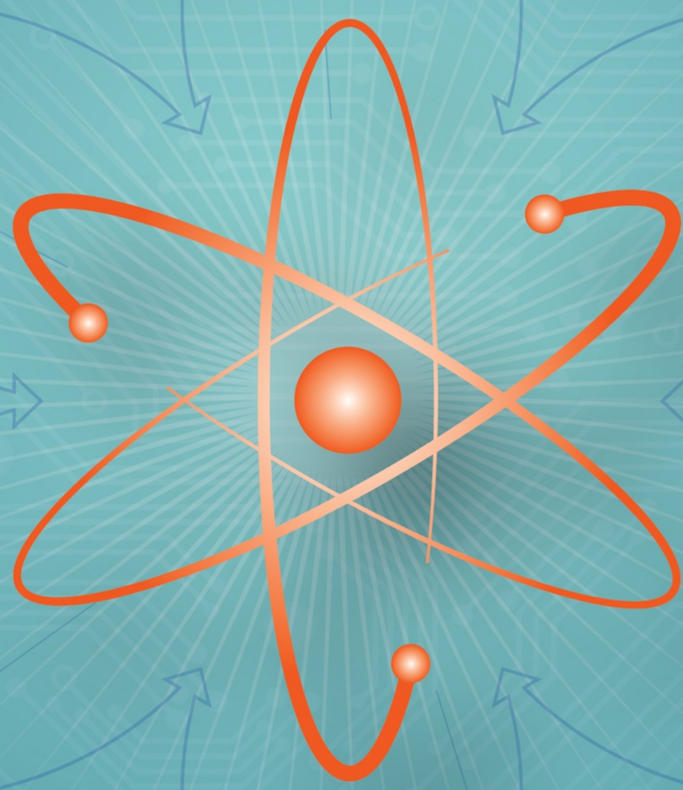
U.S. DEPARTMENT OF ENERGY

ADVANCED SENSORS AND INSTRUMENTATION

PROJECT SUMMARIES



SEPTEMBER 2021

INTRODUCTION

In 2011, the Department of Energy's Office of Nuclear Energy (DOE-NE) initiated the NEET Program 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.

Advanced Sensors and Instrumentation (ASI) is one element of the broader NEET Crosscutting Technology Development (CTD) program. The ASI program fosters the research and development (R&D) necessary to produce and deploy innovative and advanced sensors, as well as instrumentation and controls (I&C), and analytics for the current nuclear fleet and advanced reactor designs. These advanced technologies are essential to DOE-NE's R&D efforts to achieve mission goals.

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-based experiments, and to monitor aspects of fuel and materials behavior used to develop and qualify new fuels and materials for future nuclear energy systems.

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.

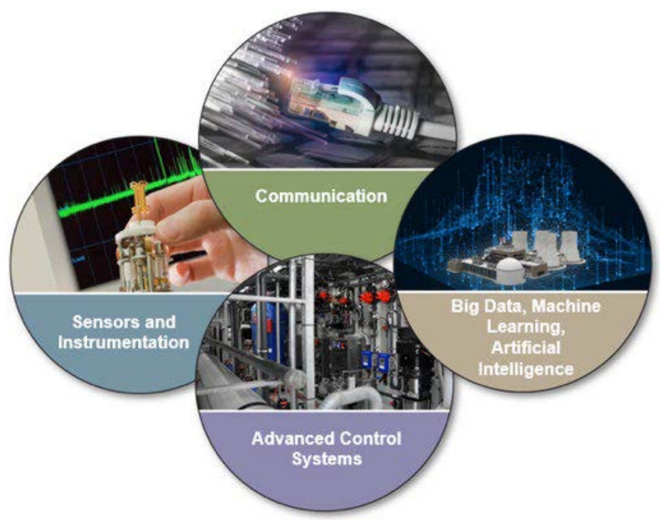
These research areas are as follows:

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.

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.



NEET ASI Research Areas

ROLES

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.
- Develop enabling capabilities addressing technology gaps across the four research areas common in all NE's R&D programs.
- Advance technology readiness levels across the four research areas in order to support transition of research first to NE's R&D programs, then to commercialization.

OVERVIEW

Since fiscal year (FY) 2011, NEET-ASI has funded 43 projects competitively for a total of $36,563,523. These projects have been successful in advancing the state of the art for measuring, controlling, and broadly managing nuclear energy systems being developed by the DOE-NE. Some of these technologies have the potential to impact systems and technologies beyond nuclear energy. They all address critical needs and gaps in current capabilities and are aimed at many of the highest priorities shared by different R&D programs. They include participation from a number of laboratories, universities, and industry. The eventual goal for this research is the deployment of these technologies in a manner that most benefits individual DOE-NE R&D programs, the nuclear energy industry, as well as other power generation sectors. As these research projects progress, the interest from stakeholders and industry has also increased, as have the number of individual technology deployments.

Since FY 2017, NEET-ASI has funded directed In-Pile Instrumentation (I2) research for a total of $25,085,379 under the Sensors and Instrumentation technical area organized as follows:

- Real Time In-Core Instrumentation: From Fuel and Materials Irradiation tests to Advanced Reactor Demonstration
- Sensors Performance Demonstration in Operational Conditions
- Sensor Advanced Manufacturing and Structural Materials Characterization
- Develop and Maintain Capabilities to Support I&C Technology Deployment
- In-Core Measurement Systems for Nuclear Materials Characterization and Codes Validation and Verification.

In FY 2020, I2 research projects have been fully integrated under the ASI program and the scope has expanded to include research under the Communication technical area.

This 2021 ASI report includes summaries of the current on-going projects. A list of completed projects is included at the end of this report and summaries can be found in previous issues saved in the ASI documents page: https://www.energy.gov/ne/advanced-sensors-and-instrumentation-asi-program-documents-resources.

A one-page summary for each of the current projects, are organized from newest to oldest, and are listed in the following pages.

FY 2021 NEET-ASI Research Summaries

1. The Real Time In-core Instrumentation element implements R&D activities to develop nuclear instrumentation that address critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development. Developmental technologies are employed in irradiation test and demonstration facilities to progress their Technical Readiness Level (TRL) and enable stakeholders to adopt them with minimal risk. Instrumentation is typically composed of one or more sensing elements, interrogation systems, data acquisition systems as well as processes and procedures to collect, analyze and calibrate data. Instrumentation is used to measure process parameters, such as temperature or pressure, independently of the experiment, component or process in which it is deployed. Summaries for the following projects are presented in this section:
    - Flux measurement
    - Temperature measurement
    - Optical Fibers
2. The Performance Demonstration in Operational Conditions area focuses R&D activities to demonstrate deployment of sensors in two areas; irradiation testing of neutron flux sensors and re-fabrication of pre-irradiated fuels and materials to include real-time instrumentation to support advanced reactors and fuel cycle development activities. These deployment activities will position stakeholders to rapidly adopt these technologies with minimal risk to program schedules. These activities have been chosen because they have already attracted interest from stakeholders for deployment and require rapid characterization and maturation to assure successful integration into program objectives. Summaries for the following projects are presented in this section:
    - Irradiation testing of neutron flux sensors in the Advanced Test Reactor Critical (ATRC) Facility
    - Re-instrumentation facility procurements, and system checks
3. The Sensor Advanced Manufacturing and Structural Materials Characterization area focuses R&D activities to develop and deploy innovate sensors and sensor technologies to support advanced reactors and fuel cycle development activities. These innovative sensors and sensor technologies will be employed in irradiation tests and demonstration facilities to progress their TRL and enable stakeholders to adopt them with minimal risk. Advanced manufactured sensors in this area have already attracted interest from stakeholders for deployment and are being rapidly matured. Summaries for the following projects are presented in this section:
    - Sensor fabrication by advanced manufacturing methods
    - Structural materials characterization test rig development
4. The I&C Technology Deployment Capabilities Support area focuses R&D activities to characterize previously developed sensors for use in irradiation experiments. These activities are separated into two tasks; the first is passive peak temperature sensors, both printed melt wire arrays and silicon carbide (SiC) peak temperature monitors, the second is Linear Variable Differential Transformer (LVDTs) calibrations and supply chain and manufacturing developments. These crosscutting development activities will continue to provide stakeholders with the current state of the art in passive peak temperature sensors (melt wire arrays and SiC temperature monitors) and LVDT-based technologies for deployment in future irradiation tests. These activities have been chosen because they have a proven history for use by stakeholders for deployment and require continued development and characterization to assure successful integration with program schedules and objectives. Summaries for the following projects are presented in this section:
    - Passive peak temperature monitors
    - Linear Variable Differential Transformer calibration and supply chain

- Assessment of Existing Technology for Measurement of Pressure and Acceleration in Irradiation Experiments

5. In-Core Measurement Systems for Nuclear Materials Characterization and Codes Validation and Verification (V&V) area focuses R&D activities to characterize previously developed methods for in-situ microstructure characterization for use in irradiation experiments. These activities are separated into two tasks; the first Laser-based Resonant Ultrasound spectroscopy (RUSL) for evaluation of phase separation through spinodal decomposition, the second is Photo Thermal Radiometry (PTR) to determine thermal conductivity and demonstrate special resolution. These innovative measurement methods represent a new evolution for in-pile sensing systems to provide data for materials characterization and code V&V activities. These activities have been chosen because they have garnered interest from stakeholders for deployment in irradiation tests for V&V of newly developed codes in support advanced materials and fuels development programs. Summaries for the following projects are presented in this section:

   - Laser-based Resonant Ultrasound Spectroscopy benchtop evaluations
   - Photo Thermal Radiometry measurement evaluations

6. Direct Digital Printing Sensors for Nuclear Energy Applications area focuses on developing and demonstrating a prototype passive wireless sensor network and deploying it at an industry location. This network will include surface acoustic wave (SAW) sensors, or other printed electronic devices as needed to measure, for example, temperature, voltage, current and hydrogen gas leakage. The sensors will be made by advanced additive manufacturing (AM) technologies for functional materials (FM) developed by Oak Ridge National Lab.

7. Sensors Database for Nuclear Energy area focuses on a previously created baseline Nuclear Energy Sensors Database website (https://nes.energy.gov/). This site is intended to fill a need of sharing information about developed sensor technology assessments for advanced nuclear reactor systems, helping identify technology gaps, prioritize R&D efforts, and create a community of subject matter experts to share information. The scope of the FY21 effort is the continued development and enhancements of the website/database to address additional needs defined over time. The current website has a baseline of functionality to maintain and search for sensor information, needs and gaps, use cases, and a user forum. As more people use the website, it is expected there will be more feedback and requests for additional functionality.

8. Radiation Hardened Instrumentation, Sensors and Electronics area focuses on radiation hardened electronics which have been the proverbial Achille’s heel in 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.

9. Develop Methods and Tools using NSUF Data to support Risk-Informed Predictive Analytics area focuses on enhancing the reliability of test/advanced reactors operation by predicting future state of the reactor. For this, the collaboration with Advanced Test Reactor and large volume of data collected will be leveraged to develop predictive models. The outcome of this project will provide technologies that could be leveraged to develop advanced autonomous operation.

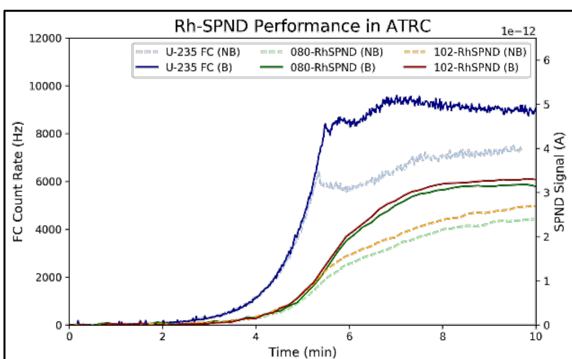
Flux Measurement

PI: Kevin Tsai – Idaho National Laboratory
Collaborators: Troy Unruh – Idaho National Laboratory
Funding: $345,056 (FY 2020-2021)

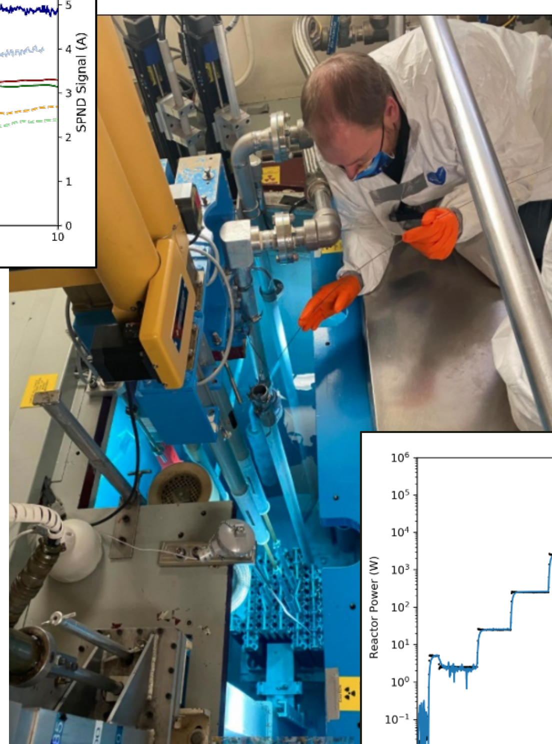
Project Description: The performance of Self Power Neutron Detectors (SPNDs) for steady-state reactor operation is being demonstrated by analyzing the data collected during testing in the Idaho National Laboratory (INL) ATRC facility, Neutron Radiography (NRAD) reactor and Idaho State University's AGN-201 reactor. R&D activities are performed to develop calibration processes for SPNDs and fission chambers, with focus on their performance at high temperature and the development of real-time temperature compensation modeling tools. Data from irradiations in four reactor facilities (ATRC, NRAD, AGN-201, and TREAT) will be used for comparative assessments of real-time flux sensors.

Impact and Value to Nuclear Applications: The performance characterization of SPNDs and fission chambers for steady-state reactor provides a demonstration of comparative assessments of neutron flux sensors that will be useful for material test reactor irradiations as well as for advanced reactor deployments requiring active flux sensing technologies. The development of calibration processes for SPNDs and fission chambers will provide valuable data for suppliers and end-users of these flux sensors.

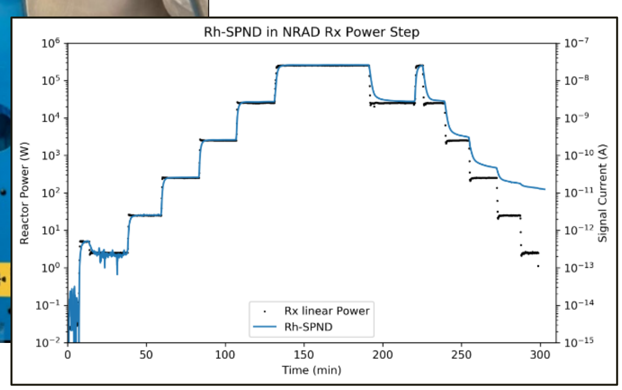
Recent Results and Highlights: SPNDs have been evaluated in four reactor facilities this year: ATRC, NRAD, AGN-201, and TREAT. Recent results from ATRC and NRAD are shown below.



Rhodium SPND performance in ATRC.



SPND installation in NRAD.



Rhodium SPND performance in NRAD.

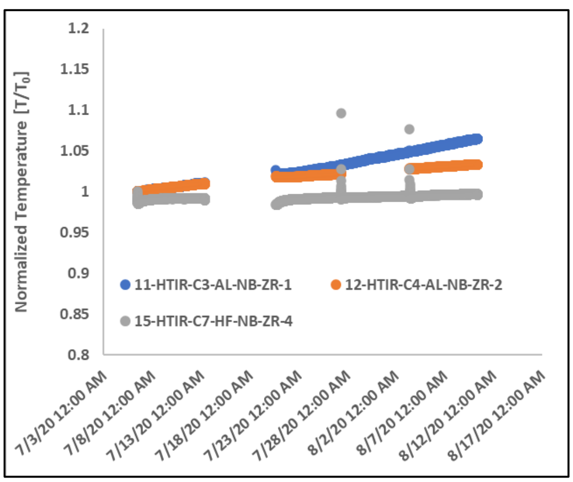
Temperature Measurement

PI: Richard Skifton – Idaho National Laboratory
Collaborators: Brian Jaques, Lan Li, Dan Deng – Boise State University
Funding: $813,746 (FY 2020-2021)

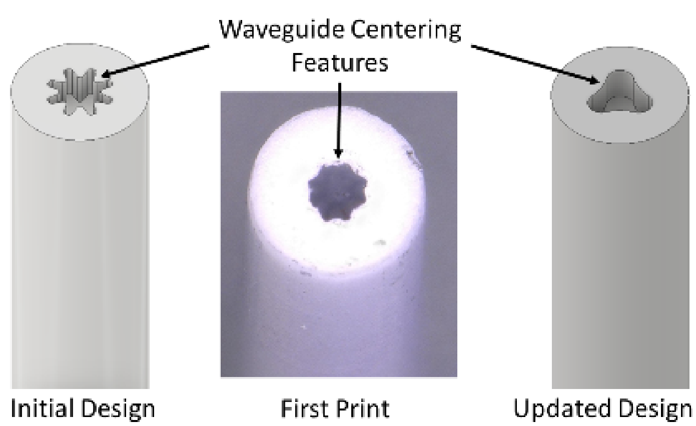
Project Description: Two established technologies, High-Temperature Irradiation Resistant Thermocouples (HTIR-TCs) and Ultrasound Thermometers (UTs), are the focus of the activities to extend the operation range, improve accuracy, and reduce performance degradation during irradiation and provide multi-point sensing capabilities. In fiscal year (FY) 2021, demonstration activities focus on the application of HTIR-TC technology to PWR conditions for their planned deployment in the ATR center loop. For UTs, the optimization of waveguide design and fabrication processes continues through high-temperature testing and performance modeling development.

Impact and Value to Nuclear Applications: Real-time temperature measurement is arguably the most important operational parameter to measure for the characterization of irradiation experiments and the control of power plant systems. Demonstration of HTIR response in non-nuclear PWR conditions in a flowing autoclave is a staged approach to measure fuel center line temperature by characterizing long term out-of-pile drift of HTIR through comparison with modeling results. This strategy separates the irradiation-reduced signal drift from the temperature induced signal drift and helps identify optimum material selection for water and oxygen interactions. The development of robust UT waveguide designs for nuclear applications will be evaluated at high-temperature testing with comparison against specially developed models to understand performance in long-duration testing prior to deployment in reactor irradiations.

Recent Results and Highlights: A coaxial designed HTIR-TC has been fabricated and evaluated to demonstrate drift over long-duration testing. Anti-sticking waveguide spacers have been redesigned and re-printed for installation in newly developed UT design.



Longevity furnace testing of HTIR-TC.



Advanced manufactured parts for UT fabrication.

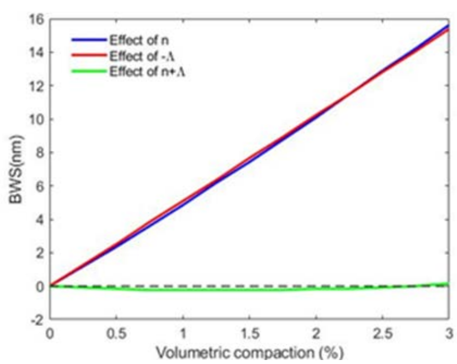
Optical Fibers

PI: Austin Fleming – Idaho National Laboratory
Collaborators: Josh Daw, Kelly McCary, & Sohel Rana – Idaho National Laboratory
Kevin Chen – University of Pittsburg
Funding: $684,348 (FY 2020-2021)

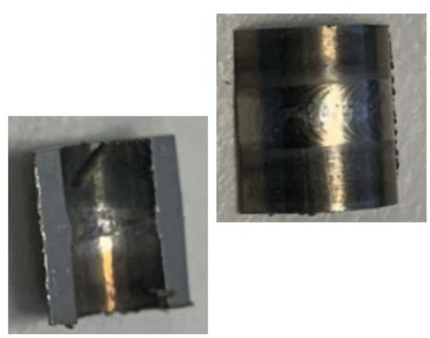
Project Description: Fiber optic sensors have been widely adopted as standard instrumentation in many industries, but the nuclear industry has been slow to adopt the technology because of specific challenges associated with the measurement environment. This project is focused on directly addressing these challenges to enable fiber optic sensors to have the same innovative impact in the nuclear industry that they have in other fields. In this project, the development of fiber optic sensors and sensor technology is prioritized by near-term applications (customers with immediate needs), straightforward path to development (little to no research and development [R&D], mostly engineering), and impact to the nuclear industry (prioritize measurements with higher impact). Fiber optic work in fiscal year (FY) 2021 will focus on demonstration of the Fabry-Perot pressure sensor developed in FY 2020 and the application of 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 will be used to characterize performance and develop active compensation techniques for data analysis to reduce uncertainty due to irradiation degradation. Aspects of enabling R&D continue as part of the deployment of optical fiber sensors and systems in irradiation experiments, with focus on the development of pressure feed-throughs.

Impact and Value to Nuclear Applications: Fiber optic sensors have many benefits of interest to the nuclear industry. Specifically, their small footprint, high-sensitivity, immunity to electromagnetic noise, high-speed, and multiplexed sensing capability are a few of the notable benefits. Fiber optic sensors under investigation will be used to monitor temperature and pressure, and provide in-core imaging. The development of active compensation techniques is needed to account for degradation of optical fiber performance in high temperature irradiation environments to minimize sensor drift and improve sensor longevity in material test reactor irradiations and advanced reactors. In addition, the development of high-pressure high-temperature optical fiber feed-throughs will be needed to install fibers in high-interest locations such as fuel pins or coolant monitoring for thermal hydraulic characterization.

Recent Results and Highlights: A journal article documenting active compensation technique to account for radiation affects in fiber optic sensors has been submitted and a variety of Fabry-Perot pressure sensors have been fabricated and tested. In-pile imaging system has been prototyped and hardware for testing in the reactor has been fabricated and will be testing later in FY 2021.



Bragg Wavelength Shift versus compaction plot for FBGs



Weld development for Fabry-Perot pressure sensor

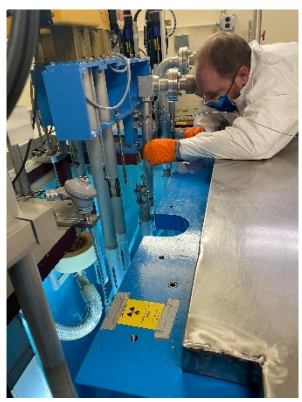
Irradiation Testing of Neutron Flux Sensors in the Advanced Test Reactor Critical Facility

PI: Joe Palmer – Idaho National Laboratory
Collaborators: Kevin Tsai, Michael Reichenberger, Troy Unruh, Calvin Downey – Idaho National Laboratory
Funding: $590,073 (FY 2020-2021)

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

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

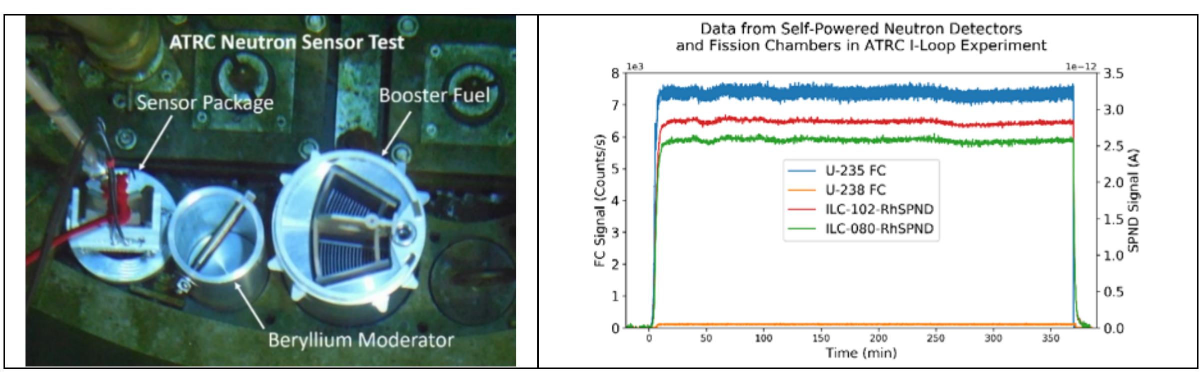
Recent Results and Highlights: An important objective for FY 2021 was to demonstrate custom-built rhodium-based Self-Powered Neutron Detectors (SPNDs) from a domestic supplier. Folded into this effort was an opportunity to provide neutron flux information for the Advanced Test Reactor (ATR) I-loop project through testing in the Advanced 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 the SPNDs would function in ATRC as predicted.



Installing SPND in NRAD reactor.

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

The I-loop project plans to use a "booster" fuel element to increase the thermal flux in a large outer position in ATR to serve as a replacement for one of the lost Halden loops. A test incorporating this booster fuel was run successfully in the ATRC in February 2021. Sensor data were able to confirm 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

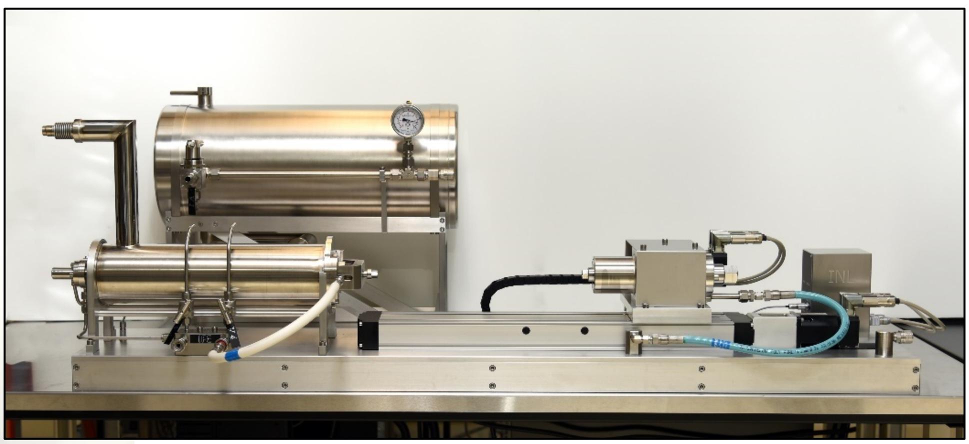
PI: Joe Palmer – Idaho National Laboratory
Collaborators: Calvin Downey, Ian Stites – Idaho National Laboratory
Funding: $979,678 (FY 2020-2021)

Project Description: Procure and begin testing a set of prototype equipment modules from the Norwegian Institute for Energy Technology (IFE) (Halden Reactor Project) to serve as a test bed for developing the capability of incorporating thermocouples, and later, advanced instruments into previously irradiated fuel rods, prior to them being re-irradiated in the Advanced Test Reactor (ATR), 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 nuclear fuels and material behaviors to address performance issues and answer regulatory questions. The HBWR was shut down in 2018. To avoid the loss of 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 back in a test reactor. This approach has been proven uniquely successful, thus invaluable, to enable in-pile measurements on irradiated nuclear fuels. This project increases the capability to deploy and demonstrate advanced in-core instrumentation and contributes to the broader effort to transfer 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 below, two of the three equipment modules from Halden have been received at INL. Initial checkout activities on this equipment have begun.

Drilling Module



Defueling Module

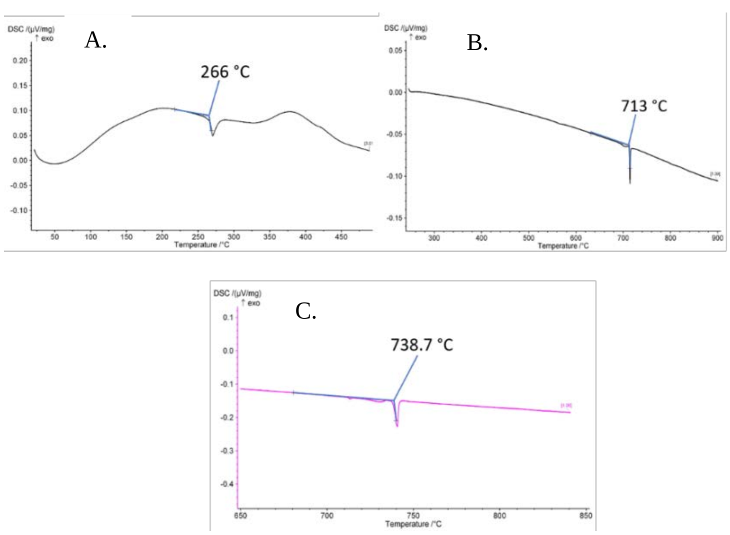
Sensor Fabrication by Advanced Manufacturing Methods

PI: Michael McMurtrey – Idaho National Laboratory
Collaborators: Kiyo Fujimoto, Amey Khanolkar – Idaho National Laboratory
Funding: $635,736 (FY 2020-2021)

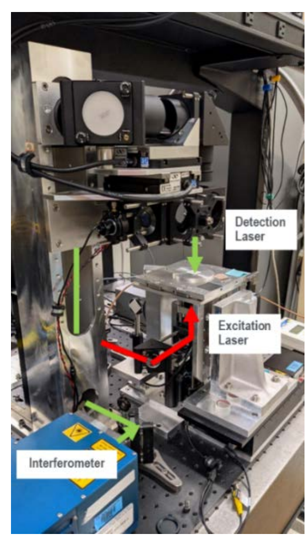
Project Description: Advanced manufacturing (AM) based on direct-write (DW) technologies has emerged as the predominant enabler for the fabrication of active and passive sensors. This project has two objectives. First, expanding the current library of commercially available feedstock materials to encompass nuclear-relevant materials that can be utilized for manufacturing in-pile sensors and advanced nuclear instrumentation. Second, the development of a post-fabrication characterization based on laser ultrasonic techniques to evaluate adhesion strength and influence of substrate surface conditions and deviations from ideal printing parameters on the quality, robustness, and integrity of the printed sensor.

Impact and Value to Nuclear Applications: High-impact enabling technologies from this research task include robust and miniaturized sensors, high-density sensor arrays, and embedded sensors for nuclear application. Significantly expanding this library of printable materials provides a necessary pathway towards incorporating these novel methods for nuclear energy applications, and it stands to revolutionize the development of in-pile nuclear sensors. Laser ultrasonic techniques developed in this project could help determine the dominant combination of factors that significantly alter sensor-substrate adhesion, and thereby provide vital process control for printing novel nuclear-relevant materials with DW technologies as well as quality control for printed sensors.

Recent Results and Highlights: Bismuth and bismuth/platinum bi-metallic nanoparticles have been synthesized using wet chemical approaches to enhance the sensitivity of melt wires for peak temperature detection. Differential Scanning Calorimetry shows the melting point of the bismuth/platinum system changes as a result of varying the ratio of the metal precursors. Measurements to probe the sensor-substrate interfacial adhesion using laser-generated ultrasound are underway.



Differential Scanning Calorimetry of (A.) bismuth nanoparticles with a melting point of 266°C, (B.) BiPt particles with a 713°C melting point when using a 32.5:62.5 wt% Bi:Pt precursor ratio (C.) BiPt particles with a 738.7°C melting point when using a 58:42 wt% Bi:Pt precursor ratio.



Laser ultrasonic experimental setup used to measure the adhesion of printed sensors on substrates.

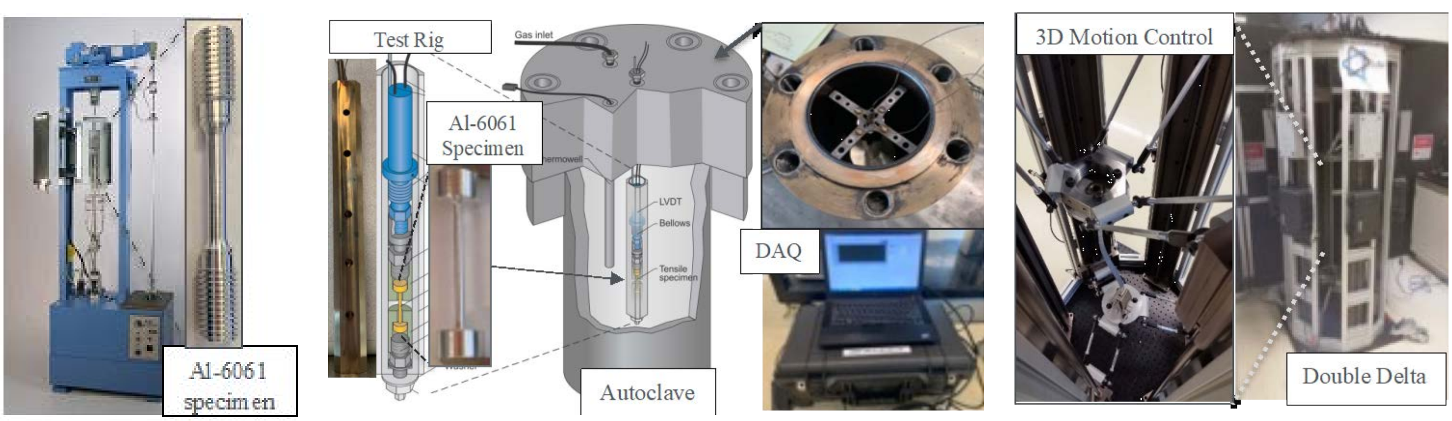
Structural Materials Characterization Test Rig Development

PI: Malwina Wilding – Idaho National Laboratory
Collaborators: Michael McMurtrey, Anthony Crawford, Kory Manning, Hollis Woodbury, Wesley Jones and Troy Unruh – Idaho National Laboratory
Funding: $510,703 (FY 2020-2021)

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 longevity of current and future nuclear reactors. Real-time measurement of structural materials during irradiation is typically accomplished through a Linear Variable Differential Transformer (LVDT)-based creep test rig. This project will update and refine previously proven Halden-based technologies and methods for use in upcoming irradiation tests interested in creep under irradiation. Once the performance of the test rigs is characterized, they will be ready for deployment in relevant irradiation tests of interest to stakeholders.

Impact and Value to Nuclear Applications: These strategies enable the 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 qualifying materials for both current and future nuclear energy systems.

Recent Results and Highlights: Further understanding of the capability for testing in-situ irradiation creep will improve structural material understanding in nuclear reactors. This will be achieved by a comparative assessment of standard creep testing and out-of-pile creep testing using aluminum samples. Additionally, investigating an alternate way of measuring creep deformation will be achieved 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 (force, vibration, thermal, etc.) 3-D reactor environments while remaining extremely controllable and accessible. Most measurement systems in this field (e.g., 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) (b) (c)

(a) Standard Creep Testing *(b) Out-of-Pile Creep Testing using Autoclave* *(c) Double Delta*

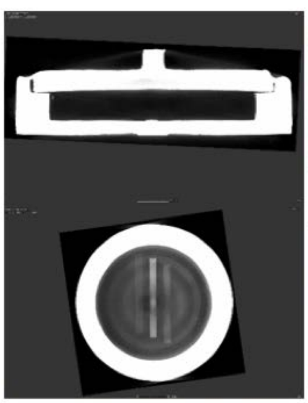
Passive Peak Temperature Monitors

PI: Malwina Wilding – Idaho National Laboratory
Collaborators: Lance Hone, Kory Manning, Kurt Davis, and Austin Fleming – Idaho National Laboratory
Kiyo Fujimoto – Boise State University
Funding: $289,193 (FY 2020-2021)

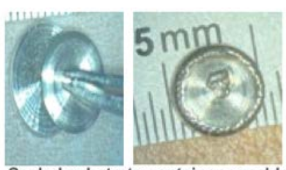
Project Description: Passive temperature monitors have been in use for many decades in irradiation testing experiments, but further innovations to these technologies will advance the state of the art by leveraging new equipment and methods that were initiated in FY 2020. An optical dilatometer was previously purchased that will be benchmarked against traditional resistivity methods for 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 higher resolutions than traditional quartz-encapsulated melt wires. These innovations have already attracted interest from stakeholders wanting to expand their passive temperature monitor deployment activities.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measure irradiation temperature and neutron fluence during post-irradiation examination while requiring no feedthroughs/leads comparable to current more-complex real-time temperature and flux sensors. They have been chosen because they have a proven history for use by stakeholders for deployment and require continued development and characterization to assure successful integration with program schedules and objectives.

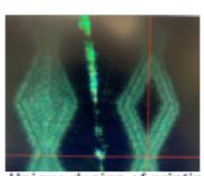
Recent Results and Highlights: The first highlight is the development of a packaging processes for printed melt wire arrays with improved geometry and higher peak temperature resolution. A new unique encapsulation design for advanced manufactured melt wires was optimized for welding process that is capable of inert-atmosphere encapsulation. Also, a new unique design of printing melt wires creates better wire sensitivity, which will also enhance X-ray-computed tomography resolution to better evaluate encapsulated materials. The second highlight is the comparative assessment of optical and resistivity measurement methods for the evaluation of silicon carbide temperature monitors. The optical dilatometry measurement method has multiple advantages over the resistivity measurement method, such as an automated process requiring minimal setup time, under vacuum treatment that removes any oxidation issues and provides faster processing time for each silicon carbide sample.



CT scan of printed Sn, Zn and Al melt wires

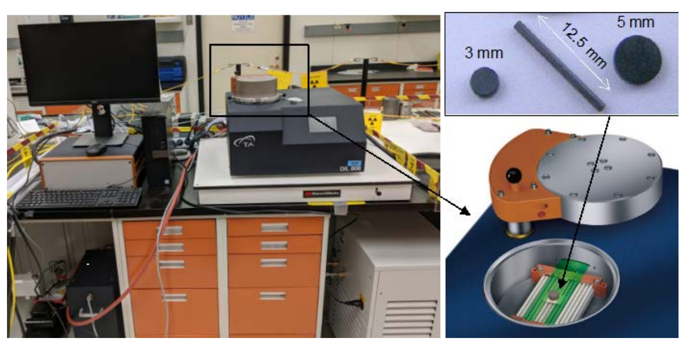


Sealed substrate container capable of inert-atmosphere encapsulation



Unique design of printing material to enhance melt wire sensitivity

Optical dilatometry method for processing Silicon carbide temperature monitors



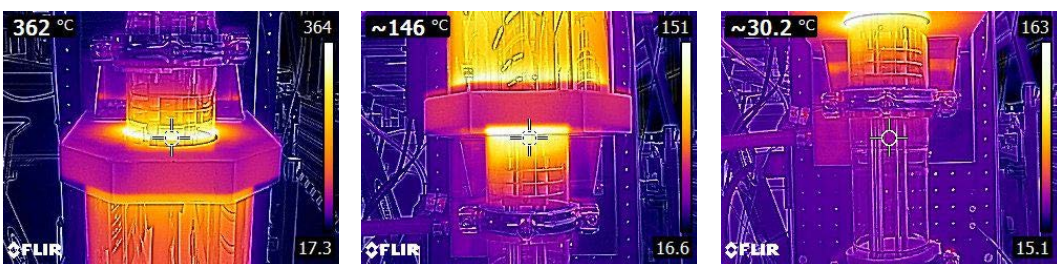
Linear Variable Differential Transformers Calibration and Supply Chain

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 Pittsburg
Steinar Solstad – Institute for Energy Technology
Funding: $641,769 (FY 2020-2021)

Project Description: Linear Variable Differential Transformers (LVDTs) have a long history of manufacturing and deploying in irradiation tests at the now-shutdown Halden Reactor. Fiscal Year (FY) 2021 activities will maintain and advance the LVDT technology for use by stakeholders requiring LVDTs in upcoming irradiation tests. Relevant test conditions include testing in inert gases at elevated temperatures. In addition, the United States supply chain of LVDTs and related components will be explored to extend the availability of robust LVDTs that can be utilized for in-pile applications.

Impact and Value to Nuclear Applications: Through collaborative activities and direct procurement of equipment from Institute for Energy Technology (IFE) in Halden, Norway, this project supports the ASI Program commitment to ensure continuity in the availability of instrumented irradiation experiments for the U.S. nuclear industry after the closure of the Halden Test Reactor. The characterization of nuclear components in operationally inert environments is crucial to advanced reactor design demonstrations.

Recent Results and Highlights: The first highlight is the completion of a supply-chain assessment for LVDTs for nuclear applications. Three companies were identified as potential suppliers for LVDTs should INL's current supply from IFE be interrupted: Newtek Sensor Solutions, Idaho Laboratories Corporation, and RDP Electrosense. The second highlight is the assembly of a test rig to enable LVDTs calibration in inert gas. Flow, temperature, and oxidation testing of the upgraded calibration rig was successfully completed. Both highlights were completed during FY2021.



Calibration test rig under inert gas keeps the linear translation motor near room temperature while the central region of the test rig is at 700°C.

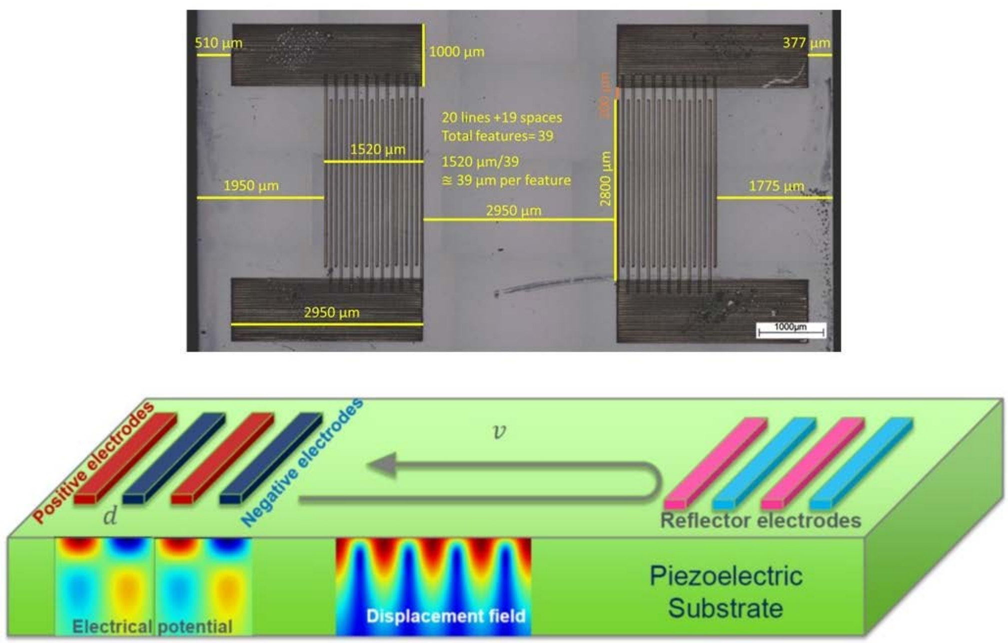
Assessment of Existing Technology for the Measurement of Pressure and Acceleration in Irradiation Experiments

PI: Joshua Daw – Idaho National Laboratory
Funding: $100,003 (FY 2021)

Project Description: Pressure and vibration sensors are increasing in demand for research test reactors, such as Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT), and for advanced power reactor (High Temperature Gas Reactor, Molten Salt Cooled Reactors, etc.) concepts. Pressure sensors are particularly important for online monitoring of fission gas release from nuclear fuel during irradiation experiments and for coolant flows in power reactors. Vibration and acceleration sensors are needed for online monitoring of reactor performance and degradation of its structural components and coolant pumps, as well as monitoring flow-induced vibrations and acoustic emissions in irradiation experiments, and structural health monitoring in advanced reactors. In each case, these sensors may be exposed to a variety of harsh thermal and chemical environments. The fiscal year (FY) 2021 activities will continue the assessment of micro-electromechanical systems (MEMS) pressure and acceleration sensors that were initiated in FY 2020, as well as planning to expand work related to surface acoustic wave (SAW)-based sensors.

Impact and Value to Nuclear Applications: The goal of the first task of this activity is to develop a prioritized list of sensing technologies to provide guidance in future selection or development of sensors for use in various irradiation experiments. The goal of the second task is to enable planning of future NEET-ASI research into SAW sensor technologies that will improve coordination between ongoing and future projects.

Recent Results and Highlights: The first highlight is a continuation of an FY 2020 assessment of MEMS pressure and acceleration sensors that focuses on identifying commercial and promising developmental sensors that may be used in an "off-the-shelf" condition, or that may require slight modifications to survive the harsh in-core environments. The second highlight is the planning and hosting of a workshop in June 2021 that will help coordinate ongoing work related to SAW-based sensors.



SAW device operating principle and piezoelectric substrate with printed electrodes.

Laser-based Resonant Ultrasound Spectroscopy Benchtop Evaluations

PI: Zilong Hua and Robert Schley – Idaho National Laboratory
Funding: $258,287 (FY 2020-2021)

Project Description: The goal of this project is the development of specific instruments to perform in-reactor measurements of critical physical properties of nuclear fuels and materials. This activity focuses on a laser-based resonant ultrasound spectroscopy instrument, which monitors irradiation-induced microstructure evolution and phase transformation of metallic fuels by examining the frequency variation of zero-group-velocity plate waves that are indirectly tied to microstructure. Zero-group-velocity plate waves are localized evanescent waves; therefore, the waves are (1) insensitive to the boundary condition imposed by the sample holder, and (2) the corresponding measurement has a high signal-to-noise ratio.

Impact and Value to Nuclear Applications: Laser-based resonant ultrasound spectroscopy has the unique capability to monitor real-time microstructure evolution induced by high irradiation and high temperature in a non-contact, remote way. Specifically, focusing on the detection of zero-group-velocity plate wave, the measurement sensitivity and tolerance to the environmental noise have been significantly improved, which are critically important for the in-reactor application.

Recent Results and Highlights: The data analysis program has been coded and validated through zero-group-velocity plate wave measurements on a series of reference metal materials. Meanwhile, high-temperature testing has been conducted, and on most of the samples, a reasonable signal can be obtained at the target temperature of 800°C.

Images/graphs/charts:

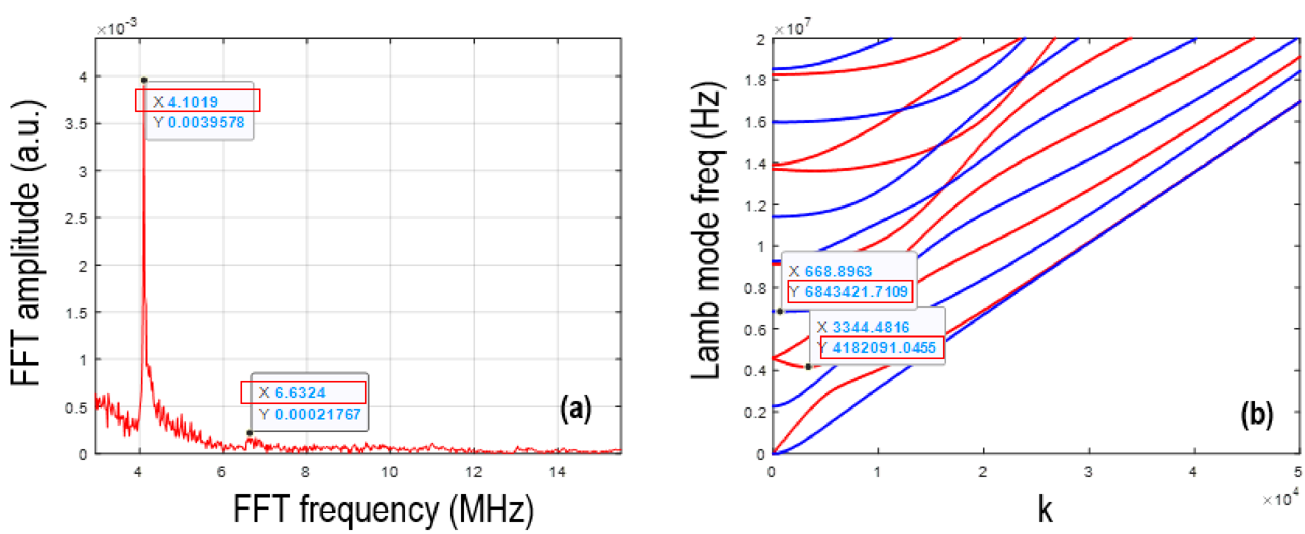


Figure 1. (a) measurement data (frequency spectrum) of zero-group-velocity plate wave on a reference material (copper) with the zero-group-velocity frequency captured and highlighted (in the boxes as X, with the unit of MHz); (b) the predicted results of zero-group-velocity plate wave frequency (also highlighted in the boxes as Y, with the units of Hz).

Photothermal Radiometry Measurement Evaluations

PI: Zilong Hua and Robert Schley – Idaho National Laboratory
Funding: $236,882 (FY 2020-2021)

Project Description: The goal of this work package is the development of specific instruments to perform in-reactor measurements of critical physical properties of nuclear fuels and materials. This activity focuses on fiber-based photothermal radiometry (PTR), which measures thermal conductivity through collecting local black-body radiation induced by an external heating source. The unique advantages of photothermal radiometry include but are not limited to (1) better performance at high temperature, and (2) are capable of dealing with unprepared, industry-grade surfaces. By providing experimental results through contactless, remote measurements, this instrument will enable direct validation and verification of advanced fuel performance codes, primarily MARMOT, and there will also be connection to BISON.

Impact and Value to Nuclear Applications: Researchers have speculated for years that the conductivity measured in-reactor can be significantly different from that measured in a post-irradiation examination environment due to supersaturation of point defects that exist during in-reactor irradiation. Photothermal radiometry provide unique, in-situ, and real-time characterization capabilities of newly developed fuels and materials for code validation and ensure rapid acceptance for end-use.

Recent Results and Highlights: In the beginning of fiscal year 2021, the free-space photothermal radiometry system was successfully modified to a fiber-based system, which greatly improved the system portability and versatility. Later, the setup was further upgraded to improve the performance at high temperature. Testing results on the reference materials were promising, but they also showed that the graphite coating suffered oxidation issue at elevated temperature. A vacuum chamber system was recently purchased to enable high-temperature testing in specific environments, such as vacuum and inert gas.

Images/graphs/charts:

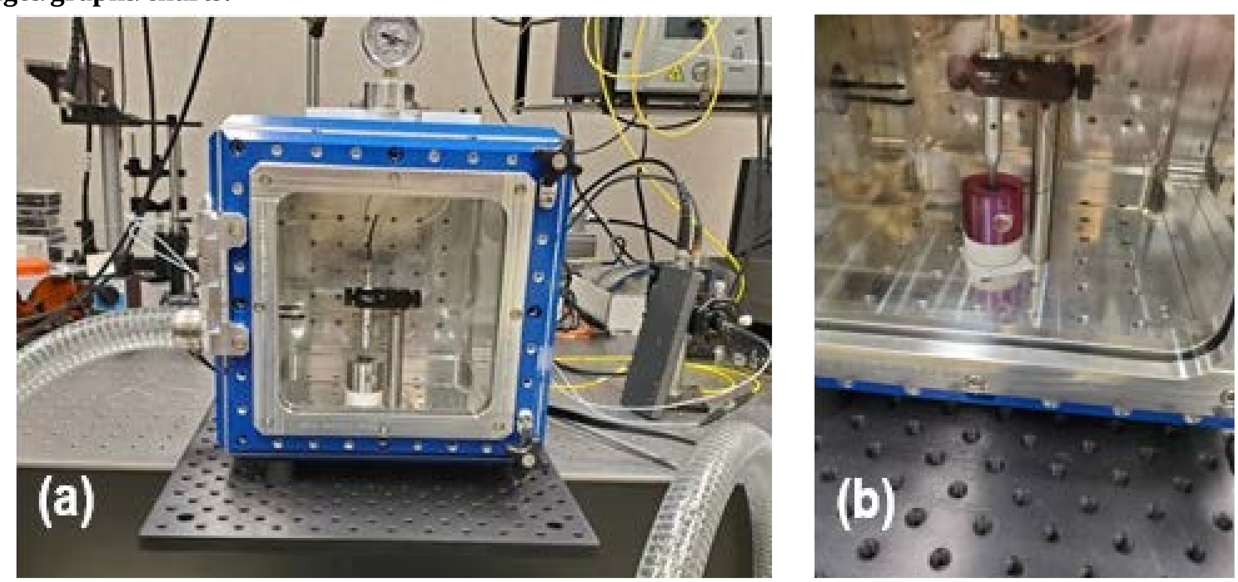


Figure 1. (a) recently purchased vacuum chamber system with the fiber-PTR instrument located inside; (b) the PTR instrument during a high-temperature test (note that the sample holder became red hot).

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
Funding: $220,000 (FY 2019-2021)

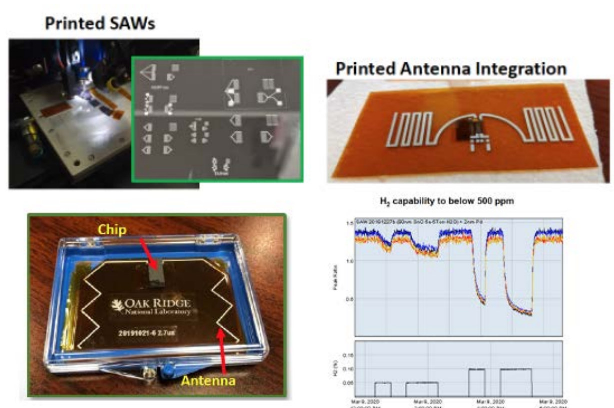
Project Description: This project is developing sensors of interest and direct digital printing (DDP) of integrated sensor systems. The (4) sensors of interest currently are temperature, hydrogen (H_2), voltage and current. AMS has allowed us to test a 5-sensor network at their facilities in Knoxville, 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 <1um. We have successfully met this goal by achieving 0.8um. 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. UCF has been a big contributor to sensor integration approaches and development and testing of the sensor interrogator.

Impact and Value to Nuclear Applications: The RF/SAW sensors being developed are completely passive sensors. They contain no battery or means to collect or produce energy. 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. In case a sensor fails or drifts out of range, another sensor can be readily deployed by human or robotic methods.

Recent Results and Highlights: We have demonstrated in the lab functional sensors operating at 915MHz, requiring DDP feature size control down to 0.8um. We have also demonstrated several additional features of the technology including:

1. Ability to communicate simultaneously with >10 sensors;
2. Communicate over large distances; up to 100 ft. or more;
3. Simultaneously monitor multiple variables such as temperature, H_2, voltage and current;
4. Communicate with sensors that are obstructed (e.g., inside a metal cabinet, around a corner); and
5. Develop and DDP integrated antennas and packaging.

Images/Graphs/Charts:



<u>Upper Left:</u> DDP RF/SAW devices; <u>Upper right:</u> RF/SAW sensor integrated with printed antenna; <u>Lower Left:</u> Integrated sensor/antenna in peel-n-stick package; <u>Lower Right:</u> Data from hydrogen sensor.

Nuclear Energy Sensors Database

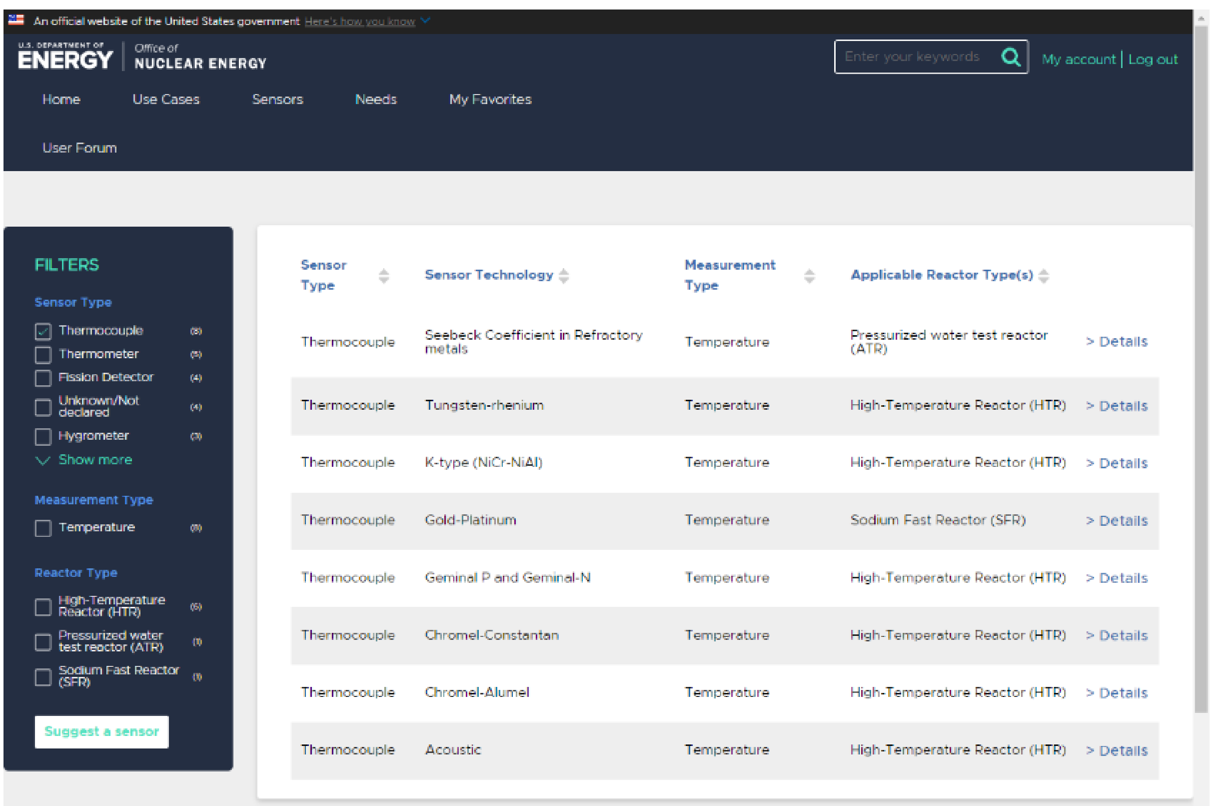
PI: Tim Downing – Pacific Northwest National Laboratory
Collaborators: Pattrick Calderoni, Yogeshwar Dayal – Idaho National Laboratory
Funding: $181,000 (FY 2019-2021)

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: Since this time last year, the initial site requirements have been completed, and the site is live for use. The initial content loaded into the website came from the published document “*Assessment of Sensor Technologies for Advanced Reactors*” available at https://info.ornl.gov/sites/publications/files/Pub68822.pdf. PNNL, in collaboration with INL and other national laboratories, is working to populate the site with additional sensor information. In addition, the site will soon be expanded to host information related to other radiation hardened technologies.



Radiation Hardened Instrumentation, Sensors and Electronics

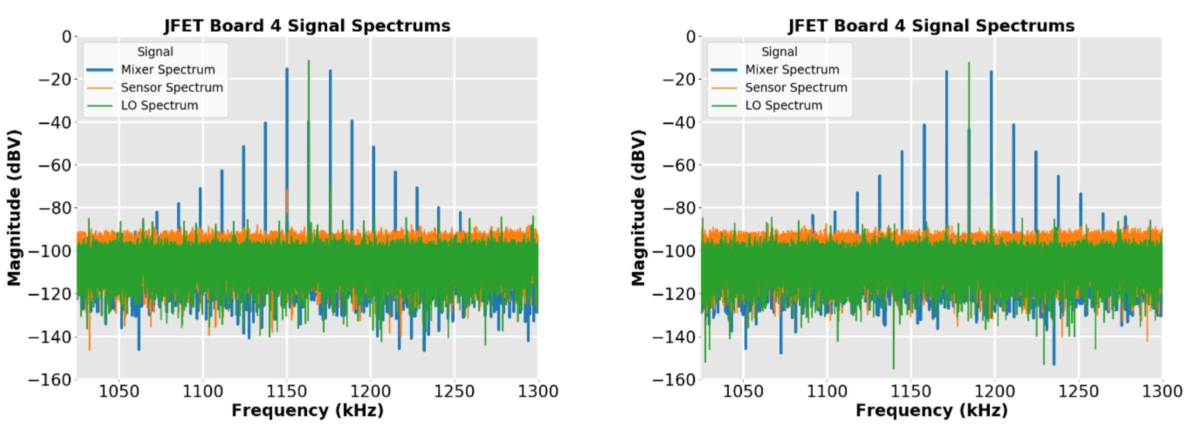
PI: M. Nance Ericson – Oak Ridge National Laboratory
Collaborators: F. Kyle Reed, N. Dianne Bull Ezell - Oak Ridge National Laboratory
Funding $170,000 (FY 2020-2021)

Project Description: To assist the DOE in defining a course for NE-funded rad-hard electronics research, ORNL will focus on three main tasks in FY21. The first task will be to investigate the survivability of silicon-junction gate field-effect transistor (Si-JFET) through a 100 Mrad total ionizing dose (TID) experiment and report these test results. The second task will investigate wide bandgap (WBG)-based JFET devices and sources. The third task is an investigation into commercially available systems and components that will be carried out to determine if a 'standardized' list of devices can be identified for reactor instrumentation application. If feasible, this list will provide direction to designers and equipment suppliers for selection of components to meet specific reactor requirements.

Impact and Value to Nuclear Applications: Radiation hardened electronics have been the proverbial Achille's heel in 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: To achieve task three, ORNL has been collaborating with Pacific Northwest National Laboratory to incorporate rad-hard electronics into the Nuclear Energy Sensors (NES) website also created under the NEET program. The database provides filters allowing users to identify rad-hard electronics to be paired with sensors based on the temperature survivability, radiation tolerance, functionality, as well as several other criteria.

Focusing on task one, ORNL has irradiated several sensing and transmission circuits using the Westinghouse Gamma Irradiation Facility (GIF). To this date, two of the four boards have been irradiated to 170 Mrad (Si) TID in the center of the circuit with only a 5% shift in the transmission frequency implying the electronics can withstand this environment with minimal impact on performance. The outcome of these irradiations will be reported in a milestone report in the fourth quarter of FY21.



(a) (b)

Spectrum of JFET sensing and transmission circuit after 1 Mrad (Si)[a] and 100 Mrad (Si)[b].

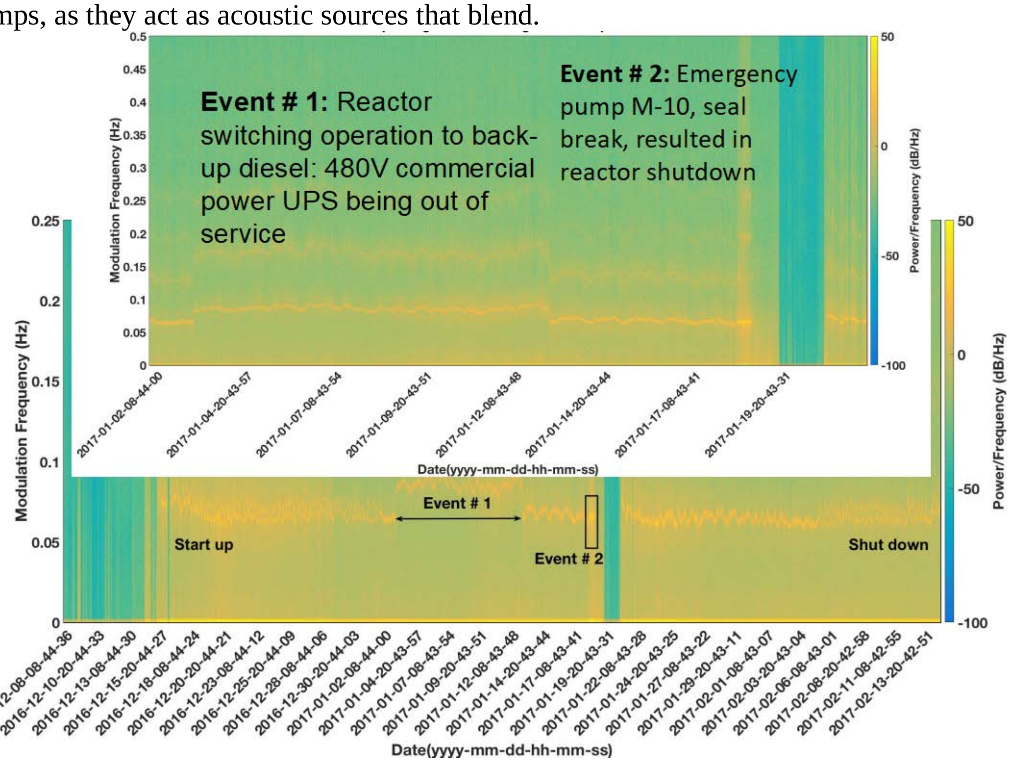
Develop Methods and Tools using NSUF Data to Support Risk-informed Predictive Analytics

PI: Vivek Agarwal – Idaho National Laboratory
Collaborators: James A. Smith – Idaho National Laboratory
Funding: $260,117 (FY 2019-2021)

Project Description: The scope of this research is to enhance the reliability of test/advanced reactors operation by predicting future state of the reactor. The specific objectives are: 1. Development of operation signatures using data (sensor data, process data, and operating logs) from the Advanced Test Reactor (ATR). 2. Development of diagnostics and prognostic models based on machine learning to understand current and future operating condition of the reactor for different operating cycle and primary coolant pump (PCP) combinations. 3. Utilizing the predictive modeling outcomes to recommend predictive maintenance strategies to enhance the reliability and availability of the reactor.

Impact and Value to Nuclear Applications: The outcome of this project will provide technologies that would enable complete state awareness of the reactor. This would lead to the development of advanced autonomous controls and risk-informed decision-making.

Recent Results and Highlights: Data from acoustically telemetered sensors, installed in the ATR nozzle trench area was collected for different PCP combinations during normal cycle and power axial locator mechanism cycle. Advanced signal processing techniques were utilized to analyze the data and to develop ATR operational signatures for different operating cycles. Each signature captures a different ATR operational change such as startup, shutdown, or other events. ATR operational signatures are dictated by the combination of primary coolant pumps, as they act as acoustic sources that blend.



Acoustic signature of ATR during normal operation with two primary coolant pumps operating. Two separate events were recording during this operation period.

FY 2020 NEET-ASI Research Summaries

1. Development of Sensor Performance Model of Microwave Cavity Flow Meter for Advanced Reactor High Temperature Fluids
    - Investigating a microwave cavity-based transducer for high-temperature fluid flow sensing.
2. Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid Improve the economic competitiveness of advanced reactors through the optimization of plant performance.
    - Improve the economic competitiveness of advanced reactors through the optimization of plant performance.

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

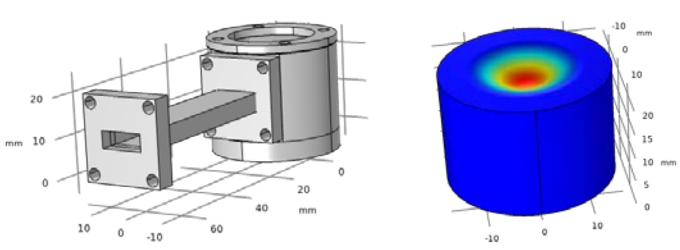
PI: Alexander Heifetz – Argonne National Laboratory
Collaborators: Sasan Bakhtiari – Argonne National Laboratory,
Miltos Alamaniotis – University of Texas San Antonio; Anthonie Cilliers – Kairos Power
Funding: $1,000,000 (FY 2021–2023)

Project Description: We are investigating a microwave cavity-based transducer for high-temperature fluid flow sensing. This sensor is a hollow metallic cavity, which can be fabricated from stainless steel, and as such is expected to be resilient to the radiation, high temperature and corrosive environment of sodium fast reactors (SFR) and molten salt cooled reactors (MSCR). A viable geometry of the sensor is that of a small cylindrical resonator. A schematic drawing of the flow sensor is shown. The principle of sensing consists of making one wall of the cavity flexible enough so that dynamic pressure, which is proportional to fluid velocity, will cause membrane deflection. A cavity is characterized by its resonant frequencies, which occur due to constructive interferences of microwave field inside the cavity. Membrane deflection causes cavity volume change, and thus a shift in the resonant frequency. Using signal readout from microwave frequency shift in a hollow 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 sensor will be achieved through a microwave waveguide, which will be an integral part of the insertion probe. The waveguide is a rigid narrow metallic tube which will be designed to be resilient to high-temperature and high-radiation environment. In principle, a waveguide can be designed to be compatible with thermocouple capillaries of an instrument tree.

Impact and Value to Nuclear Applications: High-temperature fluid reactors, such as SFR and MSCR are a promising advanced reactor option with a highly efficient thermal energy conversion cycle. Streamlining commercialization of advanced reactors involves development of new coolant sensing technologies for enhancing performance efficiency. Measurement of high-temperature fluid process variables, in particular the flow inside the pressure vessel, is a challenging task because of harsh environments of advanced reactors, which includes radiation, high temperature, and contact with highly corrosive coolant fluid. Since the microwave cavity sensing is based on fluid-structure interaction, as opposed to fluid electrical conductivity, the proposed sensor is equally applicable to liquid sodium and molten salt flow sensing.

Recent Results and Highlights: Performance of the flow sensor was estimated with COMSOL RF module computer simulations. A right cylinder stainless steel cavity with dimeter of 0.8in was investigated. Frequency shifts resulting from membrane deflections were calculated for the TM_{011} and TE_{011} modes, occurring at 15.4GHz and 22.2GHz, respectively. For purified liquid sodium with oxide concentration of 5ppm, corrosion rate is expected to be approximately 0.1mil/year. Thus, in a 10-year life span, the sensor membrane, on average, could corrode by 1mil=25.4μm. We choose membrane thickness of 10mil (254μm), so that corrosion would affect no more than 10% of the membrane. Using the properties of liquid sodium fluid, and stainless-steel material property values at 500^{o}C, we estimate frequency shift for a range of values of fluid velocity from 0.5m/s to 2m/s. Results of computer simulations indicate measurable sensitivity to flow for this cavity design.

Images/graphs/charts:



(a) (b)

(a) Conceptual drawing of waveguide-coupled microwave cylindrical cavity with flexible membrane. (b) Deflection of membrane due to dynamic fluid pressure changes cavity volume, which shifts microwave resonant frequency

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 – Argonne National Laboratory
Brendan Kochunas – University of Michigan; Anthonie Cilliers – Kairos Power, LLC
Funding: $1,000,000 (FY 2021–2023)

Project Description: The objective of this research is to improve the economic competitiveness of advanced reactors through the optimization of plant performance. To increase nuclear plants survival in deregulated electricity markets, a proposed solution is to integrate advanced reactor concepts with energy storage technologies. 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:

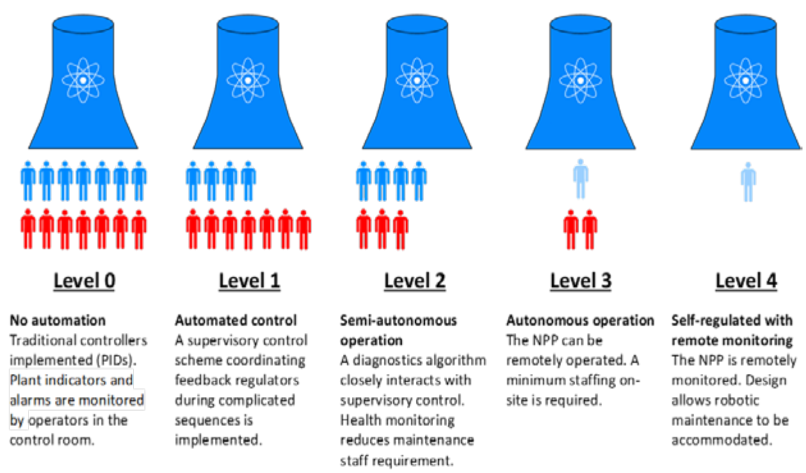
- Design of an integrated energy system (IES) that ensures reliable power production as well as flexible operation capabilities.
- Development of a comprehensive control system architecture capable of automating control sequences, monitoring the component conditions, and partially relieving the operators of the decision-making related 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 operations and maintenance costs.

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

1. Collecting technical specifications about the Pebble-Bed Fluoride Salt Cooled High-Temperature Reactor (PB-FHR) primary circuit. Started modifying the reference design to allow the interface with the Thermal Energy Storage (TES) system in the intermediate loop, and the boundary conditions mimicking the presence of the Energy Conversion cycle.
2. Literature review about operating costs and NRC staffing requirements for currently operated units.
3. Definition of the role of diagnostics to ensure the robustness of the integrated autonomous operation framework. Potential issues that might derive from adopting completely data-driven approach were considered.

Next steps include finalizing the plant simulator, defining the sensor set, and selecting the most suitable control, diagnostics, and system identification algorithms.



Definition of the different levels of autonomous operation

FY 2019 NEET-ASI Research Summaries

1. Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance
    - Develop and demonstrate advanced online monitoring to better manage nuclear plant assets, operation, and maintenance.
2. Context-Aware Safety Information Display for Nuclear Field Workers
    - Development of an "Intelligent Context-Aware Safety Information Display" (ICAD) for nuclear power plant (NPP) field workers.
3. Design of Risk-Informed Autonomous Operation for Advanced Reactors
    - Develop and demonstrate artificial reasoning systems for operator decision support, aided by autonomous control technology, for advanced nuclear power reactors.
4. Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics
    - 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.
5. Acousto-Optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control
    - Develop an integrated sensor concept that enables simultaneous measurements of temperature, pressure, and gas composition using a single sensor platform, thereby limiting the number of penetrations in a reactor vessel that are needed.

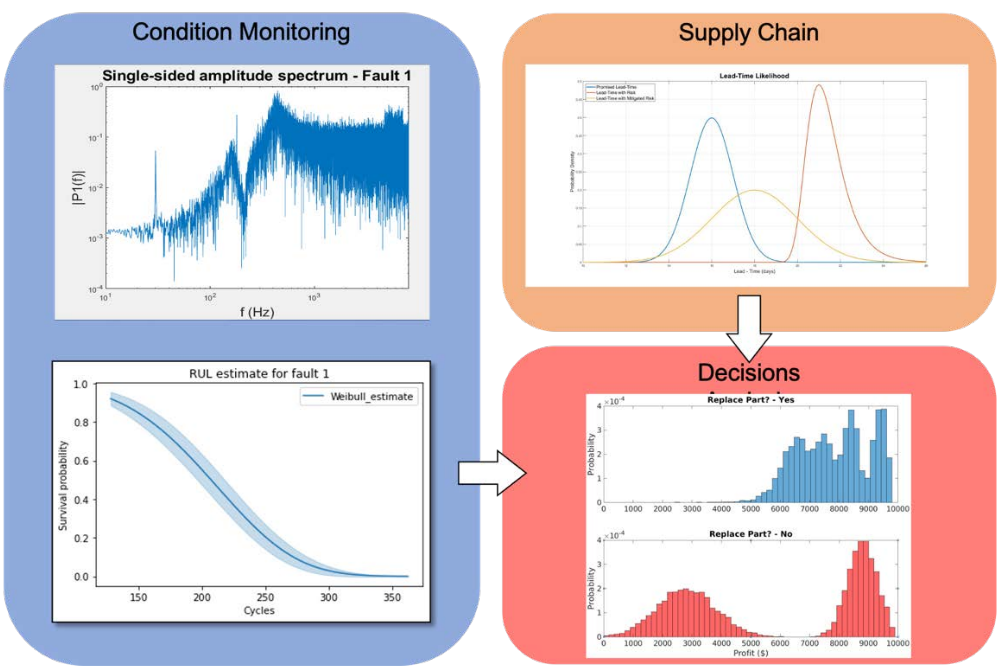
Advanced Online Monitoring and Diagnostic Technologies for Nuclear Plant Management, Operation, and Maintenance

PI: Daniel G. Cole – University of Pittsburgh
Collaborators: Heng Ban – University of Pittsburgh; Vivek Agarwal – Idaho National Laboratory
Funding: $1,000,000 (FY 2020-2022)

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.



Context-Aware Safety Information Display for Nuclear Field Workers

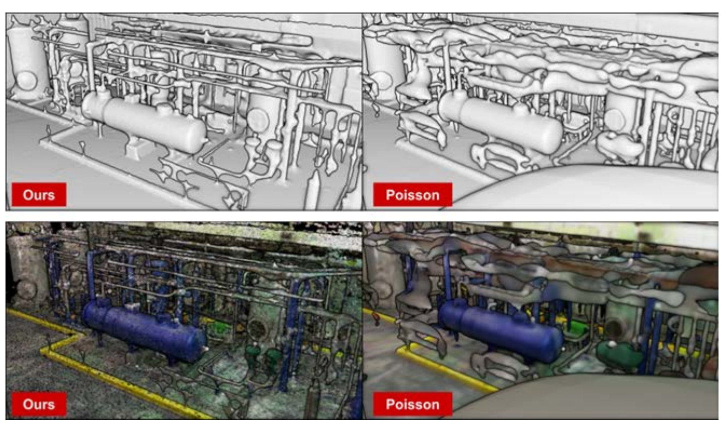
PI: George Edward Gibson, Jr. – Arizona State University;
Collaborator: Pingbo Tang – Carnegie Mellon University; Alper Yilmaz – The Ohio State University; and Ronald Boring – Idaho National Laboratory
Thomas Myers – Duke Energy
Funding: $500,000 (FY 2020-2022)

Project Description: 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 personal 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 avoid unsafe 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.

Field: AR information display example

Impact and Value to Nuclear Applications: This project will produce knowledge and technical approaches for supporting real-time safety information display to nuclear workers. More than 60% of the undesirable events in the commercial nuclear industry are due to human factors. Real-time safety information display to nuclear workers can guide field workers to reduce errors leading to incidents and accidents, thereby creating positive social, economic, and technical impacts.

Recent Results and Highlights: The project team conducted the following research activities in this reporting period: 1) analyzed field videos collected in a field worker training facility for identifying field hazards occurring because of inappropriate spatial and temporal interactions between workers, workspaces, and field activities; 2) established an image segmentation and labeling pipeline in addition to the object detection pipeline for supporting real-time field worker navigation; 3) utilize NPP worker's pupil diameter changes in real-time field operation simulations to predict human errors in simulated field operations; 4) continue the development of the computer vision algorithm with a unified structure for reliable object detection based on the integrated use of 3D point cloud and 2D images.



Mesh generated based on the collected point cloud of the Nuclear Power Plant

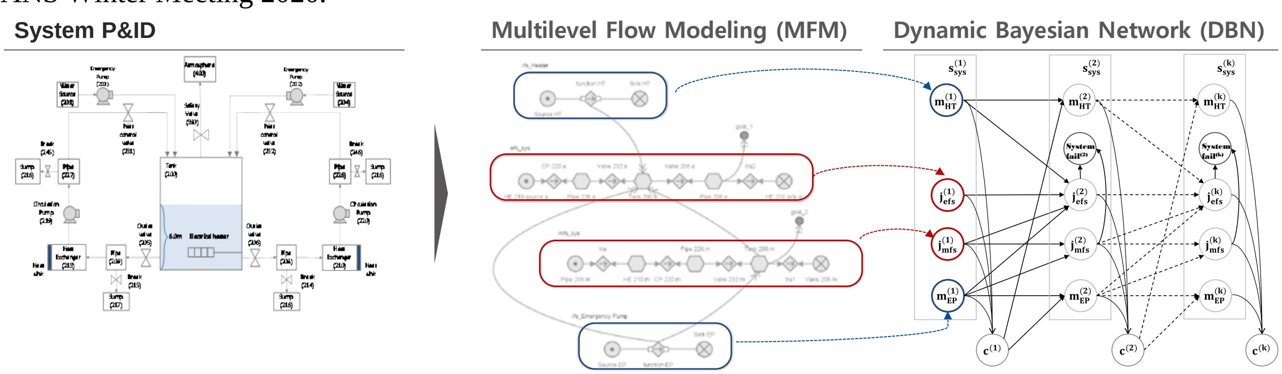
Design of Risk-Informed Autonomous Operation for Advanced Reactors

PI: Michael Golay – Massachusetts Institute of Technology; Collaborator: Hyun Gook Kang – Rensselaer Polytechnic Institute; Sacit M. Cetiner, Pradeep Ramuhalli – Oak Ridge National Laboratory; Jong Gyun Choi – KAERI, ROK Funding: $1,000,000 (FY 2020-2022)

Project Description: The objective of this project is to develop and demonstrate artificial reasoning systems for operator decision support, aided by autonomous control technology, for advanced nuclear power reactors. A critical aspect of the operator decision support technology proposed here is the integration of prognostic calculations of plant state and risk-assessment of proposed actions relative to the current and postulated future plant states. The specific technical objectives of the work include: (1) component and system diagnostics based on monitoring technology; (2) predictive assessment of degradation that may lead to failures; (3) artificial reasoning methods, along with metrics, for prioritization of resource investments, operator actions, and system control commands for maintaining and potentially improving functionality through SSC and/or human failure; and (4) trustworthy plant protection system software to ensure reliable and repeatable operator decision support.

Impact and Value to Nuclear Applications: The technology developed by this project will enable routine operator oversight of autonomous control actions while providing specific operator action options for more complex scenarios, optimizing plant availability and reliability while maintaining safety margins. It is also expected to improve the knowledge base and specific lore to a convincing level of assurance, and through such progress to strengthen its foundation. The capabilities developed in this project are applicable to both light water reactors and advanced reactors.

Recent Results and Highlights: The solution is under development to build an integrated framework of component diagnostics and plant prognostics for enhanced plant operation decision making based on the data analytic methods and the inference modeling. Developments of the integrated artificial reasoning algorithm, a Bayesian Network model for fault diagnostics and a Markov Decision Process (MDP) based decision making model for operation support are in process. Also, empirical data and expert-informed input are under collection through collaboration with MIT Central Utilities Plant (CUP) and ORNL Steam Plant. Two technical reports, "Symptom-Based Conditional Failure Probability Estimation for Selected Structures, Systems, and Components" and "Emulator-based Software V&V Toolkit for Safety-Critical PLC Applications", were published in July 2020 and September 2020 respectively. "Dynamic Risk Assessment with Bayesian Network and Clustering Analysis" was published on *RESS* in March 2020 and "System Risk Quantification and Decision Making Support using Functional Modeling and Dynamic Bayesian Network" was submitted to *RESS* in December 2020. Finally, three conference papers were published, including "Inference Rule Generation using Multilevel Flow Modeling for Fuzzy Logic-based System Control" at IWFM 2020, "Risk assessment using MFM with dynamic Bayesian Network" at IWFM 2020 and "Quantitative Reasoning and Risk Assessment with Dynamic Bayesian Network" at ANS Winter Meeting 2020.



Integrated Artificial Intelligence Reasoning Methodology.

Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

PI: David Grabaskas – Argonne National Laboratory
Collaborators: Carol Smidts – Ohio State University; Pascal Brocheny – Framatome
Funding: $1,000,000 (FY 2020-2022)

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:

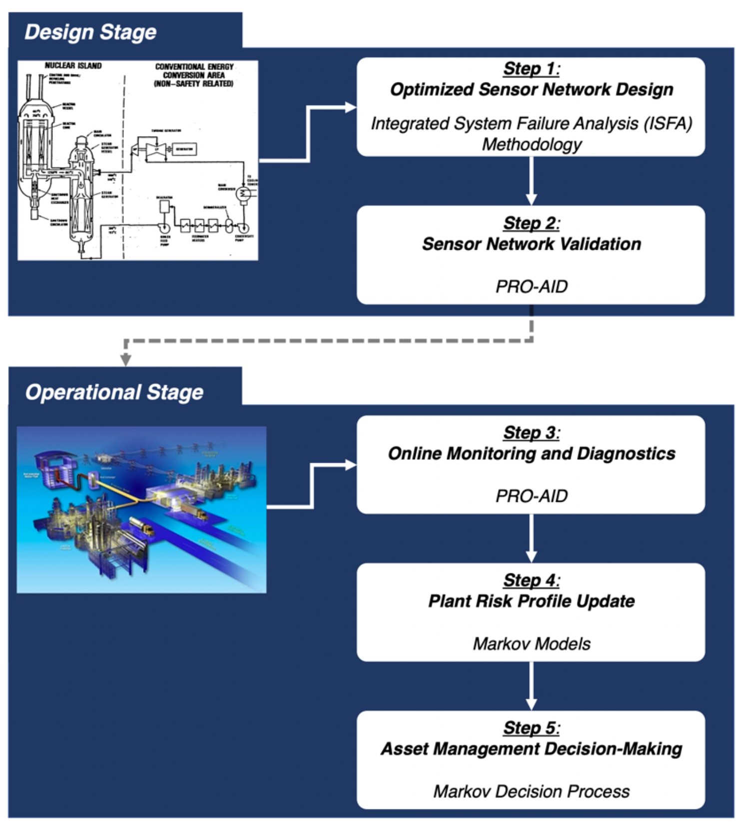
1. During the reactor design phase, it is necessary to develop a sensor network that can properly monitor and diagnose important faults and component degradation throughout the lifetime of the plant. To reduce cost, a methodology is developed that optimizes diagnostic capabilities while minimizing sensor 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. This is accomplished by developing a method to perform cost-benefit decision-making in multivariate space.

Impact and Value to Nuclear Applications: The project tasks aim to reduce advanced reactor costs during both 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: Recent efforts have focused on three major areas:

1. Expanding the capabilities of the Integrated System Failure Analysis (ISFA) approach for sensor network design optimization
2. Developing and testing a methodology for integrating the online diagnostic tool PRO-AID with the Markov component models within the plant probabilistic risk assessment (PRA) and generation risk assessment (GRA)
3. Identifying and preparing a suitable demonstration analysis of the developed project approach utilizing the General Atomics Modular High-Temperature Gas-Cooled Reactor (MHTGR)

Next steps include finalizing the asset management decision-making approach, completing the interfaces between tools, and beginning the demonstration analysis.



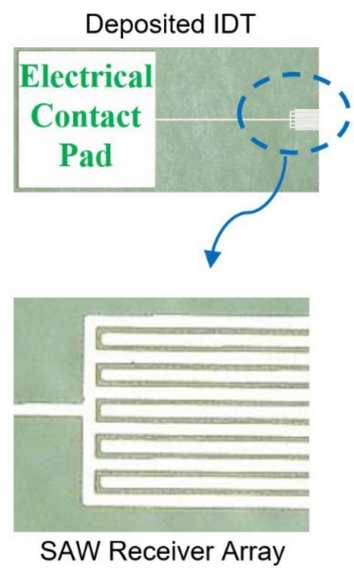
Integrated Project Approach and Methods

Acousto-Optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control

PI: Mike Larche – Pacific Northwest National Laboratory
Collaborators: Haifeng Zhang – University of North Texas
Funding: $1,000,000 (FY 2020-2022)

Project Description: Advanced reactor environments, such as moltensalt reactors, present a number of challenges for in-situ sensing including elevated temperatures, radiation, and infrequent outages.

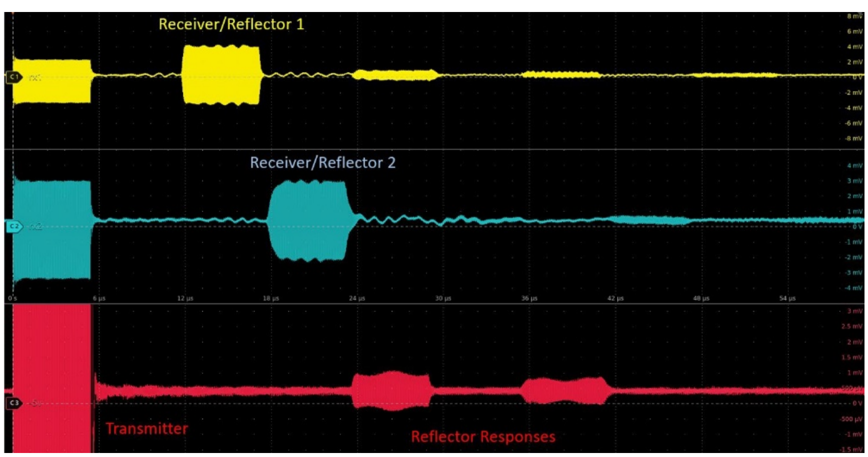
New sensors capable of operating in these harsh conditions are needed for monitoring critical parameters including temperature, flow,pressure, and fission gas composition, among other parameters. The Acousto-Optic Smart Multimodal Sensors project is developing an integrated sensor concept that enables simultaneous measurements of temperature, pressure, and gas composition using a single sensor platform, thereby limiting the number of penetrations in a reactor vessel that are needed. This sensor concept is based on the use of surface acoustic wave (SAW) devices, and uses acousto-optic coupling for high-sensitivity, high-reliability measurements in a challenging environment



Fabricate SAW Temperature

Impact and Value to Nuclear Applications: An integrated multimodal sensor platform will aid in the reduction of reactor pressure vessel penetrations. Appropriate materials selections consistent with high-temperature and harsh environments will also aid in filling gaps identified in available reactor monitoring and control sensors.

Recent Results and Highlights: Fabrication optimization efforts of low frequency temperature sensor continued, and preliminary testing is underway. One of the fabricated interdigital transducer (IDT) pairs is shown above and initial SAW data from this sensor shown below. Modeling work is continuing to investigate IDT designs, wave coupling, sensor optimization and wave mode interference.



Initial SAW Temperature Sensor Data

FY 2018 NEET-ASI Research Summaries

1. Analytics-at-scale of Sensor Data for Digital Monitoring in Nuclear Power Plants
    - Address a unique challenge in the area of digital monitoring (i.e., the application of advanced sensor technologies [particularly wireless sensor technologies] and data science-based analytic capabilities) to advance online monitoring and predictive maintenance in nuclear plants and improve plant performance.
2. Development of optical fiber-based gamma thermometer
    - Build an optical fiber-based gamma thermometer (OFBGT) and test it in two University Research Reactors (URRs) of different in-core configurations. Develop methods to process the data that is produced by OFBGTs to produce estimates of the power density in the volume of the reactor that surrounds the OFBGTs.
3. Process-Constrained Data Analytics for Sensor Assignment and Calibration
    - Develop and demonstrate data-analytic methods to address the problem how to assign a sensor set in a nuclear facility, or subsystem in the 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.

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

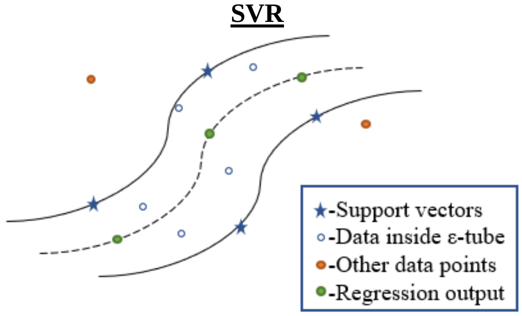
PI: Vivek Agarwal – Idaho National Laboratory
Collaborators: Cody Walker, Nancy Lybeck – Idaho National Laboratory
Pradeep Ramuhalli – Oak Ridge National Laboratory
Mike Taylor – Electric Power Research Institute
Geiger Charlotte – Exelon Generating Company
Funding: $1,000,000 (FY 2019-2022)

Project Description: This project seeks to develop and demonstrate a transformative and generalizable advanced online monitoring system to enable predictive maintenance 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 for use in equipment monitoring, (2) application of data-based models to diagnose and prognose faults using heterogenous data, (3) development of a visualization algorithm to present useful, actionable information to the relevant parties, (4) validation of developed approaches using independent data from an operating plant.

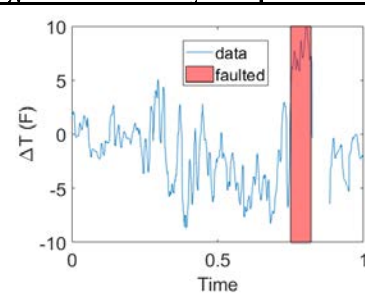
Impact and Value to Nuclear Applications: The project demonstrates how cost reduction associated with the nuclear industry's maintenance practices can be achieved. Recent research focused on diagnostics, prognostics, and preventative maintenance optimization to enable a shift from time-consuming and cost-prohibitive preventative maintenance strategy to a predictive maintenance strategy through the advances in machine-learning technologies.

Recent Results and Highlights: Data-based diagnostic models utilized temperature as a feature to identify faults within the condensate and feedwater system, and work orders data as confirmation. Support vector regression (SVR) and long short-term memory (LSTM) networks were used for short-term (ranging from 1 hour to 1 day) forecasting of component signals. The plots below were anonymized.

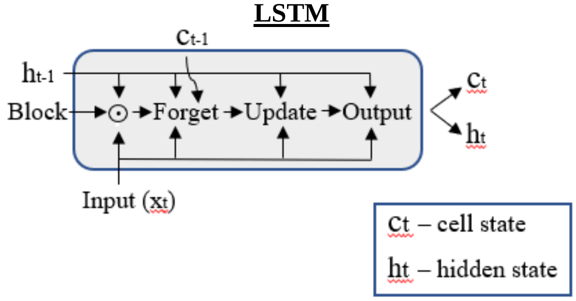
SVR



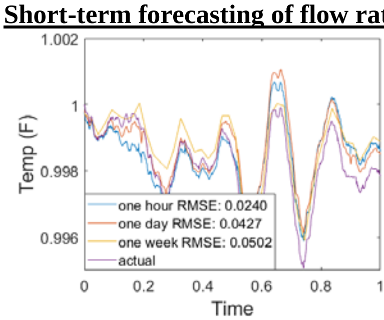
Diagnostics: Identify component failure



LSTM



Short-term forecasting of flow rate



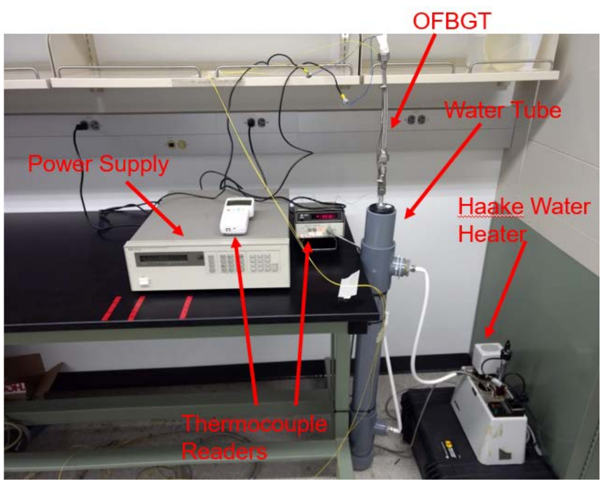
Development of an Optical Fiber Based Gamma Thermometer

PI: Thomas Blue – The Ohio State University
Collaborators: Pavel Tsvetkov – Texas A&M University
Diego Mandelli – Idaho National Laboratory
Funding: $987,730.00 (FY 2019-2022)

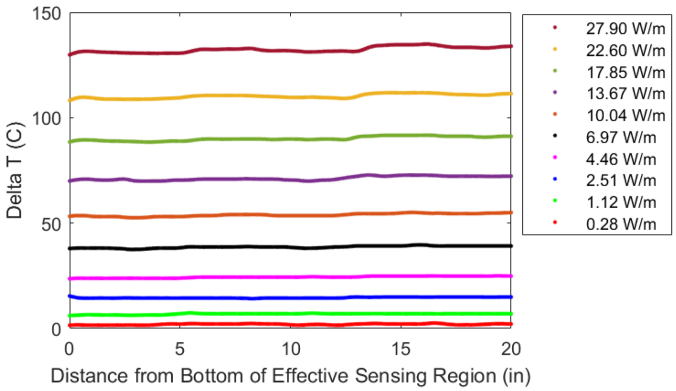
Project Description: The objective of this project is to develop an optical fiber-based gamma thermometer (OFBGT). A system of OFBGTs could be used to calibrate the power monitors in reactors. Also, utilizing data analytics, a system of OFBGTs could be used to determine the power distribution in a reactor 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 an 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

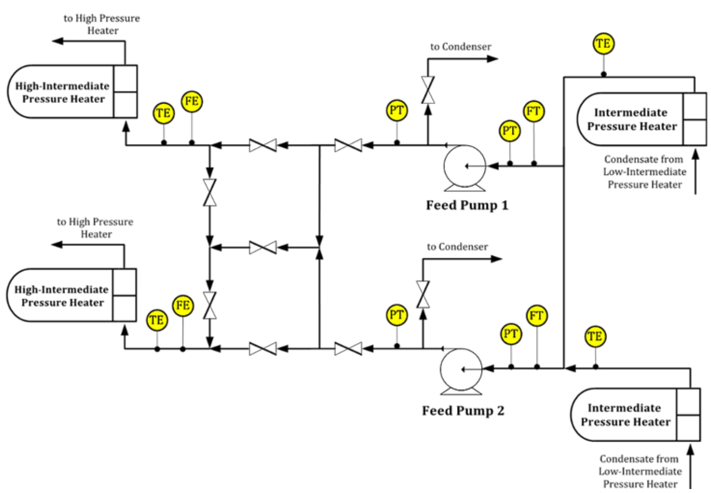
Process-Constrained Data Analytics for Sensor Assignment and Calibration

PI: Richard B. Vilim, Alexander Heifetz – Argonne National Laboratory;
Brendan Kochunas – University of Michigan;
Marc Anderson – Xcel Energy
Funding: $1,000,000 (FY 2019-2022)

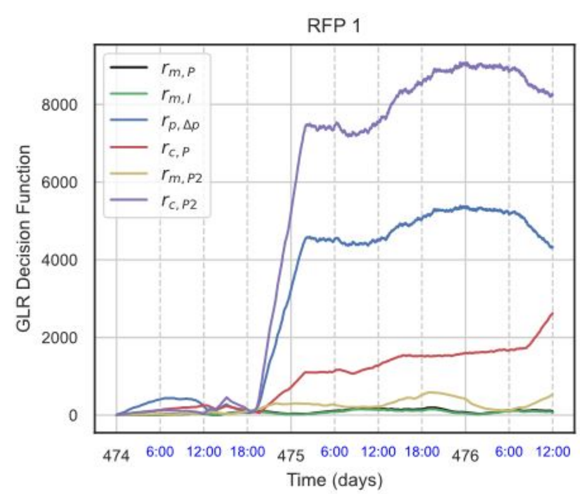
Project Description: Data analytic methods are being developed to address the problem of how to assign a sensor set in a nuclear facility such that a requisite level of process monitoring capability is realized and that the sensor set is sufficiently rich to determine the status of the individual sensors with respect to need for calibration. There is an awareness in the nuclear industry that data analytics combined with rich sensor sets represent a means to improve operations and reduce costs.

Impact and Value to Nuclear Applications: In the industry the calibration problem has been previously approached as an empirical data-driven problem with several methods having been developed. However, the experience of the utilities over the past 10 years with these methods indicate that the absence of physics-based information renders the data-driven approach less reliable. Complicating factors, such as the inherent variability of operation (both equipment alignment and operating condition), can confound a pure data-driven approach while there are no rigorous guidelines for determining what constitutes an adequate sensor set.

Recent Results and Highlights: The method developed under this award was applied to the diagnosis of equipment degradation in the feedwater pump system of an operating nuclear power plant. Data were provided by the collaborating utility without disclosing either the presence of, or the identity of the fault. So-called “blind” diagnostic analyses were conducted for five different equipment and sensor faults and all were correctly diagnosed. Pump-motor performance degradation of less than a 1% decrease in efficiency can be reliably detected and diagnosed. Furthermore, results obtained for the plant operating in flexible power mode showed that changes in operating conditions over the 50–100% power range do not have significant effects on the performance of the diagnostic algorithm. This represents an improvement compared to the data-driven methods that are the de facto standard in the nuclear power industry and indicates success in addressing one of the issues that gave rise to this work.



Reactor feedwater pump system belonging to collaborating nuclear power utility



Decision function diagnosis of fault in feedwater pump system

FY 2017 NEET–ASI Research Summaries

1. High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems
    - Develop high temperature embedded/integrated sensors (HiTEIS) and laser ultrasound transducers for remote monitoring of reactors and fuel cycle systems.
2. Integrated Silicon/Chalcogenide Glass Hybrid Plasmonic Sensor for Monitoring of Temperature in Nuclear Facilities
    - Focused on the research and development of a new in-situ, reusable, and reversible sensor concept for integrated temperature monitoring applying combination of photonic properties of radiation-hardened waveguides and temperature progress of the properties of chalcogenide glasses (ChG), specifically their crystallization.
3. Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring
    - Develop an acoustic-based sensing system that will be able to monitor phenomena such as strain, temperature, pressure, and material corrosion in real-time to better evaluate the aging and degradation of relevant structural components in nuclear facilities.

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

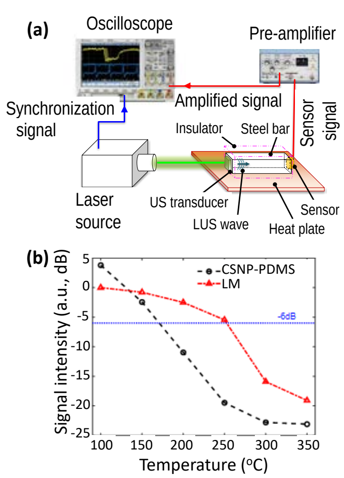
PI: Xiaoning Jiang – North Carolina State University
Collaborators: Mohamed Bourham, Mo-Yuen Chow – North Carolina State University
Funding: $999,688 (FY 2018–2021)

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.

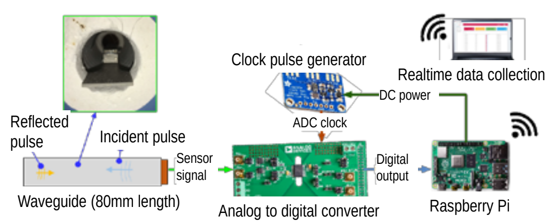
Impact and Value to Nuclear Applications: The development of HiTEIS will enable non-invasive sensing of operation status of NPPs. Remote communication system will aid to monitor a system in an NPP more frequently in reliable manner and minimize the need for human operators to be available in the vicinity 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. Meanwhile, sensor embedding methods are being studied by using a high-speed (~10 MHz) wireless communication system for transferring of ultrasound wave signals. 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.

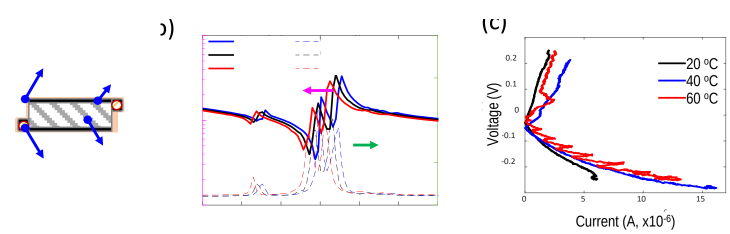
Images/graphs/charts:



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



Wireless data transfer system for HT ultrasound sensing.



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

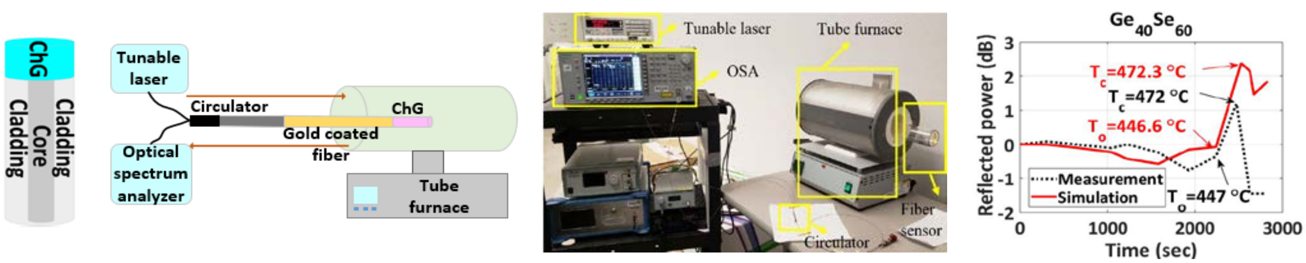
Integrated Silicon/Chalcogenide Glass Hybrid Plasmonic Sensor for Monitoring of Temperature in Nuclear Facilities

Maria Mitkova, Harish Subbaraman – Boise State University
Isabella Van Rooyen – Idaho National Laboratory
Funding $890,000 (FY 2018–2021)

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 on the fiber tip. A schematic and performance of this sensor are presented below.



(a) (b) (c) (d)

a) Cross-section of chalcogenide glass ink tip-coated fiber of an optical sensor; b) Schematic of setup for testing the temperature performance of sensors; c) Photo of the device characterization setup; d) Comparison of simulated (the red line) and measured temperature (the dotted line) sensing of the fabricated device.

The sensor consists of single-mode fiber capped with a ChG coating on the end facet. The performance of this structure is simulated in PhotonDesign (FIMMWAVE, FIMMPROP) software. For example, $Ge_{40}Se_{60}$ ink is selected to cover the gold–coated (Fiberguide AFS50/125/155G) fiber tip. When the temperature is below the ChG's crystallization temperature, the material behaves as a dielectric with low absorption and low reflection at the interface of fiber and ChG. At temperature beyond crystallization temperature ($T > T_c$) the crystallized material acts like metal. Then, most of the light is reflected into the fiber. At a well-defined temperature (T_c), the abrupt changes in reflected power occur providing information about ambient temperature. The sensor is fabricated, and the heat response of ChG coating is measured as a function of time. The sudden change in measured reflected power is observed at the crystalline temperature of $Ge_{40}Se_{60}$ (T_c= 472.3°C). There is a good agreement between the simulated and measured data.

In FY2021 waveguides based devices will be studied. Studies under irradiation will be performed to establish materials' and devices' radiation hardness and operation stability.

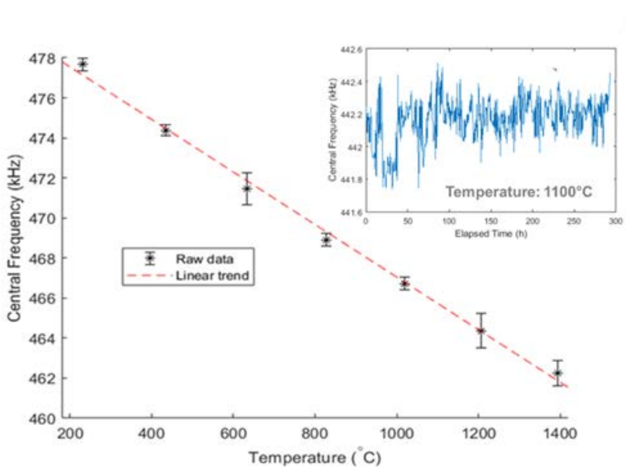
Versatile Acoustic and Optical Sensing Platforms for Passive Structural Systems Monitoring

PI(s): Gary Pickrell and Anbo Wang – Virginia Tech
Collaborators: Alexander Braatz – Oak Ridge National Laboratory; Brian Risch – Prysmian Group
Funding: $1,000,000 (FY 2018–2021)

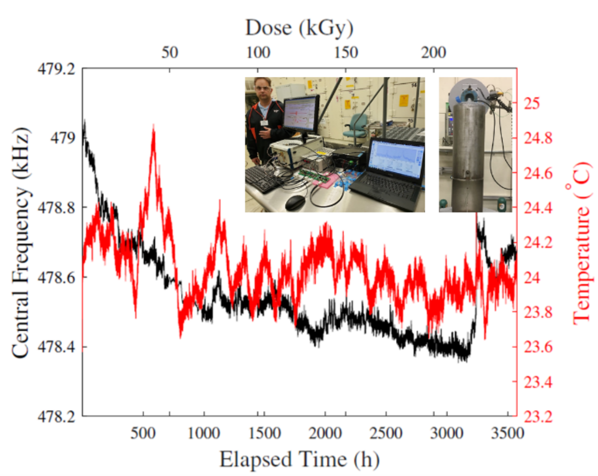
Project Description: The objective of this research program is to develop an acoustic-based sensing system that will be able to monitor phenomena such as temperature, pressure, and material corrosion in real time to better evaluate the aging and degradation of relevant structural components in nuclear facilities. A distributed acoustic fiber Bragg grating (AFBG)-based sensing system capable of simultaneous multi-parameter sensing will be designed and constructed with sensors made from proven radiation tolerant fused silica and single crystal sapphire fibers. Laboratory testing of prototype systems will be performed and benchmarked against commercially available fiber optic sensors.

Impact and Value to Nuclear Applications: The paramount importance of structural health monitoring in nuclear power plants has generated an intense interest in fiber-optic sensing technologies, but challenges remain prevalent with respect to reliability and cost. The AFBG technology will provide a first-of-its-kind sensing platform that will fill the gap between low-cost electronic sensors and high-performance fiber-optic sensors. The advanced monitoring system will be capable of fully distributed sensing of selected parameters in most harsh nuclear environments.

Recent Results and Highlights: A prototype all-single crystal sapphire acoustic fiber Bragg grating (AFBG) temperature sensing system was fully-integrated and performance tested to a temperature of 1400°C (see figure on the left). The prototype single crystal sapphire and fused silica AFBG sensing systems operated continuously for over 2300 hours and 3550 hours, respectively, in the gamma irradiator at Oak Ridge National Laboratory (see figure on the right). The single crystal sapphire and fused silica sensors exhibited excellent long-term stability upon exposure to gamma radiation and elevated temperatures (1100°C and 700°C, respectively). Emerging from early-stage research, the AFBG sensing platform has the potential to provide end users with a cost-effective alternative to fiber optic sensors without compromising performance.



Temperature response of a single crystal sapphire AFBG up to 1400°C. (insert) Long term sensor stability at 1100°C.



The AFBG central frequency over time upon gamma radiation exposure at ORNL testing facilities.

COMPLETED PROJECTS

Projects listed below have been completed and summaries can be found in previous ASI Award Summaries available on the DOE/NE Website: https://www.energy.gov/ne/advanced-sensors-and-instrumentation-asi-program-documents-resources

FY 2017

- 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)

FY 2016

- Self-powered Wireless Through-wall Data Communication for Nuclear Environments, Virginia Tech, $1,000,000 (10/01/2016–9/30/2020)
- 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 (10/1/2016–7/31/2020)

FY 2015

- 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)

FY 2014

- 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 (10/1/2014–09/30/2017)
- High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle Systems, University of Pittsburg, $987,676 (10/01/2014–09/30/2017)

FY 2013

- 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)

FY 2012

- 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)

FY 2011

- A High Temperature-tolerant and Radiation-resistant In-core Neutron Sensor for Advanced Reactors, The Ohio State University, $455,629 (9/29/2011–9/30/2014)
- 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 (9/29/2011–9/30/2014)

Fiscal Year Details

Below is a summary of the research by fiscal year (FY).

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.

In FY 2012, 10 projects 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.

In FY 2013, three 2-year projects totaling $1,199,664, were awarded competitively in the area of designing custom radiation-tolerant electronics systems and methods to quantify software dependability. These projects were completed in 2015.

In FY 2014, six 3-year projects totaling $5,963,480, were awarded competitively in the areas of advanced sensors, communications, and digital monitoring and controls.

In FY 2015, two 3-year projects totaling $1,979,000, were awarded competitively in the area of digital monitoring and controls.

In FY 2016, three 3-year projects totaling $2,986,535, were awarded competitively in the area of nuclear plant communication.

In FY 2017, four 3-year projects totaling $3,888,688, were awarded competitively in the area of advanced sensors. Additionally, the ASI program funded directed research I2 activities for a total of $5,000,000. These activities were focused on the Sensors and Instrumentation technical area.

In FY 2018, five 3-year projects totaling $5,000,000, were awarded competitively in the area of sensors, big data analytics, and application of additive manufacturing. The program also funded a 2-year project totaling $1,500,000 to advance in printed sensor capability. Additionally, direct funded research was continued under I2 for a total of $5,300,000.

In FY 2019, five 3-year projects totaling $4,500,000, were awarded competitively in the area of sensors, digital monitoring, and nuclear plant communication. Additionally, direct funding research was continued under I2 for a total of $5,500,000.

In FY 2020, two 3-year projects totaling $2,000,000, were awarded competitively in the area of advanced sensors and digital monitoring and control. Additionally, 17 directed projects were funded to continue work under I2 for a total of $4,500,000 and one new project on risk-informed predictive analytics funding in the amount of $300,000.

In FY 2021, 15 directed projects were funded to continue work for a total of $4,785,379.