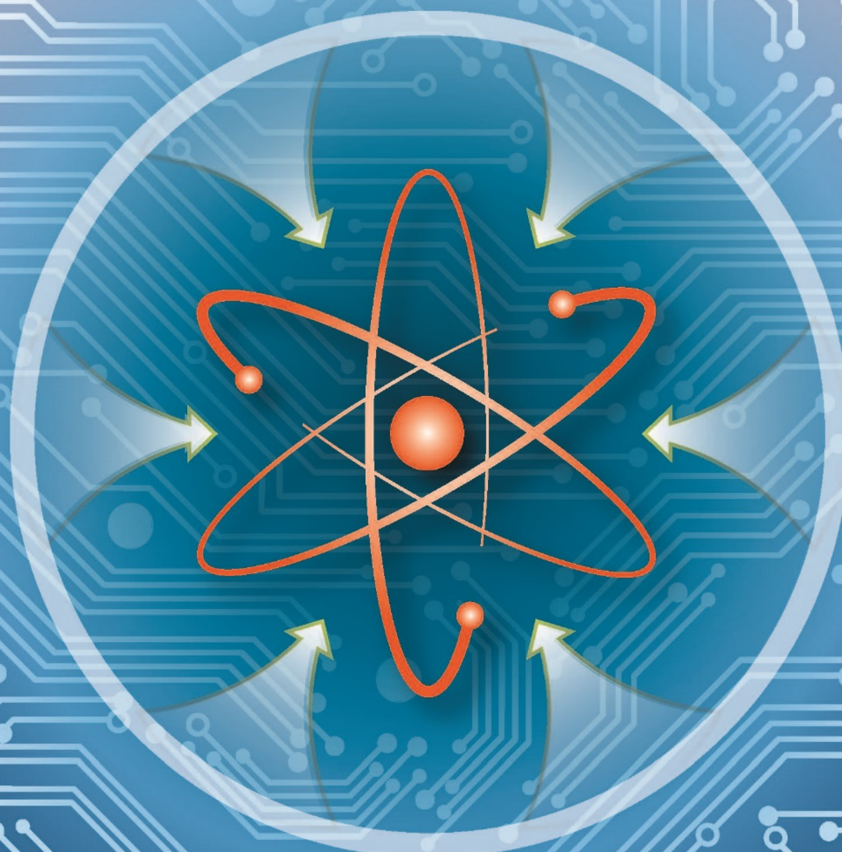
Office of Nuclear Energy

Advanced Sensors and Instrumentation Award Summaries



Nuclear Energy Enabling Technologies - Advanced Sensors and Instrumentation

June 2019

INTRODUCTION

Researchers are working to perfect measurement science to better understand existing and advanced reactors, and to support fuel cycle development. Since 2012, Nuclear Energy Enabling Technologies (NEET) has spurred innovation in the measurement science field by funding research on sensors, instruments, and controls that measure system parameters, gauge component control input, and provide power plant owners and operators critical awareness so they can plan and safely manage operational evolutions.

These systems can be referred to as the “nervous system” of nuclear power plants and other nuclear system applications. They monitor all aspects of a plant’s behavior and communicate information to plant operators for a timely response to many foreseeable conditions. They also serve a vital role in Materials Test Reactors 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.

Data from various sources in a nuclear power plant can be integrated and analyzed to develop models using advanced machine learning and artificial intelligence techniques to enable semi-automation for operation and maintenance of plant and fuel cycle systems.

In 2012, the Department of Energy’s Office of Nuclear Energy (DOE-NE) initiated the NEET Crosscutting Technology Development (CTD) Program to conduct research, development, and demonstration (RD&D) in crosscutting technologies that directly support and enable the development of new and advanced reactor designs and fuel cycle technologies.

Advanced Sensors and Instrumentation (ASI) is one program element of NEET CTD being carried out to foster the research and development required to develop and deploy innovative and advanced sensors, instrumentation, and control capabilities for current and future nuclear energy systems. ASI research aims to enable the advanced technologies essential to NE’s research and development (R&D) mission goals.

MISSION
Develop advanced sensors and instrumentation that address critical technology gaps for monitoring and controlling existing and advanced reactors, and supporting fuel cycle development

VISION
NEET ASI research results in advanced sensors and I&C technologies that are qualified, validated, and ready to be adopted by the nuclear industry

ROLES
The NEET ASI Program has the following roles:

- Coordinate sensors and instrumentation research among NE programs to avoid duplication;
- 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 into NE’s R&D programs and then into commercialization.

RESEARCH AREAS

The NEET ASI program has identified four crosscutting research areas (Figure 1) representing key capabilities for nuclear energy systems and fuel cycle facilities, in response to stakeholders' needs.

These research areas are:

Sensors and Instrumentation. Research, qualify, and develop reliable and cost-effective 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.

Advanced Control Systems. Research and develop control algorithms to enable near real-time control of plant or experimentation process variables to enhance plant reliability, availability, thermal performance, and resilience.

Communication. Research and develop resilient communication technologies to enable real-time transmission of sufficient data for online monitoring and advanced data analytics.

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.

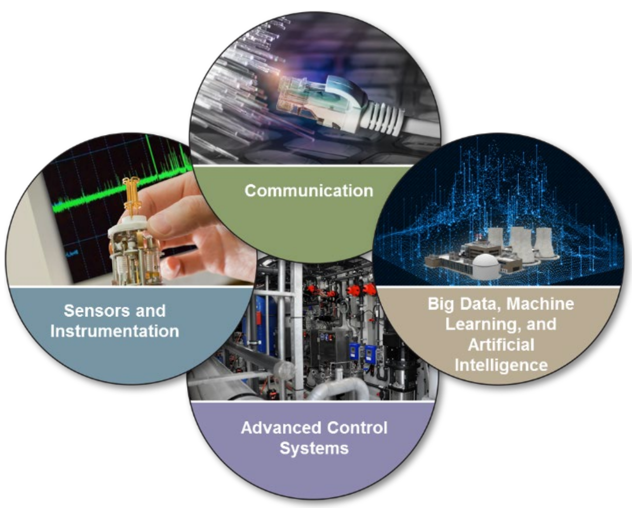


Figure 1. NEET ASI research areas.

As the stakeholders' needs evolve, new ASI strategic research areas may be added or modified.

FUNDING

In fiscal year (FY) 2011, before the 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.

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. Additionally, three 2-year projects totaling $2,475,000, were direct funded in the area of data analytics and printed sensor capability in collaboration with nuclear utilities

Since FY 2011, NEET-ASI has funded 36 projects competitively for a total of $30,006,253.

These projects are successfully advancing the state of the art for measuring, controlling, and broadly managing nuclear energy systems being developed by the DOE-NE. 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 and the nuclear energy industry. As these research projects progress, the interest from stakeholders and industry has also increased, as have the number of individual technology deployments and partnerships.

FY 2015 NEET-ASI Research Summaries

In FY 2015, the NEET-ASI program selected two 2-year projects under the following solicited topic:

Digital technology qualification demonstration for embedded digital devices:

An embedded digital device is an electronic sub-component of a plant component (e.g., instrument or circuit breaker) which uses software or software-developed logic for some aspect of its operation. The qualification method will demonstrate a cost-effective means of ensuring that the device is not subject to software common cause failure. The selected digital equipment shall be for multiple reactors or fuel cycle applications, i.e., crosscutting, include a nuclear industry partner, and the research products shall address the following technical challenges:

· Proof of acceptable software operational reliability;

· Comprehensive non-destructive testability;

· U.S. NRC regulatory requirements;

· Ability to detect defects introduced through the entire supply chain;

· Ability to qualify commercial-grade devices dedicated for safety-related usage; and

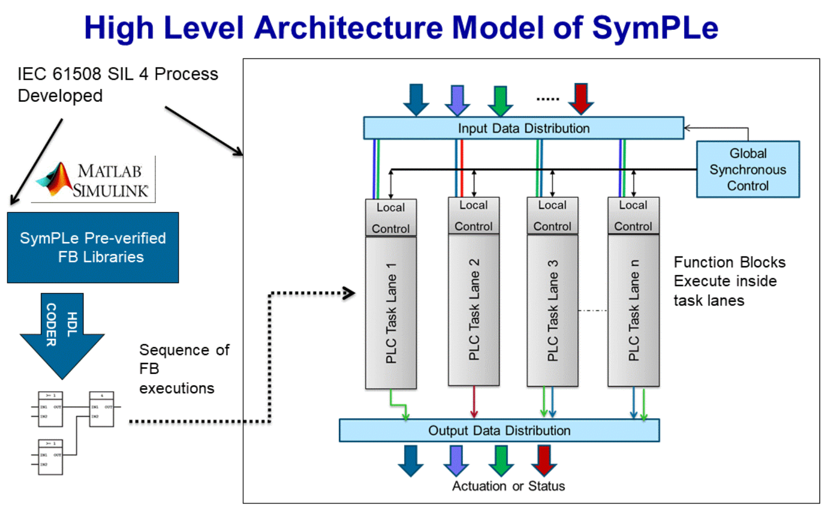
· Cost-effective and broadly applicable to multiple small plant component.

Nuclear Qualification Demonstration of a Cost Effective Common Cause Failure Mitigation in Embedded Digital Devices

Matt Gibson, Electric Power Research Institute
Dr. Carl Elks, Virginia Commonwealth University
Funding: $991,000 (10/01/2015–06/30/2019)

Project Description: This project explores an alternative approach to mitigating the unpredictable nature of software faults in safety-related instrumentation and control (I&C) systems. Many of these faults are due to the unbounded and general-purpose nature of Von-Neumann architecture CPUs commonly used in these devices. Our approach will identify and develop constrained embedded digital components that can be shown to contain no additional capabilities or characteristics other than those specially required to meet functional objectives. These verifiable and deterministic devices should have no hidden fabrication or infrastructure to complicate straightforward analysis and validation. Configurable hardware logic will be used to investigate state-driven architectures that achieve determinism by eliminating software constructs, allowing formal tools to create a high-fidelity verification.

Impact and Value to Nuclear Applications: Successful demonstration of an alternative architecture will allow deployment of deterministically-verified systems in nuclear and other safety-related applications at a fraction of the current total installed cost, and with less technical and regulatory risk. This project will also improve the understanding of constrained architectures and their use in safety and business critical applications.



Recent Results and Highlights: The project is nearing completion with final milestones concluded and final report preparation underway. The research team has successfully developed and demonstrated a hardware-based sequencer architecture that can execute deterministic hardware function blocks that replicate IEC-61131 function block constructs directly in hardware via a Hardware-in-the-Loop simulation. Called SymPle, this architecture can be reconfigured for applications while retaining formal verifiability. The team utilized a National Instruments cRIO with a Xilinx Kintex FPGA fabric to host SymPLe via a side-load. We evaluated the architecture for compliance with IEC-61508, "Functional Safety," and added self-checking and diagnostic features that add resistance to random failures, complementing the architecture's intrinsic resistance to systematic failures. While an FPGA environment will be used for prototyping, other construction modes can be used as well, such as ASICs (application specific integrated circuit) and full custom silicon. The project also developed design and verification methodologies using model-based engineering to establish the constrained and verifiable design. The architecture was developed and formally verified using off-the-shelf tools including MathWorks and Simulink Design Verifier. Additional work allowed the prototype to be the target of a mock Commercial Grade Dedication using IEC 61508 criteria. This will give insight into how a commercialized SymPle processor would be provisioned under current U.S. regulation. It will also demonstrate how the architecture may achieve a Safety Integrity Level rating under IEC-61508 to support a modernized, risk-based regulatory environment. Additional funding support will be pursued for a Phase II effort that will further develop the architecture and methods for cyber security and supply chain applications.

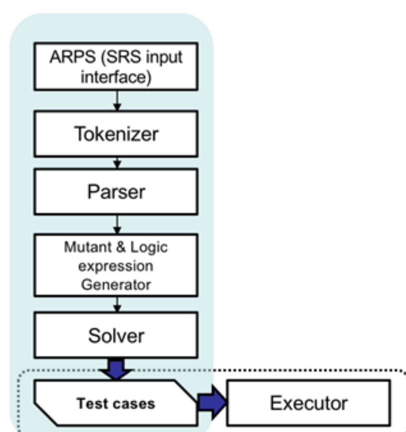
Development of Model Based Assessment Process for Qualification of Embedded Digital Devices in NPP Applications

Richard Wood, The University of Tennessee,
Carl Elks, Virginia Commonwealth University
Brent Shumaker and Hash Hashemian, Analysis and Measurement Services Corporation
Carol Smidts, The Ohio State University
Funding: $988,000 (10/01/2015–09/30/2018)

Description of Project: This project involves development and demonstration of a systematic approach to assess whether instrumentation with an embedded digital device is subject to software common-cause failure (CCF). The research advances the state of the art for qualification of digital devices by (1) developing novel methods to demonstrate proof of operational reliability, (2) applying developed methods to representative equipment with an embedded digital device (EDD) to ascertain the effectiveness of the methodology, and (3) establishing a cost-effective qualification framework compliant to existing guidance and standards. An essential element of the qualification approach is a model-based testing (MBT) methodology.

Impact and Value to Nuclear Applications: Application of advanced instrumentation is constrained by nuclear regulatory concerns about CCF in embedded digital devices. Without development of cost-effective qualification methods to satisfy regulatory requirements and that address the potential for CCF vulnerability associated with EDDs, the nuclear power industry may not be able to realize the benefits of digital technology achieved by other industries. The research develops an approach to ensure that qualification testing addresses the range of postulated systematic faults by establishing science-based evidence for fault coverage by the test suite. Through the successful demonstration of this qualification methodology, we can eliminate impediments to advanced technology use for all reactor types.

Recent Results and Highlights: The primary research outcome is development and demonstration of an MBT approach based in an extended mutation testing method. The objective of this MBT approach is to define a suite of qualification tests that can detect instances (or mutants) corresponding to each postulated fault. Recent accomplishments include incorporation of automation within the MBT framework and an experiment demonstrating the capabilities of MBT. The Automated Mutation Testing Tool (AMuTT) automates test case generation. Additionally, AMuTT incorporates the Automated Reliability Prediction System (ARPS) as its interface module for automated requirements and design input processing. The figure illustrates the AMuTT structure for addressing faults in the Software Requirements Specification (SRS). Demonstrating the methodology involves experimental application in which versions of a representative smart sensor with seeded faults undergo MBT and black-box baseline testing. Both methods proved capable of detecting faults at the code level, but MBT gives more direct evidence of fault coverage. It also provides greater detail about the nature of coding faults detected while enabling treatment of faults in requirements and design documentation. This experiment confirms the anticipated benefits of MBT.



Structure for MBT requirements module.

FY 2016 NEET-ASI Research Summaries

In FY 2016, the NEET-ASI program selected three 3-year projects under the following solicited topic:

Advanced Communication Technology to develop and demonstrate robust methods for transmitting signals and data in a nuclear environment. The selected technology should be applicable to multiple reactors or fuel cycle applications, i.e., crosscutting.

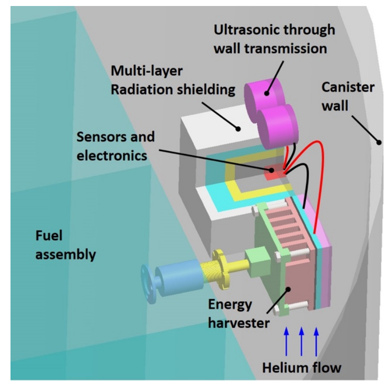
Research objectives:

- Develop and demonstrate the ability to transmit greater amounts of data and other signals through physical boundaries in nuclear facilities;
- Address new communication demands needed for advanced measurement and control technologies including protection of data;
- Take into consideration the environment and the conditions under regular operation and/or accident scenario;
- Test and validate prototype through demonstration in appropriate representative environment.

Self-Powered Wireless Through-Wall Data Communication for Nuclear Environments

Lei Zuo (PI), Yongjia Wu, Dong Ha, Virginia Tech
Haifeng Zhang, University of North Texas
Roger Kisner, Nance Ericson, Kyle Reed, Oak Ridge National Laboratory
Michael D. Heibel, Westinghouse Electric Company
Funding: $1,000,000 (10/01/2016–9/30/2019)

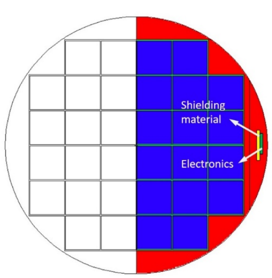
Description of Project: Monitoring temperature, pressure, radiation, humidity, and other parameters inside enclosed fuel storage vessels is crucial to ensure reactor safe operation and fuel security. However, the physical containment vessels, which are constructed of metal and concrete, present huge challenges to sensor data communications, due to the shielding of radio-frequency signals and lack of vessel wiring feedthroughs for power supplies and communications. To combat these challenges, researchers will develop and demonstrate an enabling technology for the data communications for nuclear reactors and fuel cycle facilities using radiation and thermal energy harvesters, through-wall ultrasound communications, and harsh environment electronics. The project will develop and demonstrate a robust, self-powered method enabling data communications through containment structures common in harsh nuclear environments, including spent fuel rod storage and monitoring.



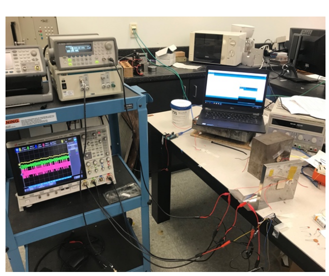
Energy harvester for powering sensing and communications.

Impact and value to Nuclear Applications: The expected impact and benefits of this technology include: (1) harvesting sufficient energy from the radiation and thermal environment in the spent fuel canister for long-term electronics powering, (2) validating the proposed advanced wireless communications through thick metal barriers as required in nuclear environments, and (3) developing and demonstrating an architecture for sensor data communication in nuclear environments, including a path forward for radiation and temperature hardening.

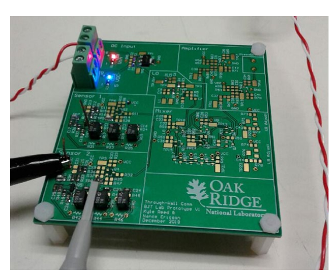
Recent Results and Highlights: In this phase, (1) the shielding performance of the W-B4C was examined using the MCNP6 simulation tool. W-B4C was identified as the material of choice where tungsten and boron were incorporated into the material for gamma and neutron shielding, respectively. (2) As a breakthrough, we experimentally demonstrated the ultrasonic TEXT communication in temperatures up to 120 °C using the one-to-one transducer configuration communication method. (3) Circuit modeling and simulation of the TRS BT200 piezoelectric transducer were completed, a 2-sensor electronics system was designed and prototyped as both a BJT- and JFET-based design using minimal active devices, and laboratory testing was performed to demonstrate correct functionality, including the ability to drive the piezo transducers.



MNCP6 model to test the radiation shielding performance.



The experimental setup demonstrating data communication through steel enclosure material.



The electronics system PCB (partially populated) used to collect sensor signals and drive the through-wall communications.

Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities

Richard B. Vilim, Alexander Heifetz, Argonne National Laboratory
Funding: $1,000,000 (10/01/2016—09/30/2019)

Description of Project: Information transmission using guided elastic waves on existing metal pipes provides an alternative communication option for nuclear facilities. The advantages of this approach include the ability to transmit information through barriers, such as the containment building wall. Furthermore, information sent over this system would only be accessible through direct physical contact with the pipes, establishing a protective layer against unauthorized eavesdroppers. A viable candidate for acoustic communication channel is a chemical volume control system stainless steel pipe, which penetrates through the containment building wall through a sealed tunnel in concrete.

Impact and Value to Nuclear Applications: Integrating advanced communication technologies into nuclear facility operation could enhance the safety and efficiency of the existing fleet of aging light water reactors, as well those of future advanced reactors.

Recent Results and Highlights: Researchers used high-temperature shear wave 700KHz $LiNbO_3$ acoustic transducers, originally developed for flow metering applications of the EBR-II reactor at Argonne, to implement a high-temperature acoustic communication system. Heating tapes, temperature controllers, and thermal insulation were installed on the laboratory stainless steel schedule 160 pipe to study acoustic communication at elevated temperature (see Figure 1). We developed and implemented the amplitude shift keying communication protocol using GNURadio software defined radio environment, and demonstrated of communication at high temperatures, including transmission of images and text files (see Figure 2). Our main achievements included transmission of 90KB ANL logo image at the bitrate of 10Kbps with bit error rate smaller than 10^{-3} across six-feet long pipe heated to 150^{o}C.

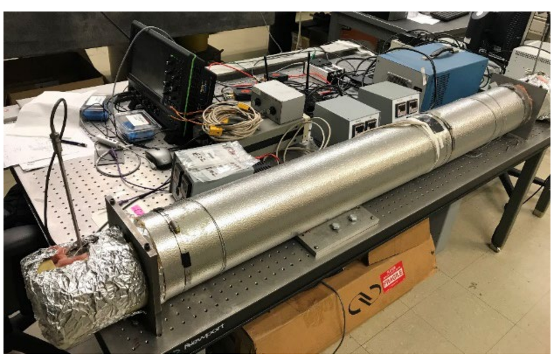


Figure 1. Laboratory setup for acoustic communication at elevated temperature using $LiNbO_3$ transducers

Figure 2. GNURadio screen capture of an image file used in data transmission demonstration

Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply

Jorge Carvajal, Michael Heibel, Westinghouse Electric Company
Dr. Kenan Unlu, Pennsylvania State University Radiation Science and Engineering Center
Funding: $986,535 (10/1/2016 – 9/30/2019)

Project Description: The project will develop the technology necessary for a wireless reactor power distribution measurement system. The system utilizes highly radiation- and temperature-resistant vacuum micro-electronics (VME) technology that continuously broadcasts self-powered detector signals and reactor coolant temperature sensor signal measurements to a receiving antenna. We will evaluate the temperature and radiation sensitivity performance of the VME device, which is the key component of the system, as well as the supporting passive components of the circuit. The project will also include the design, construction, and testing of the gamma radiation harvesting power supply.

Impact and Value to Nuclear Applications: Power distribution measurements currently utilize self-powered neutron detectors located axially within approximately 33% of the fuel assemblies. The proposed project would enable 100% of fuel assemblies to be instrumented by placing a VME wireless transmitter in each assembly's top nozzle. We expect this technology to enable plant operators to increase reactor operating margin due to improved knowledge of fuel usage. Another benefit of the gamma-powered VME wireless transmitters is that they provide a means to generate the required state variable measurements without the need for more cabling or additional penetrations in the reactor coolant system boundary.

Recent Results and Highlights: Since the Westinghouse VME system has been shown to effectively relate self-powered detector current to reactor power, we incorporated a real-time sensing system into an experimental closed-loop control system as further proof of principle. Figure 1 shows the Penn State Experimental Control Rod Drive mechanism that was used in conjunction with the VME setup to effectively control the reactor power in real time. By incorporating compensation for the detector delay, the Westinghouse VME-based system, as an integral part of an experimental closed loop feedback controller, was effective in providing a detector signal for use in a real time reactor control system. Figure 2 shows the raw detector signal in blue and the analog compensated signal in black, which matches the controller set point in red.

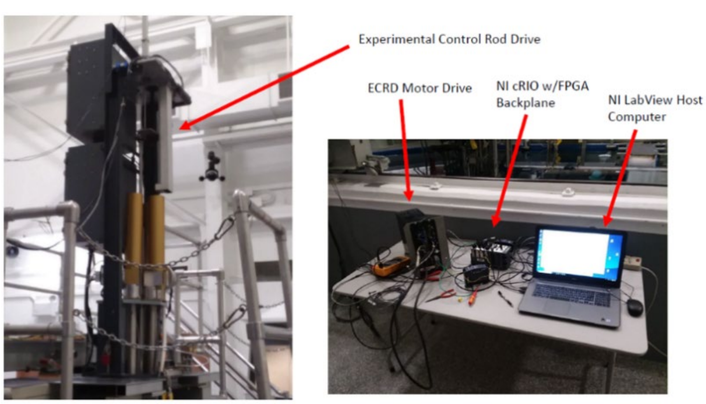


Figure 1: ECRD

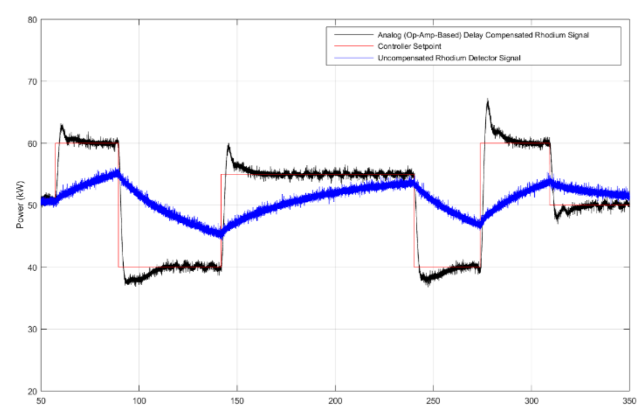


Figure 2: Analog delay compensation

FY 2017 NEET-ASI Research Summaries

In FY 2017, the NEET-ASI program selected four 3-year projects under the following solicited topic:

1. **Embedded / Integrated sensors in components and functional materials**
   Proposals are sought that develop and demonstrate the capability for embedding or integrating sensors into components or functional materials as a part of the integral design of a functional component or device. The goal of embedded and integrated design is to improve system performance by removing control loops that add data transmission, processing, and actuation time to current process control approaches in monitoring and controlling a component or system. The purpose of embedding and integrating sensors and control components is to demonstrate improved performance and reliability. Successful application of research to an application will require testing and demonstration, including a description of system metrics that are targeted through sensor and control integration / embedding, and resulting anticipated system performance improvements.

2. **3-D sensor networks for passive structural system monitoring of critical materials in nuclear energy systems**
   Passive structures, systems, and components constitute a vital aspect of nuclear energy system structural integrity and are key to the safe operation of these systems. Critical materials in nuclear energy systems include concrete that serve as structural support and primary containment of nuclear materials, metals that serve as pressure boundaries, cable insulation, spent fuel storage cask media, and others that are vital and pervasive and will continue to be so in commercial nuclear energy systems. Monitoring structural materials is a key aspect of the safe operation of nuclear facilities. Proposals are sought for 3-D sensor networks for monitoring passive structural systems with an emphasis on monitoring critical material performance of those systems. This includes the ability to collect data from these materials that are relevant to the performance of those materials over time, that relate to the major performance attributes of interest, the known modes of aging and degradation, and include diagnostic and prognostic models of material behavior in target environments of interest. Successful applicants must be capable of demonstrating a 3-D sensor network in a representative target environment of interest during the performance period of the project and demonstrate data collection, diagnostics, and prognostics within the stated goals and objectives of the project.

Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring

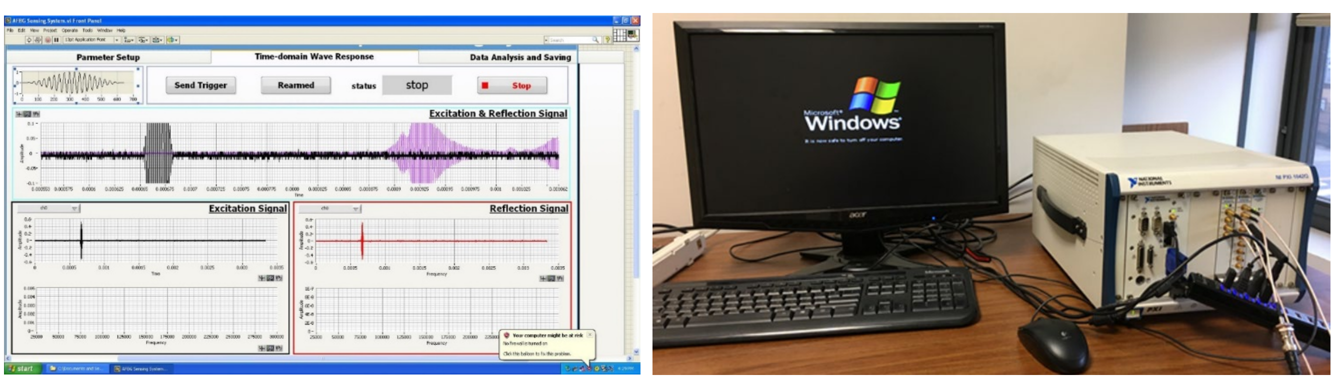
Gary Pickrell and Anbo Wang, Virginia Tech
Alexander Braatz, Oak Ridge National Laboratory
Brian Risch, Prysmian Group
Funding: $1,000,000 (10/01/2017—09/31/2020)

Description of Project: The objective of this research program is to 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. We will design and construct a distributed acoustic fiber Bragg grating (AFBG)-based sensing system capable of simultaneous multiparameter sensing 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.

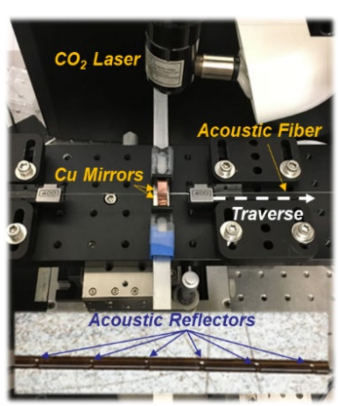
Impact and Value to Nuclear Applications: The paramount importance of structural health monitoring in nuclear power plants has generated an intense interest in fiber optic sensing technologies, but challenges remain, especially with respect to reliability and cost. The AFBG technology will provide a 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 low-cost and capable of fully distributed and multi-parameter sensing in a nuclear and high temperature environment for three-dimensional network monitoring solutions.

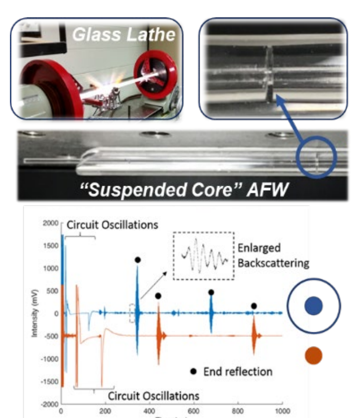
Recent Results and Highlights: An acoustic fiber waveguide (AFW) was designed via exhaustive theoretical analyses, then fabricated and tested to demonstrate strong power confinement. Acoustic reflectors and an AFBG were successfully fabricated in this fused silica "suspended core" AFW and fully characterized to verify the sensing capabilities. An acoustic sensor interrogation system was designed and constructed with a "user-friendly" interface for deployment and nuclear exposure testing at Oak Ridge National Laboratory.

AFBG interrogation system (left) and user interface (right).



AFBG fabrication via CO_2 laser inscription.





Fabrication and testing of "Suspended Core" fused silica AFW.

3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics, and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures

Douglas Adams, Kane Jennings, and Sankaran Mahadevan, Vanderbilt University
Yanliang Zhang, University of Notre Dame
Vivek Agarwal, Idaho National Laboratory
Funding: $1,000,000 (10/1/2017—9/30/2020)

Description of Project: In this project, we are developing an automated technology coupled with advanced data analytics to assess the health of pipes in nuclear power plants as the pipe material degrades due to corrosion growing from the inside out. Our interdisciplinary technology combines innovations in materials for sensing both chemical and mechanical degradation with statistical algorithms based on Bayesian modeling. Our goal is to reduce the cost of inspections, improve worker safety, prevent power outages, and enhance the economic competitiveness of nuclear energy.

Impact and value to Nuclear Applications: Today, workers must continuously inspect nuclear power plants during planned outages to certify their operational safety. One critical type of degradation difficult for workers to find is pipe corrosion. It is especially difficult to detect and monitor this type of corrosion because the chemical environment causing the material to degrade is located along the inside surface of the pipe. With ~70 miles of piping in a nuclear power plant, inspections are very time-intensive and 99% of the time, inspectors do not find any damage. By developing a technology that can, for the first time, map out and monitor the cycle of corrosion inside a structure, starting with chemical reactions that drive thinning of the material, we aim to reduce maintenance costs and outages.

Recent Results and Highlights: We have been developing films that can selectively chelate Fe^{2+} and Fe^{3+} ions. Preliminary results show a complete reaction of acyl chlorides in pNBDAC film upon exposure to dopamine and successful Fe3+ chelation. We are also developing alternating current electroluminescent (ACEL) smart coatings for the outer surface of the pipe to detect resistivity changes in the smart film as metal ions are captured on the inner surface of the pipe. Laboratory testing has shown that the maximum electroluminescent intensity of the ACEL coating was found to increase linearly as the circuit resistance was increased.

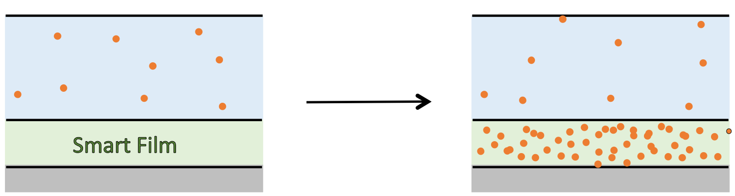


Figure 1. Schematic representation of “smart film chelating metal ions in solution.

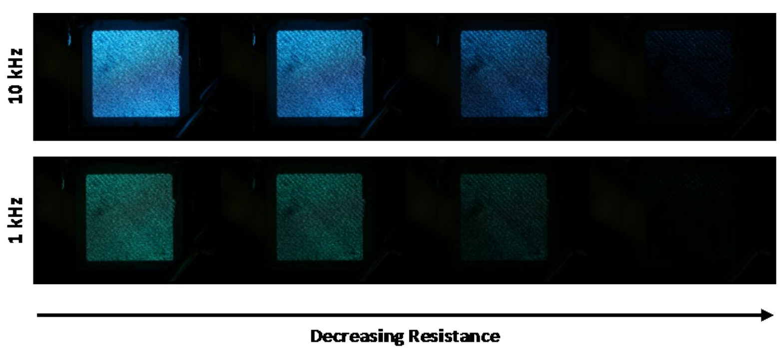


Figure 2. Optical response of 3D-printed ‘smart coating’ with decreasing resistance at various levels of excitation.

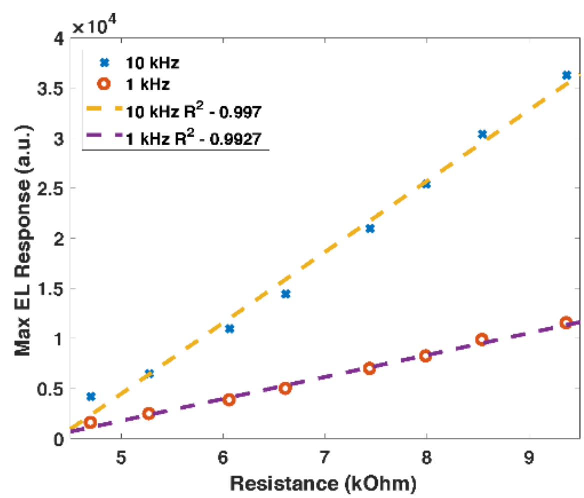


Figure 3. Maximum electroluminescent response of 3D printed ‘smart coating’ at various levels of resistance for two excitation features.

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

Xiaoning Jiang, Mohamed Bourham, and Mo-Yuen Chow, North Carolina State University
Leigh Winfrey, Penn State University
Funding: $999,688 (10/01/2017-09/30/2020)

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

Impact and Value to Nuclear Applications: The development of HiTEIS will enable monitoring of reactor and fuel cycle components. The deployment of these sensors via embedded/integrated functional components and materials also enables more frequent and thorough inspection, while removing human operators from the vicinity of high temperature (HT) and radiation hazards.

Recent Results and Highlights: We designed and fabricated non-invasive laser stress sensors, and conducted the associated concept demonstration tests using a pressurized air tank (Fig. 1). The sensing principle is based on the surface longitudinal wave speed, which is dependent on the stress of the media. The time-of-flight measured is associated with the stress. A pulse laser was used to generate the acoustic wave and an AlN HT acoustic sensor was used to receive the acoustic pulses from the laser. We developed high-temperature vibration sensors using AlN piezoelectric single crystals, and tested them with a wireless communication system (Fig. 2), in connection with a miniaturized mock-up nuclear reactor for the proposed HiTEIS application. The vibration generated by a shaker was successfully detected by an AlN sensor and the signal was communicated wirelessly in real time to a remote receiver located a few miles from the testing site.

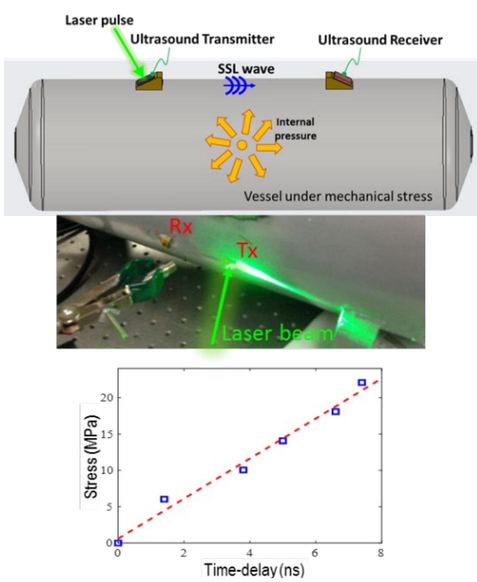


Figure 1. Laser stress sensing development.

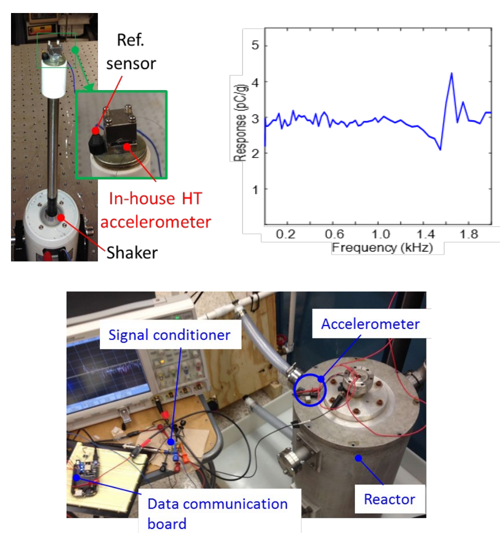


Figure 2. HT vibration sensor embedded in a miniaturized reactor with the wireless communication system.

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

Maria Mitkova, Boise State University
Harish Subbaraman, Boise State University
Isabella Van Rooyen, Idaho National Laboratory
Funding $890,000 (10/01/2017 – 09/30/2020)

Project Description: The project is focused on the research and development of a new in-situ, reusable, and reversible sensor concept for integrated temperature monitoring. The concept involves applying a combination of photonic properties of radiation-hardened waveguides and the temperature progress of the properties of chalcogenide glasses (ChG), specifically their crystallization. This sensor is typically suited to monitoring components with temperatures up to 750–800 K. It can be further employed as a paradigm for a number of hybrid electron/photonic tandem ChG/Si solutions for other characterization methods in nuclear facilities. After accomplishment and testing, the sensors could be applied to multiple components.

Impact and Value to Nuclear Applications: The sensor offers 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. We expect to deliver a novel hybrid plasmonic sensor that is easier and less costly to manufacture, and that will continue to function after radiation exposure. The sensor can be quickly and easily reset and reused for subsequent measurements.

Recent Results and Highlights: In the recent development of the project, researchers characterized in situ the optical constants of the studied films using a hot stage mounted in the ellipsometer. We are building a library of materials and their crystallization temperatures. We have also prepared inks from all synthesized glasses using two distinct methods for inks preparation: (1) milling the films to nano-size and mixing with additives to reach the necessary viscosity and surface tension; and (2) dissolving the chalcogenide glasses in basic solutions. We developed technology for fiber top cleaning. The first prototype of the fiber-based sensor was built and measured, showing a decrease in the material's reflective power in the area of the crystallization temperature. This is an excellent proof of the concept. We will next start e-beam device fabrication and simulate their performance with electrical stimulation, as well as create a periodic pattern of waveguide with grating coupler.

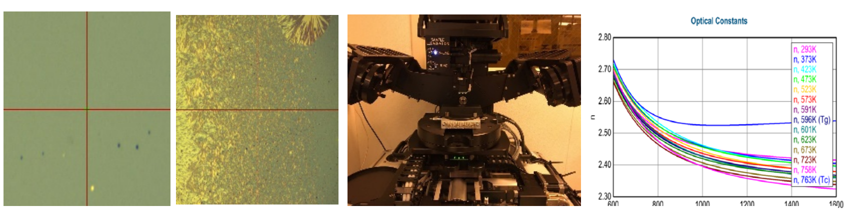


Figure 1. Amorphous and crystallized films after reaching crystallization temperature; Test equipment for in situ optical characterization; Measured optical performance of the films.

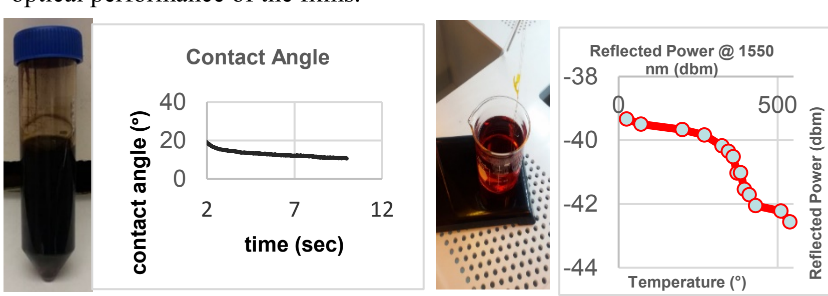


Figure 2. Powder ink; Contact angle of ink measurement; fiber top cleaning; Optical data as a function of temperature.

FY 2018 NEET-ASI Research Summaries

In FY 2018, the NEET-ASI program selected three 3-year projects under the following solicited topic:

1. **State of the art control technologies**

   Applications are sought to design and develop state of the art advanced control rooms, controls systems, and plant control technologies, including automated work management systems in order to:

   - Advance the state of the art in control room technology
   - Demonstrate improved system performance and reliability by streamlining control approaches in monitoring and controlling a component or system in nuclear environment

2. **Big data analytics and applications to improve plant operation and control**

   Applications are sought to develop and demonstrate "big data" analytics for monitoring nuclear plant operation and control. Applicants should:

   - Demonstrate ability to analyze data from plant systems and demonstrate the application to: o Improving Plant performance o Optimizing Plant Maintenance
   - Develop applications to achieve improved
     - Economics, Safety, and Security
     - Workflow optimization

3. **Sensors and instrumentation for data generation**

   Applications are sought to develop and demonstrate new sensors and instrumentation to generate data needed to support improved plant control and data analytics applications for improved plant operations. Applicants should:

   - Design sensor and corresponding instrumentation to be qualified and deployed at a nuclear facility in support of data analytics
   - Demonstrate the ability to use these sensors and instruments at location of interest without disturbing the nuclear facilities conditions and support data communication

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

Vivek Agarwal, Ahmad Al Rashdan, and Ronald L. Boring, Idaho National Laboratory
Pradeep Ramuhalli, Oak Ridge National Laboratory
Michael Taylor, Electric Power Research Institute
Scot A. Greenlee, Exelon Generation Company
Funding: $1,000,000 (10/01/2018—09/30/2021)

Project Description: The project will advance online monitoring and predictive maintenance in nuclear plants to enhance efficiency gain and economic competitiveness. Specific objectives defined to achieve the project goal include: (1) a generalized techno-economic analysis framework to support installation of wireless sensor modalities on plant assets; (2) Bayesian approach to integrate structured and unstructured heterogeneous data; (3) machine learning diagnostic and prognostic estimates of asset condition; and (4) a visualization algorithm to present the right information to the right person in the right format at the right time.

Impact and Value to Nuclear Applications: The research outcomes will enable digital monitoring in nuclear plants by bringing together advances in both sensor technologies and data science-based analytic techniques. The resulting technology will improve plant economics by enabling existing plants to transition from time-based preventive maintenance to condition-based predictive maintenance, automate data collection, storage, integration, and analysis, and optimize allocation of resources including tools and labor. The capabilities developed in this project are applicable to advanced reactors and fuel cycles. Specifically, the outcomes will lay the foundation for the concept of maintenance by design in advanced reactors.

Recent Results and Highlights: Figure 1 illustrates the proposed research scope, highlighting the fact that application of data analytics must be performed in conjunction with sensor research to ensure analytics are responsive to the new data stream and will address the needs of the nuclear industry. The team is developing a generalized framework for techno-economic analysis by taking into consideration both technical and economic aspects of wireless systems in a nuclear power plant. Historical information on plant feedwater-condensate systems is investigated to understand data completeness.

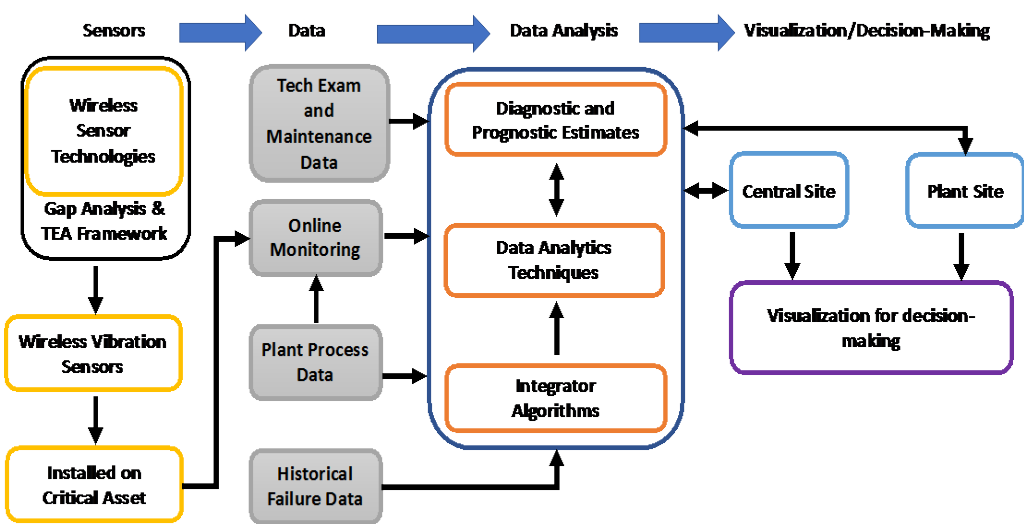


Figure 1. Proposed research scope.

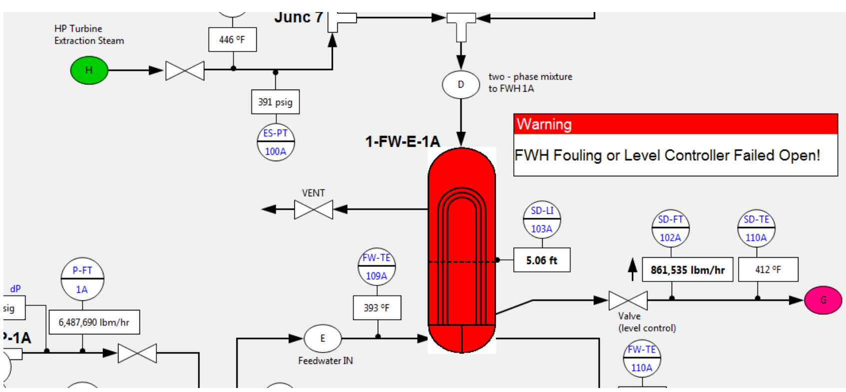
Process-Constrained Data Analytics for Sensor Assignment and Calibration

Richard B. Vilim, Alexander Heifetz, Argonne National Laboratory
Brendan Kochunas, University of Michigan
Marc Anderson, Xcel Energy
Funding: $1,000,000 (10/01/2018—09/30/2021)

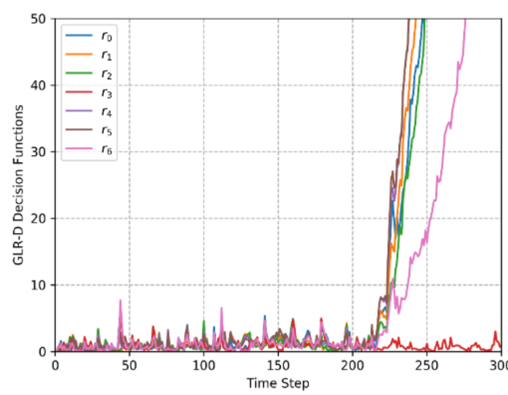
Description of Project: Data analytics combined with rich sensor sets may improve nuclear facility operations, and reduce costs. In this project, we are developing data analytic methods to address the problem of how to assign a requisite level of process monitoring capability to a sensor set in a nuclear facility, while also assuring the sensor set is sufficiently rich for calibrating individual sensors.

Impact and Value to Nuclear Applications: In the industry, calibration has been approached as an empirical data-driven problem. Although several methods have been developed, the experience of utilities over the past ten years with these methods indicates 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 conditions) can confound a purely data-driven approach. There are also no rigorous guidelines for determining what constitutes an adequate sensor set.

Recent Results and Highlights: The solution under development to overcome these shortcomings supplements the data analytic method with process information in a so-called process-constrained data-analytic approach. Simple balance equations are written for generic components (e.g., mechanical pump, valve, and heat exchanger). These do not require a priori knowledge of process parameters, such as heat transfer coefficients or friction factors. All that is needed on the part of the utility user is to identify the components and how they are connected together.



Prototypic Operator Interface for reporting of diagnostic findings.



Decision functions for change detection for a sensor fault.

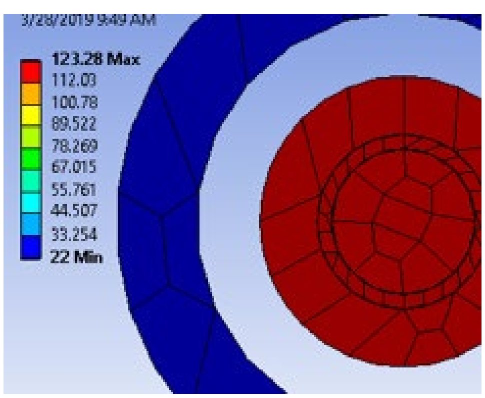
Development of an Optical Fiber-Based Gamma Thermometer

Thomas Blue and Tunc Aldemir, The Ohio State University
Pavel Tsvetkov, Texas A&M University
Diego Mandelli, Idaho National Laboratory
Funding: $987,730.00 (10/1/2018—9/30/2021)

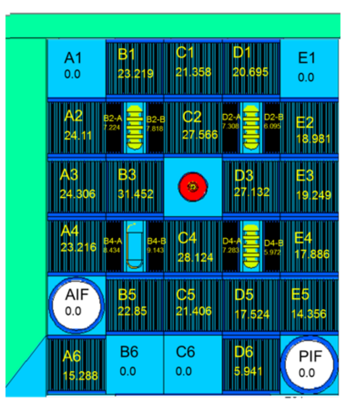
Description of Project: The objective of this project is to develop an optical fiber-based gamma thermometer (OFBGT) which may be used to determine the power distribution in a nuclear reactor. A system of OFBGTs could be used to calibrate the power monitors in both current and future reactors. We plan to develop a silica and a sapphire OFBGT, and postulate the sapphire OFBGT could withstand the extreme temperatures in next-generation nuclear power plants. We will develop data analytic methods to obtain the power distribution from the OFBGTs, which ultimately measure gamma dose. Experimental testing of the OFBGTs will take place in the Ohio State University Research Reactor (OSURR), and the Texas A&M University Research Reactor (TAMURR).

Impact and Value to Nuclear Applications: A system of OFBGTs in a nuclear reactor would be a permanent system for calibration of the power monitors, which would replace traversing in-core probes (TIPs), which are currently utilized in boiling water reactors. Unlike TIPs, which have to be inserted prior to calibration and removed thereafter because they can suffer a loss of sensitivity, OFBGTs could be left in the core. Also, one long OFBGT could be built to extend the length of an entire instrument tube, and acquire a distributed gamma 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.

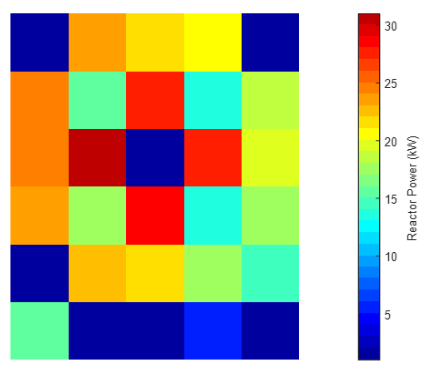
Recent Results and Highlights: We are in the process of finalizing the design of the OFBGT, which will be of aluminum alloy construction to minimize neutron activation. The preliminary design has been put into an MCNP model of the OSURR to predict the gamma dose rate measurements. Further modeling has been done in ANSYS to determine the predicted distributed temperature profile within the OFBGT, while in the central irradiation facility of the OSURR. We have made progress with regard to the data analytic methods, as well. We have modeled the distributed power profile and predicted the OFBGT response in the OSURR, and developed response functions that determine the power distribution in the OSURR from predicted OFBGT data.



ANSYS Thermal Modeling



MCNP Image of OSURR



MCNP Power Map of OSURR

Direct Digital Printing of Sensors for Nuclear Energy Applications

Timothy J. McIntyre, Oak Ridge National Laboratory
Funding: $1,500,000 (10/01/2019—09/30/2020)

Project Description: Researchers at Oak Ridge National Laboratory (ORNL) will develop and demonstrate a prototype passive wireless sensor network deployed at a recommended nuclear industry location. This network will include surface acoustic wave (SAW) sensors, or other printed electronic devices as needed for measurement of voltage, current and hydrogen. The sensors will be made by advanced additive manufacturing (AM) technologies for functional materials (FM), also developed by ORNL. An RF/SAW passive wireless sensor is shown in Figure 1. This sensor platform is inherently a temperature sensor but will be modified to detect hydrogen, voltage, and current.

Impact and Value to Nuclear Applications: This technology will reduce maintenance and costs by allowing the nuclear industry to develop inexpensive sensors to add to existing equipment for online monitoring. For example, Southern Nuclear is currently using an Ethernet-connected transceiver that can connect to 1000+ devices. They are developing machine-learning algorithms to look for anomalies from normal operation. The ability to detect incipient failures in operating equipment will allow more preventative maintenance, reducing the amount of human exposure to hazardous conditions when making measurements in the field under reactive maintenance. The types of sensors addressed in this project include hydrogen leaks from generators, and current and voltage measurements on switch gear, breakers, generators, etc.

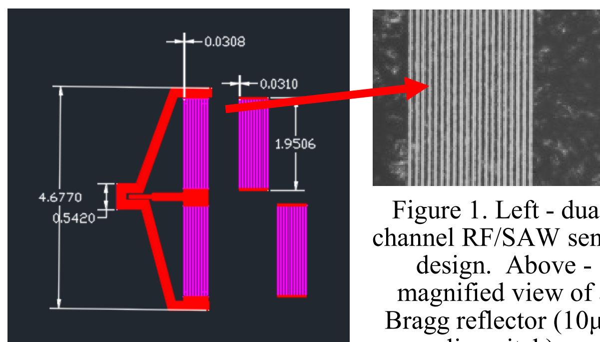


Figure 1. Left - dual-channel RF/SAW sensor design. Above - magnified view of a Bragg reflector (10µm line pitch).

Passive wireless RF/SAW sensors have no batteries, can be economically produced by AM, can sense physical parameters directly (e.g. temp., strain, pressure, voltage, current, etc.); and can be functionalized (coatings on the SAW devices) to sense many things (e.g. moisture, H_2, CH_4, CO, CO_2, C_2H_2, etc.). This approach, using very low-cost, passive, peel-and-stick sensors that are integrated wirelessly has the potential for widespread adoption throughout the nuclear industry.

Recent Results and Highlights: Researchers met with Southern Nuclear to discuss requirements for sensing hydrogen, current, and voltage using passive wireless sensors. Prototypic sensors for hydrogen detection are being tested in the laboratory. Researchers are testing in the laboratory and outdoors a prototype interrogator that will communicate with the sensors.

COMPLETED PROJECTS

Projects listed below have been completed and summaries can be found in previous ASI Award Summaries available on the DOE/NE Website: Advanced Sensors and Instrumentation (ASI) Program Documents & Resources | Department of Energy.

FY 2011

- A High Temperature-tolerant and Radiation-resistant In-core Neutron Sensor for Advanced Reactors, The Ohio State University, $455,629 (9/29/11–9/30/14)
- High Temperature Transducers for Online Monitoring of Microstructure Evolution, Pennsylvania State University, $455,628 (10/12/11–12/31/14)
- NEUP: One-Dimensional Nanostructures for Neutron Detection, North Carolina State University, $455,629 (9/29/11–9/30/14)

FY 2012

- NEET In-Pile Ultrasonic Sensor Enablement, Idaho National Laboratory, $1,000,000 (03/01/12–09/30/14)
- Micro Pocket Fission Detectors, Idaho National Laboratory, $1,015,000 (03/01/12–09/30/14)
- High-Temperature Fission Chamber, Oak Ridge National Laboratory, $574,000 (03/01/12–03/30/14)
- Recalibration Methodology for Transmitters and Instrumentation, Pacific Northwest National Laboratory, $529,000 (03/01/12–04/30/14)
- Digital Technology Qualification, Oak Ridge National Laboratory, $1,269,000 (03/01/12–06/30/15)
- Embedded Instrumentation and Controls for Extreme Environments, Oak Ridge National Laboratory, $770,000 (03/01/12–03/30/14)
- Sensor Degradation Control Systems, Argonne National Laboratory, $360,000 (03/01/12–02/28/14)
- Design for Fault Tolerance and Resilience, Argonne National Laboratory, $900,000 (03/01/12–03/30/14)
- Power Harvesting Technologies for Sensor Networks, Oak Ridge National Laboratory, $380,000 (03/01/12–06/30/14)
- 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 (03/01/12–02/28/14)

FY 2013

- Radiation-Hardened Circuitry using Mask-Programmable Analog Arrays, Oak Ridge National Laboratory, $400,000 (10/01/13–09/30/15)
- Radiation Hardened Electronics Destined for Severe Nuclear Reactor Environments, Arizona State University,$399,674 (12/16/13–12/15/15)
- 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 (12/26/13–12/25/15)

FY 2014

- Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks, Boise State University, $980,804 (01/01/15–12/31/17)
- Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation, Pacific Northwest National Laboratory, $1,000,000 (10/01/14–09/30-17)
- Operator Support Technologies for Fault Tolerance and Resilience, Argonne National Laboratory, $995,000 (10/01/14-09/30/17)
- Embedded I&C for Extreme Environments, Oak Ridge National Laboratory, $1,000,000 (10/01/14-09/30/17)
- Enhanced Micro Pocket Fission Detector for High Temperature Reactors, Idaho National Laboratory, $1,000,000 (10/1/14-09/30/17)
- High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle Systems, University of Pittsburg, $987,676 (10/01/14-09/30/17)