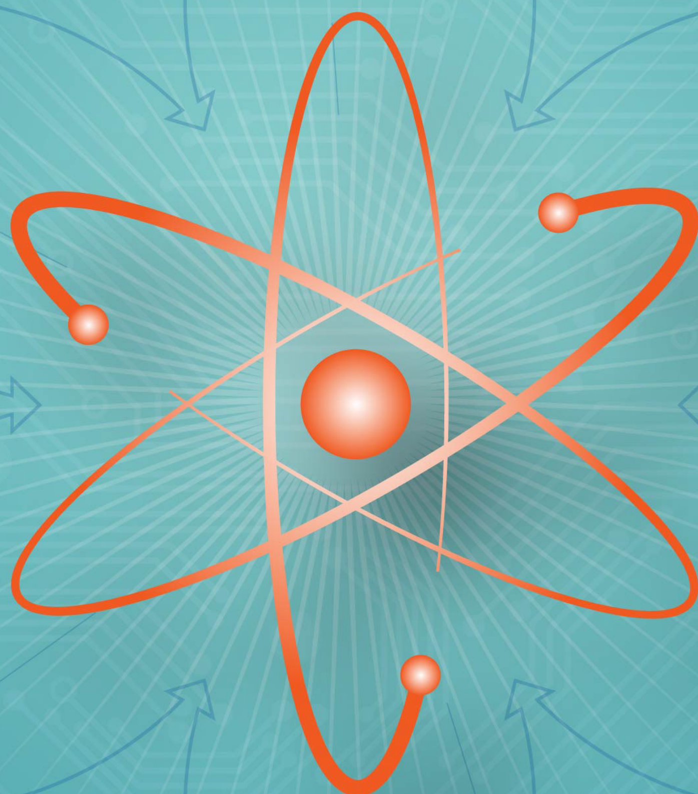
U.S. DEPARTMENT of ENERGY | Office of Nuclear Energy

ADVANCED SENSORS AND INSTRUMENTATION

2024 SUMMARY OF ACCOMPLISHMENTS



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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 ASI program's 2024 Annual Review Meeting, held virtually on November 4, 6, and 7, 2024.

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INTRODUCTION

In 2011, the Department of Energy (DOE) Office of Nuclear Energy (DOE-NE) initiated the Nuclear Energy Enabling Technologies (NEET) initiative to conduct research, development, and demonstration for crosscutting technologies that directly support current reactors and enable 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 performs the following roles:

- Coordinate crosscutting research among DOE Office of Nuclear Energy programs in order to avoid duplication; and focus R&D in support of advances in reactor and fuel cycle system design and performance.

- Advance technology readiness levels (TRLs) across the four ASI research areas so as to support maturation of R&D from first concepts to commercialization.

In the measurement science field, the ASI Program has spurred innovation by funding research to advance the nuclear industry's monitoring and control capabilities. Such capabilities are crucial for developing research solutions that reduce costs, enhance efficiencies, and increase operational safety for both current and advanced reactors. They also play a vital role in materials test reactors (MTRs) in terms of measuring thee environmental conditions of irradiation experiments and monitoring certain aspects of advanced fuel/material behavior.

RESEARCH ACCOMPLISHMENTS

This section collects—in the form of summaries—the research accomplishments presented at the ASI program's 2024 Annual Review Meeting, held virtually on November 4, 6, and 7, 2024. The content is organized based around the three meeting sessions,

- Sensors for Advanced Reactors (sessions I and II)

- Sensors for Irradiation Experiments

- Sensor Integration

Sensors for Advanced Reactors – Reactor Power Monitoring—INL

PI: Kevin Tsai – Idaho National Laboratory (INL)
Collaborators: Tommy Holschuh, Teancum Quist, Geran Call, and Michael Reichenberger – INL
Loïc Barbot and Grégoire de Izarra – French Alternative Energies and Atomic Energy Commission
Matthew Van Zile, Kevin Herminghuysen, Susan White, and Andrew Kauffman – The Ohio State University
K. C. Goetz and Anthony Birri – Oak Ridge National Laboratory

Project Description: INL's reactor power monitoring work package is aimed toward development and demonstration of in-core neutron flux sensors to enable and enhance power-monitoring capabilities for upcoming advanced reactor demonstrations. Among the development work are assessments of self-powered neutron detectors (SPNDs), fission chambers, and dosimeter wires for low-flux reactor monitoring, flux distribution measurements, and neutron energy spectra unfolding.

Impact and Value to Nuclear Applications: Development of in-core sensors capable of providing real-time neutron spectra measurements enhances the current state-of-the-art in reactor monitoring. Neutron energy spectra measurements are a necessity for validating advanced reactor models operating in the fast neutron region. The ability to perform spectra measurements in real-time further enables fuel burnup tracking, with a strong implication toward fuel relocation monitoring and batch reloading analysis. Therefore, this capability is targeted for traditional commercial reactors in regard to both fuel management and utilization, as well as for advanced reactor concepts in regard to dynamic fuel motion tracking.

Recent Results and Highlights: High-temperature irradiations of fission chambers and SPNDs were completed at the Ohio State University Research Reactor, at temperatures of up to 850°C. The temperature effects in the SPNDs were modeled to determine the primary effect of gamma radiation on insulation conductivity. Separately, SPND emitter research was performed to enable a real-time spectral measurement capability. The evaluation concluded by using a Rh- and Pt-SPND pair for fast and thermal neutron measurements. Supporting the spectral SPND development, novel dosimetry packages were demonstrated at the Advanced Test Reactor Critical Facility, and a real-time spectral unfolding technique based around SPND responses was developed. Validation of the analysis, which in fiscal year (FY) 2024 covered—high-temperature operation and spectral measurements using SPNDs, is—planned to continue in FY2025 with heated irradiations at the Advanced Test Reactor Gamma Facility (irradiation funded by Nuclear Science User Facilities rapid turnaround experiments) and at the Armed Forces Radiobiology Research Institute.

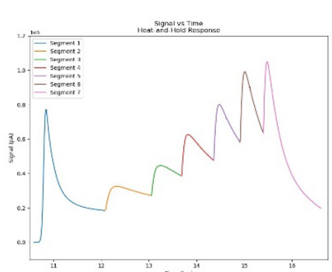


Figure 1: Measured SPND temperature effects at each temperature segment during steady-state irradiation.

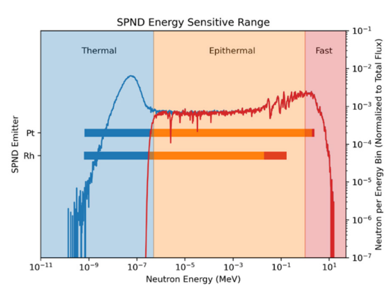


Figure 2: Rh- and Pt-SPND sensitivity range for a Testing, Research, Isotope, General Atomics (TRIGA) spectrum—both with and without a cadmium filter.

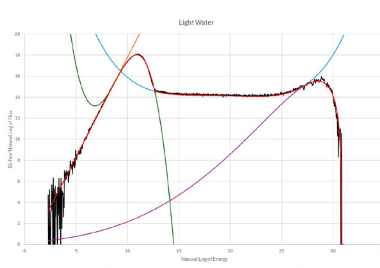


Figure 3: Novel neutron spectral fitting technique involving different energy ranges for real-time spectra measurement using SPNDs.

Demonstrating Realistic Sensor Physics and Integrating Ex-core Sensors for Power Distribution Synthesis

PI: Anthony Birri – Oak Ridge National Laboratory (ORNL)
Collaborators: K. C. Goetz, Daniel C. Sweeney, N. Dianne Bull Ezell – ORNL

Project Description:
A weighting-function-based core power synthesis method was applied to multiple Monte Carlo N-Particle reactor models, informed based on simulated self-powered neutron detector (SPND) models. The two primary goals of this project were to (1) determine the impact of utilizing realistic sensor physics on core synthesis simulations and (2) integrate ex-core sensors into the model in order to assess the extent to which the synthesis capabilities may be improved as a consequence of their inclusion. The first objective was achieved by using Geant4 SPND models, in comparison with analytical models, such that the effect of electron transport in realistic SPND geometries can be understood in terms of synthesis error and convergence time; these studies were performed with models of the NuScale small modular reactor (SMR) and Westinghouse AP1000 pressurized-water reactor (PWR). The second goal was achieved by performing synthesis with and without the ex-core detectors and by quantifying the synthesis error and the number of iterations associated with Gaussian-type perturbations in the model of the Texas A&M Testing, Research, Isotopes, General Atomics Reactor (TAMU TRIGA) reactor.

Impact and Value to Nuclear Applications:
Core power distribution monitoring (through synthesis techniques) is a critical part of reactor operations, yet fundamental studies quantifying the effects and impacts of various perturbations and sensor array characterizations are generally limited. Therefore, the simulation studies performed in this work can provide impactful and accessible data for currently operating reactors and next-generation reactor developers when considering the design and arrangement of the core monitoring sensors, as well as provide a greater understanding of the algorithms used to process the sensor outputs.

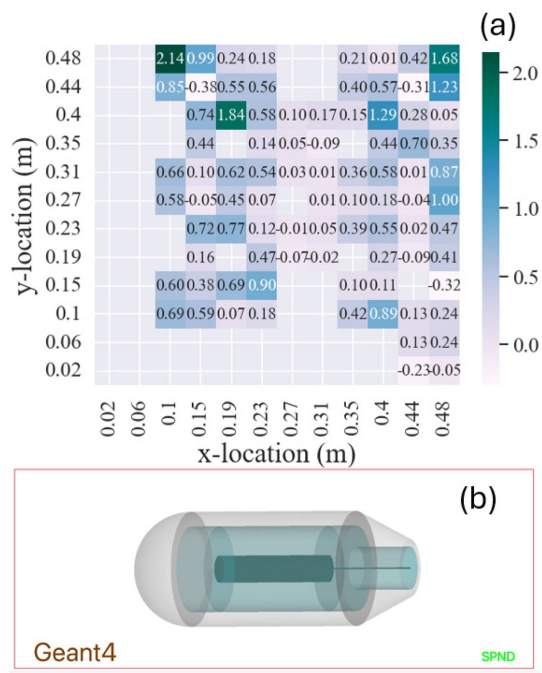


Figure 4: (a) Reduction in percent maximum error by including ex-core detectors in the TAMU TRIGA, as a function of perturbation location. (b) Geometry of the Geant4 SPND model.

Recent Results and Highlights:
The results of comparing the Geant4 and analytical SPND models indicate that similar synthesis errors were obtained for burnup-induced perturbations in both the NuScale SMR and the AP1000 PWR. However, there were marked differences between the Geant4 and the analytically informed models in terms of the iterations required to converge on the synthesized power distribution. Results from the ex-core sensor assessment with the TAMU TRIGA model indicate that including ex-core sensors drastically reduces the synthesis error of Gaussian-type perturbations close to the edge of the core, and slightly reduces synthesis errors for perturbations closer to the center of the core.

Application of printed strain gauges in prototypical nuclear reactor conditions

PI: Amey Khanolkar – Idaho National Laboratory (INL)
Collaborators: Timothy Phero, Michael McMurtrey, Bradley Benefiel, James Smith – INL
Md Omarsany Bappy, Yanliang Zhang - University of Notre Dame
Brian Jacques – Boise State University

Project Description: Advanced manufacturing (AM) via direct-write (DW) technologies such as aerosol jet printing has emerged as the predominant enabler for fabricating active/passive sensors. AM techniques for sensor fabrication address the limitations of commercial sensors in extreme temperature and radiation environments. Reliable in situ strain measurements in nuclear reactors are essential for monitoring temperature- and radiation-induced phenomena such as creep, swelling, and deformations. This project undertook development and testing of AM strain sensors to improve design and manufacturing for in-pile monitoring in nuclear reactors, considering environmental conditions, sample geometry, and material compatibility. Two types of printed strain sensors were tested: a multi-modal thermocouple and half-bridge resistive strain gauge, and an interdigitated electrode capacitive strain gauge. These sensors were exposed to mechanical strain (up to 1000 με) and high temperatures (up to 700°C). The robustness of a printed strain gauge layer in a molten-salt environment for up to 500 hours was evaluated to assess material compatibility for use in molten-salt reactors. Additionally, sensor qualification methodologies were further developed to determine the mechanical integrity, reliability, and robustness of AM strain gauge materials.

Impact and Value to Nuclear Applications: Among the high-impact enabling technologies stemming from this research task were robust miniaturized sensors for monitoring strain and temperature, high-density sensor arrays, and embedded sensors for nuclear applications. DW-based AM enables significant expansion of the library of printable materials, opening up a necessary pathway for tailoring the composition and chemistry of sensor materials as to make them compatible with their operational environments. The laser shock technique used in this project also shows potential as a facile non-destructive quality control approach for rapidly assessing the bond strength between printed layers in sensors.

Recent Results and Highlights: Uniaxial tensile and beam deflection tests, conducted on stainless steel specimens instrumented with the multimodal thermocouple + resistive strain gauge and the capacitive strain gauge, accurately measured temperature and strain when subjected to cyclic mechanical and thermal loads. Among the strategies identified to mitigate drift in the capacitance signals, as caused by cracking or failure of the insulation/encapsulation layer in the capacitive strain gauge, was the use of gradient property printed layers. Laser shock tests revealed an inverse correlation between a printed insulation layer's thickness and its mechanical integrity. The molten salt exposure tests showed considerable degradation of the printed insulation layer, highlighting the need for alternative chemistries of capping and for insulation layers that good compatibility with molten salts.

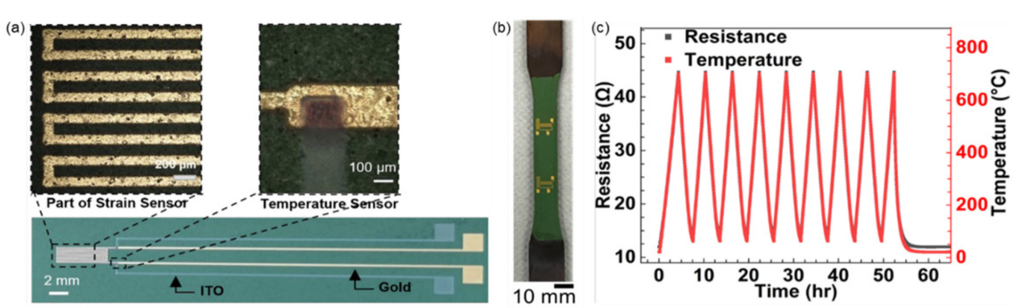


Figure 5: (a) Optical images of the printed multimodal temperature/strain sensor. (b) Tensile specimen with a printed resistive strain gauge. (c) Sensor stability under repetitive temperature cycling from room temperature to 700 °C.

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

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

Project Description: This project supports the Advanced Sensors and Instrumentation (ASI) program's mission by leveraging recent advances in both machine learning (ML) based field reconstruction techniques and diagnostic software in order to augment traditional sensor capabilities. We will develop and demonstrate integrated sensor technology for real-time monitoring of reactor vessel thermal mechanical stresses for micro high-temperature gas reactors (mHTGRs). The technology will be based on utilization of a sparse network of outer wall temperature measurements and other plant operating conditions. Convolutional neural network (CNN) approaches will be utilized to optimize the number and location of the measurement points. By leveraging the algorithms available for degradation diagnostics of the well-established PRO-AID software, the proposed technology will afford (1) real-time, reliable, and cost-effective monitoring; (2) quantification of the lifetime and integrity of the pressure vessel; and (3) improved economics for micro-reactor systems.

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

Recent Results and Highlights: This 3 year project will complete its second year at the end of FY-24. During this second year, the CNN that was developed at Argonne National Laboratory (ANL) and demonstrated by Penn State researchers reconstructed temperature fields on a vessel wall, achieving agreement within ~5% over the range of temperatures measured. Training and validation of the network occurred using numerical simulations in the MOOSE software framework; the ray tracing and conduction modules were successfully validated against experimental data (Figure 6). In parallel with validation and demonstration of the CNN to produce thermal fields under a variety of heating conditions, researchers in the Thermal-Hydraulic Research Laboratory at Texas A&M University (TAMU) began validating off-the shelf strain gauges for coupled thermal-mechanical measurements on the vessel model. Initial validation of thermal strain predictions has been completed (Figure 7). Moving into the final year of the project, the CNN will be further modified to detect off-normal operating conditions, as simulated in the experimental facilities at TAMU.

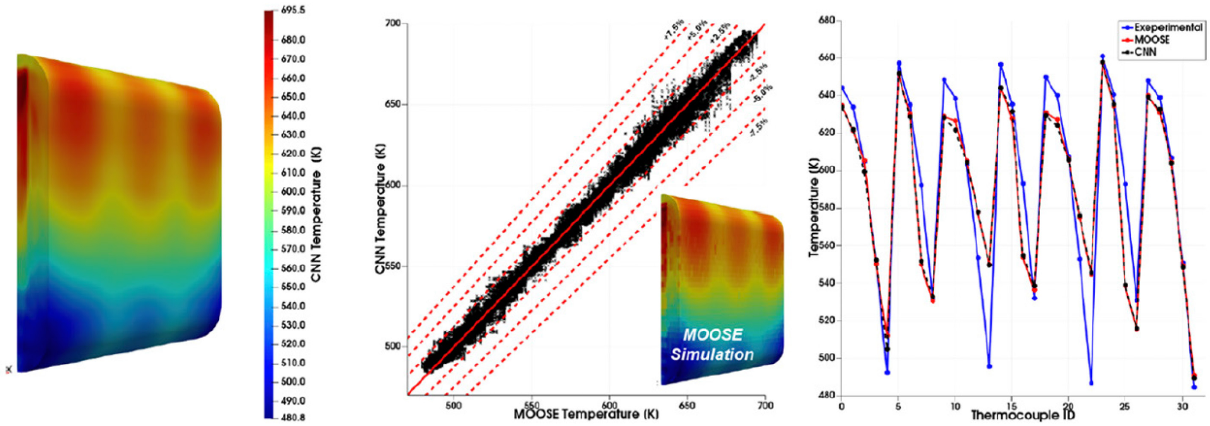


Figure 6: Validation and demonstration of the CNN for temperature prediction in the reactor vessel model

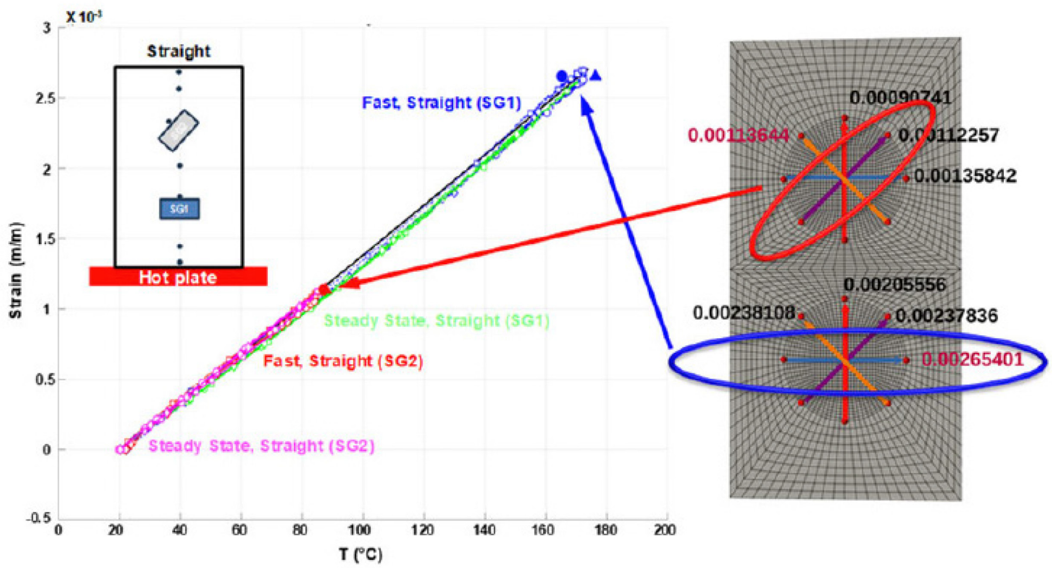


Figure 7: Prediction of thermal strains in high temperature, benchtop tests

Radiation-hardened Electronics – Johnson Noise Thermometry

PI: N. Dianne Bull Ezell – Oak Ridge National Laboratory (ORNL)
Collaborators: Kyle Reed, Dan Sweeney, K.C. Goetz – ORNL
Md Omarsany Bappy, Yanliang Zhang – University of Notre Dame

Project Description: Implementation of Johnson noise thermometry (JNT) into radiation-hardened electronics (RHE) – This task focuses on JNT, which has been proposed for space reactors and small modular reactors (SMRs) as a self-calibrating thermometry system, reducing maintenance costs and increasing reliability. The electronics used in this system were developed at Oak Ridge National Laboratory (ORNL), and the front-end low-noise amplifiers are junction field-effect transistor–based, making this a prime candidate for RHE development using commercially available parts. JNT entails application of custom front-end electronics and signal processing to a resistance temperature detector (RTD), over time acquiring an averaged signal usable for self-calibration of proximally close RTDs affected by neutron degradation. However, JNT is susceptible to noise injection on cable, and locating the pre-amplifier and differential-amplifier as close to the sensor as possible strengthens the application. Also, under this work package, ORNL staff collaborated with the University of Notre Dame to demonstrate the application of thermal electric generator technology with custom RHE. This represents a successful demonstration of collaboration in which the national laboratory raised the technology readiness level of NEUP-developed technology within the NEET-ASI program; (see Figure 8).

Impact and Value to Nuclear Applications: While JNT was originally developed for the HFIR, it is applicable to advanced reactors, and development continued under Space and SMR programs. For example, microreactors deployed in remote locations, including under the space program, will require extended operational periods, with minimal-to-no maintenance over the lifetime of the reactor. Self-calibrating instrumentation may also be required to extend the lifetime (and reduce the maintenance) of critical sensors. Placing advanced sensors and the associated electronics closer to a nuclear reactor core could improve the reactor control and operation through increased signal accuracy, precision, and fidelity. The lack of commercially available RHE has been an obstacle for instrumentation advancements for next-generation nuclear reactor environments. ORNL has focused on development and qualification of well-known front-end electronics designs with intrinsically radiation-hard commercial-of-the-shelf components. This will accelerate the technology to application in lieu of the long-term fully custom ASIC pathway.

Recent Results and Highlights: The RHE-JNT work package was delayed to FY-25, due to long-lead-time delivery of commercial parts.

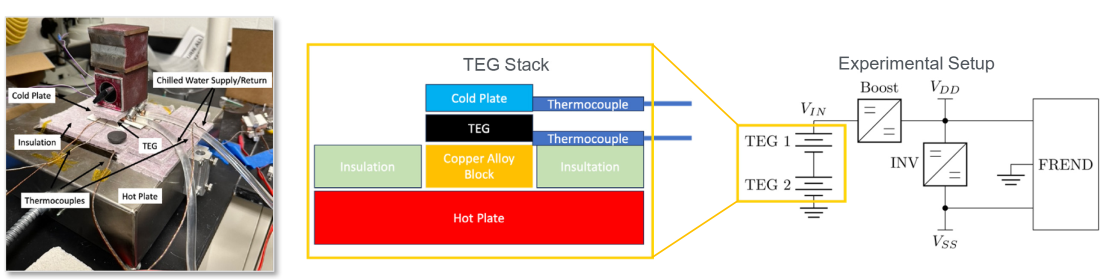


Figure 8: TEG demonstration with the FREND system – completed FY-24.

Co-existence of Heterogeneous Wireless Networks in the 2.4 and 5 GHz Spectra

PI: Vivek Agarwal – Idaho National Laboratory (INL)
Collaborators: Imtiaz Nasim and Amitabh Mishra – INL
Syed Ayaz Mahmud, Sneha K. Kasera, Mingyue Ji– University of Utah

Project Description: This project provides the technical basis for understanding wireless protocols—specifically, the coexistence of Zigbee, Wi-Fi, and fifth-generation (5G) technologies. It also developed a rate control mechanism that affords the opportunity to utilize available temporal channels to improve the network's overall performance.

Impact and Value to Nuclear Applications: In the project, which leveraged the University of Utah's experimental capabilities, a simulation was performed at Idaho National Laboratory (INL) to understand the coexistence of Wi-Fi and 5G wireless technologies. The outcome is important for informing how next-generation nuclear power plants can leverage advanced wireless technologies to achieve automation across various applications such as advanced control and remote monitoring/operation. A one-size-fits-all solution cannot be adopted, as wireless technologies are selected according to specific application needs, quality of service, and economic restrictions. Balancing of the trade-off between technical and economic requirements necessitates a multi-band heterogeneous wireless network architecture. However, the co-existence of these multi-band wireless technologies poses numerous challenges due to the dissimilarity in channel access mechanisms, transmit power levels, distance between transmitting/receiving sensor nodes, and interference among coexisting solutions.

Recent Results and Highlights: The experimental setup in Figure 9 was carried out in the Platform for Open Wireless Data-driven Experimental Research (POWDER) testbed at the University of Utah in order to evaluate the coexistence of 5G-NR-U (new radio in unlicensed spectrum). Figure 10 gives the complete network diagram used to simulate Wi-Fi and 5G-NR-U coexistence with different Wi-Fi clients, as well as access points with variable distances. Interference simulation studies were performed at difference client distances.

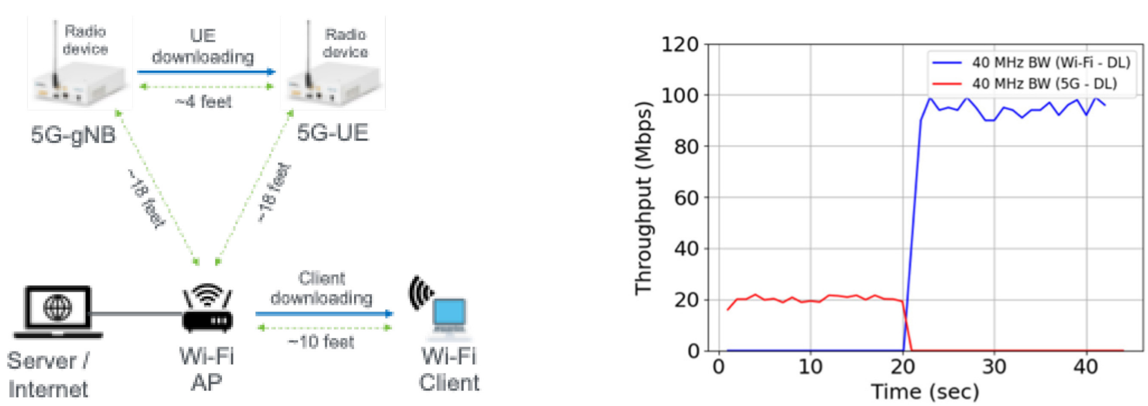


Figure 9: (Left) Wi-Fi and 5G-NR-U co-existence network setup. (Right)Throughput comparison of Wi-Fi and 5G-NR-U when coexisting and when the Wi-Fi is operating at 100 Mbps.

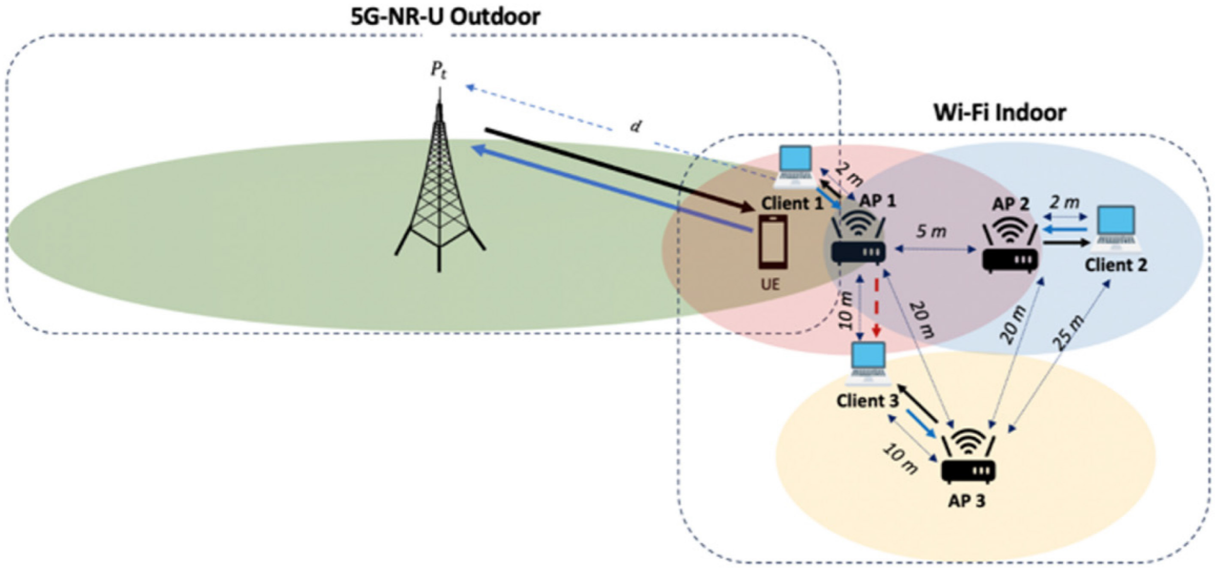


Figure 10: Simulated co-existence network diagram of Wi-Fi and 5G-NR-U.

High-Penetration Wireless Networking for Nuclear Power Plant Sensing

PI: Randall King – Operant Networks
Collaborators: Roger Jungerman, Alex Shaffer – Operant Networks
Kathleen Nichols – Pollere LLC
Varun Patel and Lixia Zhang – UCLA
Imtiaz Nasim, John Buttles, Kirk Fitzerald, and Vivek Agarwal – Idaho National Laboratory

Project Description: This project addresses the critical need for secure, cost-effective wireless sensor networks in nuclear power plants (NPPs). Traditional wired sensors are expensive as well as challenging to retrofit into these facilities so as to improve plant monitoring and operations. Furthermore, new sensors such as wireless vibration sensors can be added for predictive maintenance applications, the aim being to extend the lifespans of existing NPPs. This project introduces a novel Named Data Networking (NDN) wireless mesh architecture optimized for the LoRa wireless technology. Our prior work at the decommissioned Three Mile Island NPP demonstrated that LoRa affords the range required to penetrate the thick walls of an NPP, provided multiple intermediate hops are employed as needed. By leveraging easy-to-install, battery-powered, commercial LoRaWAN sensors this project developed and prototyped a resilient, end to end secure hybrid LoRaWAN-LoRa mesh network transport system, as shown in Figure 11.

Impact and Value to Nuclear Applications: It is critical that more advanced sensor capabilities be added to legacy NPPs, but the costs of doing so is extremely high and the lead times are long. For example, retrofit wiring installation/permitting costs are estimated at ~$2000/ft, with complete NPP sensor retrofit wiring costing several millions of dollars. To backhaul data from sensors deep in the NPP, retrofit wiring is required for either wired sensors or for a distributed antenna system (DAS) that accesses LoRaWAN sensors. By contrast, tens of mesh gateways, costing a few thousand dollars each, can be used to backhaul LoRaWAN sensor data to the limited number of broadband access points in the NPP. The resulting NDN LoRa mesh offers essential NPP wireless cybersecurity. The LoRa mesh's in-network caching improves its reliability, despite the intermittent radio connectivity and electrical interference common to the challenging RF environments of NPPs. Though the mesh was designed for LoRa, it should be applicable to other wireless transport systems such as WiFi 6, whose orders-of-magnitude-higher data rates support other possible nuclear applications, including advanced reactors.

Recent Results and Highlights: The NDN LoRa mesh protocol was optimized for the NPP wireless application, and interfaces with the LoRaWAN sensors were demonstrated. The mesh uses a novel brokerless publish/subscribe (pub/sub) architecture for added resiliency and security. The protocol was simulated at UCLA to aid in network optimization. Mesh gateway hardware (Figure 12) was adapted to include the LoRa mesh and LoRaWAN wireless radio interfaces. Pilot testing of the hardware was performed at Idaho National Laboratory (INL), and compared against a DAS system (See Figure 13). Long LoRa range was shown. When compared against the DAS, the latency proved acceptable for the NPP application (1.25 s). The in-network caching resulted in no dropped packets, despite the

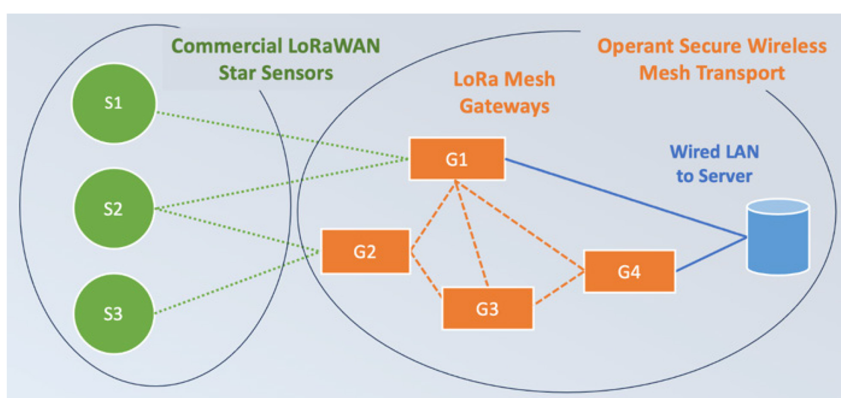


Figure 11: LoRa Mesh Transport

extensive mesh network reconfigurations and the intermittent connectivity as the gateways were deployed throughout the lab. In separate testing, the mesh was deemed cybersecure and can support secure access controls. This, combined with the INL mesh reliability and latency demonstration, proves the LoRa mesh fully capable of cost-effectively improving the reliability and lifetimes of legacy NPP systems.

Figure 12: Mesh Gateway

Figure 13: Pilot Testing

Structural Health Monitoring FY-24 ASI Summary

PI: Joshua Daw – Idaho National Laboratory (INL)
Collaborators: Bibo Zhong, Xinchang Zhang, Jorgen Rufner, Austin Fleming, and Charles Payne – INL
Dan Deng – Boise State University

Project Description: The goal of this research is to advance technologies usable for structural health monitoring (SHM) in existing and advanced reactors. Several such technologies were either developed or advanced via this work, including a method of embedding optical fibers into structural materials, a radiation-tolerant acoustic emission (AE) sensor, and methods of modeling and printing ultrasonic transducers.

Impact and Value to Nuclear Applications: Advanced SHM capabilities will foster safer operation of existing and advanced reactors by enabling early detection of operating condition changes caused by wear or damage to essential components. These reactors will also be made more efficient, as they can be safely run closer to regulatory limits.

Results and Highlights: A new capability at Idaho National Laboratory (INL) was utilized to demonstrate electric-field-assisted sintering (EFAS), a process of embedding optical fibers into structural components. EFAS uses Joule heating to heat both a die press and a powdered material that is then sintered. Controlling the current and pressure affords fine control over the final part. The embedded sensors can then monitor the condition of the part via acoustic strain monitoring. After the embedding is complete, the embedded structures and sensors are evaluated to verify sensor integrity through heat cycling to failure, thus enabling their maximum operating temperatures to be identified. INL also developed a high-temperature, radiation-tolerant AE sensor—based on radiation-hard magnetostrictive materials—for use in-core during irradiation testing, as well as in SHM. This AE sensor will operate at higher temperatures and to higher fluences than comparable commercially available sensors. Additionally, Boise State University created several multiphysics models that accurately predict the behavior and performance of both magnetostrictive and piezoelectric transducers, and developed methods of producing feedstock and printing transducers from proven radiation-tolerant ultrasonic transducers, using magnetostrictive Galfenol and piezoelectric lithium niobate.

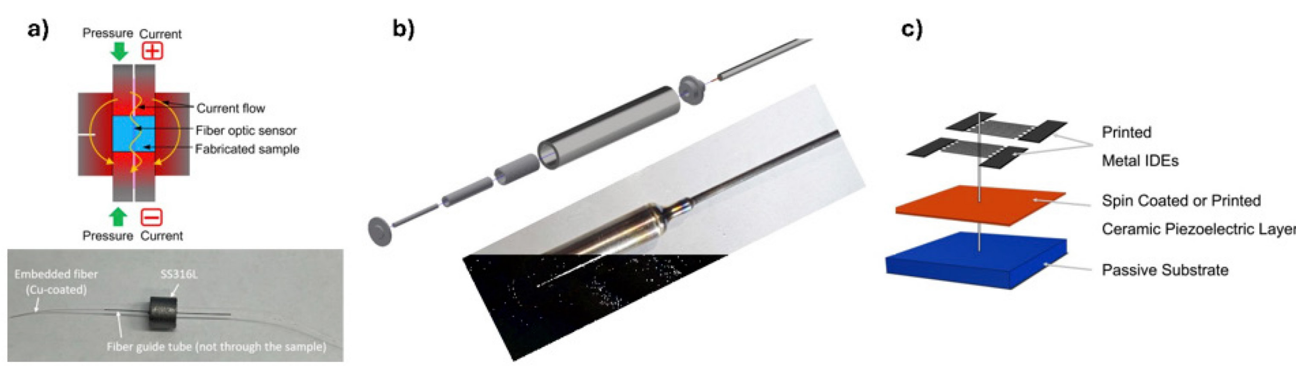


Figure 14: (a) Optical fiber embedded in steel via the EFAS process. (b) Magnetostrictive AE sensor drawing and prototype. (c) Aerosol-jet-printed piezoelectric transducer.

Project: D9H60 Cobalt Magnetostrictive Electromagnetic Acoustic Transducer

PI: S.W. Glass – Pacific Northwest National Laboratory (PNNL)
Collaborators: Morris Good, Nicholas Conway, Tianhao Wang – PNNL

Project Description: This project's goal is to demonstrate the feasibility of a permanently installed high-temperature sensor that can monitor a significant volume of pipe or vessel material for structural integrity. Nickel (Ni) magnetostrictive electromagnetic acoustic transducers (MSEMATs) are efficient at generating guided wave ultrasound at up to ~250°C. This project aims to design, build, and test a high temperature cobalt MSEMAT for higher-temperature advanced reactors – first to 350°C, using a permanent magnet EMAT with a cold spray Co coating on stainless steel. This will be followed by an electromagnet EMAT at up to 800°C. The test program will show:

- Performance (plate edge response) of permanent magnet MSEMATs as temperatures ramp from 20°C to 350°C, using a permanent magnet (no magnet wires) (actual tests were to 400°C)
- Performance with an electromagnet to 500°C, 600°C, 700°C, and 800°C.

Impact and Value to Nuclear Applications: Advanced reactors will be difficult or impossible to inspect or monitor using existing sensors and techniques. There are no commercial guided wave ultrasound sensors for long-term monitoring of vessel or piping integrity at operating reactor temperatures; however, a sensor network capable of detecting cracks, pits, and material degradation throughout a large volume of material could be useful in monitoring the reactor components and thus ensuring safe operation or the alerting of issues that require mitigation or repair—prior to them escalating into a leak or structural failure.

Recent results and highlights:

Cobalt (Co) is known to have a magnetostrictive (MS) coefficient 2-3 times that of Ni, yet initial tests showed little or no MS response unless the MS Co coating was thermally annealed to 500°C-600°C.

Cobalt was also found to be more sensitive to saturation than Ni. Initial tests with SuCo magnets required separation by more than 25mm from the coil to avoid saturation. An AlNiCo magnet with <25% the strength of the SuCo magnet was used, as it did not saturate the cold-spray Co layer. The Co also demonstrated a non-monotonic temperature response. The EMAT backwall response increases from room temperature, drops to 250°C - 350°C, then resumes rising to 600°C.

The test of the AlNiCo magnet EMAT with the cold sprayed Co MS coating showed a strong backwall response at room temperature and up to 400°C. (Figure 15).

The electromagnet had a weaker response than the permanent magnet, but still produced a strong backwall response at up to 600°C. Higher temperate tests and long-term (1 week or more) are planned.

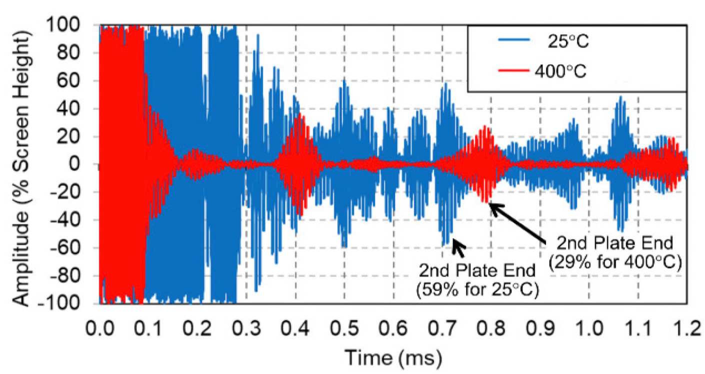


Figure 15: Room temperature and elevated temperature He cold sprayed Co annealed to 650°C and with an AlNiCo magnet EMAT previously heated to 400°C. This response demonstrates the sensor's feasibility.

Ultrasonic Multi-point Temperature Sensor for Nuclear Reactor Applications

PI: Dan Xiang – X-Wave

Summary

To meet the Department of Energy (DOE)'s need for an innovative sensor system capable of distributed, multipoint temperature measurements in order to improve and advance the sensors and instrumentation used in power reactors, material test reactors, and other similar systems and thereby support those facilities directly, X-wave Innovations, Inc. (XII), along with Idaho National Laboratory (INL), proposed to develop an Ultrasonic Multipoint Temperature Sensor (UMTS) for nuclear reactor applications. The proposed UMTS approach utilizes the XII-developed Radiation Endurance Ultrasonic Transducer (REUT) to afford a long-life operation for measuring temperatures at multiple points in harsh environments and under the types of conditions generally present in nuclear reactors and other similar applications.

In the Phase I program, XII and its collaborator successfully designed, developed and tested a UMTS prototype and demonstrated the feasibility of this approach to distributed temperature measurement along a single waveguide. The successes of the Phase I program are as follows:

- Completed a literature review and product survey of waveguide-based temperature sensors.
- Investigated different waveguide designs with frequency selective reflectors for measuring temperatures at specific points on the waveguide.
- Performed finite element analysis (FEA) simulations of the designed waveguides and adapters so as to connect the waveguides to REUT technology.
- Designed and fabricated a variety of waveguides with differently sized/shaped reflectors.
- Integrated UMTS prototypes with fabricated waveguides, adaptors, REUT sensors, and necessary electronic instruments.
- Tested UMTS prototype waveguides and conducted experiments for single-point and multi-point temperature measurements.
- Developed signal processing methods to extract temperature information from reflector responses.
- Demonstrated the proposed UMTS approach's feasibility for multi-point temperature measurements along a waveguide.

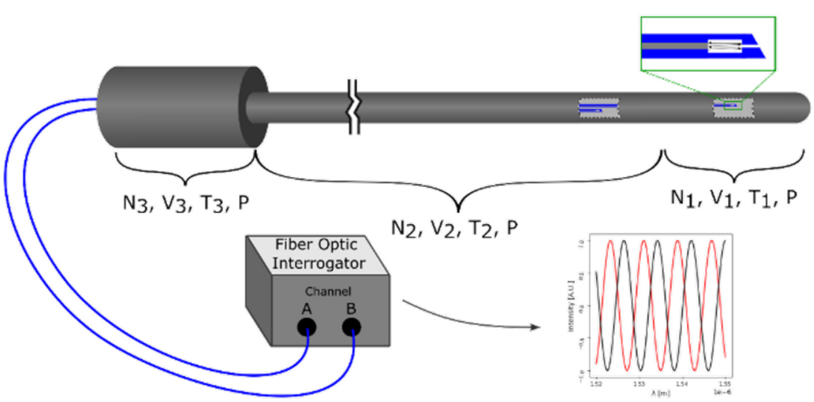
Fiber Optic Sensors

PI(s): Austin Fleming and Charles Payne – Idaho National Laboratory

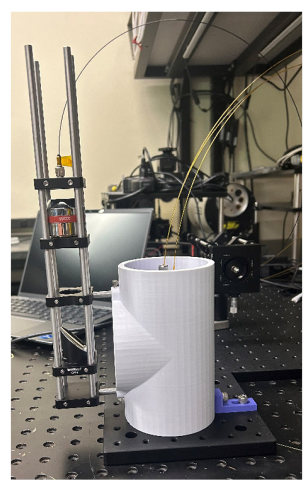
The Advanced Sensors and Instrumentation (ASI) fiber optic work package represented significant advancements in several optical fiber sensor technologies in fiscal year 2024. This included development and testing of a radiation-resistant fiber optic temperature sensor that utilizes an open Fabry-Perot interferometer, allowing the surrounding gas into the cavity. It is housed in sealed capillary tubing, with a reference volume maintained at a known temperature. The temperature sensitivity arises from the change in the index of refraction of the gas inside the cavity. The gas density changes per the ideal gas law, which in turn affects the index of refraction through the Lorentz-Lorenz law. This design allows for multipoint temperature measurement using multiple Fabry-Perot cavities. A diagram of this sensor design is shown in Figure 16a. These sensors were fabricated and tested in a furnace in a laboratory environment, showing good agreement between the experimental results and the analytical modeling of the sensor.

Significant progress was made this fiscal year in establishing in-pile imaging capabilities by using coherent fiber optic bundles. An irradiation test of an in-pile imaging system was conducted at the North Carolina State University reactor. This test utilized reflective optics for the in-core focusing optics so as to couple light into the fiber bundle. This approach proved successful in comparison to previous irradiation tests that used traditional refractive optics. The refractive optics caused the image to defocus and attenuate rapidly due to radiation-induced refractive index changes and attenuation. Such issues were not observed in the results from the North Carolina State University reactor.

In-pile fuel qualification testing is the primary use for the in-pile imaging system, especially for accident testing of nuclear fuel systems under loss-of-coolant or reactivity-initiated accidents. The Transient Reactor Test Facility (TREAT) at Idaho National Laboratory is the primary location for these in-pile tests of fuel systems. As part of this fiscal year's efforts, an in-pile imaging design was developed and prototyped so as to be compatible with the containment system in these test devices (see Figure 16b).



a)



b)

Figure 16: (a) Diagram of the developed radiation-resistant temperature sensor. (b) Prototype of the in-pile imaging system that is compatible with the accident fuel testing platforms in the TREAT facility.

Mechanisms Driving Radiation-Induced Drift and Attenuation of Fiber Optic Sensors

PI: Christian M. Petrie – Oak Ridge National Laboratory (ORNL)
Collaborators: Bryan Conry, Yan-Ru Lin, J. Matthew Kurley, Sabrina Calzada, Eddie Lopez-Honorato, Daniel C. Sweeney – ORNL

Project Description: This project evaluated the origins of some of the most important radiation-induced phenomena that limit the applicability of fiber optic sensors for various nuclear applications, including radiation-induced attenuation (RIA) of the light signal and drift of the sensor that cannot be separated from the desired measurand. Our hypothesis was that drift of fused silica optical fibers was dominated by decomposition and subsequent compaction of the polymeric fiber optic sensor coatings. Similarly, RIA in single crystal sapphire, which could enable higher temperature sensing, was hypothesized to be dominated by Rayleigh scattering of light from radiation-induced voids that form at higher temperatures.

Impact and Value to Nuclear Applications: This work fills critical data gaps regarding RIA and drift, including the mechanisms that govern them, which is important for developing mitigation strategies that could make these sensors viable candidates for deployment in nuclear energy systems.

Recent Results and Highlights: Polymer-based coatings (polyimide and acrylate) thermally decomposed under the inert conditions used in previous irradiation experiments and formed a glassy carbon that was well-bonded to the fiber.[1] Models showed that compaction of the glassy carbon under irradiation transfers a compressive strain to the fiber, agreeing well with the radiation-induced drift measured previously,[2,3] confirming our hypothesis (Figure. 17) and highlighting the importance of removing these coatings prior to irradiation. Transmission electron microscopy of previously irradiated single-crystal sapphire samples showed both voids and dislocation loops.[4] Calculated RIA from the measured distributions of each microstructural feature led to the conclusion that although voids were not the reason for the observed RIA, contributions from dislocation loops agreed much better with the experimental RIA measurements. The increased confidence in the origins of the RIA casts further doubt on the feasibility of using sapphire optical fibers for in-core applications unless an appropriate dose/temperature regime can be identified in which dislocation loops are much smaller and less prevalent.

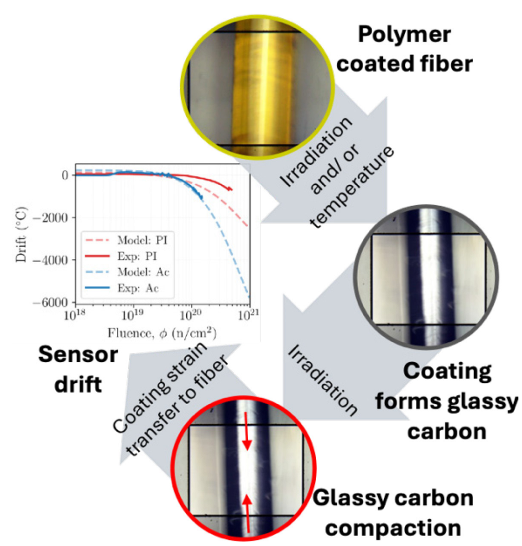


Figure 17: Process by which radiation effects in acrylate (Ac) and polyimide (PI) fiber coatings

[1] B. Conry, J. M. Kurley, D. C. Sweeney, and C. M. Petrie, "Glassy Carbon Formation from Pyrolysis of Polymeric Fiber Optic Sensor Coatings," *Mater. Des.*, under review.
[2] C. M. Petrie and D. C. Sweeney, "Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage," *J. Non-Cryst. Solids* **615** (2023) 122441.
[3] D. C. Sweeney and C. M. Petrie, "Dopant, coating, and grating effects in silica optical fibers under extreme neutron irradiation," *J. Non-Cryst. Solids* **646** (2024) 123228.
[4] Y. Lin, S. Calzada, C. M. Parish, and C. M. Petrie, "Origins of Radiation-Induced Optical Attenuation in Neutron-Irradiated Single-Crystal Sapphire at Elevated Temperatures," *J. Nucl. Mat.*, under review.

Non-contact Strain and Displacement Monitoring for Fuel Cladding Burst Detection

PI(s): Gary Pickrell and Anbo Wang – Virginia Tech
Collaborators: Idaho National Laboratory

Project Description: The objective of this research program is to develop and demonstrate a burst-onset detection system for monitoring the health and condition of nuclear fuel cladding. A fiber optics-based non-contact displacement and strain sensing system will be designed and constructed per specifications derived from a technical survey. The sensor interrogator and sensing algorithms will be integrated with the measurement probe and demonstrated via laboratory scale testing. Ultimately, a prototype sensing system will be deployed and tested at an agreed-upon national lab test facility.

Impact and Value to Nuclear Applications: Displacement, strain, and creep measurements performed on standard specimens under irradiation is of prevailing interest to the nuclear community from both a scientific and an engineering perspective. Fuel cladding integrity is a primary focus of safety testing, and remains a significant research priority for the Advanced Fuels Campaign. The non-contact displacement sensing system will support evaluation of accident-tolerant fuel candidates under simulated loss-of coolant accident conditions in order to support licensing of these materials and foster a better understanding of high-burnup fuel fragmentation, relocation, and dispersal in the event of cladding failure.

Recent Results and Highlights: A fiber optic interferometric sensing approach was selected based on a technical survey, and its feasibility was successfully demonstrated via exhaustive experimentation and theoretical modeling. Sensor interrogation schemes and algorithms were developed in concert with the design and construction of measurement probes packaged with multiple fiber optic sensing elements. Non-contact displacement measurements and the detection of tube bursting events were demonstrated via laboratory-scale testing, and calculation of the surface strain was enabled via use of a "triple sensor" probe. The successful laboratory demonstration of the proposed sensor set the stage for testing a prototype system in a nuclear reactor at an agreed-upon national lab test facility.

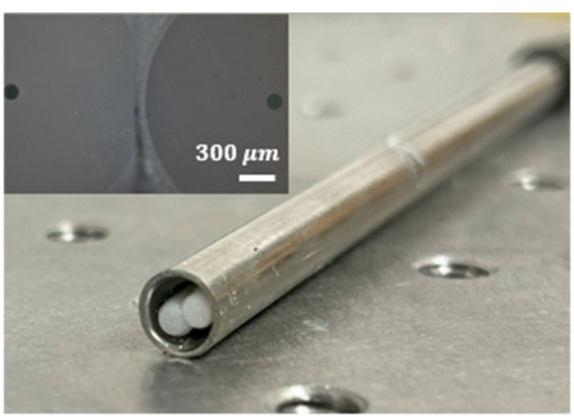


Figure 18: "Laboratory standard" dual fiber optic displacement sensing probe. (Insert) Microscope image of optic fiber polished endfaces.

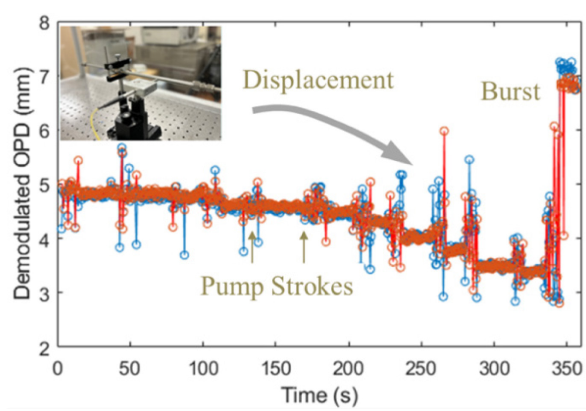


Figure 19: Demodulated response of the dual fiber optic probe sensor upon stainless steel tube expansion and burst. (Insert) Laboratory-scale test setup at Virginia Tech.

Fiber-optic Sensor System for Multi-point Pressure and Temperature Measurement

PI: Qiwen Sheng – Nusenics, LLC
Collaborators: Ming Han and Hasanur R. Chowdhury – Nusenics, LLC

Project Description: The goal of this project is to develop a fiber-optic sensor system for multi-point pressure and temperature measurement in nuclear power plants (NPPs). Each of the proposed sensors consists of a Fabry-Perot (FP) interferometer formed by a pair of identical fiber Bragg gratings (FBGs) fabricated in a side-hole fiber, which is a micro-structured single mode fiber with two holes located symmetrically on opposite sides of the fiber core.

Impact and Value to Nuclear Applications: The sensor system proposed in this program will significantly improve the resolution of the monitoring system used for temperature and pressure measurements, affording us a useful tool for diagnosing the NPP's operation status. In addition, the proposed sensor system carries the potential to be used in the new generation of nuclear reactors considering the need for highly accurate temperature and pressure measurements. Also, a novel *in-situ* calibration method for pressure measurement is utilized by the proposed sensor system to eliminate radiation-induced sensor drift.

Recent Results and Highlights: Nusenics, LLC has successfully constructed an interrogation system capable of simultaneous pressure and temperature measurements for multiple sensors, and of sensor performance characterization at different pressure and temperature levels in a laboratory environment. For the pressure measurement, the sensors show a pressure sensitivity of 17.2 – 18.7 pm/kpsi, and a resolution of <1 psi at up to the tested maximum pressure level of 1000 psi at different temperature levels. For the temperature evaluation, the sensor has a sensitivity of 11.5 pm/°C and a resolution of < 0.01°C at different temperature levels, up to the tested maximum of 300°C. The system also shows good repeatability and low temperature cross-sensitivity. Nusenics, LLC also studied the proposed in-situ calibration method, which shows a pressure stability of 17.4–19.0 pm/kpsi. The calibrated sensor pressure sensitivities are all very close to the tested pressure sensitivity, thus the sensitivity derived from the in-situ calibration method can be directly employed as the sensor pressure sensitivity.

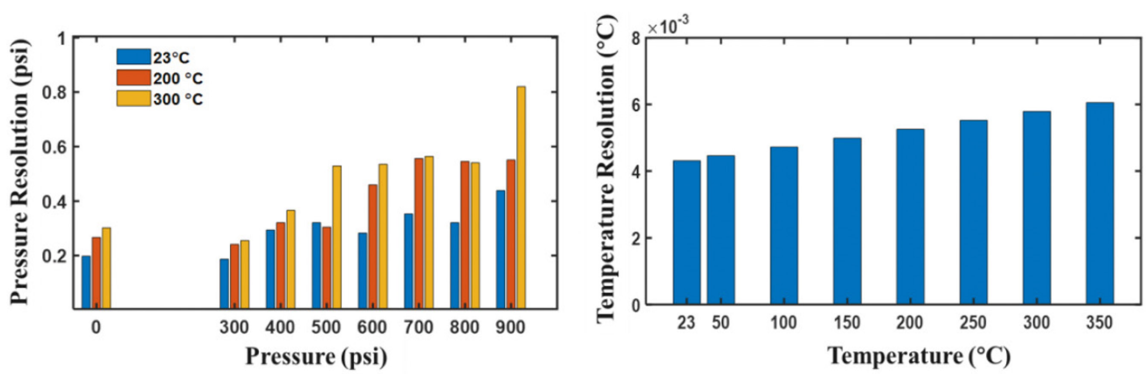


Figure 20: (Left): Sensor pressure resolution vs. pressure at different temperature levels. (Right): Sensor temperature resolution at different temperature levels.

Scaled Reduced Mode Sapphire Fiber Production (RMSF) Towards High Temperature Radiation Resilient Sensors

PI: Derek Rountree – Luna Innovations, Inc.

During this DOE STTR Phase I award, Luna and The Ohio State University (OSU) have made significant advances toward scaled production of innovative reduced mode sapphire distributed sensors utilizing the novel approach for generating reduced mode sapphire fiber (RMSF) developed at OSU. During the period of this effort, Luna and OSU:

1. Demonstrated packing of greater than 18 meters of multi-mode 100 μm and 75μm sapphire fibers with a $^{6}Li_2CO_3$ annuli for transmutation to RMSF in the Massachusetts Institute of Technology Nuclear Reactor Laboratory's Neutron Transmutation Doping of Silicon 6TH1-2 facility.
2. Demonstrated unpacking of sapphire fibers in irradiation fixtures with no breakage.
3. Evaluated the index profile of RMSF from earlier production.
4. Developed heat treatment methods for bulk treatment of post irradiation transmutated fibers.
5. Advanced methods for cladding mode stripping
6. Advanced manufacturing of RMSF towards processing cost reduction by an order of magnitude per meter of RMSF.

This effort has proven that the single-mode light propagation has been achieved in an internally clad sapphire fiber and represents the first practical implementation when compared to the literature. The sensor advancements made during this Phase I effort have demonstrated the feasibility of OSU's RMSF technology for nuclear applications and aided in identifying a path towards advanced sensors for high radiation, very high temperature, and high corrosion markets moving forward. Specifically for Gen IV nuclear reactor development, we expect the Phase II award to advance sensor and interrogator development and analysis techniques to the level where they provide critical feedback for advanced fuel tests at Idaho National Laboratory's Advanced Test Reactor (ATR) and Transient Reactor Test (TREAT) facilities. Beyond nuclear fission reactors, the concentrated solar power industry and fusion energy reactors have expressed considerable interest in such sensors for high-temperature molten salt environments.

Fiber-embedded Wireless Sensors

PI: Joseph Pegna – Free Form Fibers
Collaborators: Thomas Budka – RF Diagnostics

This project seeks to innerve composite structures by using multifunctional structural reinforcement fibers as the substrate for device integration. Our aim is to achieve levels of functional integration comparable to current microelectronics and skin nerve endings. Of course, this will require the ability to mass produce extremely low-cost devices that can be interrogated absent of physical wiring.

A sample fiber integrated device vehicle is proposed here seeks to demonstrate the first-ever prototype of a wireless thermocouple fully integrated into a silicon carbide fiber. Phase I of this work addresses the demonstration of an integrated transducer—namely, a molybdenum (Mo)-niobium (Nb) thermocouple or thermopile. Phase II targets the demonstration of a wireless fiber integrated transmitter based on a novel Gunn diode architecture.

The Phase I goal has been achieved. A junction between two thin films of Mo and Nb was deposited onto a silicon carbide fiber via laser-induced chemical vapor deposition. The resulting structure was evaluated in a house-built environmental chamber, see the figures below.

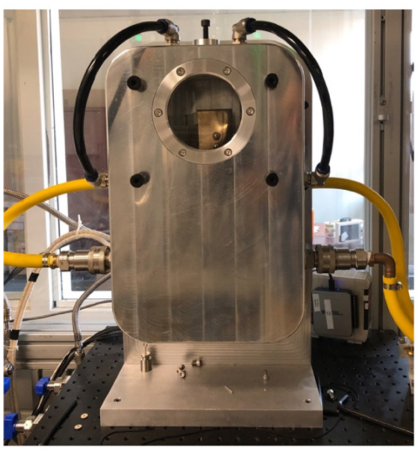


Figure 21: Using a 1700°C-capable MXI microheater cell to ensure a symmetrical thermal field.

Figure 22: The Mo-Nb junction was characterized.

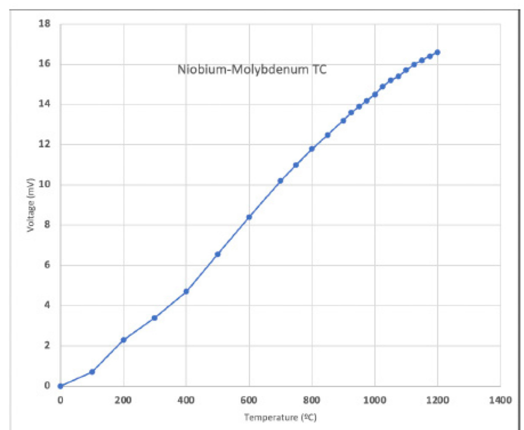


Figure 23: Found comparable to published data on thermocouples made out of similar materials.

Integrated Stand-Off Optical Sensors for Molten Salt Reactor Monitoring

PI: Kevin Chen – University of Pittsburgh

This project will develop a single radiation-hardened fused silica rod as the optical port to remotely access reactor cores or flow loops. The integrated stand-off optical sensors can perform coolant level, flow rate, and metal impurity characterization in real time to ensure safe, efficient operation of molten salt reactors (MSRs).

This project would produce low-cost laser sensing instrumentation for highly accurate, real-time measurements of MSR coolant levels, flow rates, and metal impurities—measurements previously impossible. The success of this project will provide nuclear industry engineers and national laboratory scientists a set of powerful sensor tools to harness real-time data crucial for safe, efficient operation of MSRs. This project will drastically improve the technology readiness levels (TRLs) of proposed optical sensors and sensor instrumentations, thus helping them progress toward TRL5. In Year 1:

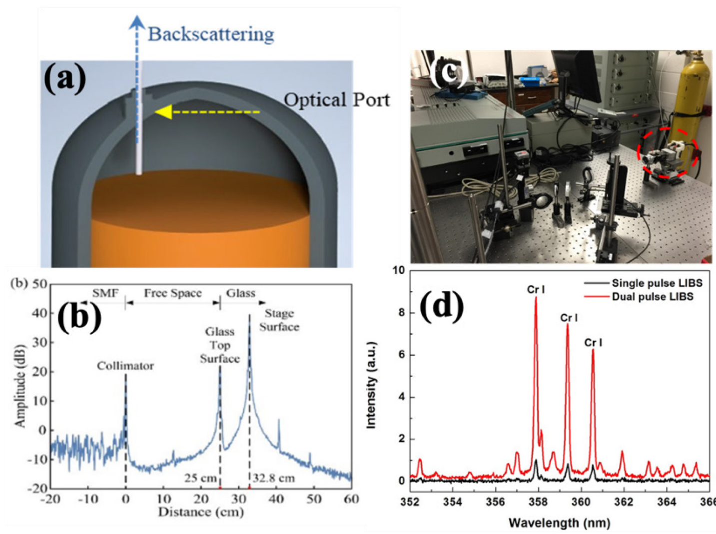


Fig. 24: (a) Schematic OFDR Lidar level sensing, (b) representative measurement of molten salt level measurement, (c) photo of a dual-pulse LIBS system, and (d) over ten-times enhanced LIBS signal using a dual-pulse LIBS in the detection of Cr.

- We completed the first milestone and performed a detailed numerical analysis of OFDR LidAR performance amid mode hopping. The results show that liquid-level sensing at molten salt conditions can be achieved within 1-mm accuracy, even with random mode-hopping

- We developed a VCSEL control circuit board that effectively controls a tunable VCSEL with a scanning rate of 100kHz. Continuous scanning operation has validated the device's performance over a time period of 2 days.

- We constructed a simulated flow loop to perform flow measurements using OFDR LidAR.

- Dual-pulse laser-induced fluorescent spectroscopy (LIBS) has been developed for ultra-high sensitivity metal element detection and quantification in molten salts.

Acknowledgements:

1. Qirui Wang, Guangyin Zhang, Kehao Zhao, Jieru Zhao, Shuda Zhong, and Kevin P. Chen, "Real-Time Airborne Particle Density Detection with High Spatial Resolution Using OFDR LiDAR", CLEO2024 DOI:10.1364/CLEO_AT.2024.ATh3E.2 (2024).
2. Qirui Wang, Nageswara Lalam, Ruishu Wright, and K. P. Chen, "Analysis of mode hopping impacts on OFDR sensing performance," Photonics, DOI: 10.3390/photonics11060580(2024)
3. Y. Li, J. Zhao, G. Ma. S. Zhong, M. Buric, M. Li, and K. P. Chen "Low-cost Multi-point Raman Fiber-optic Temperature Sensors Enabled by CCD Cameras," in Journal of Lightwave Technology, doi: 10.1109/JLT.2024.3443749 (2024).

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

PI: Alexander Heifetz – Argonne National Laboratory (ANL)
Collaborators: Sasan Bakhtiari – ANL
Anthonie Cilliers – Kairos Power

Project Description: We are investigating a microwave-cavity-based transducer for high-temperature fluid flow sensing. This sensor is a hollow metallic cavity that, can be fabricated from stainless steel and is thus expected to be resilient to the high radiation, high-temperature, corrosive environments of sodium fast reactors (SFRs) and molten-salt reactors (MSRs). A viable geometry for this sensor is that of a small cylindrical resonator. The principle behind the sensing consists of making one wall of the cavity flexible enough that dynamic pressure, which is proportional to fluid velocity, will cause membrane deflection. A cavity is characterized by its resonant frequencies, which occur due to constructive interferences of the microwave field inside the cavity. Membrane deflection causes cavity volume changes and, thus, shifts in the resonant frequency. Using the signal readout from the microwave frequency shift in a hollow cavity is advantageous for applications in high-temperature and high-radiation environments, because no electronic components are placed inside the transducer. Energy coupling to and from the sensor is achieved via 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, a waveguide can be designed to be compatible with the thermocouple capillaries of an instrument tree.

Impact and Value to Nuclear Applications: High-temperature fluid reactors such as SFRs and MSRs are a promising advanced reactor option with a highly efficient thermal energy conversion cycle. Streamlining the commercialization of advanced reactors involves 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, including high levels of radiation, high temperatures, and contact with highly corrosive coolant fluids. Since the microwave cavity sensing is based on the fluid-structure interaction, as opposed to fluid electrical conductivity, the proposed sensor is equally applicable to liquid sodium and molten salt flow sensing.

Recent Results and Highlights: We have identified an existing liquid sodium experimental setup for demonstrating flow sensing in an environment similar to that of an advanced reactor. The setup consists of a cylindrical vessel and center feed line, where a transducer inserted through the lid will measure the velocity of the impinging liquid jet (see Figure 25a). We developed a cylindrical resonant cavity whose length and diameter are equal to 22.2 mm. The cavity was machined from stainless steel 316 (SS316) and then silver-plated on the interior. The cylindrical cavity was excited via a subwavelength hole on the side of the cylinder wall, with a 50 cm brass WR-42 waveguide enclosed in a protective SS-316 tube. A photograph of the transducer is shown in Figure 25b. The assembly was installed in a liquid sodium vessel. The cylindrical cavity was excited in the TE_{011} mode with resonant frequency $f \approx 17.8$GHz. The frequency shift of the cavity spectral response was obtained by gradually increasing the power of the liquid sodium pump. The corresponding monotonic increase of resonant frequency was observed to shift by several hundred kHz (see Figure 25c).

Images/graphs/charts:

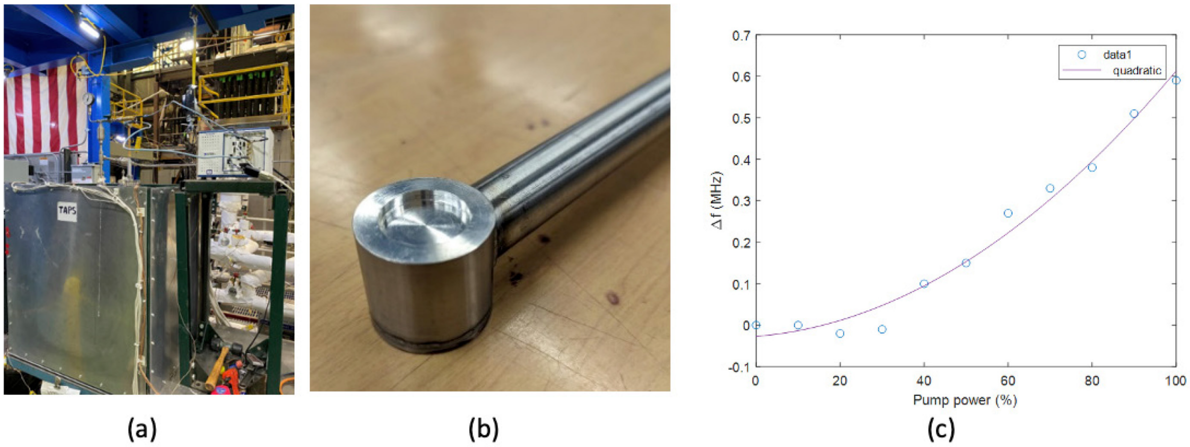


Figure 25: (a) Liquid sodium vessel. (b) Stainless-steel transducer compatible with a high-temperature fluid environment. (c) Preliminary results of flow sensing in liquid sodium at 350°C.

Thermometry

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

Complete characterization of advanced insulation materials for use in advanced nuclear sensors for high temperature applications – This task focused on the development of high-temperature (> 2000 °C) insulation materials for nuclear instrumentation (e.g., thermocouples, ultrasound thermometry, and SPNDs). The primary goal of the project is multifaceted and includes assessments of thermodynamic behavior, relevant temperature-dependent properties (electrical resistivity and thermal conductivity), neutronic properties, chemical stability, and advanced manufacturability. A primary need is the manufacturability and/or advance manufacturing capabilities for such technical ceramics, which includes consideration of oxide insulators as well as non-oxide materials such as aluminum nitride (AlN), silicon carbide (SiC), etc. The high-temperature insulator materials enable sensors to reach higher temperatures without influencing (or with minimal effect on) their nature of function during extended operation. The main tests were performed on thermocouple-relevant materials, but the advanced insulation materials apply to other sensors as well. Accordingly, materials selected as benchmark materials are those that Idaho National Laboratory (INL) has developed (i.e., the high-temperature irradiation-resistant thermocouples [HTIR-TCs]) - for temperature sensing in Generation IV nuclear reactors. These thermocouples are composed of phosphorus-doped niobium (Nb-P) and lanthana-doped molybdenum (Mo-LaO) thermoelements, an alumina (Al2O3) insulation, and a niobium sheath. The stability of alternative high-temperature ceramic insulators was investigated with HTIR-TC relevant materials. Per previous work, niobium was found to be the culprit behind much of the sensor instability stemming from high-temperature and extended-duration experiments.

Down selection of insulation materials was performed based on programmatic interest, thermodynamic predictions, electrical resistivity, and thermal conductivity at elevated temperatures, and empirically determined chemical stability with niobium and molybdenum. Diffusion couples between insulation materials (AlN, SiC, H-BN, and ZrO2) and niobium were investigated at temperatures of up to 2000 °C. Adverse reactions were found in AlN, SiC, and H-BN systems at 1700 °C, and a clear liquid phase formed in the SiC-Nb diffusion couple at 2000 °C.

In addition to the discussion above, advanced manufacturing techniques were trialed in order to make porous (and therefore crushable) insulation with complex geometries. Two techniques were investigated: (1) digital light processing and (2) powder packing of thermocouple geometries. The latter has led to a patent application, now currently under review.

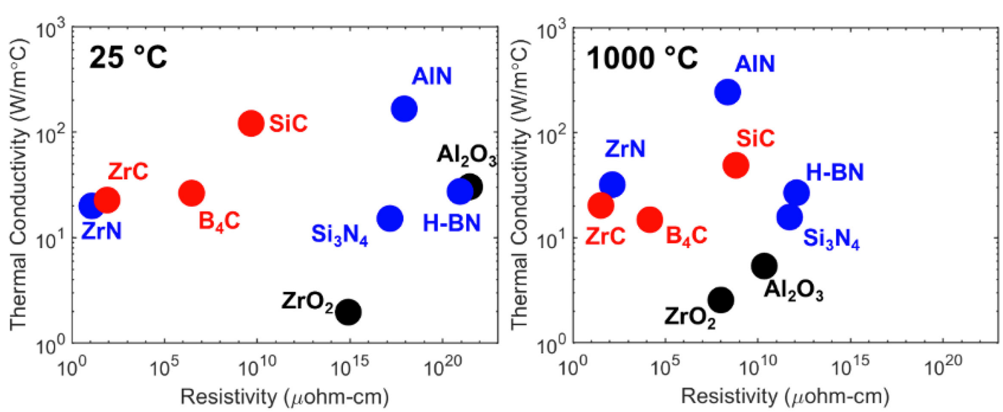


Figure26: Ashby plots showing the relationship between the electrical resistivity and thermal conductivity of relevant insulator materials at 25°C and 1000°C. Notable that the fact that electrical resistivity significantly decreases with increasing temperature is an important consideration for sensor development.

Mechanisms Engineering Test Loop Facility (METL) Sensor Test

PI: Richard Vilim – Argonne National Laboratory

Project Description: Several liquid metal reactor (LMR) systems are currently under development in the U.S. The deployment of these reactor concepts comes with unique measurement requirements. This project reviewed and identified sensor qualification needs of the LMR industry. Items of interest are sensors for high-temperature liquid sodium measurements. Liquid metal thermal hydraulic facilities already exist at Argonne National Laboratory for immersion testing of sensors in water, Galinstan and sodium. To facilitate a test article approach to high temperature qualification for non-immersion sensors, the applicability of the TAPS facility was investigated. Modifications to the facility to support this are described.

Impact And Value to Nuclear Applications: To understand the impact of high-temperature environment and ensure the facility can safely and effectively accommodate the test article approach, simulations were conducted using the COMSOL Multiphysics software. These simulations provided insights into how the facility would perform under the specified conditions, helping to identify any potential issues and confirm the facility's readiness. The findings not only validate the modified facility’s performance but also provide a clear pathway for integrating these advanced measurement devices into liquid sodium facilities, thereby enhancing measurement accuracy and operational safety.

Results and Highlights: Modifications to the TAPS facility were proposed to incorporate a test article within the piping system, allowing vendors and national laboratories to test flow and pressure sensing devices under high temperature conditions. The test article is flanged into the test section as shown below. This enhancement will enable the facility to accommodate various sensor designs for rigorous testing and validation, supporting a robust array of measurement technologies. To calibrate newly designed sodium flowmeters, a Coriolis flowmeter needs to be integrated into the same flow loop such that the Coriolis meter acts as the reference standard.

Results of the thermal stress analysis conducted on the vessel and piping, including the test article, within the upgraded facility under high-temperature conditions of 600 °C were reported. As a major outcome, the analysis confirmed that there are no mechanical issues resulting from the modifications made to the facility structure under the new environmental operating conditions.

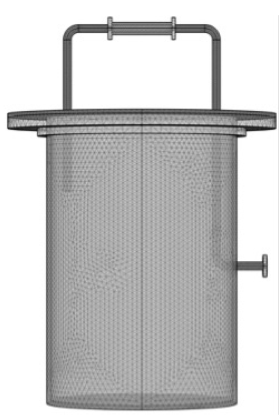


Figure 27: Mesh for thermal and structural analysis of TAPS Vessel and test article

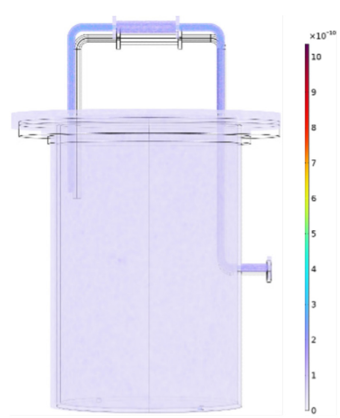


Figure 28: Graphical representation of Von Mises stress of TAPS vessel and test article at operating conditions

Optical Sensors for Impurity Measurement in Liquid Metal-cooled Fast Reactors

PI: Milos Burger – University of Michigan
Collaborators: Edward Kent – Argonne National Laboratory
Igor Jovanovic – University of Michigan
Robert De Saro – Energy Research Company

Project Description: Advanced sodium-based liquid metal-cooled fast reactors (LMCFRs) require a sodium purity monitoring technology that addresses the limitations of traditional plugging meters. An ideal instrumentation would not only provide accurate readings of sodium purity but also directly detect other impurities that may indicate system degradation, such as those from structural components, fuel cladding, or fission products. The primary goal of this project is to evaluate the potential of optical techniques for sensitive, robust, and convenient in-situ, real-time detection of trace impurities in liquid sodium coolant, with a particular focus on the unambiguous monitoring of oxygen levels. A secondary goal is to conduct preliminary assessments of these sensors' ability to detect other impurities typically associated with sodium-based LMCFRs.

Impact and Value to Nuclear Applications: The integration of such technology as embedded, real-time, in-line sensors (capable of operating at high temperatures and in intense radiation fields) could greatly enhance the safety and lifespan of future LMCFRs.

Recent Results and Highlights: Development and validation of the LIBS setup (Figure. 29a) was completed at the University of Michigan (UM), in consultation with Argonne National Laboratory (ANL) and the Energy Research Company (ERCo). The optical sensor system, which uses laser-induced plasma, demonstrated its ability to generate and detect spectral emissions that resemble the composition of molten sodium (Figure. 29b). Identification of distinct sodium and oxygen spectral lines (Figure. 29c) highlights the system's potential for analytical measurements. Upcoming research will focus on refining recording parameters and applying calibration procedures to enhance our interpretation, such as extracting species concentrations and observing their temporal behavior in the plasma environment. Aside from consulting, an additional contribution is the development of a system that will be used to pull a sodium sample from the METL facility to deliver to the UM team. The impurity levels in the METL sodium are quantified and are well below those of commercially available sodium samples. This affords clean sodium that will represent the lower level of impurity detection, as well as produce the clean sodium whose impurity levels can be incrementally increased by the addition of solid sodium hydroxide.

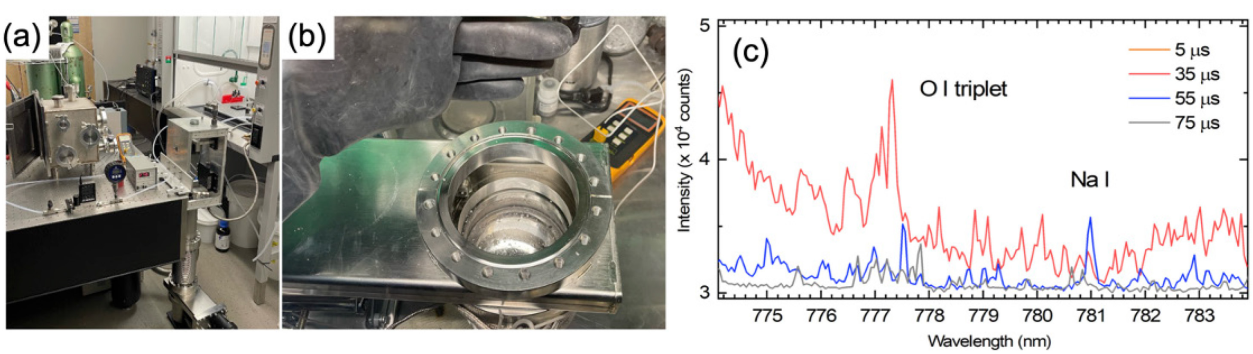


Figure 29: (a) Liquid-sodium test assembly at UM (b) Liquid sodium sample preparation inside the glovebox. (c) Spectral signatures of atomic oxygen and sodium from laser-induced plasma

Linear Variable Differential Transformers

PI: Kurt Davis – Idaho National Laboratory (INL)
Collaborators: Malwina Wilding, Geran Call, Austin Fleming, and Chase Case – INL
Michael Marciante – Newtek Sensors Solutions

Project Description: A linear variable differential transformer (LVDT) is an electromechanical transducer that converts the motion of an object into a corresponding electrical signal with submicron motions. Many phenomena produce, or can be used to produce, length changes that can in turn be measured and converted into a measurement of the phenomenon (e.g., pressure and temperature). The commercial LVDT has proved robust and versatile, but falls short when used at elevated or fluctuating temperatures, or when irradiated (because of the materials used in its construction). In fiscal year 2023 and 2024, our research was dedicated to the development and qualification testing of a commercial prototype LVDT. This specific LVDT was created by a reputable U.S. supplier, Newtek Sensor Solutions, whose selection was based on recommendations from our comprehensive supply chain study. This pivotal cross-cutting development initiative aims to ensure that stakeholders have continued access to the most advanced LVDT-based technologies for deployment in forthcoming irradiation tests. Additionally, our research group at Measurement Science Laboratory (MSL) figured out a way to enhance the Institute for Energy Technology (IFE)'s miniature LVDT with inherent temperature monitoring capabilities.

Impact and Value to Nuclear Applications: The fact that IFE stands as the world's only source of reactor-grade LVDTs for in-pile testing needs makes the global nuclear research community vulnerable to LVDT supply limitations. In recognition of this critical need, our current research endeavors to enhance our comprehension of LVDT performance via future irradiation tests, while also diversifying the LVDT supplier base. Additionally, expanding the LVDTs to not only measure in-pile pressure or elongation, but also temperature as well, frees us from the need to use thermocouples (and provide space for their feedthroughs) during complex and costly instrumented experiments.

Recent Results and Highlights: We evaluated two LVDT prototypes from Newtek Sensor Solutions as showing promise as viable alternatives to the IFE-manufactured LVDTs. Testing occurred in the out-of-pile INL LVDT calibration furnace, where the first prototype failed at 400℃ and the second failed at 450℃. However, the second prototype's internal parts (no encapsulation) successfully tested at up to 700℃. Identified design enhancements for the encapsulation hold promise for elevating this commercial LVDT to a performance level comparable to IFE's LVDTs. The Enhanced Linear Variable Intrinsic Sensor (ELVIS) was developed and tested to measure temperatures by using the IFE's miniaturized LVDT. ELVIS II, which allows for integrated LVDT temperature sensing, provides accurate real-time temperature data in addition to the elongation/pressure measurement required for in-pile testing needs.

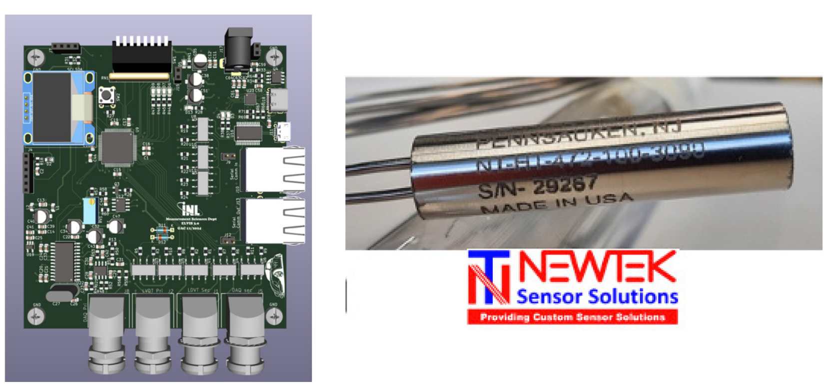


Figure 30: (Left) A computer-aided design (CAD) model of the ELVIS II board. (Right) A picture showing the commercial LVDT offered by NewTek.

Passive Temperature Monitors

PI(s): Malwina Wilding and Kiyo Fujimoto – Idaho National Laboratory
Collaborators: Rene Rodriguez – Idaho State University
Padhraic Mulligan and Anne Campbell – Oak Ridge National Laboratory

Project Description: Thermocouples are generally used to provide real-time temperature measurement in instrumented tests performed at research reactors. Passive temperature monitors (TMs), such as silicon carbide (SiC) and melt wires may also be included as an independent way of detecting irradiation temperatures. In less-expensive passive capsule tests, which have no leads attached for real-time data transmission, passive TMs are essentially the only possible means of peak temperature indication. Use of a melt wire involves placing materials (wires) of a known composition and melting temperature in an irradiation test. The wire can only detect whether a single temperature has been exceeded (the melt wire either becomes melted or it does not). The Measurement Science Laboratory (MSL) maintains an inventory of melt wires that range in temperature from 30°C to 1500°C; however, this inventory is limited when it comes to the high temperature range (700°C – 900°C). SiC TMs, which can also be used to detect peak irradiation temperatures during irradiation, are advantageous because a single monitor can enable determination of the peak temperature reached within a relatively broad range (100°C – 1000°C). Researchers observed that SiC's neutron-irradiation-induced lattice expansion annealed out when the post-irradiation annealing temperature exceeded the peak irradiation temperature. Therefore, irradiation temperature is determined by measuring a property change after isochronal annealing or during a continuously monitored annealing process using specialized equipment at MSL. However, the way we analyze each SiC TM has not been standardized in regard to the various types of research reactors, analytical equipment, and material suppliers available.

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

Recent Results and Highlights: The FY-24 work regarding melt wires centered around a scoping study to identify potential melt wire material candidates in order to expand INL's current library of commercially available melt wire materials for the 700°C-800°C range. Two melt wire candidates were identified: Cu-Ag (melts at 780°C), and Fe-Sb (melts at 748°C). Synthesis of each material candidate was performed by Idaho State University, and the final furnace testing will demonstrate the feasibility of both materials for melt wire applications. FY-24 work for SiC passive monitors investigated, in collaboration with Oak Ridge National Laboratory (ORNL), standardizing the way SiC TMs are analyzed. ORNL hosted a best engineering practices meeting that saw participation from various laboratories, universities, and international organizations. First, the dilatometry method was chosen to undergo attempted standardization; with the types of SiC material, equipment (optical and push-rod dilatometer), and research reactors all being considered.

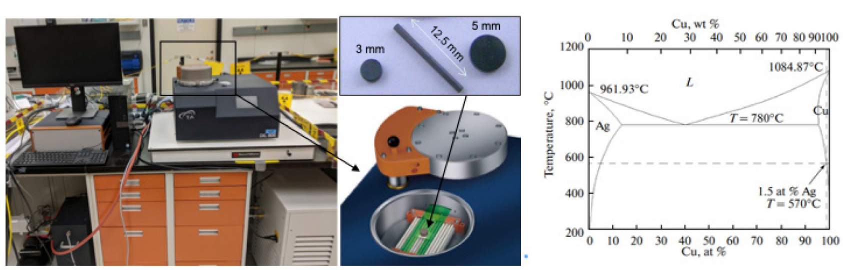


Figure 31: (Left) Optical dilatometer for processing SiC TMs at INL. (Right) Melt wire candidate that melts at 780

Passive Temperature Monitors – Silicon Carbide

PI: Padhraic Mulligan – Oak Ridge National Laboratory (ORNL)
Collaborators: Malwina Wilding – Idaho National Laboratory
Anne Campbell, Hsin Wang, and David Glasgow – ORNL

Project Description: Silicon carbide (SiC) is often used as a passive temperature monitor in irradiation experiments because it does not require instrumentation leads, can be machined into compact geometries, and provides a continuous indication of experiment temperatures between approximately 200°C–1000°C. However, widely accepted specifications for SiC material quality and post-irradiation measurement techniques have not been established. The first component of this project is to create plans for developing an ASTM standard for SiC passive temperature monitors and round-robin testing of previously irradiated SiC. The second component of this project is to apply a well-known analytical technique in semiconductor characterization—deep-level transient spectroscopy (DLTS)—to determine irradiation temperatures in single-crystal SiC temperature monitors.

Impact and Value to Nuclear Applications: In-core experiments are necessary to determine radiation effects in new materials proposed for cladding, structural components, and fuel in nuclear reactors. Measuring the temperature of these experiments is critical for understanding how thermal conditions impact these effects, and is often required to support licensing and regulatory requests. Establishing an ASTM standard for SiC passive temperature monitors will enable better comparison of experiments performed in different research reactors and will facilitate broader adoption of the technique in irradiation experiments. Developing DLTS as a SiC monitor analytical method would also enable the use of more compact SiC monitors in low-neutron-fluence experiments.

Recent Results and Highlights: The Silicon Carbide Passive Thermometry Workshop (May 8 and 9, 2024), held on the ORNL campus, included 27 attendees from the United States, international laboratories, and industry. Discussions on the various analytical methods and best practices for using SiC passive monitors were held, and a high-level plan to develop an ASTM standard and conduct round-robin testing was presented. In parallel, a DLTS instrument was commissioned and used to characterize unirradiated SiC material. Several SiC specimens were irradiated in the High Flux Isotope Reactor and will be analyzed using this instrument.

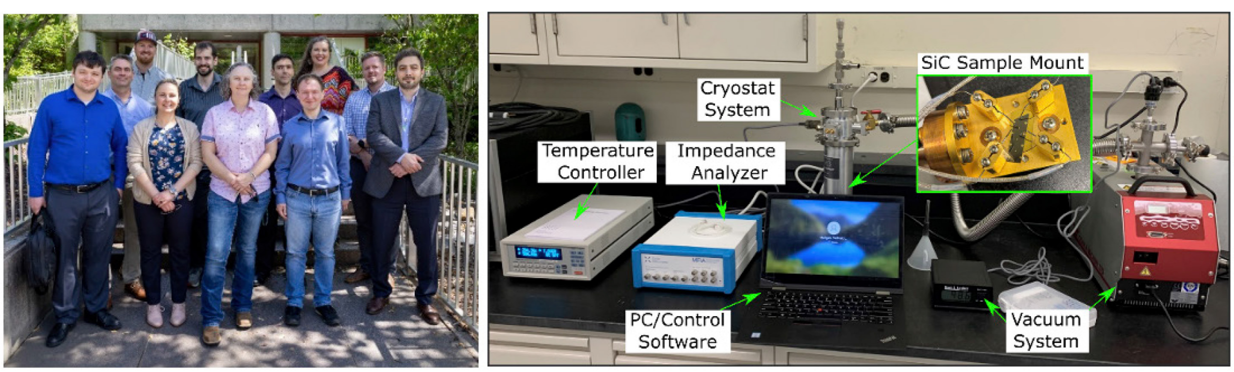


Figure 32: (Left) Attendees of the SiC passive thermometry workshop. (Right) Recently commissioned DLTS instrument.

Qualification of Advanced Sensors and Instrumentation

PI(s): Austin Fleming and Kevin Tsai – Idaho National Laboratory

Advanced reactors of many forms have been under development in the last few decades. Most will require novel and advanced instrumentation for qualification of their fuel systems and operation. Many such sensors have undergone preliminary testing in harsh environments, but few have been qualified for rigorous safety-significant applications. The Sensor Qualification activity under the Advanced Sensors and Instrumentation (ASI) program focused on establishing qualification methodologies for temperature and neutron sensors in fiscal year 2024.

The Temperature Qualification Device (TQD) underwent prototype testing in the laboratory, including testing of all critical functions. The TQD has a reference and a test zone, with sensors located in each. Retractable sensors move between these two zones to enable comparison between the reference sensors and the test sensors being irradiated, ensuring measurement traceability for the in-core sensors. Laboratory testing included evaluating the temperature distribution in the device (axially and radially) and testing the performance of the retractable sensor at temperature. The retractable sensor performed 1,350 insertion-and-retraction cycles at room temperature, and 332 at 400°C. The limiting factor at 400°C was due to aluminum galling onto the retraction sensor. Higher-temperature versions of the TQD will not be manufactured from aluminum, so even higher lifetimes are expected in future iterations. The TQD can house up to 20 sensors in total. Significant modeling efforts have been conducted to optimize allocation of these 20 sensors (as either reference, retraction, or test sensors) to provide the best estimate of in-core test sensor performance. The Armed Forces Radiobiology Research Institute (AFRRI) facility was identified as the preferred location for heated Neutron Qualification Device (NQD) sensor testing. There, the large exposure rooms, which feature cadmium-or lead-lined walls, offer significant space in which to position the test device nearby the reactor, with easy configuration of shielding or flux filters so as to tailor the spectrum of interest. A conceptual design of a heated test setup was developed, including Monte Carlo N-Particle (MCNP) modeling of the device to provide a uniform flux between the neutron sensors undergoing evaluation and the reference dosimetry. These efforts will ensure that the facilities and devices are ready to qualify the performance of advanced sensors for reactor control and fuel qualification.

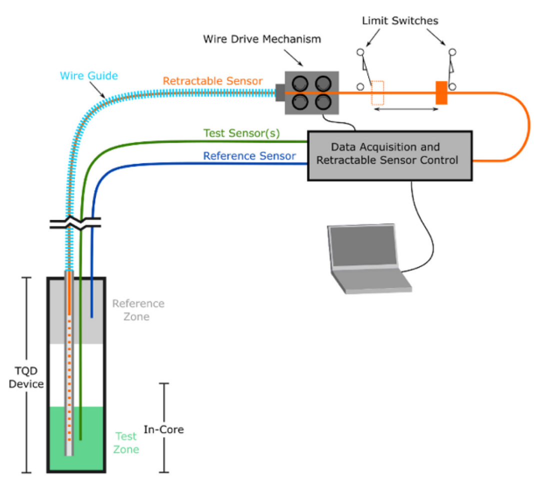


Figure 33: Diagram of the TQD.

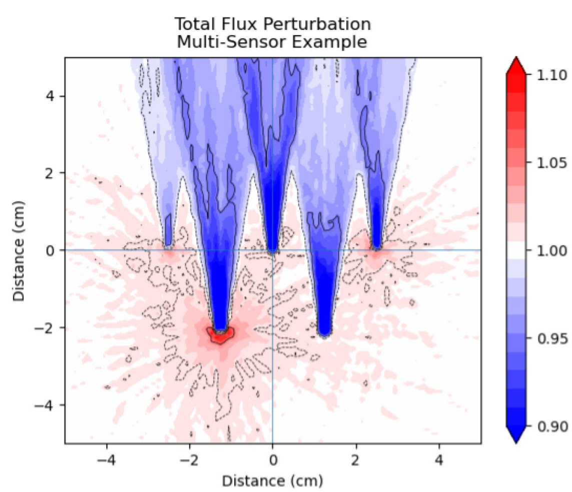


Figure 34: MCNP modeling of the sensor placement in the NQD.

Advanced Controls
FY 2024 Accomplishments

PI: Richard Vilim – Argonne National Laboratory

Project Description: This project investigated the possibility of developing an innovative approach for monitoring and managing core performance for micro reactors and advanced reactors. To reconstruct the power distribution within the core, a technique combining physics-informed machine learning, high-fidelity modeling and real-time ex-core measurements are being developed, thereby reducing the dependence on in-core detectors. The project selects Purdue University Reactor Number One (PUR-1), an operating small light water reactor, as the target of high-fidelity modeling and the testbed for planned demonstrations.

Impact And Value to Nuclear Applications: Traditional techniques for reconstructing power distribution in Light Water Reactors need ~102 sensors placed at various positions within the core. However, this approach cannot be applied to Advanced Reactors or Microreactors due to the harsh environment and limited space, respectively. ANL-Purdue team aim to reconstruct the power distribution with reduced dependence on in-core sensors, which paves a way for a non-intrusive core monitoring approach that only needs ex-core sensors. It will enhance the reactor economic performance via reduced fuel cycle cost by improving fuel utilization and outage scheduling, increased energy production by recovering thermal margin, and increased radioisotope production efficiency.

Recent Results and Highlights: High-fidelity neutronics models were developed to generate datasets for the data-driven algorithm. Specifically, the latest PUR-1 core configuration was modeled in MCNP6 first, and then migrated to OpenMC for future burn-up calculation. Both models were validated against data collected during an experimental campaign in July 2024, in which thirty gold foils were placed in three Irradiation Assemblies within the PUR-1 core, and the neutron flux at various core locations was estimated based on the measured activity of the irradiated foils. A satisfactory agreement was observed between the collected data and the virtual sensors mimicking the response of in-core sensors (Figure 35).

In addition, the theoretical formulation of power reconstruction algorithm is investigated. The algorithm is inspired by Kirchhoff-Helmholtz (K-H) Integral Equation, which is widely used in inferring the acoustic wave propagation in a field using the measurements on the boundary. The same equation can also be used for neutron field reconstruction, where Green's Function is the key ingredient for linking the boundary measurements and field variables. In complicated geometries, Green's function can be more efficiently represented by the parameters of Convolutional Neural Networks (CNN), and a prototype of network is proposed (Figure 36).

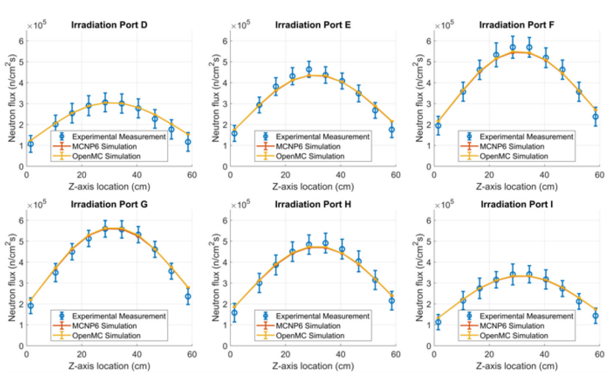


Figure 35: Comparison between simulated and measured neutron fluxes

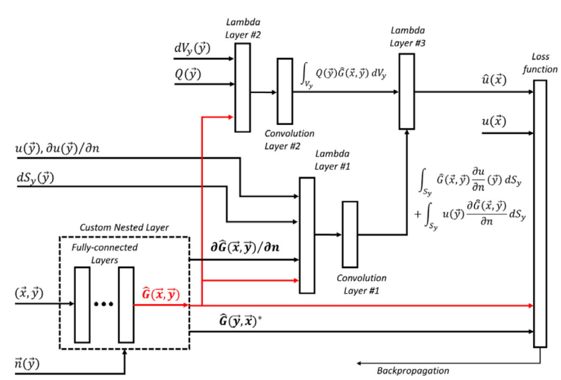


Figure 36: CNNs proposed for achieving a numerical approximation of Green's Function

Transitioning Control Methods from Simulation to Real-World Setups for Advanced Nuclear Reactors

PI: Ahmad Al Rashdan – Idaho National Laboratory

Advanced nuclear reactors are vital to the future of energy in the United States and worldwide. Unlike the current fleet, these reactors will be deployable in remote locations and will be expected to operate semi-autonomously or autonomously. This advancement necessitates a new reactor control paradigm.

As these reactors are still under development in the United States, control methods for autonomous operations have primarily been developed through systems modeling and simulation. However, successful deployment of these methods hinges on their ability to transition seamlessly from simulation to real-world application. In fiscal year (FY) 2024, the Department of Energy (DOE) Advanced Sensors and Instrumentation (ASI) program investigated this critical transition by comparing control performance in simulation vs a real-world setup.

To conduct this comparison and analyze the impact of unmodeled or unexpected dynamics in real-world setups on control performance, an experimental reactor testbed was required. The DOE Microreactor Program has been working on developing a non-nuclear testbed to support microreactor control research. Although this setup is not an actual nuclear reactor, our DOE ASI program augmented it with real reactor physics models from INL's Microreactor Applications Research Validation and Evaluation (MARVEL). This leveraged a control-dedicated platform also developed by our ASI program in FY-23 and FY-24, resulting in a testbed considered a physical twin to MARVEL.

Using this augmented testbed, we designed a power-following controller for an advanced reactor and tested it to evaluate how control methods would transfer from simulations to the testbed. While the controller performed well in simulations, the overall system performance degraded when applied to hardware. Specifically, larger error values were observed between the reactor's power response and the desired power, along with persistent oscillations in reactor power. In addition, several factors were introduced that were expected to be present throughout the lifecycle of real plants, including actuator aging and realistic communication or processing delays, thereby further exacerbating these issues. In conclusion, controllers developed solely through theory and simulation often do not perform as expected in real-world applications, potentially leading to unacceptable behavior when transitioned into real reactor settings.

Future iterations of this work will be aimed at understanding the discrepancies between simulated and real-world performance in advanced nuclear reactors, and at developing advanced control methods that are likely to succeed when deployed. This is especially critical because the controllers' performance degrades due to reactor aging, particularly if the reactors are to operate for years, and because we plan to use artificial intelligence to tune these controllers to compensate for this aging, with minimal human intervention. This will enable the industry to design more reliable, more effective control systems.

Development of Cable Insulation Materials for Advanced Reactors

PI: Casey Sexton – AMS
Collaborators: Trevor Toll, Patrick Ward – AMS

Project Description: In general, industry experts do not know if insulation materials currently used in nuclear power plant cabling can meet the demands of new advanced reactor environments or if novel materials must be developed. Due to the variety of environmental conditions/stressors expected in advanced reactors, there will not be a single type of insulation material that is suitable for all cables and applications, and it is likely several classes of materials (i.e., polymers, composites, ceramics) will be needed to meet the demands of advanced reactor environments. This project aims to supply reactor developers and cable manufacturers with the tools and information required to identify and select cable materials suitable for their reactor environments and service conditions or create new cable constructions where existing options are insufficient.

Impact and Value to Nuclear Applications: Challenges related to the survival of advanced reactor cabling under thermal, moisture, and radiation exposure must be addressed. Significant R&D has been performed in the areas of degradation and condition monitoring of cable insulation exposed to harsh environmental conditions. However, this work has been focused on cables and environments found in existing light water reactor (LWR) designs. Additionally, while much research is being performed on advanced instrumentation and control (I&C) sensors, there is less time and attention being devoted to the cabling that will connect them to processing electronics and power sources. This project will ultimately aid in filling these knowledge gaps and help advanced reactor designers in their continued push for regulatory approval and deployment within the next decade.

Recent Results and Highlights: This project, being performed through the Department of Energy (DOE) Small Business Innovation Research (SBIR) program, began in June of 2022. It has consisted of: 1) acquiring a wide selection of candidate insulation materials, 2) exposing these materials to elevated temperatures that encapsulate a broad range of advanced reactor environments, 3) performing radiation exposures on the insulations at multiple total doses and dose rates, 4) subjecting the candidate materials to various Design Basis Event (DBE) simulations, and 5) assessing material performance through post-exposure materials and electrical testing. Polymer-based insulations such as silicone rubber and polyether ether ketone (PEEK) have undergone over 150 days of sustained thermal aging at 250°C, while composite-based insulations such as mica tape have been thermally aged for 60 days at 500°C. DBE simulations and materials/electrical testing have already revealed potential areas of improvement in the chosen cable insulation materials that could be explored by cable manufacturers to create high-temperature polymer, composite, and ceramic cables that can be employed in advanced reactors.

Figure 37: Thermal aging environment with examples of a silicone rubber cable aged at 250°C for 1,000 hours

COMPLETED PROJECTS AND FUNDING PROFILE

The ASI program activities are implemented through the following 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-12, directed research activities (totaling $7,622,000) were initiated to address a range of common and crosscutting needs identified by the DOE-Office of Nuclear Energy R&D programs. These projects were concluded in FY -14 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-13, three projects (totaling $1,199,664) were awarded competitively to design custom radiation-tolerant electronics systems/methods for quantifing 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-14, 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-15, two projects (totaling $1,979,000) were awarded competitively and completed in 2018 and 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-16, three projects (totaling $2,789,228) were awarded competitively and completed in 2019 and 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-17, five projects (totaling $4,889,688) were awarded competitively and completed in 2021 and 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) that were implemented at Idaho National Laboratory (INL) in collaboration with Boise State University (BSU), and focused on development and demonstration of sensors to deploy in material test reactor irradiation experiments, particularly the Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT). The activities were framed as the in-pile Instrumentation (I2) initiative.

In FY-18, 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 Oak Ridge National Laboratory under the 2-year project “Direct Digital Printing of Sensors for Nuclear Energy Applications.” The project was 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 INL under the I2 initiative—for a total of $5,300,000.

In FY-19, five projects (totaling $4,500,000) were awarded competitively and completed in 2023:

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

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

In FY-20, two projects (totaling $2,000,000) were awarded competitively and are expected to be completed in 2024:

- Development of Sensor Performance Model of Microwave Cavity Flow Meter for Advanced Reactor High Temperature Fluids, Argonne National Laboratory, $1,000,000 (10/01/2020–09/30/2023)
- Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid, Argonne National Laboratory, $1,000,000 (10/1/2020–09/30/2023)

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

- 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-21, one project totaling $999,000 was awarded, and is expected to be completed 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 INL, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory. The directed funded projects were organized into the following technical areas:

- Sensors for advanced reactors;

- Advanced materials and manufacturing methods for sensors applications;

- Instrumentation for irradiation experiments;

- Digital technology.

In FY-22, one project totaling $800,000 was awarded competitively and is expected to be completed in 2025:

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

The ASI program provided $5,452,000 to fund directed research activities at INL, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory. The directed funded projects were organized into the following technical areas:

- Sensors for Irradiation Experiments

- Sensors for Advanced Reactors

- Sensor Integration

In FY-23, two projects totaling $2,000,000 were awarded competitively and are expected to be completed in 2026:

- Integrated Stand-Off Optical Sensors for Molten Salt Reactor Monitoring, University of Pittsburgh, $1,000,000 (10/1/2023 – 09/30/2026)

- Optical Sensors for Impurity Measurement in Liquid Metal-cooled Fast Reactors, University of Michigan, $1,000,000 (10/1/2023 – 09/30/2026)

The ASI program provided $4,899,600 to fund directed research activities at Argonne National Laboratory, INL, Oak Ridge National Laboratory and Pacific Northwest National Laboratory. The directed funded projects were organized into the following technical areas:

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

In FY-24, four projects (totaling $4,200,000) were awarded competitively and are expected to be completed in 2027:

- Magnetostrictive Guided-wave Transducers for Nuclear Reactor Piping System Monitoring, Boise State University, $1,100,000 (08/01/2024 – 07/30/2027)
- Monitoring Ceramic Fuel Fracture via Fiber Optic Acoustic Emission Sensors, Virginia Polytechnic Institute and State University, $1,000,000 (08/01/2024 – 07/30/2027)
- Inference of Flow Conditions from In-core Detector Measurements for Accelerating SMR Licensing, Massachusetts Institute of Technology, $1,000,000 (08/01/2024 – 07/30/2027)
- Non-Destructive Plutonium Assay in Pyroprocessing Bulk Materials with a 3D Boron-Coated-Straw Detector Array, University of Illinois at Urbana-Champaign, $1,100,000 (08/01/2024 – 07/30/2027).

The ASI program provided $4,130,000 to fund directed research activities at Argonne National Laboratory, INL, Oak Ridge National Laboratory and Pacific Northwest National Laboratory. The directed funded projects were organized into the following technical areas:

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

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