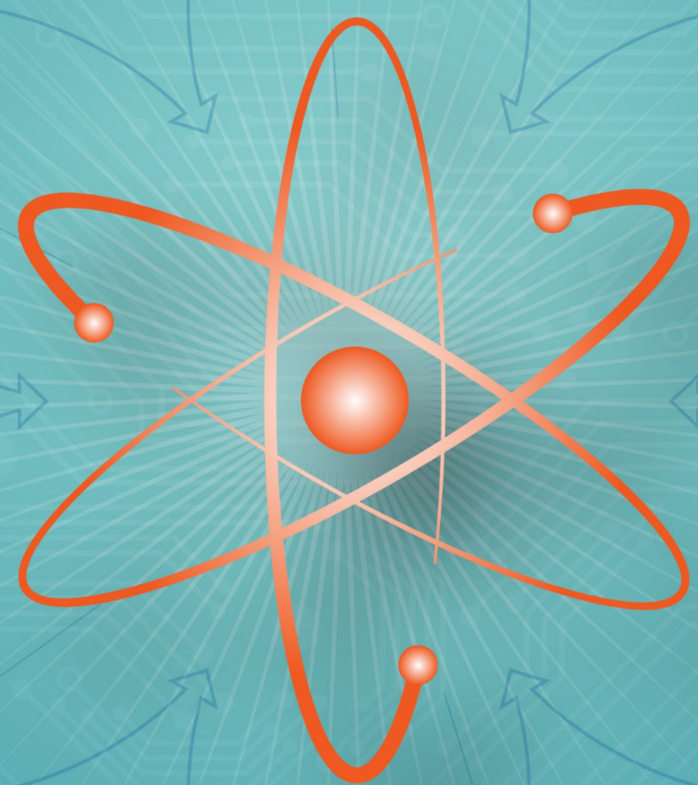
U.S. DEPARTMENT OF ENERGY

ADVANCED SENSORS AND INSTRUMENTATION

2021 SUMMARY OF ACCOMPLISHMENTS



ABSTRACT

The Advanced Sensors and Instrumentation (ASI) program is the element of the Nuclear Energy Enabling Technologies (NEET) initiative dedicated to Instrumentation and Control (I&C) technology. This document collects in the form of summaries the research accomplishments presented at the program 2021 Annual Review meeting, which was held virtually between November 15 and November 18, 2021.

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INTRODUCTION

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

The NEET ASI Program has the following roles:

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

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

Research Areas

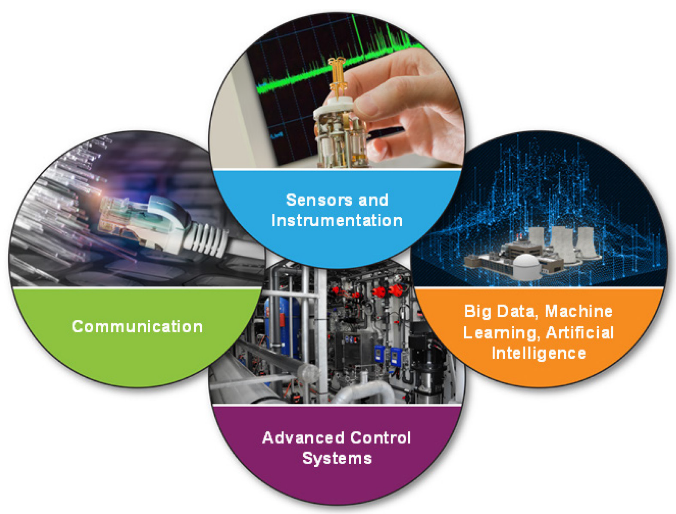
The NEET ASI program has identified four research areas representing key capabilities for nuclear energy systems and fuel cycle facilities. These research areas support crosscutting research in response to stakeholders' needs.

These research areas are as follows:

1. ***Sensors and Instrumentation***. Research, qualify, and develop reliable and cost-effective new sensors that are able to provide real-time, accurate, and high-resolution measurements of the performance of existing and advanced reactors' cores, fuel cycle systems, and plant systems.

2. ***Advanced Control Systems***. Research and develop and enable real-time control of plant or experimentation process variables to enhance plant thermal performance and to reduce operation and maintenance (O&M) costs through advanced risk-informed approaches to monitoring and control.

3. ***Nuclear Plant Communication***. Research and develop a resilient, secure, and real-time transmission of sufficient data enabling online monitoring, advanced control strategies, and big data analytics.



NEET ASI Research Areas

4. ***Big Data Analytics, Machine Learning, and Artificial Intelligence***: Research and develop machine learning and artificial intelligence capabilities to enable semi-autonomous operations and maintenance by design using heterogeneous and unstructured data.

RESEARCH ACCOMPLISHMENTS

This section collects in the form of summaries the research accomplishments presented at the ASI program 2021 Annual Review meeting, which was held virtually between November 15 and November 18, 2021. The content is organized following the four meeting sessions, as follows:

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

Sensors for Advanced Reactors

Nuclear Energy Sensors Database

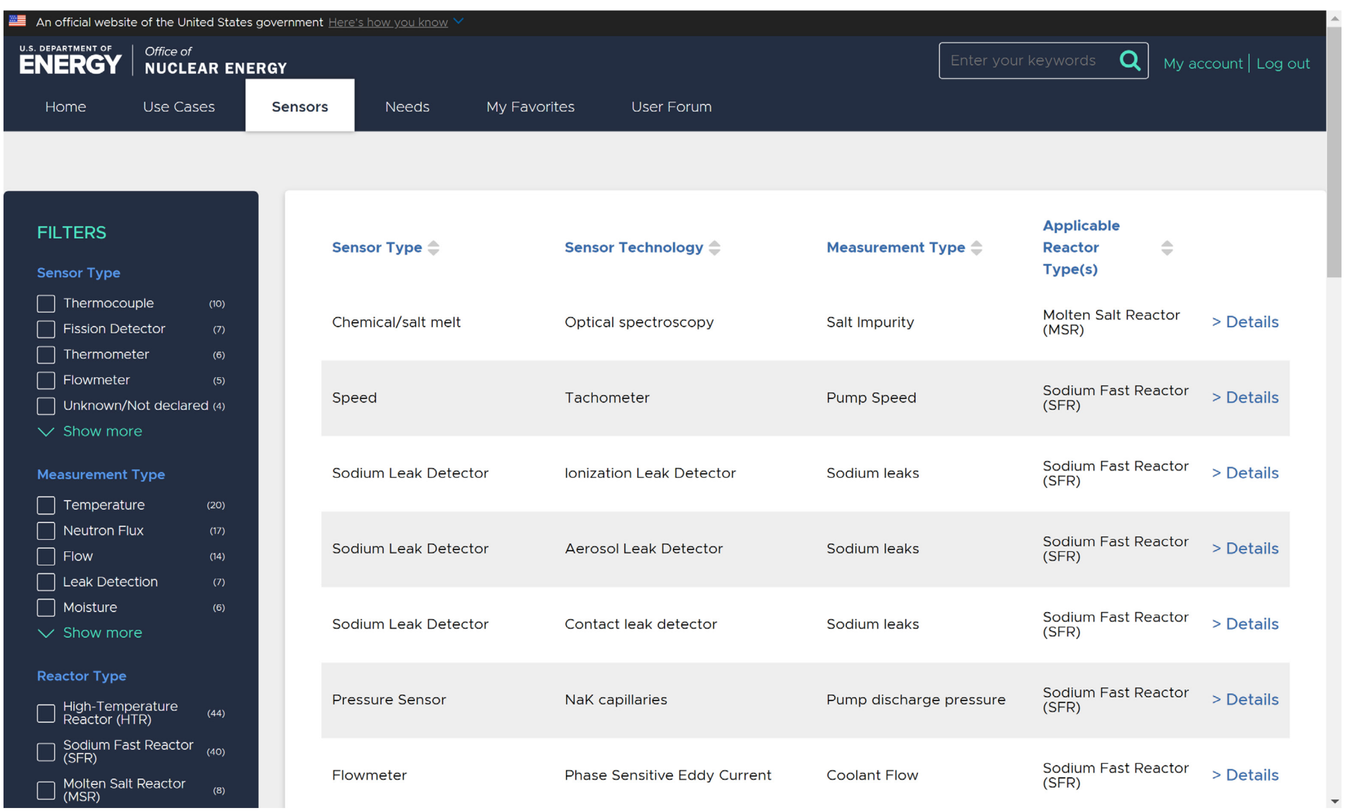
PI: Tim Downing, Andrew Casella – Pacific Northwest National Laboratory
Collaborators: Pattrick Calderoni, Yogeshwar Dayal – Idaho National Laboratory

Project Description: Previously developed sensor technology assessments for advanced nuclear reactor systems have helped identify technology gaps and prioritize R&D efforts. However, there was a need for improved access and visualization of information to aid in these decisions.

To address this need, a Nuclear Energy Sensors website database (https://nes.energy.gov) was created for nuclear facilities, universities, and industry staff members to find sensor information used in the nuclear energy field.

Impact and Value to Nuclear Applications: This website is intended to be used as a “one stop shop” to search for information related to nuclear energy sensors, existing use cases, and prioritized needs and gaps. In addition to providing this content, the website also supports a user forum for subject matter experts to build a community and provide additional suggestions for new sensors or site enhancements.

Recent Results and Highlights: The initial site went live in early FY21, and much of FY21 has been focused on gathering, clearing, and posting additional sensor information. In FY21, new sensors relevant to BWRs, SFRs, MSRs, and PWRs were added.



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

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

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

Impact and Value to Nuclear Applications: The development of HiTEIS will enable non-invasive sensing of operation status of NPPs. Remote communication system will aid to monitor a system in an NPP more frequently in reliable manner and minimize the need for human operators to be available in the vicinity of high temperature and radiation hazards.

Recent Results and Highlights: Laser ultrasound (LUS) transducers are developed for the remote ultrasound wave generation at elevated temperatures (e.g., > 250°C). Specifically, LUS transducers using candle soot nanoparticle (CSNP) and liquid metal (LM, e.g., Field's metal) materials were prototyped and characterized. The LM LUS transducer showed a relatively more stable performance compared to the CSNP composite LUS (Figure 1) at. Meanwhile, sensor embedding methods are being studied by using a high-speed (~10 MHz) wireless communication system for transferring of ultrasound wave signals (Figure 2). Lastly, a sensor shielding technique is investigated using a plasma-enhanced chemical vapor deposition technique. A thin layer (~100 nm) of ZrO_2 (Zirconium dioxide) was deposited on sensing material (e.g., aluminum nitride single crystal (AlN)), where the sensor could perform stably at either high temperature (HT) (~1,100°C) or corrosion (pH 6.1) condition (Figure 3).

Images/graphs/charts:

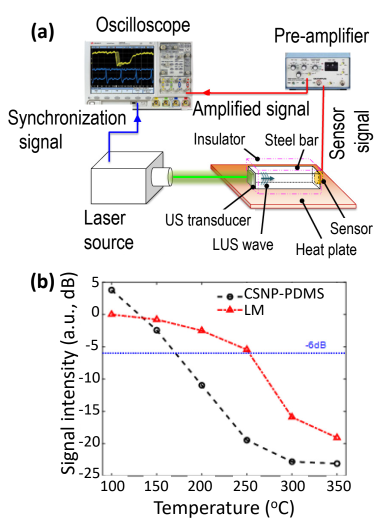


Figure 1. LUS transducer test setup (a) and signal intensity comparison of the LM and the CSNP LUS transducers (b).

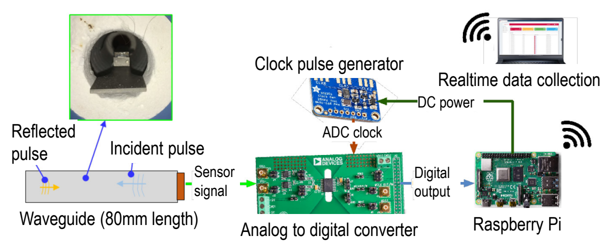


Figure 2. Wireless data transfer system for HT ultrasound sensing.

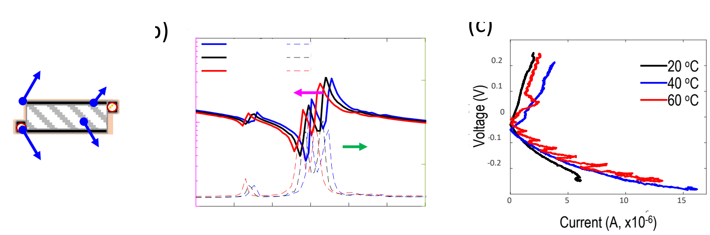


Figure 3. (a) Sensor shielding method, (b) impedance spectrum of the shielded sensor, (c) corrosion effect (pH 6.1) measurement.

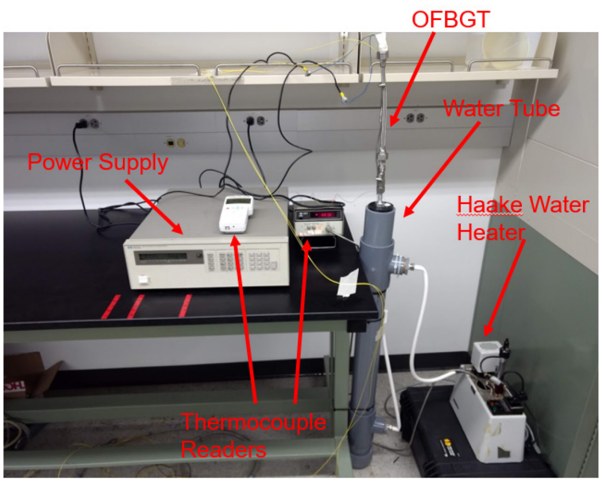
Development of an Optical Fiber Based Gamma Thermometer

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

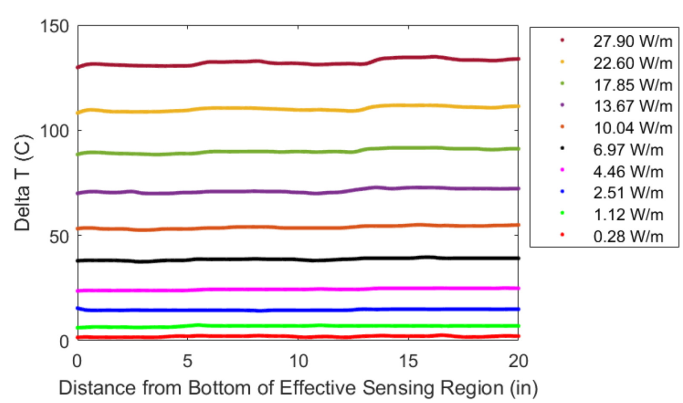
Project Description: The objective of this project is to develop an optical fiber-based gamma thermometer (OFBGT). A system of OFBGTs could be used to calibrate the power monitors in reactors. Also, utilizing data analytics, a system of OFBGTs could be used to determine the power distribution in a reactor directly. We have developed a silica-fiber OFBGT, and are developing a sapphire-fiber OFBGT. We postulate the sapphire-fiber OFBGT could withstand the extreme temperatures in next generation reactors. We have developed data analytic methods to obtain the power distribution from the OFBGTs, which fundamentally measure gamma-ray (and to a lesser extent, neutron) absorbed dose in the OFBGT thermal mass. A silica-fiber OFBGT has been tested in the Ohio State University Research Reactor (OSURR), and will be tested in the Texas A&M University Research Reactor (TAMURR).

Impact and Value to Nuclear Applications: A system of OFBGTs in a nuclear reactor would enable a permanent system for calibration of power monitors, which would replace traversing in-core probes (TIPs), which are currently utilized in boiling water reactors. Also, an OFBGT can extend the entire length of an instrument tube, and acquire a distributed gamma-ray absorbed dose rate along its length. TIPs, or even thermocouple-based gamma thermometers, act as point sensors, and do not possess such a capability. OFBGTs are, therefore, particularly useful with regard to "Big Data" generation, and enable a higher resolution measurement of the 3D distribution of core power than can be obtained with ion chambers.

Recent Results and Highlights: We have completed and iterated the design, construction, calibration, and testing of a silica-fiber OFBGT for University Research Reactors (URRs). The OFBGT design has: 1) a thermal response that is high enough for low measurement uncertainty, but which is far lower than the temperature limits of the sensor materials; 2) a low sensor calibration error, due to strategic choices in the sensor materials and dimensions; and 3) a design with little potential for neutron activation. The data analytic methodology, which will be used to infer the reactor power from the OFBGT response, has been developed and tested, assuming theoretical reactor power (and corresponding OFBGT response) distributions.



OFBGT Calibration Station.



Delta T over the effective sensing region for various linear heating rates.

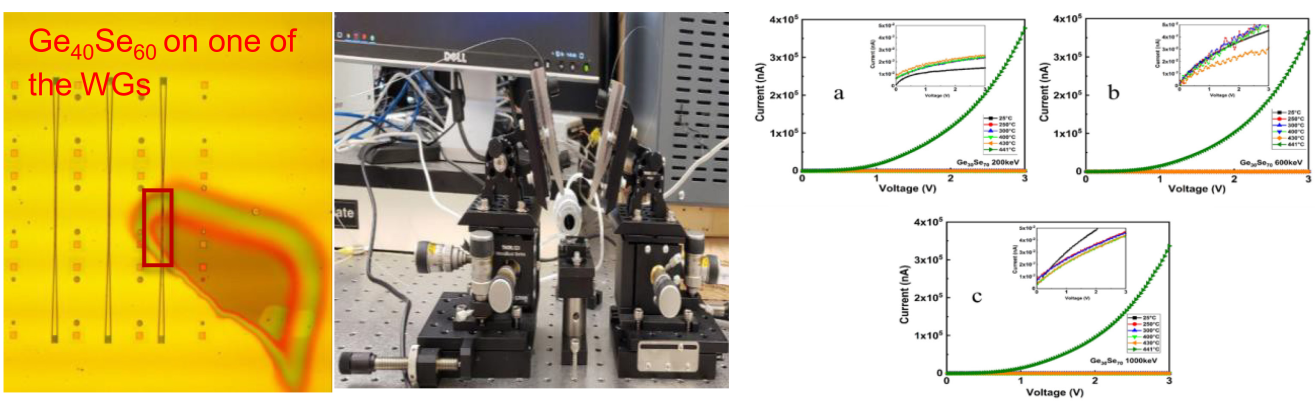
Integrated Silicon/Chalcogenide Glass Hybrid Plasmonic Sensor for Monitoring of Temperature in Nuclear Facilities

PI: Maria Mitkova, Harish Subbaraman – Boise State University
Collaborators: Isabella Van Rooyen – Idaho National Laboratory

Project Description: The project is focused on the research and development of new in-situ, reusable, and reversible sensor concepts for integrated temperature monitoring, applying a combination of photonic properties of radiation-hardened waveguides and temperature progress of chalcogenide glasses (ChG) properties (their crystallization). These sensors are typically suitable for monitoring of Light Water Reactors' (LWR), metallic, and ceramic reactors' components within a temperature range of 400°C – 650°C.

Impact and Value to Nuclear Applications: The sensors offer an opportunity for nuclear safety, in particular—for facilities, their employees, and the public—by offering increased sensor system accuracy, real-time monitoring, reliability, and efficiency. The technology addresses nuclear materials quantification and tracking, as well as delivery of a novel hybrid fiber sensor that is easier and less costly to manufacture and functions well under irradiation. It can be quickly and easily reset for subsequent measurement by electric stimuli at room T.

Recent Results and Highlights: Development and fabrication of a temperature sensor based on waveguide. A schematic of this sensor is presented in Figure 1 (a) and the testing set up – in Figure 1 (b).



(a) (b) (c)

Figure 1. a) Waveguide device covered with chalcogenide glass b) Grating coupling set up for devices characterization; c) IV characteristics of devices at irradiation with initial ions energy of 200, 600, and 1000keV. To study the performance of the sensor under irradiation it has been irradiated with xenon (Xe) ions. Our choice is based on the fact that Xe is chemically inert, nonradioactive, and one of the typical fission products, offering a cost-effective and safer alternative to neutron irradiation. Data for the radiation hardness – Figure 1(c) were collected through the electrical operation of phase change temperature sensors, which demonstrated very high stability. Since the sensor structure is built by several overlaying films, their stress with increasing of temperature was studied by applying a laser grid to measure the change in shape and structure of the substrate on which the films are deposited, using KMOS tool. The results demonstrated weak stress increase in horizontal direction and remarkable steadiness in vertical direction, which is an indication about the sensors applicability for monitoring of cladding temperature of LWR and ceramic reactors.

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

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

Project Description: We are investigating a cylindrical microwave cavity-based transducer for high-temperature fluid flow sensing in advanced reactors. 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 (Figure 1a). Cavity volume change due to membrane deflection causes a shift in the microwave resonant frequency. Using signal readout from a hollow microwave cavity is advantageous for applications in high temperature and high radiation environment because no electronic components are placed inside the transducer. Energy coupling to and from the sensors achieved through a microwave waveguide, which is an integral part of the insertion probe. A waveguide is a rigid narrow hollow metallic tube resilient to high temperature and high-radiation environment.

Impact and Value to Nuclear Applications: Measurement of high-temperature fluid flow inside the pressure vessel is a challenging task because of harsh environments of advanced reactors. 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 corrosive environment of sodium fast reactors (SFR) and molten salt cooled reactors (MSCR).

Recent Results and Highlights: Using computer simulations with COMSOL RF and Structural Mechanics modules, we have developed a preliminary design for a microwave K-band sensor. A cylindrical resonator prototype was fabricated from brass for initial tests (Figure 1b). The external dimensions of the cavity are matched to the flange of a standard WR-42 waveguide (Figure 1c). Microwave field is coupled into the resonant cavity through a subwavelength-size aperture. A test article was developed consisting of a piping Tee with a bulkhead WR-42 microwave waveguide installed in a leak-proof assembly (Figure 1d). Preliminary spectral characterization of cavity spectral response was performed with a microwave vector network analyzer (VNA) (Figure 1e).

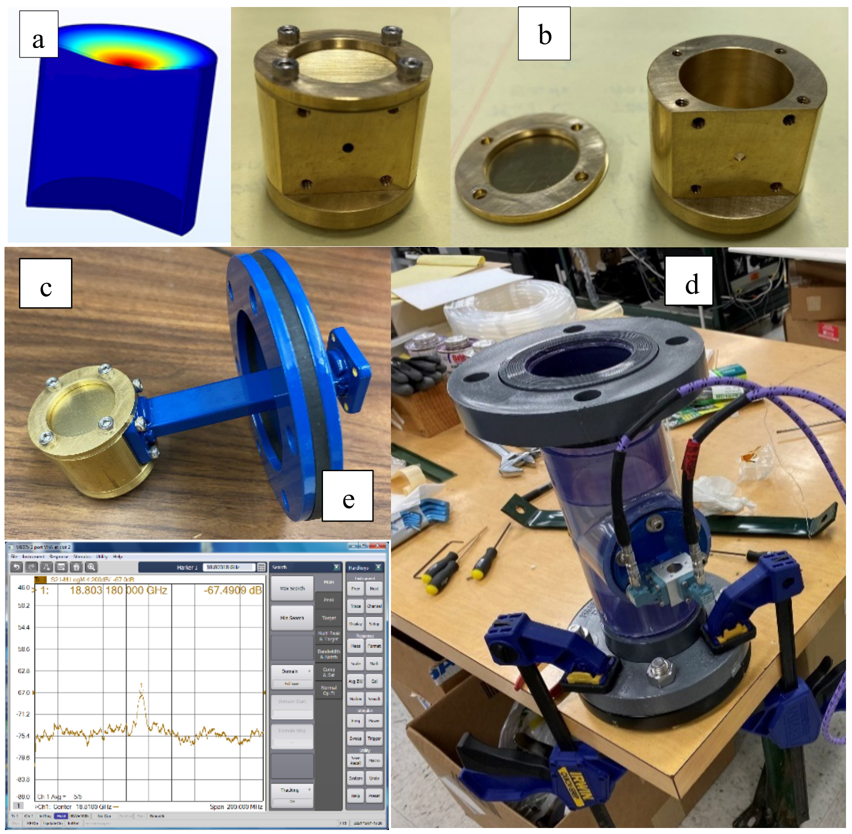


Figure 1. (a) Visualization of membrane deflection. (b) Photograph of K-band cylindrical microwave cavity. (c) Cylindrical cavity coupled with K-band bulkhead microwave waveguide. (d) Piping test article for leak-proof insertion of transducer. (e) Signal measured with microwave VNA.

Real-time In-core Instrumentation: From Fuel and Materials Irradiation Tests to Advanced Reactor Demonstration – Neutron Flux Sensors

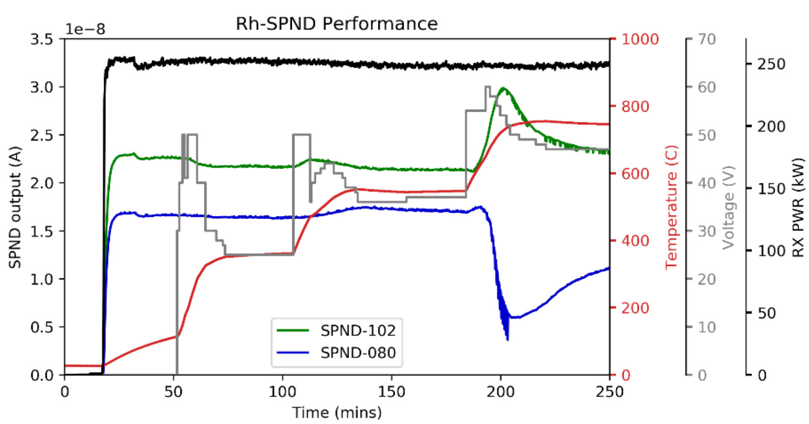
PI: Kevin Tsai – Idaho National Laboratory
Collaborators: Joe Palmer, Michael Reichenberger, Troy Unruh, and Calvin Downey – Idaho National Laboratory

Project Description: In-core neutron flux sensors provides localized neutron flux data in real-time. This data is crucial for supporting advanced fuel cycle development as well as monitoring and controlling existing and advanced reactors. This project directly addresses the development and qualification of the sensor technologies. Activities include designing a sensor, establishing a fabrication/procurement pipeline, and demonstrating sensor performance in representative advanced reactor environments. In fiscal year (FY) 2021, work was primarily focused on the demonstration of rhodium-based self-powered neutron detectors (Rh-SPNDs) that were designed and fabricated in FY 2020 for steady-state reactor operation and use in high-temperature (upwards of 800°C) environments. The micro-pocket fission detector (MPFD) had also undergone a design update with irradiation testing alongside the Rh-SPNDs.

Impact and Value to Nuclear Applications: Performance characterization of SPNDs and fission chambers in research reactors provides a calibration pathway for the development and use for in-core flux sensors —a crucial step toward qualifying sensors for neutron flux measurements. The demonstration and comparative assessment of neutron flux sensors will provide local neutron measurements for material test reactor irradiations as well as advanced reactor deployments requiring active flux-sensing technologies.

Recent Results and Highlights: SPND testing and benchmarking against fission chambers and dosimetry were performed in three reactor facilities: Idaho National Laboratory's Advanced Test Reactor Critical facility, Neutron Radiography facility, and Idaho State University's AGN-201m test reactor facility. Additional high-temperature testing was also performed at the Neutron Radiography facility. These experiments demonstrated SPND signal linearity in response to thermal flux for over five decades in magnitude. The data collected provides calibration factors for the SPNDs, provides information for the sensitivity models under development, and serves as the basis for developing active temperature compensation tools.

Sensor insertion into NRAD heated rig.



SPND performance in heated irradiation at NRAD.

Optical Fibers

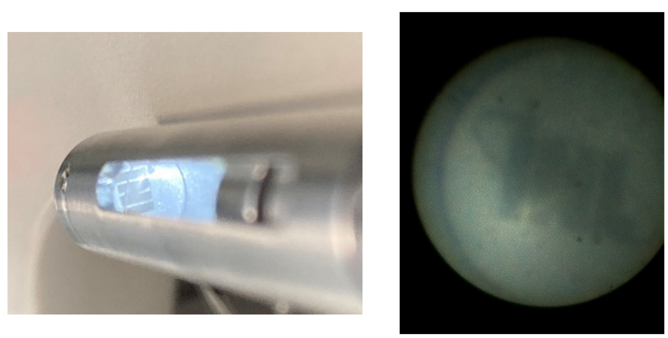
PI: Austin Fleming – Idaho National Laboratory

Project Description: Although fiber optic sensors have been widely adopted as standard instrumentation in many industries, the nuclear industry has been slow to adopt this technology because of certain challenges associated with the measurement environment. This project aims to directly address these challenges so that fiber optic sensors can have the same innovative impact on the nuclear industry as they do in other fields. In the development of fiber optic sensors and sensor technologies, this project prioritizes near-term applications (customers with immediate needs), straightforward paths to development (little to no R&D, mostly engineering), and impact to the nuclear industry. Fiber optic work in fiscal year (FY) 2021 focused on demonstrating the Fabry-Perot pressure sensor developed in FY 2020, as well as applying fiber bundle technology to perform in-core imaging. Data from intrinsic temperature sensors deployed in Transient Reactor Test Facility (TREAT) and Advanced Test Reactor (ATR) experiments were used to characterize sensor performance and develop active compensation techniques for data analysis in order to reduce the uncertainty caused by irradiation degradation. Aspects of enabling R&D continued as part of the deployment of optical fiber sensors/systems with a focus on establishing techniques for fabricating sensors capable of withstanding high temperatures.

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

Recent Results and Highlights: Fiber optic sensing technology for in-pile applications was advanced on several fronts throughout FY 21. For the first time, in-pile testing of a fiber optic imaging bundle was conducted. Several iterations of this test were performed using various light sources and filters to enhance the image and suppress spurious radiation-induced emissions such as Cherenkov radiation and radioluminescence. Significant advances have been made in developing an active compensation technique for removing or minimizing sensor drift due to radiation-induced effects.

Photograph of the active compensation prototype sensor using cascaded Fabry-Perot cavities.



Photograph of the fiber optic image system tested in pile.

Acoustic Sensors

PI: Joshua Daw – Idaho National Laboratory
Collaborators: Dan Deng – Boise State University
Marat Khafizov – The Ohio State University

Project Description: The goal of this research activity is the design and fabrication optimization of an INL-developed ultrasonic thermometer (UT) temperature sensor, assessment of the state and potential of piezoelectric acceleration and pressure sensors for use in nuclear applications, and prioritization of research activities related to surface acoustic wave (SAW)-based sensors.

Impact and Value to Nuclear Applications: Acoustic and ultrasonic transducers can serve as a base technology in numerous sensors for measuring a multitude of parameters including temperature, gas pressure, and vibration. The ability of some ultrasonic sensors to make spatially distributed and multiplexed measurements, sometimes without direct access to the sample to be measured, is highly valuable for use in the compact systems encountered in nuclear reactors and irradiation experiments. Accurate online monitoring of test parameters including temperature and strain will greatly reduce the time and cost associated with developing, demonstrating, and licensing new nuclear technologies. The UT temperature sensor that is based on an acoustic waveguide is being developed for in-core, multi-point temperature monitoring in the extreme conditions found in a nuclear reactor. The targeted applications are experiments in test reactors and core temperature monitoring for high-temperature advanced reactors. Although design and fabrication activities are focused on temperature sensing applications for in-core applications, acoustic sensors is a term that encompasses a very wide variety of sensors that can be applied to any commercial or test reactor application or ex-core subsystem.

Recent Results and Highlights: Based on prior experimental results, diffusion bonding between the UT temperature sensor waveguide and protective sheath (a process known as "sticking") was observed to limit the maximum operating temperature. One focus of the research activities was to develop and demonstrate methods for reducing the high temperature sticking. Several such methods were designed, fabricated, and evaluated. The most promising design was a 3-D-printed ceramic spacer with features integrated to minimize contact between the waveguide and sheath as shown in Figure 1. In addition, a planning meeting was held with research collaborators to prioritize research tasks related to the development of SAW-based sensors beyond the UT temperature sensor activities.

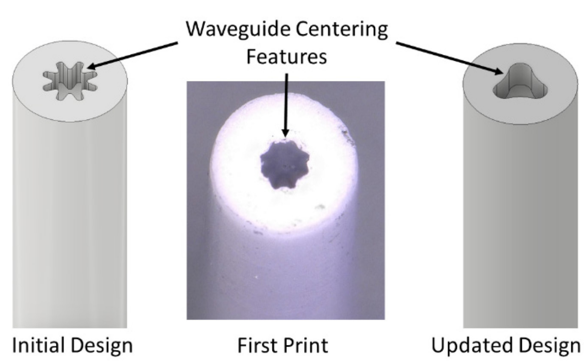


Figure 1. 3-D-printed spacer for mitigation of sticking effects in waveguide-based ultrasonic thermometers.

Nuclear Thermocouples

PI: Richard Skifton – Idaho National Laboratory
Collaborator: Brian Jaques, Lan Li – Boise State University

Project Description: For temperature measurements, thermocouple (TC) instrumentation is typically comprised of one or more sensing elements, interrogation systems, and a data acquisition system, as well as processes and procedures to collect, analyze, and calibrate data. The instrumentation is used to measure process parameters (e.g., temperature) independently of the experiment, component, or process in which it is deployed. The focus of this activity is to extend the operation range, improve the accuracy, and reduce the performance degradation of TCs under irradiation. The demonstration activities in fiscal year (FY) 2021 focused on three main topics: 1) apply the High Temperature Irradiation Resistant Thermocouple (HTIR-TC) technology to pressurized water reactor (PWR) conditions for planned deployment in the ATR center loop, 2) leverage modeling and simulation to guide optimum material selection for water and oxygen (O_2) interaction, and 3) leverage DOE-NE TCF to commercialize HTIR-TC.

Impact and Value to Nuclear Applications: Real-time temperature measurement is arguably the most important operational parameter for characterizing irradiation experiments and controlling power plant systems. Potential areas of application are material test reactors, advanced fuel validation tests, and advanced nuclear power plants. Certain impacts to these fields include getting closer proximity to the fuel, either through the surface cladding or inside the fuel itself, thus reducing the uncertainties in fuel burnup, fuel/coolant interaction, and modeling (i.e., digital twinning). Another outcome is higher temporal resolution during nuclear transients. In summary, better "drivability" of the reactor fuel can be achieved.

Recent Results and Highlights: Quantifiable drift of nuclear grade TCs in an out-of-pile furnace was recently performed, and the results showed the drift of the HTIR-TCs to be 1–1.15% after ~125 effective full power days. Both traditional two-wire, ungrounded HTIR-TCs and coaxial, single wire HTIR-TCs were tested. Further, modeling and experimentation on both the localized Seebeck coefficient and oxidation intercalation into the niobium and molybdenum thermoelements was performed. Our simulations suggest Mo-1%Nb would be the most resistant of the studied alloys to both oxidation and corrosion. Of the predominantly Nb alloys, Nb-1%Zr is most oxidation resistant up to 600°C while Nb-1%Mo is most oxidation resistant from 600 to 1600°C. Nb-1%Mo is also expected to have the best overall corrosion resistance of the Nb alloys.

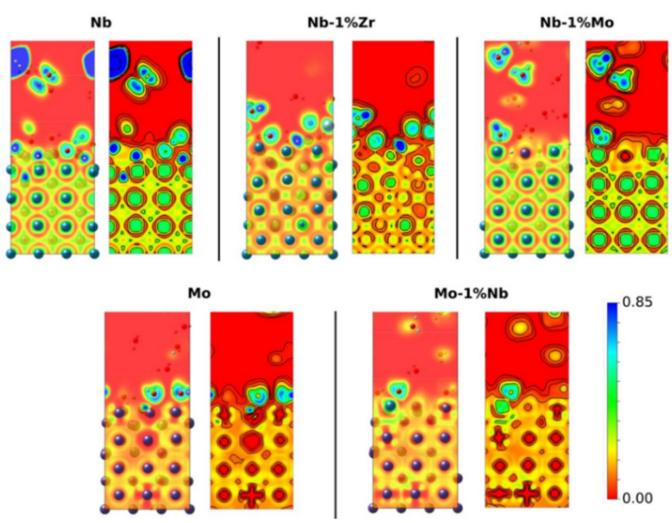


Figure 1. Electron Localization Functions of metal surfaces under H_20 after 1 ps at 1600°C.

Advanced Materials and Manufacturing Methods for Sensors Applications

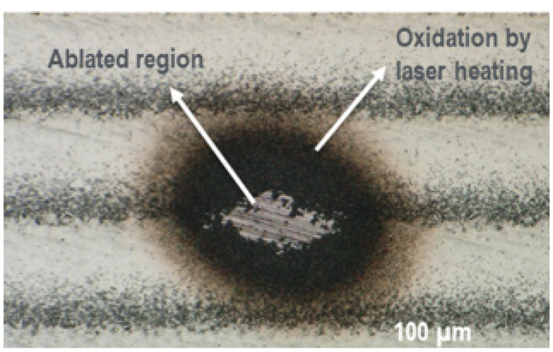
Advanced Manufactured Sensors: Feedstock Development, Fabrication, and Process Control

PI: Michael McMurtrey – Idaho National Laboratory
Collaborators: Kiyo Fujimoto, Amey Khanolkar – Idaho National Laboratory
David Estrada – Boise State University

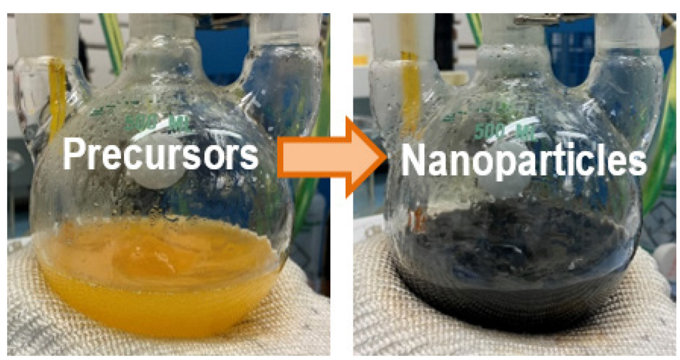
Project Description: Advanced manufacturing (AM) based sensor development using direct-write (DW) technologies such as aerosol jet printing (AJP), plasma jet printing (PJP), and micro-dispense printing (MDP) has emerged as the predominant enabler for the fabrication of active and passive sensors deployable in the types of harsh operating environments seen in a nuclear reactor. This activity aims to expand the current library of commercially available feedstock materials so as to encompass nuclear-relevant materials utilizable for manufacturing in-pile sensors and advanced nuclear instrumentation. Such sensors must withstand degradation against the coupled extremes of high-temperature and high-radiation fields. To this end, a post-fabrication process control protocol using laser-based techniques is being developed to evaluate the influence of substrate surface conditions—as well as that of deviations from ideal printing parameters—on the quality, robustness, and integrity of the printed sensor. Print parameters that affect the performance of active sensors will also be assessed via electrical resistivity measurements.

Impact and Value to Nuclear Applications: The limiting factor in implementing AM for novel sensor design is the current selection of commercially available feedstock materials that are compatible with these technologies. Significantly expanding this library of materials will enable the necessary pathway for incorporating these novel methods into nuclear energy applications, potentially revolutionizing the development of in-pile nuclear sensors. The laser-based techniques developed in this project for sensor-substrate adhesion measurement are expected to aid in determining the dominant combination of factors that significantly alter sensor durability, thus providing vital process control for printing novel nuclear-relevant materials via DW technologies.

Recent Results and Highlights: Feedstock development efforts elucidated a synthesis pathway for bismuth and bismuth-platinum (BiPt) bi-metallic nanoparticles – a pathway aimed at enhancing the temperature resolution of printed melt wires. While slight deviations from the theoretical melting point values occurred, the varying melting point of each different BiPt composition showed that the melting point can be altered by varying the composition of the BiPt nanoparticles. Additionally, a laser ablation technique was used to systematically study the influence of substrate roughness, substrate surface energy, and post-printing ink sintering conditions on the sensor-substrate adhesion strength of AJP-printed sensors. The ink sintering duration and temperature were found to be the dominant factors affecting adhesion, while substrate surface roughness was a secondary factor



Optical micrograph showing the region of the sensor ablated by a pulsed laser beam.



Reduction of bismuth and platinum ions to form BiPt nanoparticles, with nanoparticle formation being indicated by color change.

Direct Digital Printing of Sensors for Nuclear Energy Application

PI: T. J. McIntyre – Oak Ridge National Laboratory
Collaborators: University of Central Florida (UCF)
AMS, Corporation and Southern Company

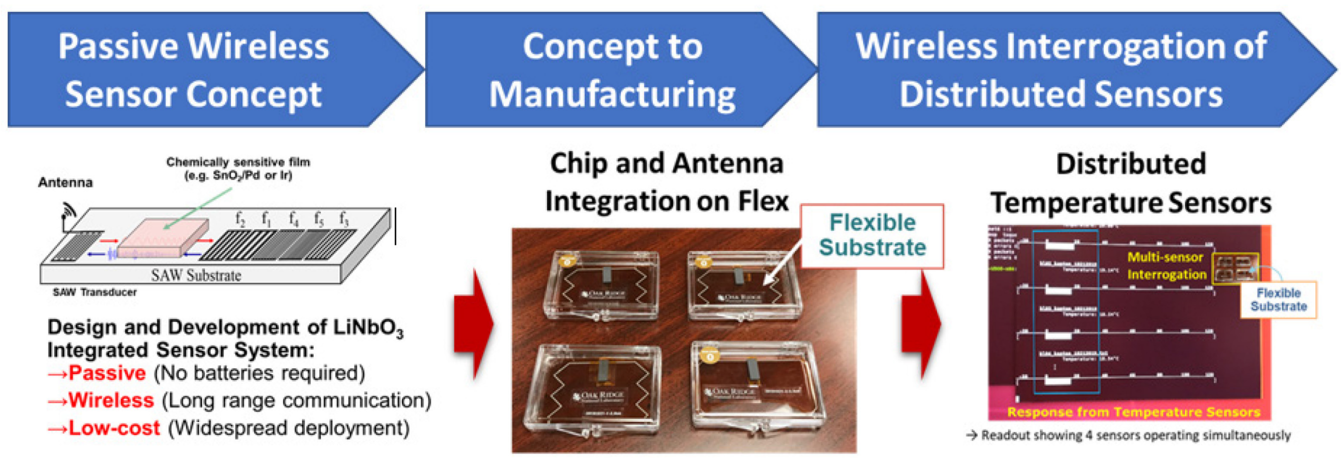
Project Description: This project is developing sensors of interest and direct digital printing (DDP) of integrated sensor systems. The sensors of interest currently are temperature, hydrogen, voltage and current. AMS has allowed us to test a 5-sensor network at their facilities in Knoxville, TN and Southern Company would like to deploy a 6-10 sensor network on a steam turbine generator at one their generation facilities. We have developed DDP additive manufacturing technology in collaboration with advanced DDP companies including Optomec, Super Ink Jet Technologies (SJIT), and XTPL. The goal of the collaboration with printer technology OEMs is to push the state of the art of DDP to feature sizes of <1µm. The second main thrust has been development of methods to functionalize a radio frequency (RF), surface acoustic wave (SAW) platform to measure the variables of interest. Lastly, we have developed integration strategies that allow us to use DDP to print the RF/SAW platform, functionalize it and print an integrated antenna and a sensor package that enables easy deployment of a sensor network.

Impact and Value to Nuclear Applications: The RF/SAW sensors being developed are completely passive sensors. As such, these sensors can be fabrication in large numbers (100s), are very inexpensive (<$1.00/unit) and can be easily deployed using a peel and stick approach. This allows plant operators to minimize sensor system calibration and maintenance by deploying redundant sensor networks.

Recent Results and Highlights: We have demonstrated in the lab functional sensors operating at 915MHz. An invention disclosure has been filed on SAW-based electronic impedance-based sensor. We have also demonstrated several additional features of the technology including:

1. Model-based design, fabrication, and testing of compact antennas for PWST nodes
2. Improved understanding of multi-sensor effects on measurand extraction capability: algorithm limits
3. Development of practical functionalization approaches for hydrogen, voltage, and current sensitivity
4. Field tests/demonstrations at (1) Southern Company and (2) AMS

Images/graphs/charts:



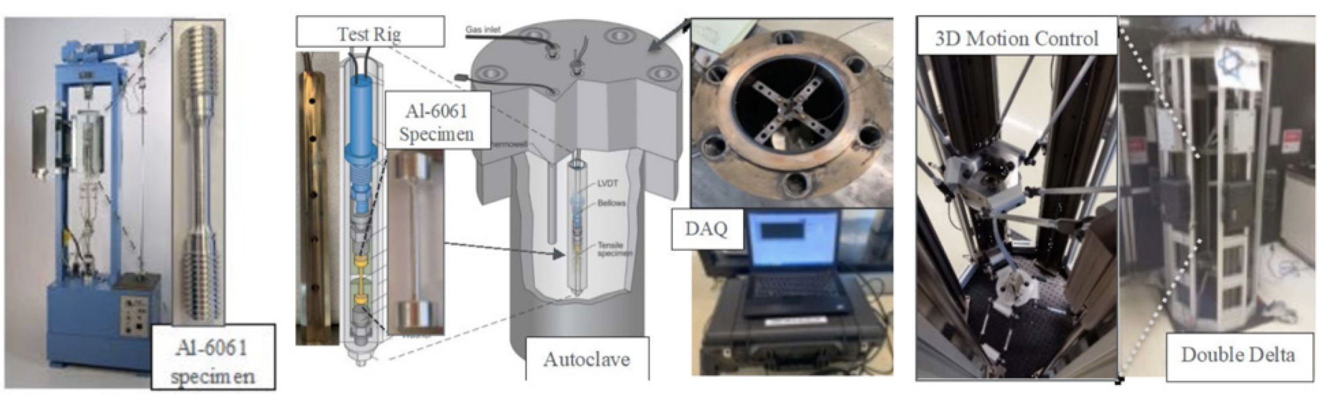
Development of a Test Rig for Structural Materials Characterization

PI: Malwina Wilding – Idaho National Laboratory
Collaborators: Michael McMurtrey, Anthony Crawford, Kory Manning, Hollis Woodbury, Wesley Jones, and Troy Unruh – Idaho National Laboratory
Brian Jaques – Boise State University

Project Description: The Structural Material Characterization work package focuses on research and development (R&D) activities to develop and deploy innovative sensors and sensor technologies in support of advanced reactors and fuel cycle development activities. Material and mechanical properties are critical for addressing safety concerns and the longevity of both current and future nuclear reactors. Real-time measurement of structural materials during irradiation is typically accomplished using a linear variable differential transformer (LVDT)-based creep test rig. This project will update and refine previously validated Halden-based technologies and methods for use in upcoming irradiation tests focused on creep under irradiation. Once the performance of the test rigs is characterized, these rigs will be ready for deployment in relevant irradiation tests that are of interest to stakeholders.

Impact and Value to Nuclear Applications: These strategies enable the U.S. Department of Energy (DOE) to establish core capabilities and respond to complex in-pile measurement objectives identified by different stakeholders and DOE Office of Nuclear Energy R&D programs, while also qualifying materials for both current and future nuclear energy systems.

Recent Results and Highlights: A better understanding of the capability to conduct in-situ testing on irradiation creep will also improve our understanding of nuclear reactor structural materials. This will be achieved through comparative assessment of standard creep testing and out-of-pile creep testing, using aluminum samples. Additionally, an alternative method of measuring creep deformation will be investigated using a Double Delta testing device combined with high-temperature strain gauges. The Double Delta device employs two concentric opposing three-dimensional (3-D) motion delta platforms equipped with force/torque sensors to closely assimilate multi-physic (e.g., force, vibration, and thermal) 3-D reactor environments, while still remaining extremely controllable and accessible. Most measurement systems in this field (e.g., the Stewart platform configuration) are typically limited to one of these aspects, and lack the breadth to study interactive phenomena, especially when also being driven by representative 3-D motions/loadings.



(a) *Standard Creep Testing.*

(b) *Out-of-Pile Creep Testing Using Autoclave.*

(c) *Double Delta.*

High-Performance Nanostructured Thermoelectric Materials and Generators for In-Pile Power Harvesting

PIs: Yanliang Zhang – University of Notre Dame
Josh Daw – Idaho National Laboratory
Mercouri Kanatzidis – Northwestern University

Description of Project: The goal of this project is to investigate the in-pile performance of high-efficiency nanostructured bulk thermoelectric materials, and to develop radiation-resistant thermoelectric materials and devices for in-pile power harvesting and sensing. We will fabricate high-performance nanostructured bulk thermoelectric materials and devices and study their in-pile performance and the irradiation effect on material properties and device performance. The large temperature gradient available in the nuclear reactor makes the thermoelectric generator (TEG) an ideal power harvesting technology to enable self-powered sensors, which has the potential to become a crosscutting enabling technology for in-pile sensors and instrumentation.

Impact and Value to Nuclear Applications: The majority of sensors and instrumentation require an external power supply. High-temperature and irradiation resistant power harvesters can enable self-powered sensors that offer significant expansion on in-pile sensors and measurements. Further, the thermoelectric power harvesting technology has crosscutting significance to all DOE Nuclear Energy research and development programs, as it will enable self-powered sensors in multiple nuclear reactor designs.

Recent Results and Highlights: We have successfully developed high-temperature and high-power-density TEGs and associated instrumentation for in-pile irradiation and in-situ testing of the TEG power output. The TEG performance was continuously measured in the core of a nuclear reactor for 30 days to an exposure of 153 megawatt-days. Despite an initial drop in TEG power when operating at relatively lower temperature, the TEG showed a 1900% increase in power output due to in-situ annealing and a significant recovery of both the Seebeck coefficient and electrical conductivity when operating at increased temperature and reactor power. These results indicate that with proper control over the TEG operating temperatures, the TEG can produce stable power and operate indefinitely in the core of a nuclear reactor.

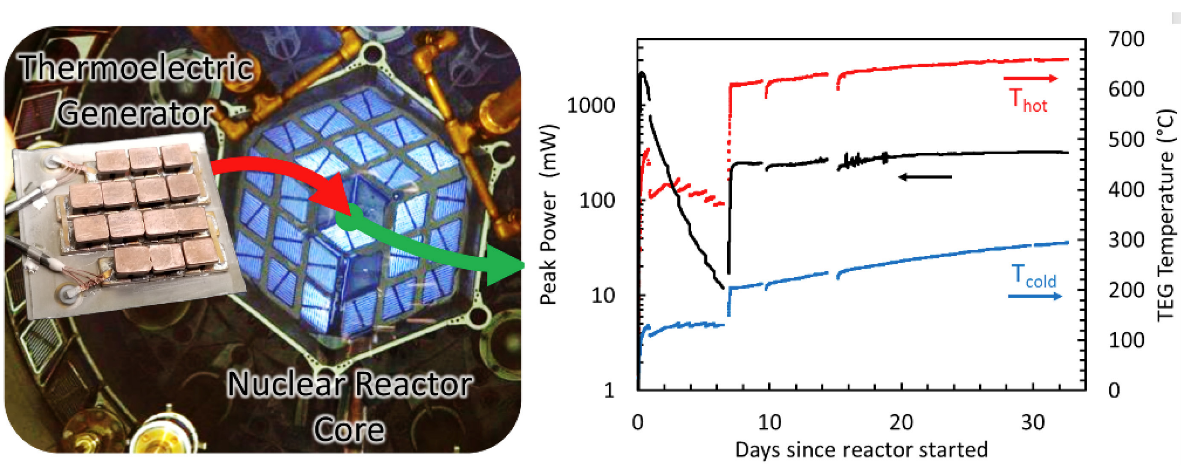


Figure 1. The thermoelectric generator (TEG) for power generation in the core of a nuclear reactor. From left to right: photograph of the high-temperature and high-power-density TEG inserted into the core of the nuclear reactor at MIT NRL; TEG peak power (black) along with TEG hot-side temperature T_{hot} (red) and cold-side temperature T_{cold} (blue) as a function of days of irradiation in the reactor core.

Instrumentation for Irradiation Experiments

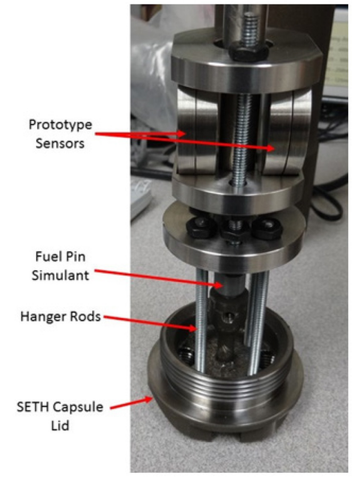
Ultrasonic Sensors for TREAT Fuel Condition Measurement and Monitoring

PI: Andy Casella – Pacific Northwest National Laboratory
Collaborators: Pradeep Ramuhalli – Oak Ridge National Laboratory
Josh Daw – Idaho National Laboratory

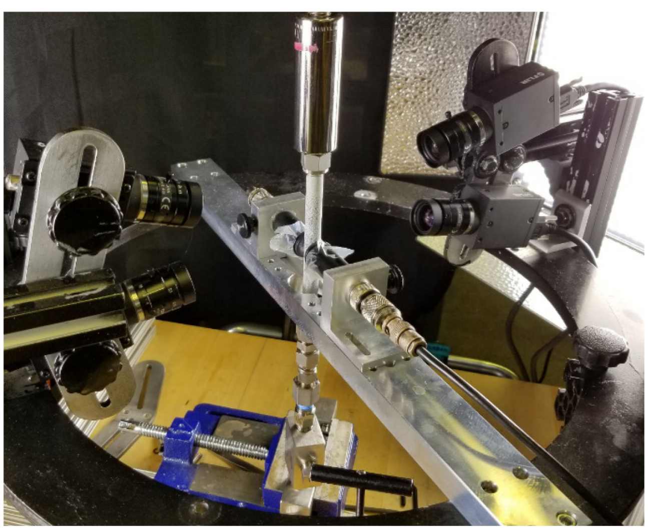
Project Description: The objective of this project was to provide a new measurement capability that enables in-situ characterization of fuel pin deformation during a transient irradiation test in the Transient Reactor Test (TREAT) Facility. The target technology was an ultrasonic sensor that could fit within a Separate Effects Test Holder (SETH) capsule and measure the change in the diameter of a fuel pin as it expanded during a TREAT test.

Impact and Value to Nuclear Applications: The ability to measure the dimensional changes in fuel rods during transient events provides valuable data that characterizes the response of existing and advanced fuels.

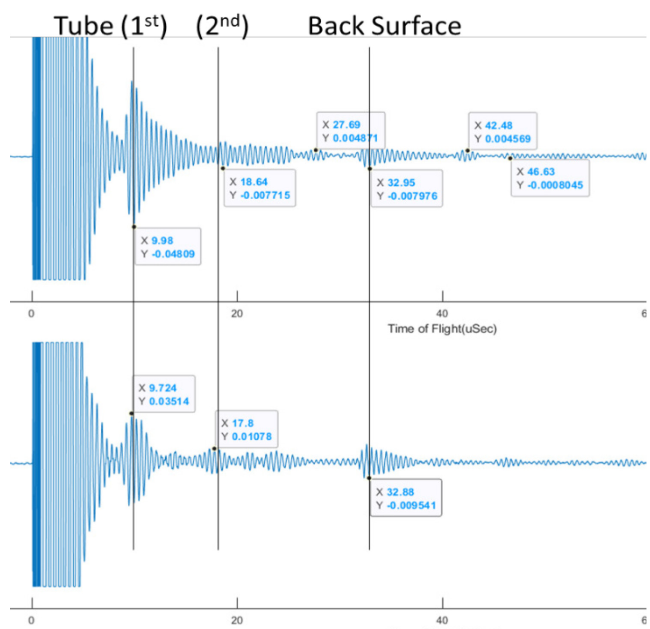
Recent Results and Highlights: This project identified and tested a promising sensor arrangement for in-situ measurement of fuel pin diameter during a transient irradiated test. At the end of this project, key sensor parameters such as the size and composition of the piezoelectric element and backing; electrode configuration; relative importance of a faceplate and casing; and bonding materials were assessed. While promising results were obtained, a more in-depth investigation of adhesive mixture and fabrication/bonding techniques for high temperature, submerged environments is recommended as successfully bonding the sensor prototypes studied throughout this project would provide useful sensors in environments in which none exist to date.



Prototype sensor integrated into the SETH hanger structure.



Test of sensor ability to measure tube expansion due to internal pressurization.



Example sensor signals before and after a 4 hour soak in water.

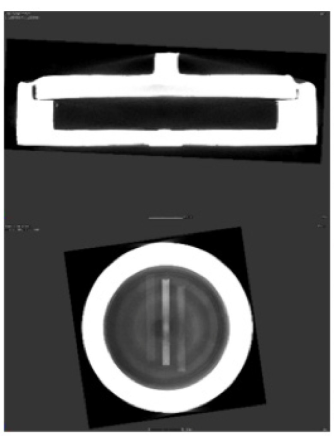
Passive Peak Temperature Monitors

PI: Malwina Wilding – Idaho National Laboratory
Collaborators: Lance Hone, Kory Manning, Kurt Davis, Austin Fleming, and Kiyo Fujimoto – Idaho National Laboratory

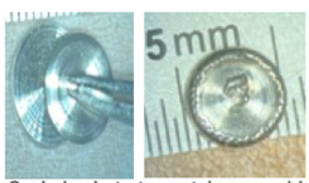
Project Description: Passive temperature monitors have been used for many decades in irradiation testing experiments, but further innovations to these technologies will advance the state of the art by leveraging new equipment and methods initiated in FY 2020. A previously purchased optical dilatometer will be benchmarked against traditional resistivity methods for determining the post-irradiation evolution of silicon carbide temperature monitors. In addition, advanced manufactured passive temperature melt arrays (i.e., melt wires) will be optimized for miniaturization and for affording higher resolution than traditional quartz-encapsulated melt wires. These innovations have already attracted interest from stakeholders wanting to expand their passive temperature monitor deployment options.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measuring irradiation temperature during post-irradiation examination, while requiring none of the feedthroughs/leads found in current, more complex real-time temperature sensors. They were chosen for their proven history of deployment by stakeholders; and require continued development and characterization to ensure successful integration with program schedules and objectives.

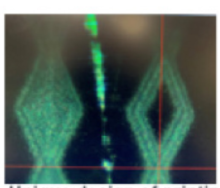
Recent Results and Highlights: The first highlight is the development of packaging processes for printed melt wire arrays with improved geometries and higher peak temperature resolution. A new and unique encapsulation design for advanced manufactured melt wires was optimized for a welding process that can produce inert-atmosphere encapsulation. Also, this new and unique design for printing melt wires improves wire sensitivity, thus also enhancing x-ray-computed tomography resolution in order to better evaluate encapsulated materials. The second highlight is the comparative assessment of optical and resistivity measurement methods for evaluating silicon carbide temperature monitors. The optical dilatometry measurement method has multiple advantages over the resistivity measurement method (e.g., an automated process requiring minimal setup time) thanks to a vacuum treatment that removes any oxidation issues and reduces the processing time for each silicon carbide sample.



CT scan of printed Sn, Zn and Al melt wires

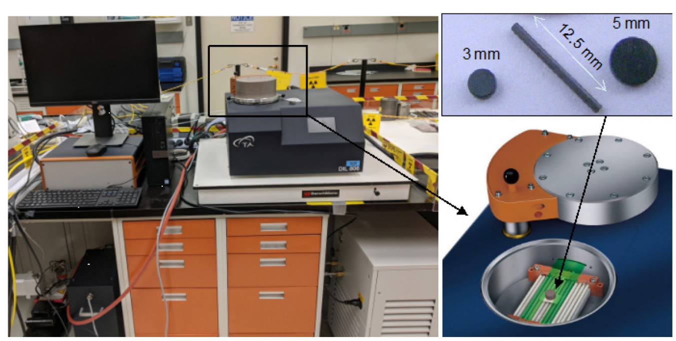


Sealed substrate container capable of inert-atmosphere encapsulation



Unique design of printing material to enhance melt wire sensitivity

Optical Dilatometry Method for Processing Silicon Carbide Temperature Monitors.



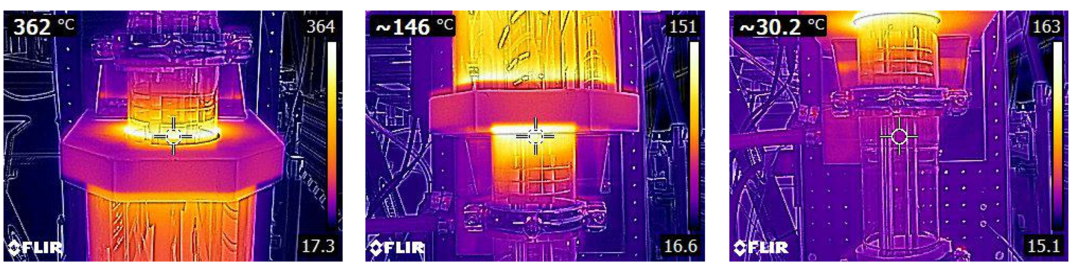
Linear Variable Differential Transformer Calibration and Supply Chain

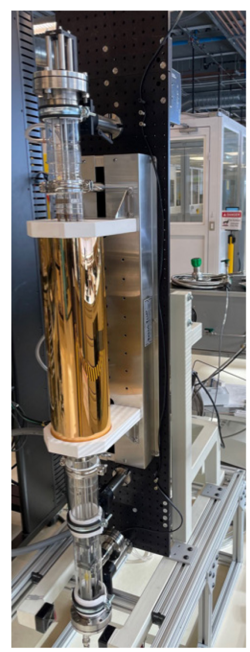
PI: Kurt Davis – Idaho National Laboratory
Collaborators: Malwina Wilding, Austin Fleming, and Kory Manning – Idaho National Laboratory
Brian Jaques, Zhangxian Deng, and Alex Draper – Boise State University
Heng Ban – University of Pittsburgh
Steinar Solstad – Institute for Energy Technology

Project Description: The Institute for Energy Technology (IFE) is a pioneer in linear variable differential transformer (LVDT) development for in-pile testing. INL and the international testing community depend on IFE for their supply of LVDTs and corresponding sensors. Budgetary constraints have limited IFE's ability to develop and deploy LVDTs. Fiscal Year (FY) 2021 activities will maintain and advance LVDT technology so it can be used by stakeholders requiring LVDTs in upcoming irradiation tests. Relevant test conditions include testing under inert gases at elevated temperatures. In addition, the U.S. supply chain of LVDTs and related components will be explored in order to extend the availability of robust LVDTs.

Impact and Value to Nuclear Applications: Through collaborative activities and direct procurement of equipment from IFE, this project supports the Advanced Sensors and Instrumentation (ASI) program's commitment to sustain and enhance instrumented irradiation experiments for the U.S. nuclear industry. Characterization of nuclear components in operationally inert environments is crucial for advanced reactor design demonstrations.

Recent Results and Highlights: First is the completion of a supply-chain assessment for LVDTs. Three companies were identified as potential LVDT suppliers for in-pile testing. Second is the assembly of a test rig to enable LVDT calibration under inert gas. Flow, temperature, and oxidation testing of the upgraded calibration rig were successfully completed. Both highlights were completed during FY 2021.





The calibration test rig (under inert gas) keeps the linear translation motor near room temperature and the central region of the test rig at 700°C.

In-Core Measurement Systems for Nuclear Materials Characterization

PIs: Zilong Hua and Robert Schley – Idaho National Laboratory
Collaborator: David Estrada – Boise State University

Project Description: Two instruments for in-reactor measurements of the critical physical properties of nuclear fuels and materials have been in development over the past fiscal year: fiber-based photothermal radiometry (fiber-PTR), and laser-based resonant ultrasound spectroscopy targeting the zero-group-velocity Lamb mode plate waves detection (RUS-ZGV). The fiber-PTR instrument monitors thermal wave propagation by collecting the local blackbody radiation in order to measure thermal conductivity. This instrument is ideal for high-temperature measurements. In addition, it requires little or no surface preparation and only one-side access to the sample. The RUS-ZGV instrument monitors the ZGV plate wave propagation and relates it to the microstructure evolution. ZGV plate waves are localized evanescent waves with a significantly higher signal-to-noise ratio than that of other wave modes. Therefore, the ZGV measurements are less sensitive to the boundary condition and the background noise.

Impact and Value to Nuclear Applications: Current modeling efforts for predicting the real-time, in-reactor behavior of nuclear materials can only be validated through post-irradiation examination (PIE). However, important information may not be correctly captured by PIE testing, due to the continuous microstructure evolution after the reactor shuts down. The instruments developed under this work package aim to fill this technical gap. Once finalized and deployed, these instruments are expected to greatly boost the development of advanced nuclear fuels and materials for end use by producing critical experimental data for validating and verifying advanced fuel performance codes.

Recent Results and Highlights: High-temperature in-situ tests were conducted on reference materials on both instruments. As expected, ZGV plate waves show greater tolerance to the mounting approach, and the fiber-PTR measurement signal increases significantly at high temperatures. Meanwhile, a probe head with different spatial resolutions was fabricated for the fiber-PTR system to increase the measurement range.

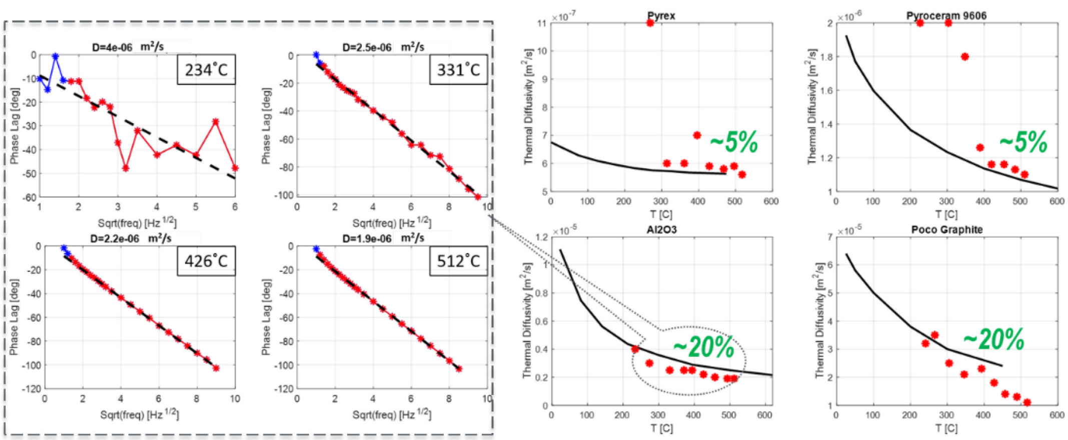


Figure 1. Right panel: Measured thermal diffusivity on the reference materials by fiber-PTR. The temperature range is 260–515°C. Experimental values (red stars) are 5–20% different than the values found in the literature (solid line). Left panel: The raw data on Al_2O_3 at different temperatures were given to show the signal improvement with temperature.

Irradiation Testing of Neutron Flux Sensors in the Advanced Test Reactor Critical Facility

PI: Joe Palmer – Idaho National Laboratory
Collaborators: Kevin Tsai, Michael Reichenberger, Troy Unruh, and Calvin Downey – Idaho National Laboratory

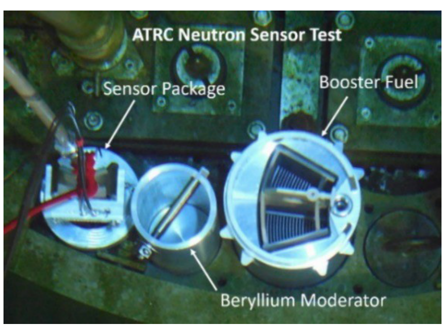
Project Description: Advanced instrumentation enables testing of nuclear fuels and materials in support of the U.S. advanced nuclear technology industry. In fiscal year (FY) 2021, this project was focused on testing neutron flux sensors and temperature sensors in a variety of reactor environments.

Impact and Value to Nuclear Applications: Irradiation experiments in ATR and other high-power U.S. test reactors are typically not equipped with real-time neutron detection. This limits the ability of researchers to understand the environment their specimens experience. Neutron sensor deployment in reactor experiments and advanced reactors is significantly different than in commercial reactors. The early stages of sensor development can be conducted outside of a reactor environment, but full technical readiness requires the experience gained from in-core performance testing, which is the focus of this project.

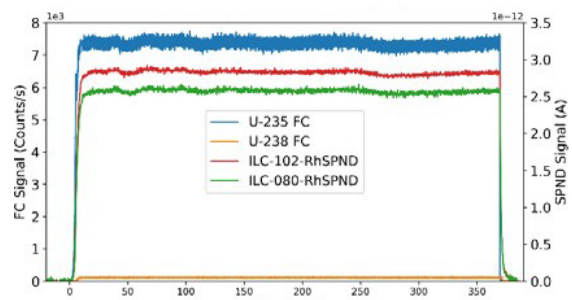
Recent Results and Highlights: An important objective for FY 2021 was to demonstrate custom-built rhodium-based Self-Powered Neutron Detectors (SPNDs) from a domestic supplier. Folded into this effort was an opportunity to provide neutron flux information for the Advanced Test Reactor (ATR) I-loop project through testing in theAdvanced Test Reactor Complex (ATRC). Prior to irradiation in ATRC, a duplicate Rh-SPND was irradiated in Idaho National Laboratory's Neutron Radiography (NRAD) reactor to characterize sensor performance. This work helped improve the data acquisition system and confirmed that the SPNDs would function in ATRC as predicted.

Installing SPND in the NRAD reactor.

Testing the data acquisition system in the cask tunnel next to the NRAD reactor.



Hardware installed in ATRC to conduct the neutron sensor test.



Data from self-powered neutron detectors and fission chambers in ATRC I-Loop experiment.

The I-loop project will use a "booster" fuel element to increase the thermal flux in a large outer position in ATR, acting as a replacement for one of the lost Halden loops. A test incorporating this booster fuel was run successfully in ATRC in February 2021. Sensor data confirmed a ~22% increase in thermal neutron flux due to the booster fuel, which compares favorably with dosimetry and the project's early estimates.

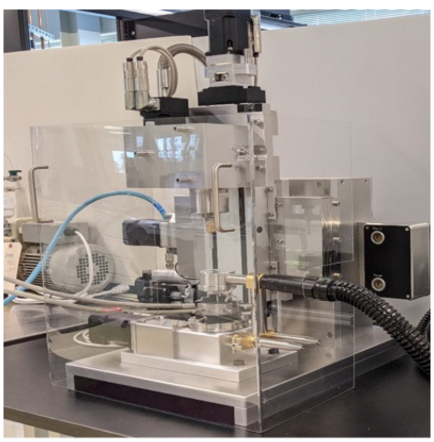
Re-instrumentation Facility Procurements and System Checks

PI: Joe Palmer – Idaho National Laboratory
Collaborators: Calvin Downey, Ian Stites – Idaho National Laboratory

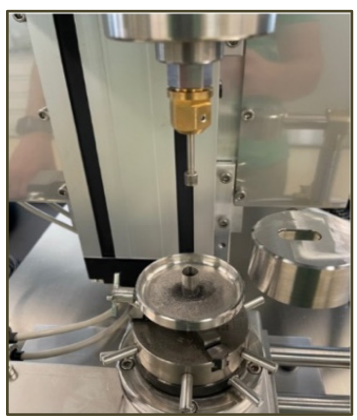
Project Description: To procure and begin testing a set of prototype equipment modules from the Norwegian Institute for Energy Technology's (IFE) Halden Reactor Project to serve as a test bed for developing the capability to incorporate thermocouples—and later, advanced instruments—into previously irradiated fuel rods, prior to re-irradiating them in the Advanced Test Reactor (ATR), the Transient Reactor Test Facility (TREAT), or a similar test reactor.

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

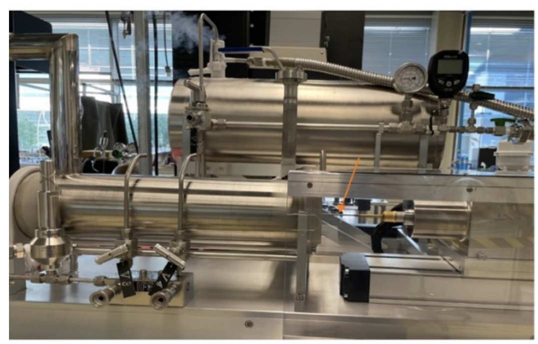
Recent Results and Highlights: As shown in the images below, two of the three equipment modules from Halden have been received at INL. Initial checkout activities on this equipment have begun.



Picture of the defueling module.



A picture showing a fuel rod with the top pellet removed and oxidation cleaned from inner and outer surfaces of the cladding.



Picture of the drilling module during a cryo-drilling test.

Digital Technology

Process-Constrained Data Analytics for Sensor Assignment and Calibration

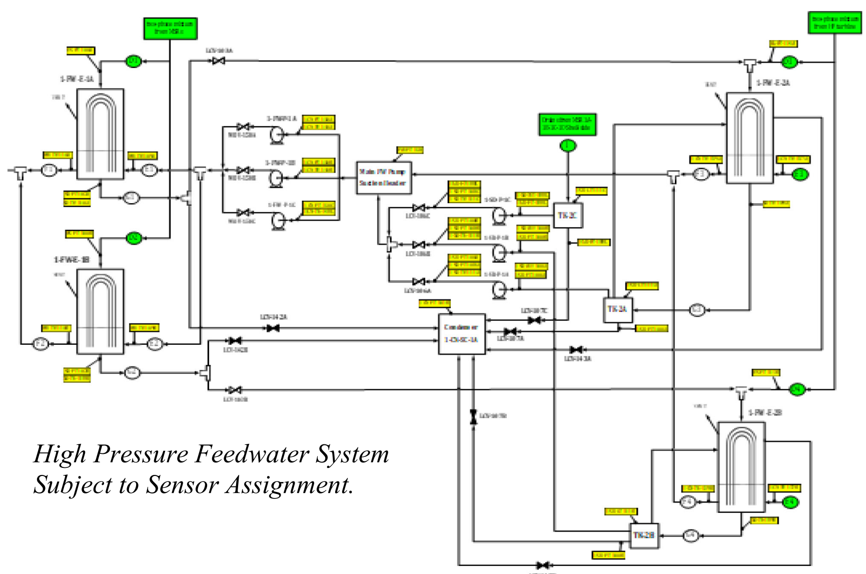
PI: Richard Vilim – Argonne National Laboratory
Collaborators: Brendan Kochunas – University of Michigan
Tim Kibler – Xcel Energy

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

Impact and Value to Nuclear Applications: Presently, sensor calibration is performed at the end of each cycle regardless of whether each sensor needs calibration. Calibration of a sensor that is not out of calibration is an inefficiency that unnecessarily increases utility O&M costs. By selecting the sensor set which will deliver on the desired monitoring capabilities, a utility performing end-of-cycle sensor calibrations can confine that task to only those instruments that actually require recalibration.

Recent Results and Highlights: Blind fault tests using archived data were performed for a feedwater pump system from a currently operating nuclear power plant. Data for plant operation events were provided by utility collaborators without disclosing either the presence of, or the identity of a fault. So-called “blind” diagnostic analyses were conducted where the utility withheld this information and did not disclose it until after a diagnosis was made. The blind study consisted of five different equipment and sensor faults. The two equipment fault events were correctly diagnosed, and the results demonstrated the high detection sensitivity of the physics-based approach. Three sensor fault scenarios were also correctly diagnosed and showed the ability of the approach to detect and uniquely identify sensor faults.

In a second application that involved the high-pressure feedwater system (see figure) of a pressurized light water reactor, it was shown that an improved health monitoring capability can be achieved using a sensor set that is 20 percent fewer in number. Maintenance of this system can amount to millions of dollars per year if equipment health issues go undiagnosed and lead to loss of function. We showed that compared to the installed sensor set there exists a more strategic assignment of sensors that will furnish better health monitoring capability and with fewer sensors. Where the problem defies solution by manual inspection, as is the case here, one can be found by an algorithm. The solution was obtained in four hours using 30 computational cores.



High Pressure Feedwater System Subject to Sensor Assignment.

Design of Risk-Informed Autonomous Operation for Advanced Reactors

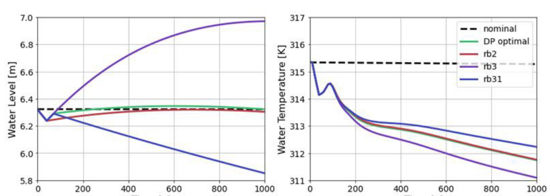
PI: Michael Golay – Massachusetts Institute of Technology
Co-PIs: Hyun Gook Kang - Rensselaer Polytechnic Institute; Birdy Phathanapirom – Oak Ridge National Laboratory
Collaborators: Xingang Zhao – Oak Ridge National Laboratory; Xinyan Wang – Massachusetts Institute of Technology
Junyung Kim, Kyle Warns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

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

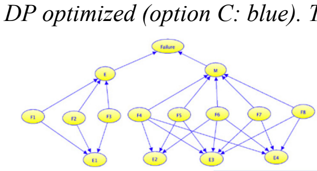
Impact and Value to Nuclear Applications: The use of autonomous control systems (ACSs) can greatly improve the reliability of nuclear power plants because human errors are the dominant contributor to nuclear failures. However, the basis for the implementation of ACSs must improve to the point that potential adopters are sufficiently confident of their feasibility and reliability. The work being performed is expected to improve the knowledge base and specific lore to a convincing level of assurance, and through such progress to strengthen its foundation.

Recent Results and Highlights: The latest progress includes successful development of a components fault diagnostics model and two decision-making approaches for operator decision support.

1. Bayesian network (BN) framework for cooling tower fan motors was developed with the experienced engineers and component monitoring data in MIT's Central Utilities Plant. Causalities and conditional probability tables are quantified using the manual and field experts' knowledge. With the probability propagation function, the model is able to figure out the failure modes based upon observed evidence (symptoms).
2. A decision-theoretic approach was applied to optimize the control logic which frames the problem as a Markov decision process (MDP) that is solved using dynamic programming. Simulation results from a two-loop heating system provide operating information to demonstrate the MDP model.
3. A novel system status modeling technique based on a dynamic Bayesian network (DBN), Multilevel flow modeling (MFM), and state-space discretization was developed. It was also demonstrated by using the simulation data of two-loop heating example system.



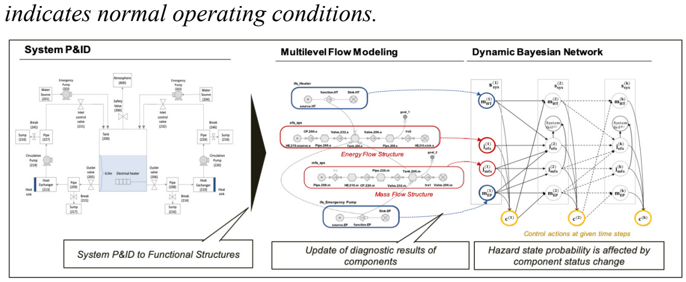
Water level and temperature during system transient based on different release rates of water inventory backup tank. Cases shown are: DP optimized control (green), constant medium-release rate (option A: red), constant maximum-release rate (option B: purple) and maximum release rate with lesser leveling off than DP optimized (option C: blue). The dashed black line indicates normal operating conditions.



Labels	Sensor Features (Symptoms)
E1	Motor Over Heating
E2	Bearing Over Heating
E3	Noise
E4	Vibration

Labels	Faults
F1	Unbalanced Voltage
F2	Open Stator Winding
F3	Grounded Winding
F4	Misalignment
F5	Insufficient Grease in Bearing
F6	Dirt in Bearing
F7	Rotor out of balance
F8	Bent Shaft

BN Diagnostic Model.



DBN Built Based on MFM.

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

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

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

Impact and Value to Nuclear Applications: The project demonstrates how to achieve cost reductions regarding the nuclear industry's maintenance practices. Recent research focused on diagnostics, prognostics, and PM optimization using advancements in machine learning (ML) technologies. The developed methodologies were then validated on new, independent datasets in order to demonstrate the strength and applicability of the research results.

Recent Results and Highlights: The notable outcomes include 1) PM optimization, 2) feature selection using Shapley additive explanations (SHAP) values, and 3) validation of the approach to forecasting model development. PM optimization was performed by comparing work order and component condition data with industry standards in order to eliminate unnecessary maintenance. ML short-term (ranging from 1 hour to 1 day) forecasting models utilized SHAP values to select features (Table 1) based on their importance. Validation of the approach to forecasting model development (i.e., data preprocessing, feature selection, model optimization, and forecasting) was performed for three different plant subsystems and covered support vector regression (SVR) and long short-term memory (LSTM) networks using a cross validation approach (see Figure 1 and Table 2).

Table 1. Feature Selection Based on SHAP Values.

Feature	Importance
Turbine Speed	0.608
Turbine Rotor Expansion	0.309
Turbine Differential Expansion	0.161
Flow to Turbine	0.151
Shell Expansion	0.029

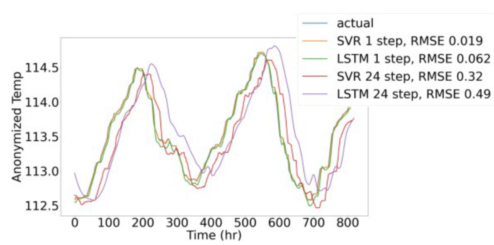


Figure 1. Forecasting Results.

Table 2. Validation Results of Forecasting Models in Terms of Mean Root Mean Square Error (RMSE).

Data set			1-step ahead		24-steps ahead	
Plant	Parameter Predicted	Model	Mean RMSE	Std Error	Mean RMSE	Std Error
PWR 1	Main Turbine Bearing Temp	LSTM	0.0796	0.0411	0.7932	0.5450
		SVR	0.0214	0.0080	0.3194	0.1202
PWR 1	Generator Output	LSTM	0.2871	0.2031	2.2636	2.8338
		SVR	0.0806	0.0422	1.5611	1.2424
PWR 2	Steam generator flow	LSTM	2.4792	3.0455	12.435	17.333
		SVR	1.4070	2.4270	5.6299	5.3154
BWR	Condensate Pump Bearing Temp	LSTM	0.0792	0.0722	0.2991	0.2724
		SVR	0.0323	0.0496	0.2238	0.2184

Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

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

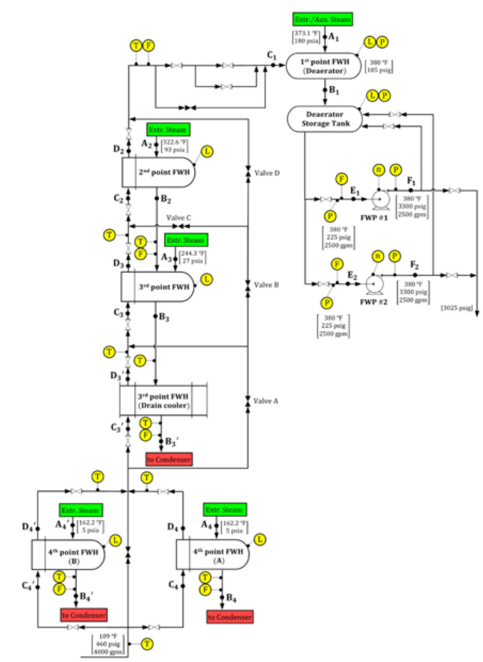
Project Description: The objective of the project is to improve the economic competitiveness of advanced reactors through the optimization of cost and plant performance, which can be achieved by coupling intelligent online monitoring with asset management decision-making. To achieve this goal, two key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

1. During the reactor design phase, it is necessary to develop a sensor network that can properly monitor and diagnose important faults and component degradation throughout the lifetime of the plant. To reduce cost, a methodology is developed that optimizes diagnostic capabilities while minimizing sensor quantity and system penetrations.
2. Once reactor operation begins, the asset management approach must seamlessly integrate online monitoring information and the plant's risk profile to develop an optimized plant operation and maintenance plan.

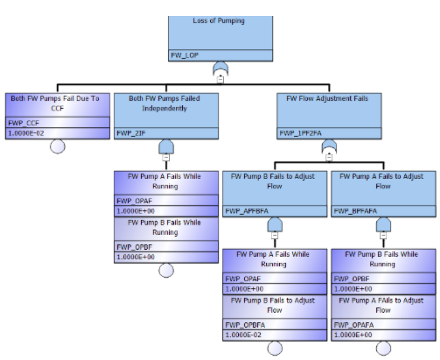
Impact and Value to Nuclear Applications: The project tasks aim to reduce advanced reactor costs during construction, through optimization of the sensor network design, and also operation, through intelligent cost-benefit decision-making related to asset and supply chain management.

Recent Results and Highlights: The capabilities of the Integrated System Failure Analysis (ISFA) approach for sensor network design optimization have been expanded to allow for new optimization criteria, such as sensor cost, reliability, observability, sensitivity, etc. In addition, a range of evolutionary and greedy optimization algorithms were evaluated to determine the most appropriate approach for the sensor network design problem.

For use during plant operation, several strategies were developed to link the online diagnostic tool PRO-AID with Markov component models within the plant probabilistic risk assessment (PRA) and generation risk assessment (GRA). A procedure was also developed to identify and evaluate alternative operational plans based on the real-time plant risk profile (PRA and GRA), as part of the intelligent asset-management decision-making framework.



Developed MHTGR Feedwater System. Piping and Instrumentation Diagram.



Preliminary Feedwater Pump Fault Tree.

Lastly, a demonstration problem was identified utilizing the General Atomics Modular High-Temperature Gas-Cooled Reactor (MHTGR) feedwater system, and work was initiated detailing and modeling the system for the FY22 assessment. This includes development of a system simulator for online monitoring and also creating the plant PRA and GRA to develop the real-time risk profile for asset-management decision-making.

Method and Tool Development Using NSUF Data to Support Risk-Informed Predictive Analytics

PI: Vivek Agarwal – Idaho National Laboratory
Collaborator: James A. Smith – Idaho National Laboratory

Project Description: The scope of this research encompasses enhancing the reliability of test/advanced reactor operation by understanding their current and future states. The specific objectives are to 1) develop operational signatures by using data from the Advanced Test Reactor (ATR), and 2) develop classification models using machine learning (ML) to accurately classify any deviation from normal operation. This knowledge will enable the integration of predictive-model development with reactor risk assessments, leading to predictive maintenance strategies that enhance the reliability and availability of these reactors.

Impact and Value to Nuclear Applications: This project will foster technologies that enable complete state awareness of the reactor. Such awareness would lead to the development of advanced autonomous operation and risk-informed decision making.

Recent Results and Highlights: Data from acoustically telemetered sensors installed in the ATR were collected for different operating cycles. The real-time acoustic data from the ATR's primary coolant pumps (PCPs) were analyzed using recursive short-time fast Fourier transformation (STFFT), which allows for tracking the beat frequency when two or three PCPs are operated under different operating conditions. The beat frequency captures the baseline acoustic signatures, along with other events. Binary ML classifiers, support vector machine (SVM), and linear discriminant analysis (LDA) were developed to automate the classification of acoustic data (from the M7 and M8 PCP combination) into "normal" and "event" categories (see Figure 1 and Table 1). A similar approach can be applied to other acoustic spectrograms from other PCP combinations. For data collected through different PCP combinations, a data fusion approach can potentially be applied to build in robustness.

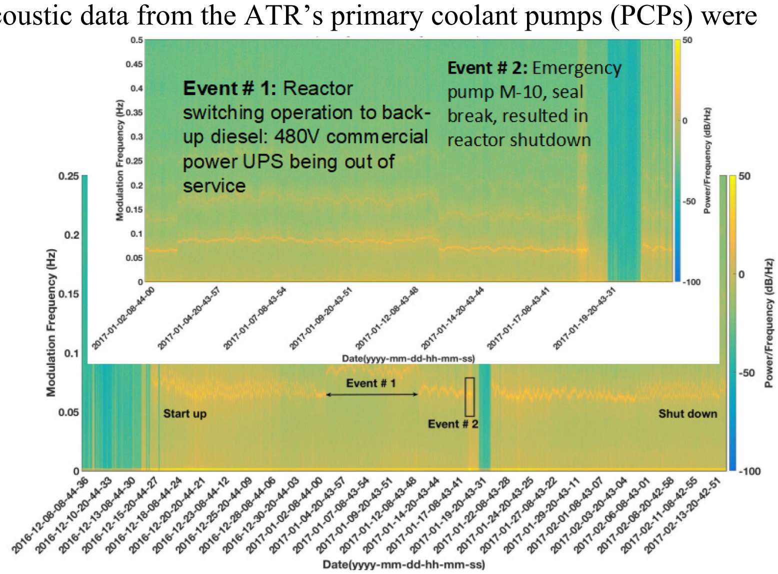


Figure 1. ATR acoustic baseline signature for the M7 and M8 PCP combination with two operational events.

Table 1. Classification results from using LDA and SVM models.

Models	LDA model			SVM Model		
Test samples 3,240	Predicted Class 1 (Normal)	Predicted Class 2 (Events)	Accuracy	Predicted Class 1 (Normal)	Predicted Class 2 (Events)	Accuracy
Actual Class 1	1,575	45	0.9720	1,600	20	0.9815
Actual Class 2	50	1,570	0.9691	35	1,585	0.9782

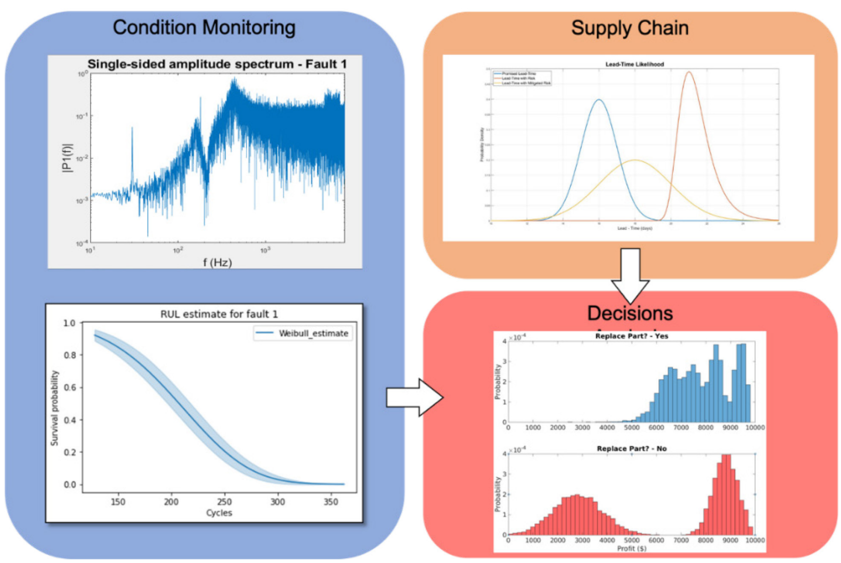
Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance

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

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

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

Recent Results and Highlights: We are developing Bayesian networks to detect faults of rotating machinery and to determine root cause of machine failure. By combining survival analysis with Bayesian statistics, we can estimate remaining-useful-life of a pump, conditional to different fault types. We are developing models of the financial penalties of risks in the supply chain products using Bayesian networks, and we are using Bayesian signal processing to estimate the inventory of upstream suppliers and their risk in asset management. This includes modeling fluctuations in supply chains due to changes in demand. Finally, we have simulated the results of multiple decision paths over multiple outages to find the optimal solution that balances risk and maintenance.



Information about the condition of devices in the plant and the supply chain affects resource availability to make O&M decisions.

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

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

Project Description: The objective of this research is to improve the economic competitiveness of advanced reactors through the optimization of plant performance. To help nuclear units survive in deregulated electricity markets, the integration of advanced reactor concepts with energy storage technologies is considered. The operational complexity of coordinating these two thermally-coupled systems can be addressed by adopting an architecture comprised of an automated reasoning system that closely interacts with a multi-layer control system. To achieve this goal, three development steps are necessary:

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

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

Recent Results and Highlights: Recent efforts have focused on three major areas:

1. Development of the simulator of the PB-FHR primary circuit coupled with the Thermal Energy Storage (TES) system in the intermediate loop by adopting the SAM code. As for the primary circuit, the KP-FHR design was adopted. As for the TES, the molten salt-based technology (traditionally used for concentrated solar power) was adopted, and the tanks were dimensioned as a function of the desired performance.
2. The control strategy (pairings between available input variables and outputs) was defined. Corresponding PID controllers were implemented in the system simulator.
3. Expected power transients (i.e., reactor load-following, TES charging/discharging) were simulated by manually imposing suitable sequences of control signals.

Next steps will be focused on the implementation of the on-line system identification algorithm and the Reference Governor as supervisory controller.

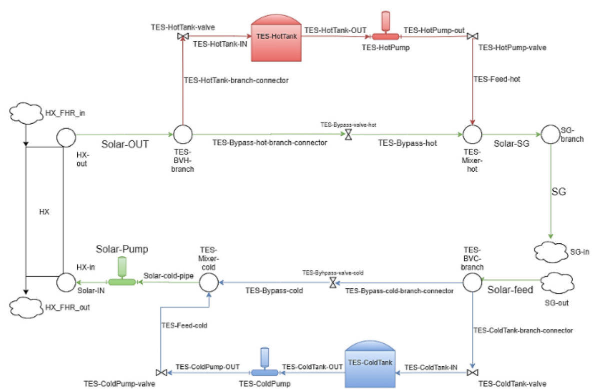
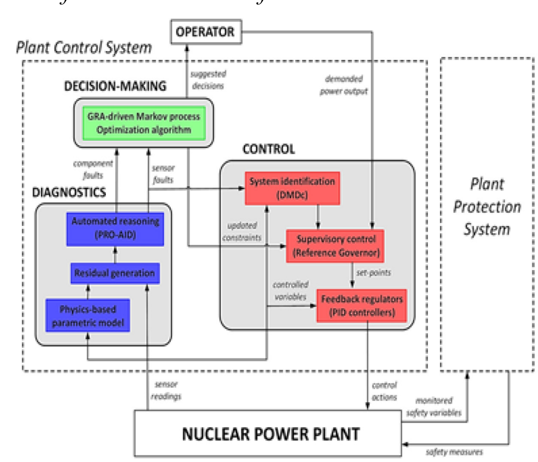


Diagram of the SAM model of the Intermediate Circuit.



Proposed control system architecture.

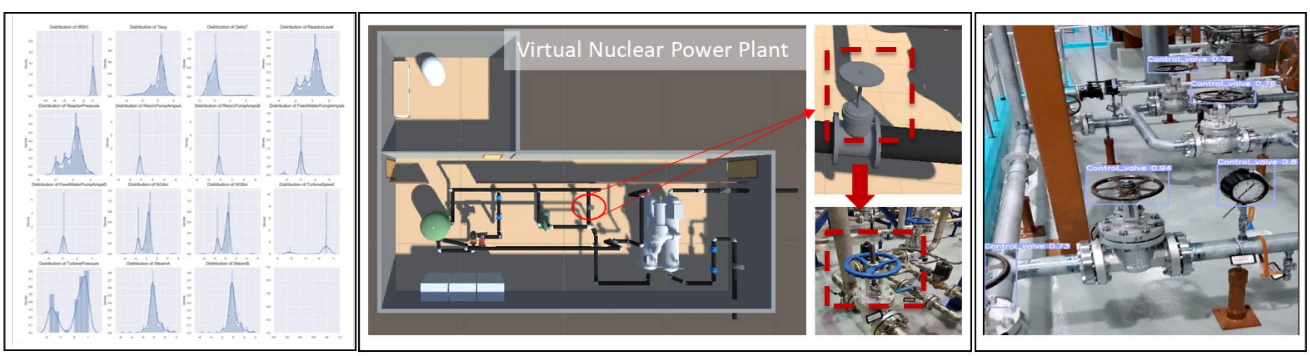
Context-Aware Safety Information Display for Nuclear Field Workers

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

Description of Project: The project team plans to develop an "Intelligent Context-Aware Safety Information Display" (ICAD) for Nuclear Power Plant (NPP) field workers. Research activities related to the project goals include: 1) Assisting NPP field workers in recognizing their current locations and identifying the targeted maintenance sites to support their workspace navigation; 2) Automatically highlighting the correct processes of operating NPP equipment in real-time video views of Augmented Reality (AR) glasses; 3) Highlighting critical task-related objects and facility conditions (e.g., water level, temperatures of objects) in real-time AR video views for guiding field workers to complete safe operations; 4) Developing methods that can predict the likely conditions of typical flow loops (e.g., water levels) when the real-time data transmission for the AR device is disrupted due to network service disconnection; and 5) Reducing the computational resource needs of the computer vision and intelligent maintenance process visualization algorithms so that mobile AR devices with limited computing power can execute these algorithms.

Impact and Value to Nuclear Applications: This project will produce knowledge and technical approaches for supporting real-time safety information display to nuclear workers who need to perform tasks safely in changing operation contexts.

Recent Results and Highlights: The project team conducted the following research activities in this reporting period: 1) developed process analysis methods that utilize NPP sensor data to identify critical control objects for executing various tasks with real-time situation awareness. 2) Tested computer vision algorithm, augmented by multiple field data sources (e.g., Inertial Measurement Unit data), for NPP field operator positioning, navigation, and real-time detection of process-safety-critical objects in the field. The testing results indicate that integrating these algorithms can achieve real-time safety-related object detection with 95% accuracy.



(a) Nuclear Power Plant sensor data. (b) The developed virtual Nuclear Power Plant based on Duke Energy's Oconee training site. (c) Computer vision algorithm achieved 95% accuracy.

Figure 1. The project utilizes Nuclear Power Plant (NPP) sensor data to reason critical control objects in different operation scenarios. Then the location information of identifying the critical control objects will be extracted from a virtual Nuclear Power Plant model to assist computer vision algorithm to detect the safety-critical sensor and control objects in the operation field.

Rad-Hard Electronics for Reactor Data Communications and Controls

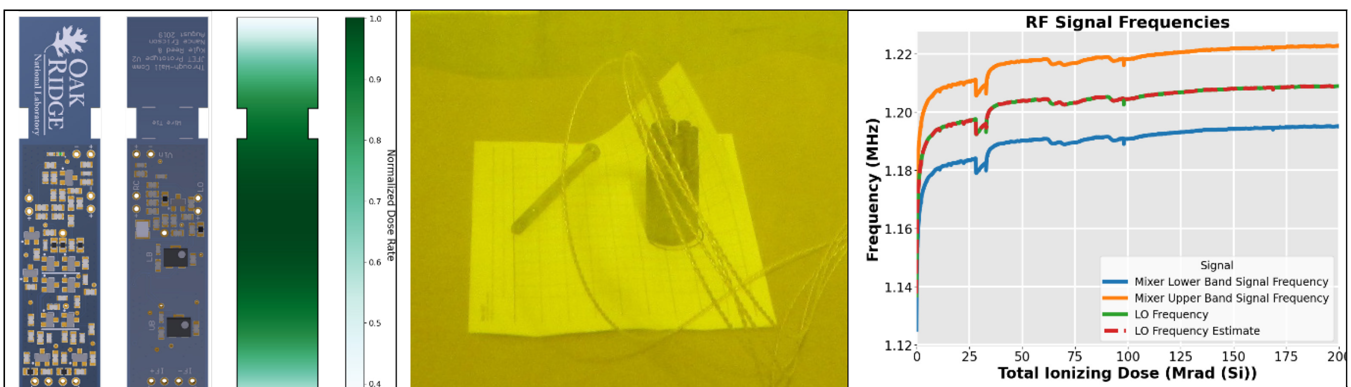
PI: M. Nance Ericson – Oak Ridge National Laboratory
Collaborators: F. Kyle Reed and N. Dianne Bull Ezell – Oak Ridge National Laboratory

Project Description: To assist the DOE in defining a course for NE-funded rad-hard electronics research, ORNL focused on two main tasks in FY21. The first task was to investigate the survivability of silicon-junction gate field-effect transistors (Si-JFETs) through a 100 Mrad (Si) total ionizing dose (TID) experiment and to report these test results. The second task was to investigate wide bandgap (WBG)-based transistor devices.

Impact and Value to Nuclear Applications: Radiation hardened electronics will push the limitations of nuclear sensing and instrumentation. Advanced sensors placed closer to the reactor core will improve reactor control and operation resulting in safer and more efficient energy production. Due to the extremely harsh neutron and gamma radiation doses coupled with the elevated temperature environment, research and development for new electronics and electronic materials technologies is essential for enabling improved monitoring and control of the existing nuclear reactor fleet and next generation reactors including microreactors.

Recent Results and Highlights: Focusing on task one, ORNL has irradiated several sensing and transmission circuits using the Westinghouse Gamma Irradiation Facility (GIF). Three boards were irradiated to over 100 Mrad (Si) with the final board being irradiated to over 200 Mrad (Si) as seen at the edge of the board (>340 Mrad (Si) at the board center). Minor magnitude variations were observed in the signals, but frequency drive of the communications carrier shifted by beyond 6%. An initial software-based frequency error correction was tested which reduced the sensor frequency error from over 17% to ~2% implying that the circuit will withstand harsh radiation. Further correction methods are under investigation. The outcomes of these irradiations have been reported in a milestone report in FY21-Q3, and a journal paper was recently submitted to the American Nuclear Society titled, "A 100 Mrad (Si) JFET-Based Sensing and Communications System for Extreme Nuclear Instrumentation Environment."

A comprehensive review of the state-of-the-art in wide bandgap semiconductors for extreme radiation and temperature environments was performed and written. The three most common WBG semiconductors (SiC, GaN, and Ga_2O_3) were compared in terms of performance and maturity. All three of these technologies show promise of increasing the radiation hardness of active devices beyond that of silicon-based devices.



(a) (b) (c)

Radiation dose profile (a), hot cell irradiation (b), and frequency output (c) of the irradiated JFET-based communications system.

COMPLETED PROJECTS AND FUNDING PROFILE

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

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

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

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

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

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

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

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

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

In FY 2014, six projects totaling $5,963,480, were awarded competitively in the areas of advanced sensors, communications, and digital monitoring and controls. These projects were completed in 2017:

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

In FY 2015, two projects totaling $1,979,000, were awarded competitively in the area of digital monitoring and controls. These projects were 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 2016, three projects totaling $2,789,228, were awarded competitively in the area of nuclear plant communication. These projects were 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 2017, five projects totaling $4,889,688, were awarded competitively in the area of advanced sensors and instrumentation. Four were completed in 2021 and one is expected to be completed in 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 in the area of sensors and instrumentation for a total of $5,000,000. These activities were implemented at Idaho National Laboratory in collaboration with Boise State University (BSU) and focused on the development and demonstration of sensors to deploy in Material Test Reactors irradiation experiments, in particular the Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT). The activities were framed as the In-Pile Instrumentation (I2) initiative.

In FY 2018, three projects totaling $2,987,730, were awarded competitively in the areas of sensors, advanced control systems and big data analytics. The projects are expected to be completed in 2022:

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

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

In FY 2019, five projects totaling $4,500,000, were awarded competitively in the area of sensors, advanced control systems and nuclear plant communication. The projects are expected to be completed in 2022:

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

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

In FY 2020, two projects totaling $2,000,000, were awarded competitively in the area of advanced sensors and control systems. The projects are expected to be completed in 2023:

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

The scope of the ASI program directed funded activities was extended to encompass all the program research areas described in the Introduction and implemented across the Idaho National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory for a total of $4,800,000.

In FY 2021, one project totaling $999,000, was awarded competitively in the area of sensors and instrumentation.

- 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 in all program research areas at the Idaho National Laboratory, Oak Ridge National Laboratory and Pacific Northwest National Laboratory.

Additional research activities funded by ASI are implemented as part of National Science User Facilities projects, also awarded through the DOE CINR funding opportunity, and the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR). More details on the projects and research activities listed above can be found in documents available on the DOE/NE Website: https://www.energy.gov/ne/advanced-sensors-and-instrumentation-asi- program-documents-resources

PUBLICATIONS

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

Xiaoning Jiang – North Carolina State University

Publications

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- Kim, T., H. Kim, and X. Jiang. 2021. "Laser ultrasonic defect localization using an Omni-arrayed candle soot nanoparticle patch," *Japanese Journal of Applied Physics*, 60(10). doi: 10.35848/1347-4065/ac2012.
- Peng, C., M. Chen, J. Spicer, and X. Jiang. 2021. "Acoustics at the nanoscale (nanoacoustics): A comprehensive literature review. Part I: Materials, devices and selected applications," *Sensors and Actuators: A. Physical*, 332(2):112719. doi: 10.1016/J.SNA.2021.112719.
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Development of an Optical Fiber Based Gamma Thermometer

Thomas Blue – The Ohio State University

Publications

- Birri, A. 2021. "The Development of an Optical Fiber Based Gamma Thermometer," Ph.D. Thesis, Ohio State University. http://rave.ohiolink.edu/etdc/view?acc_num=osu1626189906070566.
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- Birri, A., C. M. Petrie, K. McCary, and T. E. Blue. 2021. "Comparison of Calculated and Measured Performance of an Optical Fiber Based Gamma Thermometer," *Transactions of the American Nuclear Society*, 124(1):263-266. doi: 10.13182/T31134.

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

Alexander Heifetz – Argonne National Laboratory

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