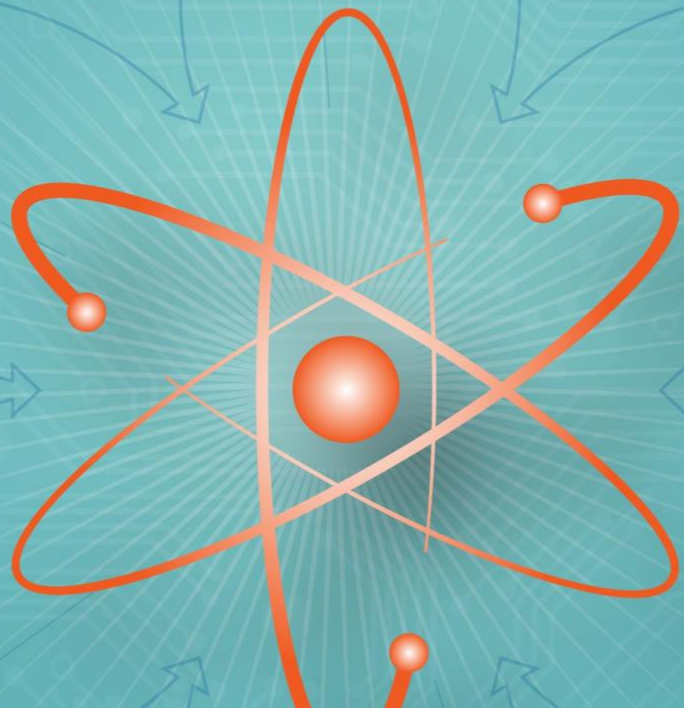
U.S. DEPARTMENT of ENERGY | Office of Nuclear Energy

ADVANCED SENSORS AND INSTRUMENTATION

2025 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 2025 Annual Review Meeting, held virtually on December 9, 10, and 11, 2025.

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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 three 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 2025 Annual Review Meeting, held virtually on December 9, 10, and 11, 2025. The content is organized based around the meeting sessions as follows:

- Sensors for Advanced Reactors (Sessions II and III)

- Sensors for Irradiation Experiments (Session IV)

- Sensor Integration (Session V)

Reactor Power Monitoring

PI: Kevin Tsai – Idaho National Laboratory (INL), Co-PI: Johnathan Grissom – INL
Collaborators: Tommy Holschuh, Teancum Quist, and Michael Reichenberger – INL

Project Description: The goal of the INL reactor power monitoring work package is to develop and demonstrate in-core neutron flux sensors to enable and enhance power monitoring capabilities for upcoming advanced reactor demonstrations. Development work focuses on the application of self-powered neutron detectors (SPNDs) for both real-time neutron spectroscopy and operations in high-temperature environments.

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.

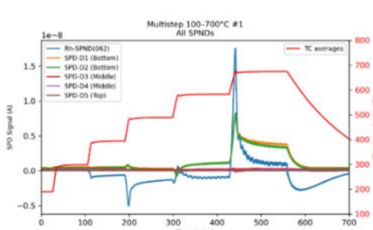


Figure 1: High-temperature SPND results

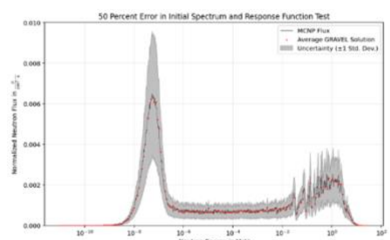


Figure 2: Computational results using GRAVEL with 50% uncertainty in initial conditions

Figure 3: Prototype SPND fabricated at INL

Impact of Time-Dependent Reactor and Sensor Physics on Core Power Synthesis

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

Project Description: In this project, a weighting-function-based core power synthesis method, called the point-based iterative (PBI) method, was applied to a representative low-enriched uranium (LEU) pressurized water reactor (PWR) model, which was modeled using the using the Polaris/Purdue Advanced Reactor Core Simulator (PARCS) approach to account for both time- and spatial-dependent power distributions. Simulated self-powered neutron detector (SPND) models were informed by isotopic transmutation calculations with the Oak Ridge Isotope GENeration (ORIGEN) code. This framework allowed for a simulated study of the effectiveness of the use of the PBI method to accurately perform power synthesis operations based on simulated SPND responses, as the fuel burns up, and the emitters of the SPNDs transmute to isotopes that are significantly less effective in producing electrical current and, thus, SPND signals.

Impact and Value to Nuclear Applications: Core power distribution monitoring is a critical part of reactor operations; however, fundamental studies quantifying the effects and impacts of sensor degradation and fuel burnup are limited. Moreover, methodological details of codes that are implemented commercially are typically limited because of their proprietary nature. Given the industry's push for longer fuel cycles in both Generation II and Generation III reactors, the promoted use of higher burnup and accident tolerant fuels in PWRs, and the ongoing development of Generation IV reactors with higher temperatures and higher in-core fluxes, the nuclear industry can benefit greatly from studies that provide insight and direction to optimize in-core monitoring systems and algorithms. These studies can provide more accurate core power synthesis by minimizing negative impacts of sensor degradation.

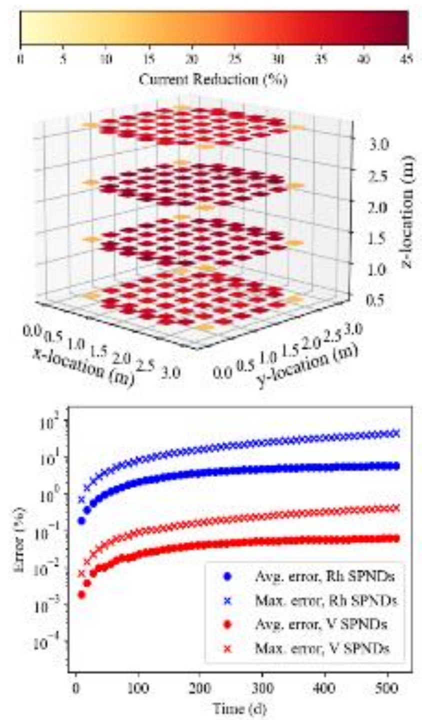


Figure 4: Reduction in Rh-SPND electrical current due to Rh emitter transmutation as a function of SPND location in the PWR (top), and injected synthesis errors if effects of emitter isotopic transmutations were not accounted for in Rh and V SPNDs (bottom).

Recent Results and Highlights: The collaborators of this work have discovered that it is permissible to have slightly inaccurate a priori assumptions about fuel burnup (so that the burnup may be slightly under- or over-approximated by roughly 9.3 full power days of accumulated burnup), but not accounting for burnup at all in the a priori assumption leads to severe error, approaching 25% at maximum. The collaborators also discovered that V SPNDs are extraordinarily robust in the low-enriched uranium fuel cycle considered in this modeling work, whereas Rh-SPNDs undergo significant transmutation that can result in large errors (up to 42% as shown in Figure) in the synthesized power distribution. The results have been documented in detail in an ORNL report (ORNL/TM-2025/4157); the next phase of this study will be focused on a representative LEU+ (i.e., with 5%–8% uranium enrichments) PWR core model

An Innovative Monitoring Technology for the Micro-HTGR Vessel

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

Project Description: The project supports the mission of the Advanced Sensors and Instrumentation (ASI) program by leveraging recent advances in both machine learning (ML)-based field reconstruction techniques and diagnostic software to augment traditional sensor capabilities. We will develop and demonstrate integrated sensor technology for real-time monitoring of thermal mechanical stresses in micro-high-temperature gas reactor (mHTGRs) vessels. The technology will be based on the use of a sparse network of outer wall temperature measurements and other plant operating conditions.

Convolutional neural network (CNN) approaches will optimize the number and location of measurement points. By leveraging the algorithms available for degradation diagnostics of the well-established PRO-AID software, the proposed technology will provide (i) real-time, reliable, and cost-effective monitoring methodology, (ii) quantification of the lifetime and integrity of the pressure vessel, and (iii) improved microreactor systems economics.

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

Recent Results and Highlights: During the third year of this project, the team expanded the CNN to include off-design conditions. Training and validation of the network was completed using numerical simulations in the MOOSE software framework; the ray tracing and conduction modules were successfully validated against experimental data acquired under off-design operating conditions. Various numerical datasets were used to train the network, and the accuracy of these predictions was evaluated based on comparisons with numerical data. The predictive performance of the network was also evaluated based on variable inputs from the sensors; this exercise led to a study of optimal sensor placement on the outer vessel wall. Finally, the accuracy of the network was quantified through an in-depth study of uncertainty propagation through each layer of the network. On the experimental side, an algorithm for real-time monitoring and incident detection was developed and tested. Thermocouples and strain gauges are monitored. These sensors were integrated as real-time inputs into the CNN; when the sensors deviate from the prediction of the network, the user is notified of a potential fault within the system.

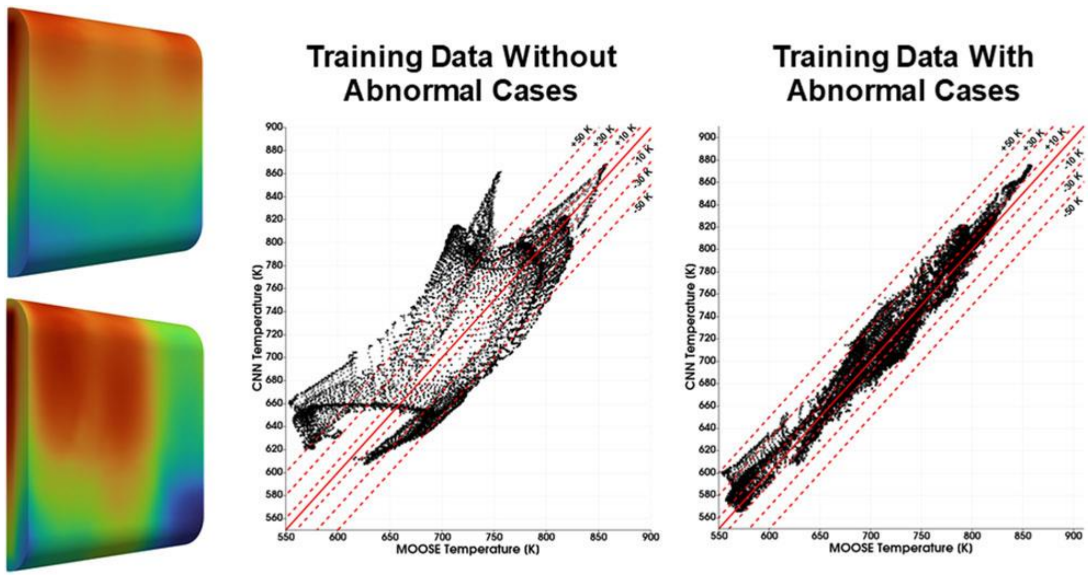


Figure 5: CNN prediction of off-design operating conditions for the reactor vessel wall.

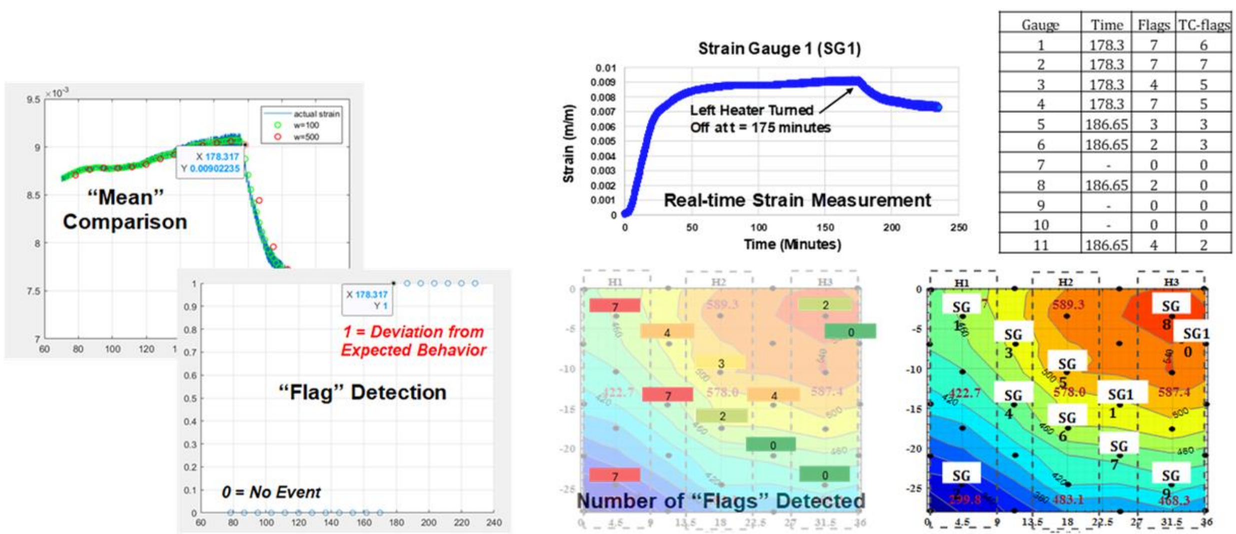


Figure 6: Real-time temperature and strain monitoring on the reactor vessel model.

Challenges Implementing Johnson Noise Thermometry Using Space-Rated Electronics

PI(s): N. Dianne Bull Ezell and F. Kyle Reed – Oak Ridge National Laboratory (ORNL)
Collaborators: Dan Sweeney – ORNL

Project Description: The random motion of charge carriers in an electrical conductor is a function of its temperature. This phenomenon generates an electrical signal, referred to as Johnson noise, that is present in all analog signals. The temperature dependence of the Johnson noise spectrum enables a direct measurement of absolute temperature and provides a secondary measurement for sensors such as RTDs and Johnson noise thermometry (JNT). For nuclear environments, this is of particular interest in correcting for RTDs signal drift caused by accumulation, transmutation, and displacement damage caused by neutron and gamma irradiation.

Impact and Value to Nuclear Applications: The components of JNT instruments are susceptible to radiation damage in and around nuclear reactors. Radiation-hardened components developed for space applications, though often qualified using surrogate particles, could enable JNT systems to be developed for nuclear repower applications. To test the feasibility of using commercial off-the-shelf (COTS) space-rated components to enable JNT measurements in nuclear reactors, a JNT instrument was developed using radiation-hardened analog-to-digital converters (ADCs) that could enable their physical placement within a test reactor while maintaining the signal processing hardware and microcontroller (MCU) within a clean environment.

Recent Results and Highlights: The prototype JNT instrument could measure Johnson noise, though its practical use was limited by three factors. First, the signal integrity of the digital communication between the ADC via a serial peripheral interface (SPI) protocol limited the length of the cables connecting the ADCs to the MCU to ≤15 cm, beyond which the ADC peripheral was unable to overcome the cable impedance. Second, the ADCs were capable of a maximum gain of 1,024, which, in the absence of additional preamplifiers, were unable to span most of the ADCs' full dynamic range. Third, the ADCs' 40 kS/s maximum sampling rate limited the bandwidth of the JNT measurements, resulting in excessively long measurement times and increased measurement uncertainty. Together, these three factors limit the practicality of the present implementation in real-world applications of the prototype JNT instrument, in the absence of additional or different hardware. However, these challenges are not insurmountable, and the utilization of space radiation-rated electronics in terrestrial and space reactors could yet be leveraged to address the imminent radiation survival requirements of next-generation reactor designs.

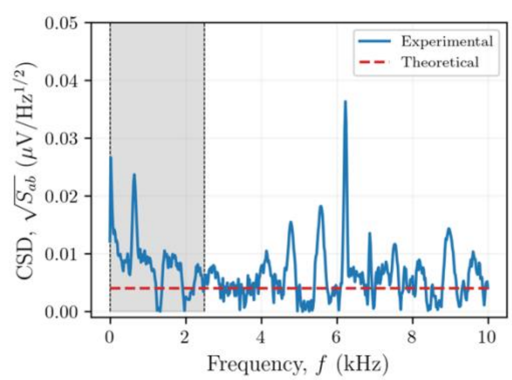


Figure 7: Johnson noise measured using the prototype instrument.

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

PI(s): F. Kyle Reed, M. Nance Ericson, and N. Dianne Bull Ezell – Oak Ridge National Laboratory (ORNL)
Collaborators: Brett Witherspoon, Adam Buchatler, Tyler McCormick, Lloyd Clonts, Kevin Deng, and Emma Brown – ORNL
Siddharth Rajan, Raymond Cao, Chandan Joshi, Hyunsoo Lee, Adithya Balaji, and John Cobbinah – Ohio State University (OSU)

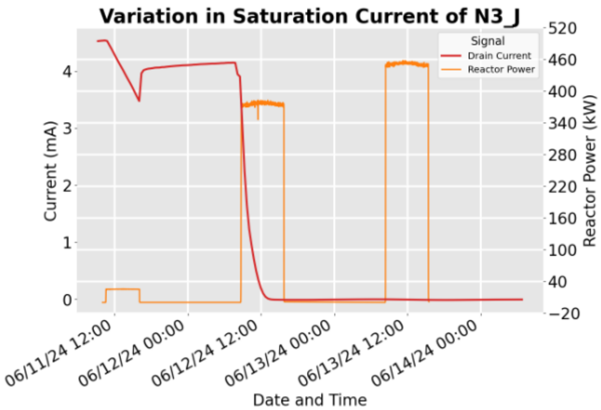
Project Description: This project investigates the use of gallium nitride (GaN), a wide-bandgap semiconductor technology, to meet the specialized needs of sensor interface electronics and communications in nuclear reactors.

Impact and Value to Nuclear Applications: Recent advances in nuclear power generation technologies offer significant potential for efficient energy production. Fully realizing this potential will require development of electronics capable of withstanding high radiation levels and extreme temperatures. While industry has addressed harsh-environment electronics for low Earth orbit satellites, the far more severe conditions faced by electronics near or within a reactor core remain largely unmet.

Recent Results and Highlights: In the project's final year, efforts focused on evaluating the neutron fluence limits of Ohio State University (OSU)-fabricated GaN HEMTs and comparing radiation-induced parameter changes with commercially available GaN HEMTs from EPC Space and SiC JFETs fabricated at NASA Glenn Research Center. Simultaneous irradiation experiments were conducted at the OSU Nuclear Reactor Laboratory using the Dry Well Facility (DWF) and the Auxiliary Irradiation Facility (AIF). Sixteen devices—comprising six OSU GaN HEMTs, five NASA Glenn SiC JFETs, two EPC Space eGaN HEMTs, and three parasitic devices on the NASA Glenn SiC die—were characterized in situ in the DWF during irradiation to a light-water reactor–spectrum neutron fluence exceeding 10^16n/cm^2. Concurrently, six OSU GaN HEMTs were measured during irradiation in the AIF.

The OSU GaN HEMTs and NASA Glenn SiC JFETs tested in the DWF exhibited similar trends under reactor radiation exposure, including a reduction in saturation current and an increase in threshold voltage with increasing neutron fluence. However, degradation effects were more pronounced in the SiC JFETs than in the GaN HEMTs. The EPC Space devices began to exhibit oscillatory behavior during irradiation, limiting assessment of their radiation performance.

Overall, the ORNL-OSU team advanced the understanding of light-water reactor–spectrum radiation effects, including both neutron and gamma contributions, on wide-bandgap semiconductor devices. The results suggest that OSU-fabricated GaN HEMTs may be better suited for higher-radiation environments, whereas NASA Glenn SiC JFETs appear more favorable for applications requiring elevated temperatures.



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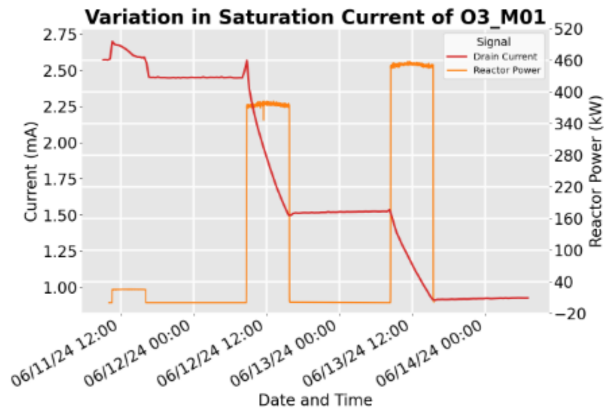


b)

Figure 8: Saturation current variations of (a) NASA Glenn SiC JFETs and (b) OSU GaN HEMTs simultaneously irradiated in the OSU DWF.

Structural Health Monitoring

PI: Joshua Daw – Idaho National Laboratory (INL)
Collaborators: Amey R. Khanolkar, Timothy L. Phero, and Bibo Zhong – INL
Md Omarsany Bappy and Yanliang Zhang – University of Notre Dame
Zhangxian Deng, Brian J. Jaques, and David Estrada – Boise State University

Project Description: The goal of this research is to advance technologies 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.

Recent Results and Highlights: In FY-25, the additive manufactured (AM) strain gauges were exposed to neutron irradiation at The Ohio State University Research Reactor (OSURR) with a Nuclear Science User Facility (NSUF) rapid turnaround experiment. The experiment was performed in a dry tube (Figure a). Shown in Figure b is the response of three (3) AM strain gauges that survived deployment into the reactor. Strain gauge-1 and Strain gauge-2 are in the furnace within the dry tube and a high neutron and gamma flux region of the reactor. Strain gauge-3 is located just outside the furnace in a low neutron and gamma flux region. As seen in Figure b, neutron and gamma irradiation cause hysteresis, degradation, and an eventual loss of signal from the strain gauges.

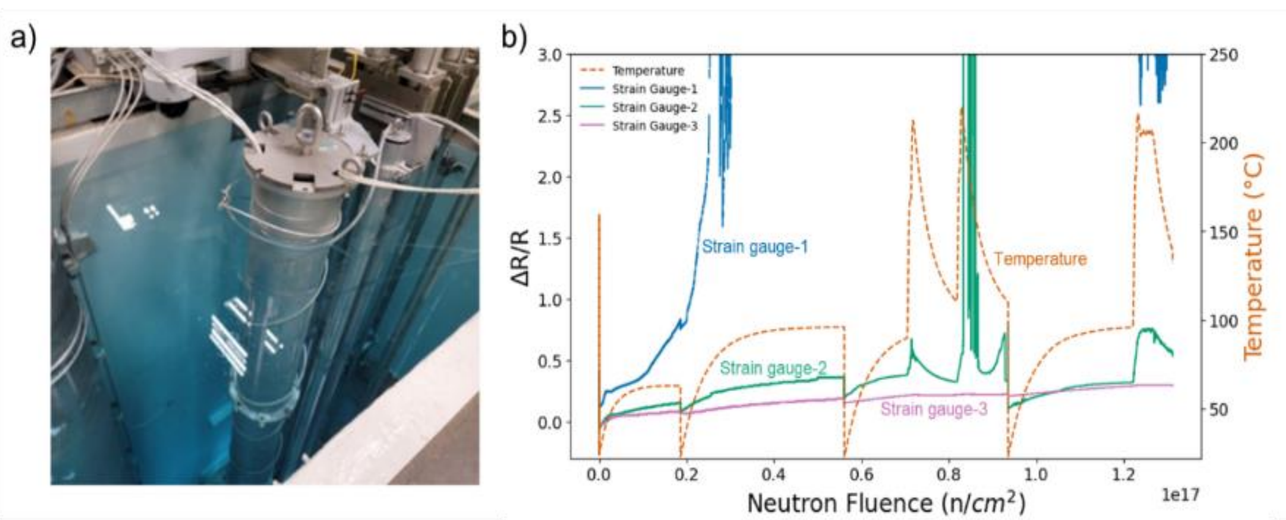


Figure 9: (a) The 9.5-inch dry tube used at The Ohio State University Research Reactor. (b) Results from three strain gauges in the reactor.

Other work in FY-25 included optimization and testing of a radiation-tolerant acoustic emission sensor that was originally developed in FY-24. Several design improvements were evaluated. Methods were developed and demonstrated for in situ sensor health testing via active interrogation of the AE sensor. This allows detection of a faulty sensor before initiation of an irradiation experiment and any degradation of the sensor during or after an experiment.

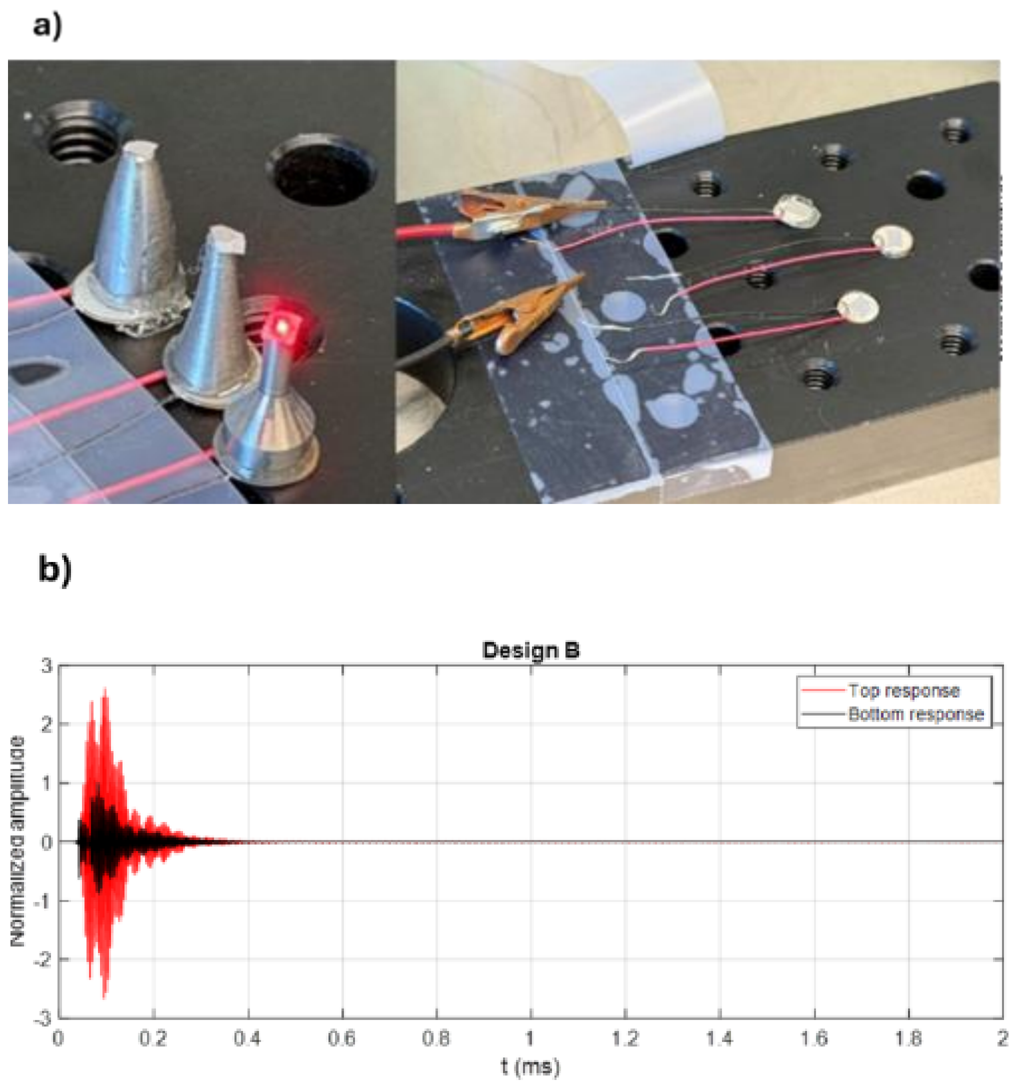


Figure 10: (a) Evaluated acoustic horn designs. (b) Signal recorded for AE sensor with and without acoustic horn.

D9H60 Cobalt Magnetostrictive Electromagnetic Acoustic Transducer

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

Project Description: The goal is to demonstrate the feasibility of a permanently installed high-temperature sensor to monitor a significant volume of pipe or vessel material for structural integrity (SI). Currently available SI sensors are limited to **<300°C**, but the need is for liquid metal sensors to **~ 500°C** and molten salt sensors to **~ 700°C.**

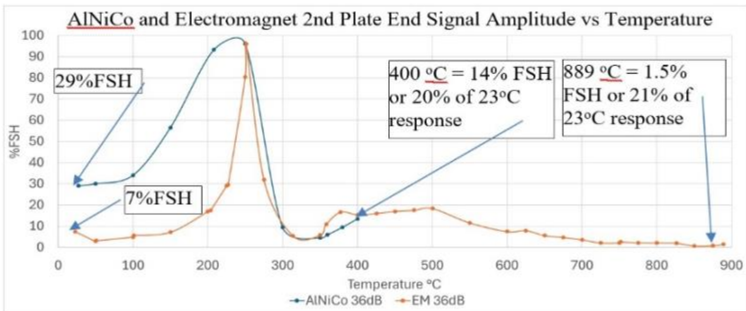


Figure 11: A1NiCo and Electromagnet 2nd Plate End Signal Amplitude vs Temperature

Impact and Value for Nuclear Applications: Advanced reactors will be difficult or impossible to inspect or monitor using existing sensors and techniques. There are no commercial ultrasound sensors for long-term monitoring of reactor SI at operating reactor temperatures. A sensor network capable of detecting cracks, pits, and material degradation throughout a large volume of material could be useful, or even critical. Such a network could ensure safe operations or alert operators to issues that require mitigation or repair prior to them escalating into a leak or structural failure.

Results and highlights: In FY-24, we showed that Cobalt (Co) (which is known to have a magnetostrictive [MS] coefficient 2–3 times that of Ni) exhibited 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 25 mm from the coil to avoid saturation. An AlNiCo magnet with a lower field strength proved superior.

We also demonstrated in FY-24 a permanent magnet MS electromagnetic acoustic transducer (EMAT) worked well to 400°C where the test was stopped to avoid magnet operation above rated temperature.

In FY-25, we tested an electromagnet EMAT to failure at 889°C (see Figure). The failure was at the connection of the high temperature lead-wire to the electromagnet, plus some wire insulation and mica support structures were embrittled and damaged.

The lead-wire connection was reinforced, and a new mica wafer was tested for 10 days at 700°C with no performance degradation. Although this is not confirmation of long-term operation, it is encouraging that long-term operation is possible.

Results were presented at the June 2025 American Society for Nondestructive Testing research symposium, showing feasibility for a significant advancement in monitoring over the current state of the art.

Fiber Optic Sensors

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

Project Description: Significant advances were made in FY-25 to progress fiber optic sensing technology for in-core applications. Work was conducted to perform detailed analysis of in-core data collected during the High Dose Graphite (HDG) experiment in the Advanced Test Reactor (ATR). A design revision was conducted of an INL developed Fabry-Perot interferometry-based pressure sensor to improve manufacturability and measurement performance. A customizable fiber-optic-coupled, high-speed photodiode-based pyrometry system was developed and tested in a laboratory setting.

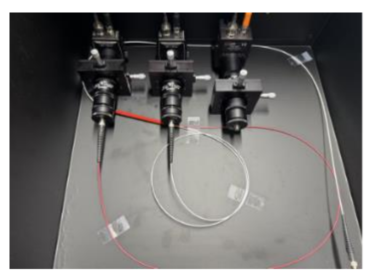
Impact and Value for Nuclear Applications: Fiber optic technologies have high potential impact because of their inherent small footprint and radiation compatibility. Fiber optics lend themselves well to low neutron fluence applications because of their susceptibility to radiation induced attenuation, compaction, and emission. However, this does not preclude their use in high flux and fluence environments where appropriate use of fiber dopants and measurement strategies minimize the deleterious effects of radiation on the measurement.

Results and highlights: The HDG experiment includes two optical fibers with pure silica cores and fluorine-doped cladding, and each fiber was etched with nine fiber Bragg gratings. Prior to the irradiation, one fiber was heat treated up to 750°C and the other at 650°C. The irradiation was conducted at approximately 500°C and experienced a neutron fluence greater than 10^{21} n/cm^2. These sensors experienced significant drift, up to an approximately 12.5-nm shift as a result of the irradiation.

The design revisions for the Faby-Perot-based fiber optic pressure sensor centered around improving the manufacturability of the sensor and reducing sensor drift. These improvements made a significant improvement on the yield rate of working sensors produced, and reduced sensor drift results from small leaks at the sensing diaphragm. The design revision's motivation, modifications, and results are presented in INL/RPT-25-88050.

A custom-developed high-speed pyrometry system was designed with in-pile high-temperature thermometry applications in mind. The system utilizes wavelengths in the near infrared, which has a transmission window in silica optical fibers. This wavelength range has much less radiation-induced attenuation compared to the visible wavelength range. The system uses changeable bandpass filters to customize the measurement wavelengths and avoid other challenges such as radiation-induced emissions interfering with measurements. The system was tested in a laboratory setting with error measurements typically less than 5°C when compared to a black body furnace.

a)



b)

Figure 12: (a) Photograph of updated fiber optic pressure sensor. (b) Photograph of the photodiode-based high-speed pyrometry system.

Embedded Fiber Optic Sensors for Structural Health Monitoring

PI(s): Christian Petrie, Holden Hyer, Anthony Birri – Oak Ridge National Laboratory (ORNL)

Project Description: Structural health monitoring (SHM) is a critical component of any nuclear reactor's Reliability and Integrity Management (RIM) program. Fiber-optic sensors are one of the leading technologies for high-temperature SHM. In addition to their ability to operate at high temperatures and moderate radiation dose, these sensors provide highly accurate measurements of temperature, strain, and vibration (among other parameters), with some techniques offering spatially distributed measurements. The primary challenge in deploying these sensors for advanced reactor SHM is developing an approach to economic bonding or embedding the sensor to or within a reactor component to enable strain or vibration measurements. For some applications, sufficient information can be obtained by simply bonding the sensor to the surface of the component. Others may require internally locating the sensor, which lends itself to advanced or additive manufacturing approaches. The latter is the focus of a new ASI-funded activity that was launched at the end of FY-25 and will be completed in FY-26. This project is evaluating multiple approaches to reducing the tensile strains during high-temperature operation or even introducing compressive stresses during the sensor embedding process.

Impact and Value for Nuclear Applications: From an economic perspective, successful implementation of fiber-optic sensors for SHM could lead to the ability to detect signs of degradation and perform preventative maintenance during the next scheduled reactor outage and eventually develop more-predictive maintenance schedules. The spatially distributed sensing capabilities of fiber-optics could also offer the ability to more rapidly localize the origins of damage, which could save significant time and cost in what might otherwise require time-consuming visual examinations. The latter is particularly important for microreactors that may introduce challenges in accessing some components or systems because of their reduced physical size.

Results and highlights: FY-25 focused on identifying suitable brazing alloys and geometries. Initial tests showed non-uniform solidification following horizontal brazing in a small tube, likely caused by capillary action. Subsequent tests were performed within "boats" with an open "U-shaped" cross-section that allowed for easier examination of the braze (see Figure). The initial alloy selected (BAg-7) comprised Ag, Cu, Zn, and Sn. Testing showed incomplete melting of the braze following heating beyond the liquidus temperature (651°C) in an inert atmosphere. It was suspected that this occurred due to Zn volatilization. A second experiment was performed with a different alloy (BAg-8) that is better suited to furnace brazing. This resulted in complete melting of the braze and a much higher compressive residual fiber strain, at least in some portions of the fiber, after cooling to room temperature. The latter provides confidence that the embedded fiber could survive high temperatures. BAg-8 has the added benefit of having an even higher solidus temperature (780°C), which could allow for higher temperature operation.

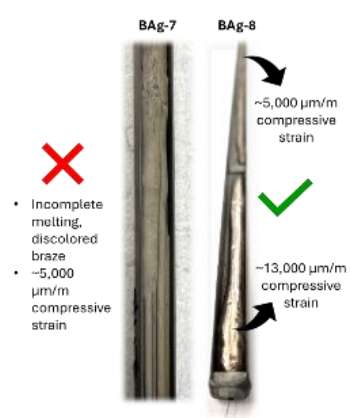


Figure 13: Images and measured fiber strains following brazing with BAg-7 (contains Zn) and BAg-8 (no Zn) alloys.

Monitoring Ceramic Fuel Rods via Fiber Optic Acoustic Sensors

PI: Gary Pickrell – Virginia Tech (VT)
Collaborators: Daniel Homa – VT
Joshua Daw – Idaho National Laboratory (INL)
Logan Theis – Sentek Instrument
Brian Risch – Prysmian

Project Description: The purpose of the program is to develop and demonstrate a distributed acoustic emission (AE) sensing system for event detection in elevated temperature radiation environments. The proposed monitoring system will leverage a proven fiber optic sensing technology to enable ultra-sensitive vibration measurements with increased sampling rates (≥ 60 kHz) to monitor ceramic fuel rods and structural components in nuclear power plants. The ability of the robust sensors to detect acoustic phenomena associated with ceramic fuel fracture, coolant boiling and recombination, clad bursts, and pellet-cladding interactions will be evaluated in simulated laboratory and reactor environments.

Impact and Value to Nuclear Applications: The research conducted under this program is supportive of the nuclear energy mission and will provide the framework for an acoustic sensing system that will be qualified, validated, and ready to be embraced by the nuclear industry for real-time, accurate, and high-resolution measurements. The technology is well positioned to take advantage of artificial intelligence (AI) and machine learning (ML) methods to create the next-generation health and condition monitoring systems that will be at the forefront of the "American Nuclear Renaissance."

Recent Results and Highlights: A mock fuel rod assembly and coolant (water) flow loop was constructed and the commercially available picoDAS (~36 kHz sampling rate) was deployed to successfully detect acoustic events commensurate with a cladding burst, cracking of a ceramic "rod," changes in the coolant (water) flow rate, the onset of coolant boiling, and impacts at multiple locations in the system. Sensors were fabricated via femto-laser inscription through the polyimide coating of a Prysmian "Super RadHard" polyimide-coated single-mode fiber by the point-by-point method. The performance of the picoDAS system was enhanced to allow for sampling rates up to 574 kHz and successfully demonstrated at spatial resolutions of 2 and 5 meters. The "success criteria" for the milestones were met or exceeded per the agreed-upon schedule. The prototype acoustic emission monitoring system will be fully integrated and validated in a laboratory environment prior to deployment and operation in a university nuclear reactor.

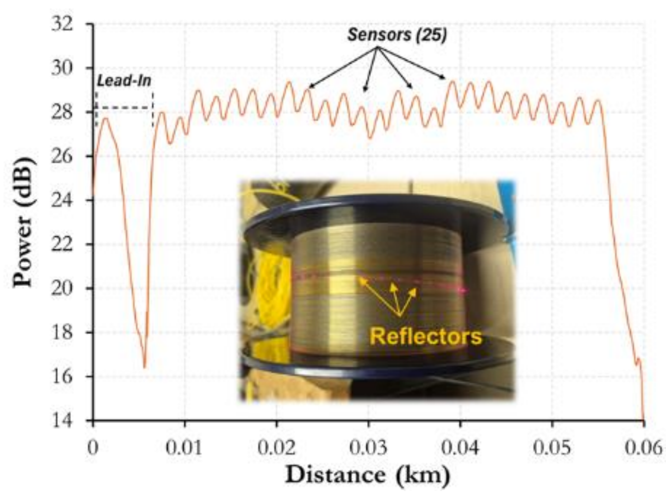


Figure 14: Radiation-tolerant high-temperature picoDAS sensing fiber. Twenty-five sensors were fabricated in a Prysmian polyimide-coated "SuperRadHard" single-mode fiber.

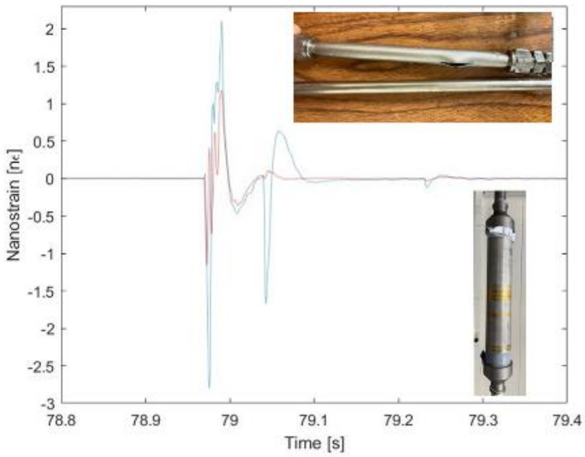


Figure 15: "Remote" detection of a cladding burst event (insert) with the commercially available picoDAS deployed on the assembly vessel (insert).

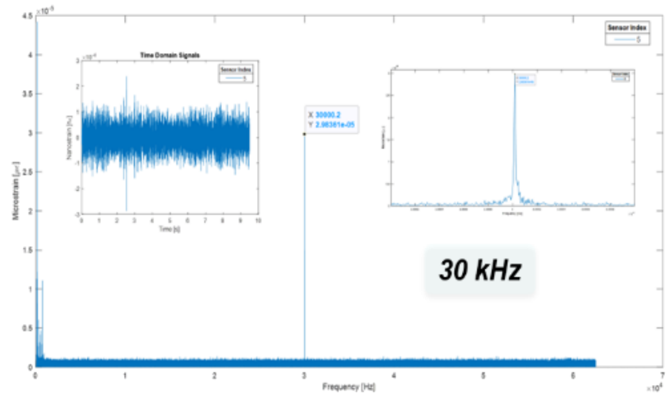


Figure 16: Demonstration of an acoustic event (30 kHz) with an enhanced picoDAS (125 kHz sampling rate). Dynamic strain response shown in the insert.

Magnetostrictive Guided-Wave Transducers for Nuclear Reactor Piping System Monitoring

PI: Zhangxian (Dan) Deng – Boise State University
Collaborators: Joshua Daw – Idaho National Laboratory
Susan White – The Ohio State University

Project Description: The goal of this project is to develop an integrated guided-wave structural health monitoring (SHM) system and evaluate its performance under high-temperature and radiation conditions. We will print magnetostrictive materials onto metallic structures, characterize their multi-physics properties and interfacial strength, and use our existing finite-element model to prototype a guided-wave SHM system that includes printed transducers, a wired data-acquisition circuit, and an interactive interface. Finally, we will examine how temperature and radiation affect the behavior of magnetostrictive materials and demonstrate the full SHM system at The Ohio State University Research Reactor.

Impact and Value to Nuclear Applications: Nuclear reactor piping degrades over time due to erosion-corrosion, stress-corrosion cracking, and high-temperature creep/aging. Traditional maintenance approaches, including periodic reactor overhauls and nondestructive testing by certified engineers, result in significant operational and maintenance expenses. The guided-wave SHM technology developed in this project offers a strategic alternative by enabling continuous, autonomous monitoring of structural integrity, supporting a shift from scheduled to condition-based maintenance, and reducing the risks associated with human error and unexpected degradation.

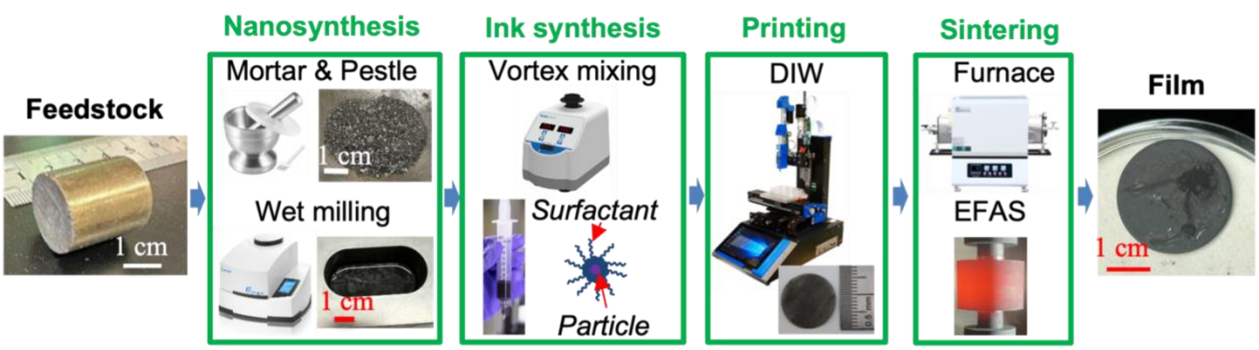


Figure 17: A comprehensive additive manufacturing process for Terfenol-D. Terfenol-D nanoparticles were synthesized using the EMAX high-energy ball mill. The resulting ink is printed using a Hyrel DIW printer and sintered using Electric Field Assisted Sintering (EFAS) or thermal sintering.

Recent Results and Highlights: New nanosynthesis capabilities, including a glovebox and a cryogenic high-energy ball mill, have been established at Boise State University. Using these tools, we developed and validated a comprehensive direct ink writing (DIW) approach for magnetostrictive terbium–iron–dysprosium (Terfenol-D) alloys, as shown in the Figure. We successfully printed and sintered Terfenol-D thin films on zirconium and stainless-steel substrates. To further reduce sintering temperatures and minimize thermal strain at the film–substrate interface, we employed aerosol jet printing and pulsed-light sintering to fabricate Terfenol-D films on Kapton tapes at room temperature. In addition, we investigated similar methods for printing magnetostrictive iron–gallium (Galfenol) alloys, which offer enhanced high-temperature and radiation resilience. We synthesized Galfenol inks containing high-aspect-ratio nanoflakes, printed them using the same DIW system, and thermally sintered the resulting films in a tube furnace.

Inference of Flow Conditions from In-Core Detector Measurements for Accelerating SMR Licensing

PI: Benoit Forget, Massachusetts Institute of Technology (MIT)
Collaborators: Emilio Baglietto, MIT
Majdi Radaideh, University of Michigan
Kent Welter, NuScale
Jason Christensen, Idaho National Laboratory

Project Description: Reactor modeling relies on the detailed description of reactor systems. But these descriptions often lack the true, as-built characteristics of a system, so certain details often cannot be realistically modeled a priori. This lack of knowledge can lead to large discrepancies between the observables and modeling and simulation predictions. In a real production system, there is often insufficient instrumentation or access to correct the lack of information. This proposal aims to use all the information available between measurements and simulations to infer key knowledge gaps.

Impact and Value to Nuclear Applications: The goal of this proposal is to develop a framework that can learn from all the reactor information available and apply it across physical fields. As a demonstration, the framework will be tested on a pressurized water reactor (PWR) benchmark based on a real operating reactor for which we have first cycle operating data. This benchmark was selected due to the large initial tilt observed in neutron detector data from a symmetric design, with the leading cause of the tilt being flow-induced bowing from an unknown flow asymmetry in the inlet plenum. This demonstration aims to identify fuel bowing distribution and flow disparities in as-built conditions.

Recent Results and Highlights: This project recently concluded year 1 out of 3 with a focus on model development for the related fields and some initial optimization work. Our team developed a detailed, realistic model of the inlet plenum from open-source information gathered in the literature and performed CFD simulations to assess potential flow variations. Initial ML techniques have been tested to identify correlations between the flow channels. Our team also leveraged and refined existing reactor physics for the benchmark and identified potential ways to mimic the effect of fuel bowing on core power distribution. Several optimization and regularization approaches were tested to identify potential distributions that could replicate the observed detector signals. As we further improve these models, the goal becomes to use the CFD-predicted correlations in the flow to regularize reactor physics optimization.

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Integrated Stand-Off Optical Sensors for Molten Salt Reactor Monitoring

PI(s): Kevin P. Chen – University of Pittsburgh (Pitt)
Elvis Dominguez-Ontiveros – Oak Ridge National Laboratory (ORNL)
Collaborators: Kairos Power LLC (Kairos)

Project Description: This project develops integrated, stand-off optical sensors to perform real-time, multiparameter measurements in harsh radiation environments. Designed specifically for molten salt reactors (MSRs), these sensors monitor critical variables—such as coolant levels, flow rates, and metal impurity characterization—to ensure the safe, efficient, and reliable operation of next-generation nuclear systems. By utilizing a single radiation-hardened fused silica rod as a robust optical port, the system provides reliable remote access to reactor cores or high-temperature flow loops without compromising structural integrity or introducing complex mechanical seals. The project focuses on the advancement and integration of three distinct, high-impact technologies.

Impact and Value to Nuclear Applications: Through active and ongoing collaboration with Oak Ridge National Laboratory and various industry partners, this project aims to bridge the critical gap between laboratory-scale research and practical field deployment. The ultimate goal is to enhance the Technology Readiness Level (TRL) of these sensors, paving the way for their integration into the primary instrumentation and control (I&C) systems of future commercial molten salt reactors. To date, this multifaceted research effort has resulted in seven peer-reviewed journal articles, one pending patent, and one provisional patent, reflecting its significant contribution to the field of nuclear engineering.

Recent Results and Highlights: A low-cost rad-hard Optical Frequency Domain Reflectometry (OFDR) Lidar leverages the impressive coherent length of affordable, commercial-off-the-shelf telecom diode lasers. The project integrates high-temperature stable, radiation-hardened fiber probes embedded directly in metal to create a robust optical feedthrough. This setup has successfully demonstrated molten salt sensing at a 15-meter standoff distance with an exceptional 1-mm spatial resolution. Additionally, the technology enables high-precision monitoring of molten-salt pump speeds, covering a range of 0–2000 rpm with a 0.1% measurement accuracy even in extreme environments. A compact dual-pulse laser-induced breakdown spectroscopy (LIBS) sensing for critical corrosion detection utilizes state-of-the-art additive manufacturing (3D printing) to produce compact, dual-pulse passive and active Q-switch YAG lasers. The innovative unibody design allows all mechanical components of a solid-state laser to be fabricated in a single additive process, ensuring unparalleled mechanical stability and a footprint significantly smaller than traditional alternatives. Through the strategic optimization of lattice structures, the project developed a high-performance laser weighing less than 150 g that delivers a powerful 40-mJ pulse energy. By precisely tuning the pulse-to-pulse timing for optimal plasma emission, the project has demonstrated a tenfold improvement in detection sensitivity for Ni, Fe, and Co impurities, providing a transformative and affordable diagnostic tool for the nuclear industry. A vertical-cavity surface-emitting laser (VCSEL)-based laser doppler flow sensor exploits the self-mixing effect inherent in VCSEL arrays, to develop ultra-compact flow sensors. These sensors measure molten salt flow speeds through specialized radiation-hardened optical fiber leads and robust feedthroughs. The project's experimental results confirm that it is entirely feasible to perform precise, real-time flow measurements in high-temperature, high-radiation zones. Furthermore, the adoption of VCSEL array technology facilitates simultaneous, multipoint flow measurements via flexible optical standoff configurations, providing a comprehensive map of fluid dynamics within the reactor system.

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, which can be fabricated from stainless steel, and, as such, is expected to be resilient to radiation, high temperature, and the corrosive environment of sodium fast reactors (SFR) and molten salt-cooled reactors (MSCR). A viable geometry of the sensor is that of a small cylindrical resonator. The principle of sensing consists of making one wall of the cavity flexible enough so 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 a microwave field inside the cavity. Membrane deflection causes cavity volume change, and thus a shift in the resonant frequency. Using signal readout from a 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 will be achieved through a microwave waveguide, which will be an integral part of the insertion probe.

Impact and Value to Nuclear Applications: High-temperature fluid reactors, such as SFRs and MSCRs, are promising advanced reactor options with highly efficient thermal energy conversion cycles. Measurement of high-temperature fluid process variables, in particular the flow inside the pressure vessel, is a challenging task because of the harsh environments of advanced reactors, which include radiation, high temperature, and contact with highly corrosive coolant fluid. Since the microwave cavity sensing is based on 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 demonstration of 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 velocity of the impinging liquid jet (see Figure (a)). We have developed a cylindrical resonant cavity with length and diameter equal to 22.2 mm. The cavity was machined from stainless steel 316 (SS316) and silver-plated on the interior. The cylindrical cavity was excited through a subwavelength hole on the side of the wall of the cylinder with a 50-cm brass WR-42 waveguide enclosed in protective SS316 tube. A photograph of the transducer is shown in Figure (b). The assembly was installed in a liquid sodium vessel. The cylindrical cavity was excited in the TE011 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. A corresponding monotonic increase of the resonant frequency shift by several hundred kHz was observed (see Figure (c)).

a) *b)* *c)*

Figure 18: (a) Liquid sodium vessel. (b) Stainless steel transducer compatible with high-temperature fluid environment. (c) Preliminary results of flow sensing in liquid sodium at 350°C.

Photothermal Radiometry with Localized Temperature Measurement

PI: Zilong Hua – Idaho National Laboratory

Project Description: In this project, an instrument based on photothermal radiometry was designed to perform in-reactor, real-time thermal property measurements of nuclear fuels and materials. This instrument uses one optical fiber to locally heat the sample surface and a second fiber to probe the corresponding temperature variation through blackbody radiation. The in-reactor testing was conducted at the Massachusetts Institute of Technology (MIT) Research Reactor through a Nuclear Science User Facility (NSUF) Rapid Turnaround Experiment (RTE). The measured thermal diffusivity of the preloaded sample silicon carbide was significantly lower than the literature value at the same temperature due to the irradiation-induced microstructure damage. Meanwhile, the real-time thermal diffusivity value continuously reduced with time, indicating the dynamic microstructure generation and evolution.

Impact and Value to Nuclear Applications: Thermal conductivity is arguably one of the most important material properties in nuclear fuels. Low thermal conductivity would reduce the energy transport efficiency and raise the local temperature, leading to potential fuel-melting accidents. The thermal conductivity of nuclear fuels during their lifetime consistently reduces due to the generation and evolution of irradiation-induced microstructural defects. A better understanding of these complicated processes and the impacts of different types of defects on thermal transport can help predict the in-reactor fuel performance and boost advanced fuel development. Current studies of this phenomenon rely on the use of computational tools and validating the simulation results with post-irradiation examination (PIE). This approach may raise questions since point defects, one of the primary phonon and electron scatters, significantly anneal after the reactor shutdown and before PIE measurements can be performed. This photothermal radiometry-based instrument is meant to fill the technical gap and enable the real-time, in situ monitoring capability of fuels' thermal conductivity in extreme reactor environments.

Recent Results and Highlights: In the past year, we optimized this photothermal radiometry-based instrument to accomplish real-time thermal conductivity measurements of nuclear fuels from reactors at the MIT Research Reactor. The real-time thermal diffusivity of the cladding candidate material, silicon carbide (SiC), was successfully measured at the temperature of 617°C and the irradiation damage-induced continuous reduction was observed within 40 hours. The last-measured thermal diffusivity shows a 90% reduction compared to the value from the pre-irradiation materials. Meanwhile, the irradiation-induced fiber darkening prevented further data collection, which will be the primary objective for future optimization. This instrument has the potential to become a standard in-reactor characterization tool, enabling the efficient investigation of real-time defect evolution in nuclear fuels during their service life.

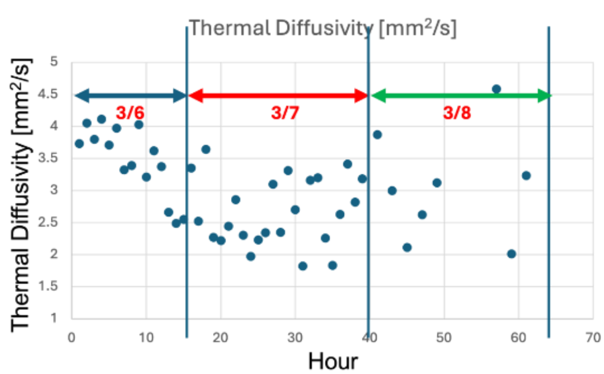

Figure 19: Thermal diffusivity of preloaded SiC sample measured in real time from the in-reactor environment.

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

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

Project Description: Liquid metal-cooled fast reactors (LMCFRs) are a promising next-generation nuclear technology, offering efficient fuel utilization, reduced long-lived actinides, and low-pressure safety advantages. However, monitoring impurities like oxygen and hydrogen in sodium coolant is challenging, as they accelerate corrosion and degradation. Current tools lack specificity, necessitating advanced real-time sensors to enhance safety and longevity. The project evaluates laser-induced breakdown spectroscopy (LIBS) for in situ trace impurity detection in liquid sodium, focusing on oxygen, with secondary assessments for other LMCFR impurities.

Impact and Value to Nuclear Applications: The advanced optical sensors using LIBS and laser-induced fluorescence (LIF) techniques for in situ impurity detection in liquid sodium coolant have the potential to provide critical real-time monitoring capabilities that substantially enhance the safety, operational lifetime, and efficiency of liquid metal-cooled fast reactors by precisely identifying corrosion-inducing elements like oxygen and hydrogen, thereby reducing structural degradation, and facilitating proactive maintenance.

Recent Results and Highlights: Parametric studies and validation of the LIBS probe performance were conducted at the University of Michigan. The optical sensor system demonstrated its capability to generate and detect distinct spectral signatures for sodium, potassium, and oxygen in liquid sodium under varying conditions, with immersion depth and argon flow optimizing signal stability and recirculation. Proof-of-concept experiments combining two-photon absorption laser-induced fluorescence (TALIF) with LIBS on a copper target in air yielded about 30-fold enhancement in signal-to-noise ratio for the oxygen line at 844.36 nm, underscoring the potential for sensitive, species-specific impurity analysis, with preliminary measurements in liquid sodium also performed. Upcoming research will emphasize limit-of-detection assessments in calibrated samples, further optimization of LIBS-TALIF in liquid sodium, and initial measurements in the Mechanisms Engineering Test Loop facility to refine real-time monitoring.

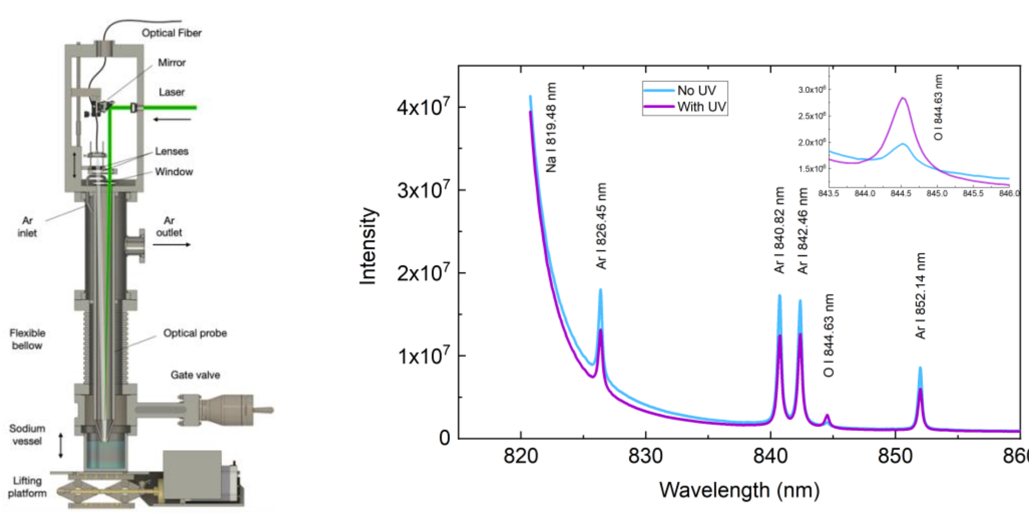

Figure 20: (Left) Laboratory testbed at the University of Michigan. (Right) Spectra obtained using liquid sodium with and without resonant ultraviolet excitation of atomic oxygen.

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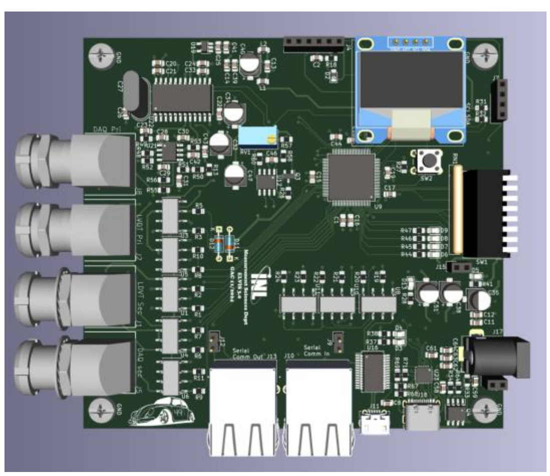


Figure 21: Computer-aided design (CAD) model of the ELVIS III board.

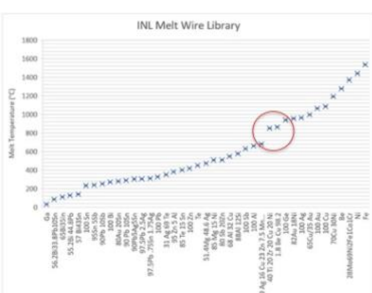
Enhancing Passive Temperature Monitoring with Silicon Carbide and Melt Wire Temperature Sensors

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
Alica Fedorikova and Marek Miklos – Research Centre Řež in Czech Republic

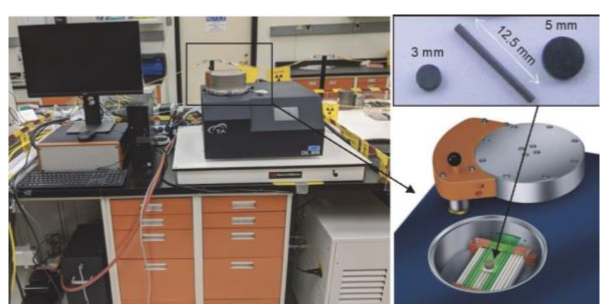
Project Description: Thermocouples are generally used to provide real-time temperature measurements in instrumented tests performed at research reactors. Passive temperature monitors (TMs), such as silicon carbide (SiC) and melt wires, may also be included as an independent technique for detecting irradiation temperatures. Also, passive temperature monitors are used in experiments where real-time sensors are not possible or too expensive, such as in drop-in capsules, to indicate the temperature reached during an irradiation. An inventory for melt wires ranging from 30°C to 1500°C is maintained at the Measurement Science Laboratory (MSL); however, it has a limited number of commercially available melt wire materials for high-temperature testing needs (above 700℃). SiC TMs, which can also be used to detect peak irradiation temperatures during irradiation, are advantageous because a single monitor can determine the peak temperature reached within a relatively broad range (100°C–1200°C). However, the way we analyze each SiC TM has not yet been standardized between the various types of research reactors, analyses equipment, or material suppliers.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measuring irradiation temperature during post-irradiation examination. They do not require feedthroughs/leads, which is the case when highly complex real-time temperature sensors are used. These monitors were chosen for deployment because of their proven track record with stakeholders, but they require continued development and characterization to ensure they are successfully integrated with program schedules and objectives that impact the next-generation research reactor qualification.

Recent Results and Highlights: The purpose of FY-25's work on the melt wires was to characterize two potential melt wire materials investigated in FY-24 to expand MSL's melt wire inventory between 700°C and 800℃. Two melt wire materials were characterized: Cu-Ag, which melted at 776.6°C, and Ag-Sb, which melted at 699.5°C. Idaho State University used the Magnetron Sputtering System to make each alloy, followed by melt behavior characterization via differential scanning calorimetry. Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) collaborated in FY-24 to investigate standardizing how SiC TMs are analyzed. The most used and understood method for reading SiC TMs is dilatometry; therefore, the first set of round-robin testing necessary for the standardization will use the optical dilatometer at INL. Different types of SiC material and suppliers, equipment, and research reactors will also be considered for future work.



Sample	Sb%	Ag%	Point (°C)
AS3	15.6	84.4	701.5
AS5	15.6	84.4	699.8
AS6	16.0	84.0	697.1
Average	**15.7**	**84.3**	**699.5**
Sample	**Cu%**	**Ag%**	**Point (°C)**
SB9	42.9	57.1	777.7
AS2	40.1	59.9	776.2
AS4	49.1	50.9	776.0
Average	**44.0**	**56.0**	**776.6**



a) *b)* *c)*

Figure 22: (a) MSL melt wire inventory, (b) Melting points for both melt wire alloys, and (c) MSL's optical dilatometer.

Developing Accurate Techniques for Passive SiC Temperature Monitoring of Miniature Samples for Cross-Cutting Applications

PI(s): Eddie Lopez Honorato, Ryan Heldt, Stephanie Curlin, Adrian Schrell – Oak Ridge National Laboratory (ORNL)
Collaborators: Christian M. Petrie, Annabelle Le Coq, Hsin Wang, and Takaaki Koyanagi – ORNL

Project Description: Passive thermometry is required to estimate irradiation temperatures and properly analyze and interrupt any results obtained from post-irradiation examination (PIE) of non-instrumented fuels and materials irradiation experiments. ORNL staff are evaluating alternative approaches to analyzing the annealing behavior of irradiated SiC TMs, including differential scanning calorimetry (DSC) and Raman spectroscopy, which could enable recovery of higher irradiation temperatures using smaller samples and potentially allow for an estimation of the spatial variation in temperature throughout the TM.

Impact and Value to Nuclear Applications: Qualification of new nuclear fuels and materials, or even existing fuels and materials for a different application, requires extensive irradiation data in test reactors. The vast majority cannot be instrumented due to access constraints and, more importantly, time and cost considerations. The passive thermometry techniques that are being evaluated, optimized, and eventually standardized provide the only indications of irradiation temperature for passive (i.e., non-instrumented) experiments. Such passive thermometry data is essential to properly interpret post-irradiation examination data and provide confidence in that data to a regulator.

Recent Results and Highlights: Samples of dense, beta-phase SiC produced via chemical vapor deposition were previously irradiated at nominal temperatures ranging from 240°C to 1000°C at doses of 2 to 10 displacements per atom (dpa). Other important variables included the continuous dilatometry (CD) sample length (~20 mm), DSC sample mass (19–94 mg), and temperature ramp rates (1°C –10°C/min) during annealing. Each sample was cut into multiple pieces so that the same material (i.e., with identical irradiation histories) could be evaluated using CD, DSC, and Raman spectroscopy.

The Raman results demonstrated the ability to spatially map irradiation temperatures, with the average temperatures generally agreeing with the CD results, albeit with a larger range of minimum and maximum temperatures. DSC consistently over-predicted temperatures compared to CD estimates, which was attributed to the higher temperature ramp rate used during the DSC annealing runs. Additional tests performed at lower ramp rates suffered from poor curve fitting, which may have been caused by the sample mass being too small as opposed to purely ramp rate effects.

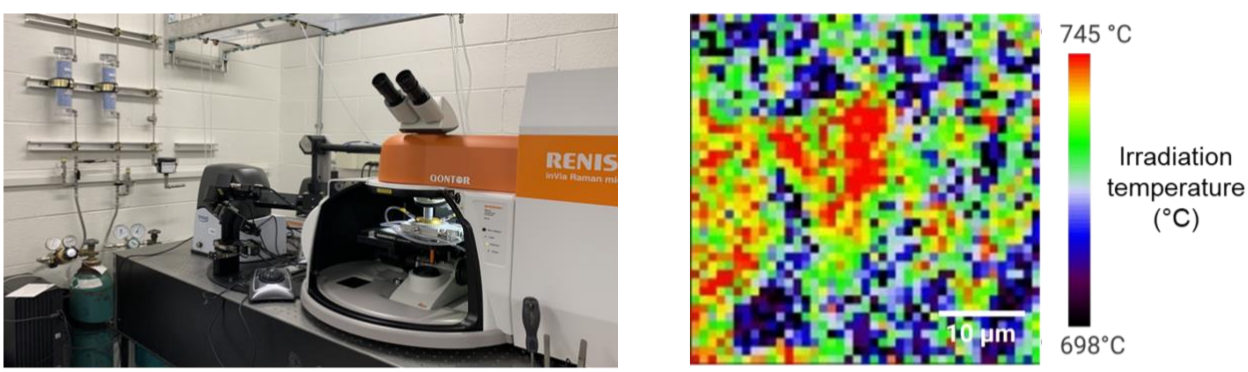


Figure 23: (left) Raman spectroscopy setup and (right) example data of irradiation temperature maps estimated from LO band Raman shifts in a SiC sample tested to 2 dpa at nominally 600°C.

Design of a Neutron Qualification Device

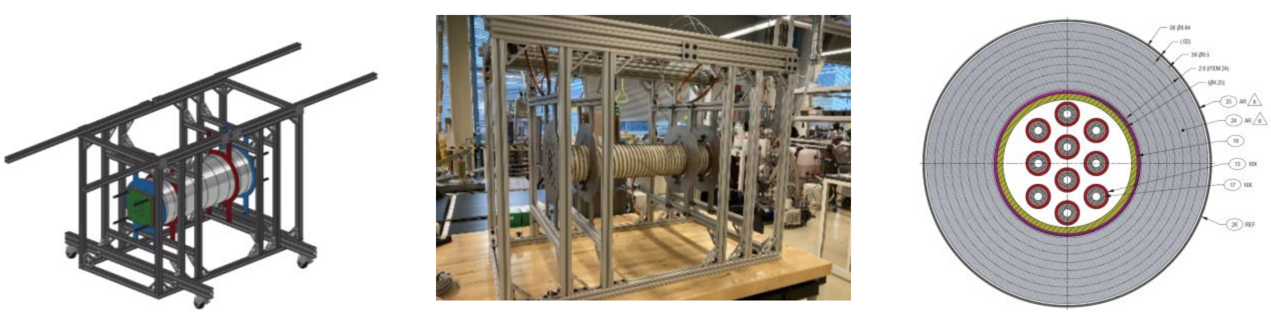
PI(s): Austin Fleming and Kevin Tsai – Idaho National Laboratory

Project Description: Advanced reactors of many forms have been under development in the last few decades. Most of these reactors will require novel and advanced instrumentation for qualification of their fuel systems and operation. Many of these sensors have undergone preliminary testing in harsh environments, but most have not been qualified for rigorous safety-significant applications.

Impact And Value to Nuclear Applications: The purpose of the neutron qualification device (NQD) is to establish a capability to quantify the uncertainty of neutron sensors for steady-state irradiation conditions at temperatures and neutron flux spectra of advanced reactors.

Recent Results and Highlights: In FY-24, the Armed Forces Radiobiology Research Institute (AFRRI) exposure rooms were identified as the preferred locations for heated neutron sensor qualification testing. The large exposure rooms with cadmium or lead-lined walls provided significant space for a test device to be located adjacent to the reactor, with easy configuration of shielding or flux filters to tailor the spectrum of interest.

In FY-25, the design of the NQD was completed based on conceptual modeling of experiments at AFRRI. It features ten total sensor positions with seven positions in the front two columns dedicated to neutron flux sensors. The sensor positions' separation and angular offsets minimize the neutron flux perturbation from albedo and shadowing effect to less than 5%. Alumina (Al_2O_3) tubes and aluminum frames are used to minimize flux depression and material activation. However, to allow for sensor testing beyond 600°C, titanium plates and clamps are used to support the alumina tubes, cable heaters, and thermocouples within the frame. Three cable heaters are used to independently control each zone separated by the titanium plates to provide a uniform heated region. Assembly and furnace testing of the NQD continues into FY-26 alongside the expected irradiation of self-powered neutron detectors and standard flux wires. These efforts will ensure that the facilities and devices are ready to qualify the performance of advanced neutron flux sensors for reactor power monitoring and fuel qualification.



a) b) c)

Figure 24: (a) MSL melt wire inventory, (b) Melting points for both melt wire alloys, and (c) MSL's optical dilatometer.

Advanced Controls

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 microreactors 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 is 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 ~10^2 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. The ANL-Purdue team aims 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, increase energy production by recovering thermal margin, and increase radioisotope production efficiency.

Recent Results and Highlights: The high-fidelity neutronics models were improved with more detailed geometry and material specification, and a better alignment with the experimental measurement was achieved. A more careful theoretical formulation was developed to address the non-homogeneous boundary condition for the Kirchhoff-Helmholtz (K-H) Integral Equation, and the physics-informed data-driven 3D field reconstruction algorithm was improved based on this theoretical work. The latest algorithm can be trained on the neutron flux simulated over a cuboid geometry that corresponds to one control rod configuration and predicts the in-core flux distribution corresponding to another unseen control rod configuration using only the neutron flux and gradients on ex-core sensors. An average relative error of 3.99% was achieved in the predicted neutron flux distribution.

In addition, a new experimental campaign was carried out by Purdue University collaborators to prove the concept of ex-core neutron flux gradient measurement. A quadrupole detector was prototyped using four copper wires, and the neutron flux on each wire was calculated through Neutron Activation Analysis (NAA) after 1 hour of irradiation at 6 kW reactor power. Despite the agreement achieved on a small portion of the axial location tested, inconsistencies were observed in the measurements. The Purdue team will repeat the analysis using gold wires, with more flexibility in experiment planning and to avoid possible errors.

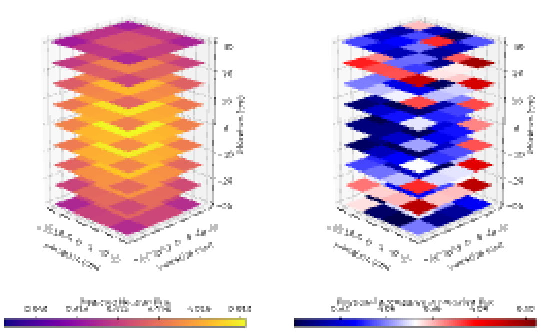


Figure 25: Neutron flux field reconstruction result for the 3D test geometry.

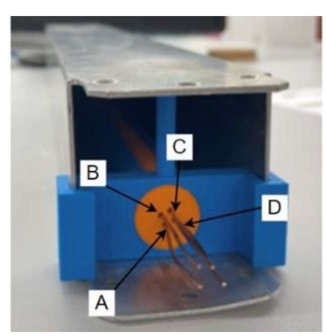


Figure 26: Proof-of-concept quadrupole detector constructed by copper wires.

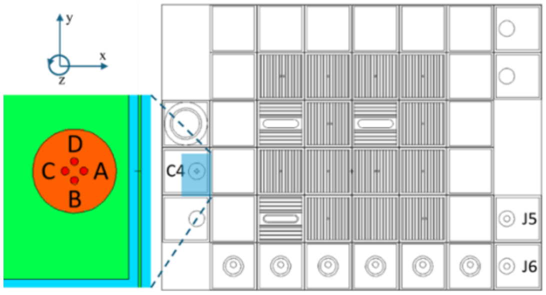


Figure 27: Irradiation experiment layout for the proof-of-concept quadrupole detector.

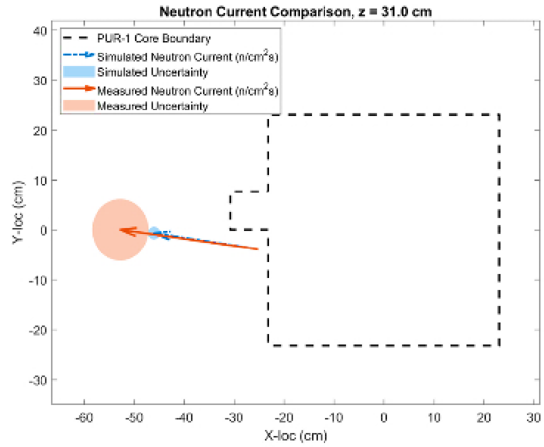


Figure 28: Comparison between the measured and simulated neutron current at z = 31.0 cm.

Advanced Controls - Demonstration of AI in Control for Advanced Reactors

PI: Ahmad Al Rashdan – Idaho National Laboratory (INL)
Collaborators: Joseph Oncken, Jacob Farber, and Marcio de Queiroz – INL

Project Description: In FY-25, the Department of Energy's (DOE) Advanced Sensors and Instrumentation (ASI) program explored the impact of artificial intelligence (AI)-based methods for reactor control through hardware demonstrations of AI-based supervisory reactor control strategies and compared it to other non-AI methods of control. Specifically, a supervisory control strategy was developed to manage core power tilt for the Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor.

Impact and Value to Nuclear Applications: 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 are expected to operate semi-autonomously or autonomously. Achieving an autonomous operations model requires advanced reactor control systems to increase complexity to replicate a human operator's decision making. This necessitates the integration of substantial new technologies and monitoring systems, including numerous additional sensors and the deployment of advanced technologies such as AI.

Recent Results and Highlights: Three supervisory controllers designed to reduce reactor core tilt were developed using both traditional and AI-based control methods and were subsequently demonstrated on the Microreactor Automated Control System (MACS) reactor physical twin of MARVEL. The first controller employs rules-based methods, utilizing a predefined, logic-based control law derived from expert knowledge of the system. Although this control method produces predictable and intuitive outputs, it did not achieve optimal performance. This method of control requires adjustments or calibrations, and additional rules are often needed to handle edge cases and improve performance. The second controller is optimization-based, actively learning the system state and selecting the optimal control action to minimize tilt without necessitating prior system knowledge. This entirely data-driven approach led to non-linear and sometimes unpredictable performance, influenced by the stochastic nature of the measurements and the algorithm itself. Despite this, the implementation of this control method is straightforward and requires only tuning to achieve a good performance. However, the algorithm operates slowly as it must learn the system dynamics in real-time. The third AI-based controller utilizes reinforcement learning to develop a control law. A control agent was trained offline on numerous reactor simulations with varying core tilts and control actions. This method requires accurate system models to learn to make optimal decisions, especially in challenging scenarios. Control performance is generally predictable unless the controller encounters scenarios not covered during training. Due to pre-training, the reinforcement learning-based controller is the quickest of the three in identifying and compensating for reactor tilt, leveraging the control policy embedded during training.

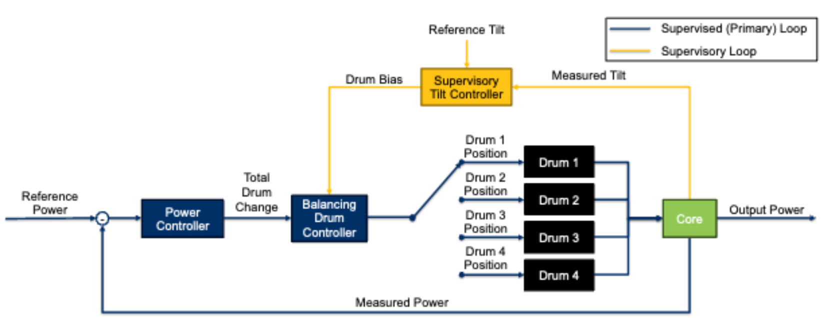


Figure 29: Tilt-compensating reactor power control architecture with power control loop (blue) and supervisory tilt control loop (yellow).

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

In FY-25, the ASI program provided $5,182,100 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/#/.