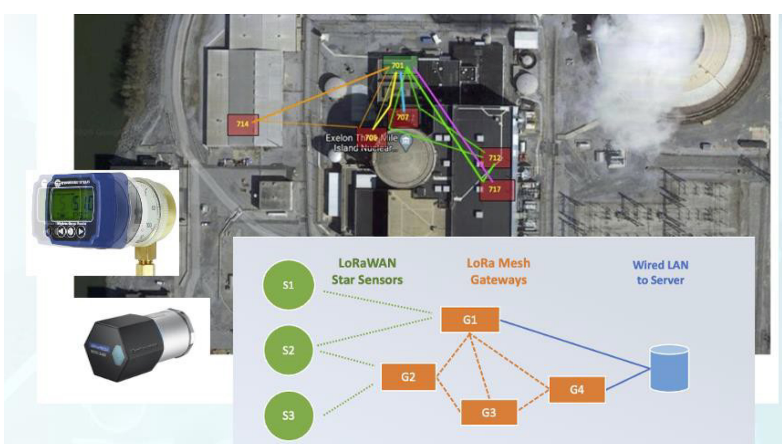


Figure 1. Example use case and network topology.

Laser Ultrasonic Testing of Nuclear Fuel Rod Internal Pressure and Cladding Wall Thickness

PI: Bradley Bobbs – Intelligent Optical Systems
Collaborators: Electric Power Research Institute (EPRI); Westinghouse Nuclear Services

Project Description: This project applies laser ultrasonic testing (LUT) to measure shifts in the resonant frequencies of fuel rod cladding and then relate them to internal pressure and cladding wall thickness.

Impact and Value to Nuclear Applications: LUT can verify the integrity—and hence the safety—of fuel rods during periodic maintenance in a cooling pool by revealing evidence of cracks, pinholes, and other defects that cause gas leakage, pressure loss, and possible water ingress; overpressure from excess reaction gases, especially under high-burnup conditions; changes in free volume; and cladding corrosion or oxide layer buildup. A radiation-resistant LUT probe can perform all these measurements without each rod having to be laboriously removed from its array assembly. This is unlike current testing methods, which require such disassembly and/or measure fewer indicators of compromised rod integrity.

Recent Results and Highlights: A laboratory setup (Figure 1) is being used to measure cladding resonances in air and water for PWR and BWR surrogate rods. Plots of a calibrated metric for resonance shifts in air show a strong linear correlation to helium fill gas pressure (Figure 2), while cladding wall thickness measurements are consistent within 0.4%. More advanced laboratory setups are being built for continuously varying the fill and fission gas pressures, and for optical-fiber-delivered laser beams.

Images/graphs/charts:

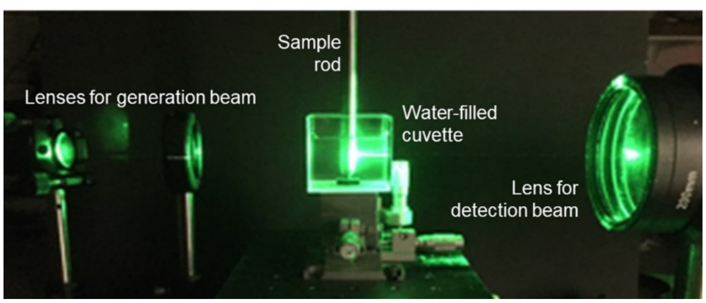


Figure 1. Laboratory setup with free-space laser beams at 532 nm and 1064 nm wavelengths.

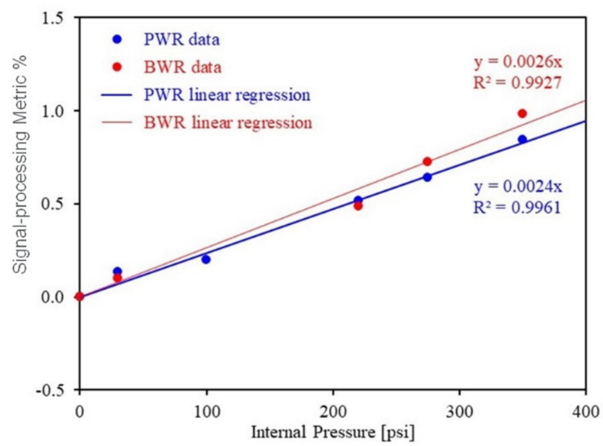


Figure 2. Calibrated metric for cladding resonance shifts in air show strong linear correlation to He fill gas pressure.

Laser Ultrasonic Testing for Nuclear Waste Canister Crack Depth Profile Evaluation

PI: Marvin Klein – Intelligent Optical Systems
Collaborators: Pacific Northwest National Laboratory (PNNL);
Electric Power Research Institute (EPRI); Robotic Technologies of Tennessee

Project Description: This project applies laser ultrasonic testing (LUT) to measure shifts in the time of flight of an ultrasonic pulse diffracted by a stress corrosion crack, and then relate those shifts to the crack depth.

Impact and Value to Nuclear Applications: During periodic monitoring for the formation of stress corrosion cracks that could lead to leaks, LUT can verify the integrity—and hence the safety—of a nuclear waste canister in a dry cask storage system. A radiation-resistant LUT probe mounted on a robotic crawler with magnetic wheels can enter the canister area via ventilation ports, fitting between canisters even when there is only 2 in. of space.

Recent Results and Highlights: A laboratory LUT B-scan of a test crack sample (Figure 1) shows clear indications of the crack, and data from B-scans with parameter variation were analyzed to generate consistent crack depth profiles. Mechanical tests performed at PNNL on a crawler-mounted LUT probe (see Figure 2) demonstrated the achieving of access for conducting measurements on a canister in a dry cask storage system mockup.

Images/graphs/charts:

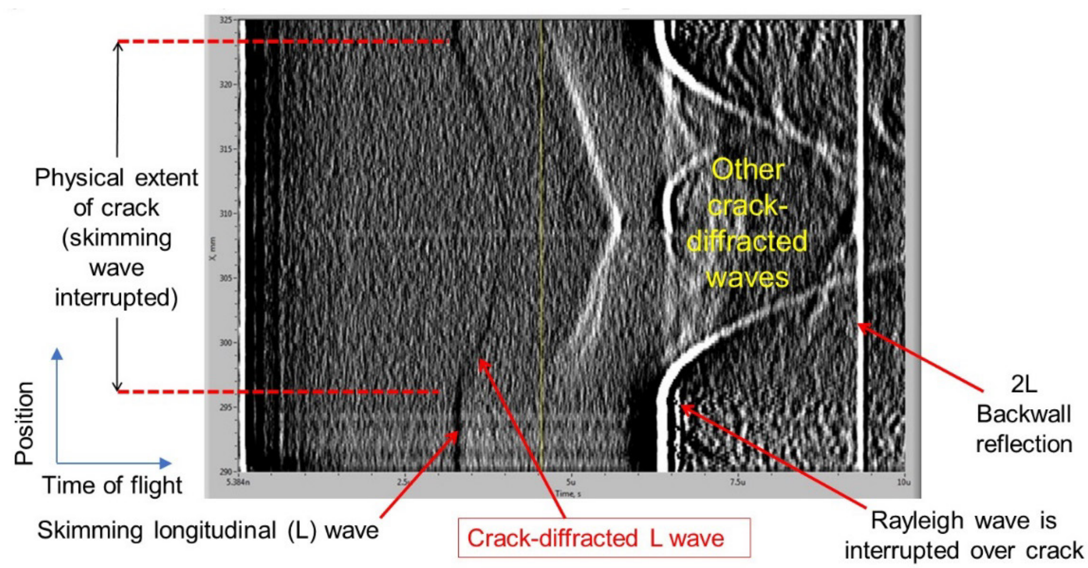


Figure 1. Laboratory LUT results on a test crack sample.

Laser Ultrasonic Testing to Measure Molten-Salt Flow Rates

PI: Marvin Klein – Intelligent Optical Systems
Collaborator: Haori Yang – Oregon State University

Project Description: This project applies laser ultrasonic testing (LUT) to measure the differences between phase shifts in upstream and downstream flow, and then relate it to the flow rate.

Impact and Value to Nuclear Applications: Non-contact LUT can, for testing and monitoring purposes, be employed to measure the flow rate of high-temperature molten salts used for heat transfer in next-generation nuclear reactors. Current flow-rate instrumentation that comes in direct contact with the flow pipe are limited to temperatures of under 600°C.

Recent Results and Highlights: A double-LUT laboratory setup (Figure 1) measured four flow rates in room-temperature water. The results (see Figure 2) demonstrated, within the range of experimental uncertainty, agreement with finite-difference simulation results. A molten-metal flow system was built at Oregon State University for further testing.

Images/graphs/charts:

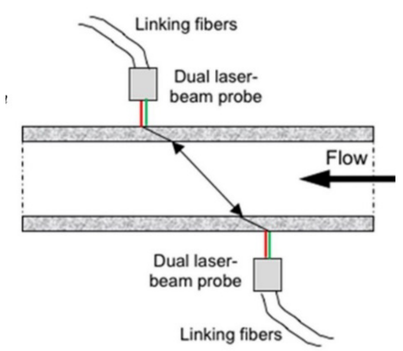
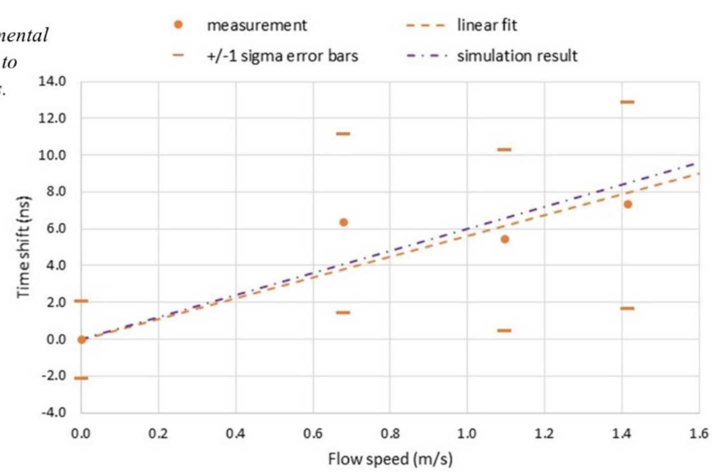


Figure 1. Double-LUT laboratory setup showing propagation of ultrasonic waves across cross-section of flow pipe.

Figure 2. Experimental results compared to simulation results.



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 are expected to complete 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 2023:

- 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 $4,015,000 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

Additional research activities funded by ASI are implemented as part of National Science User Facilities projects, also awarded through the DOE CINR funding opportunity, and 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/#/.