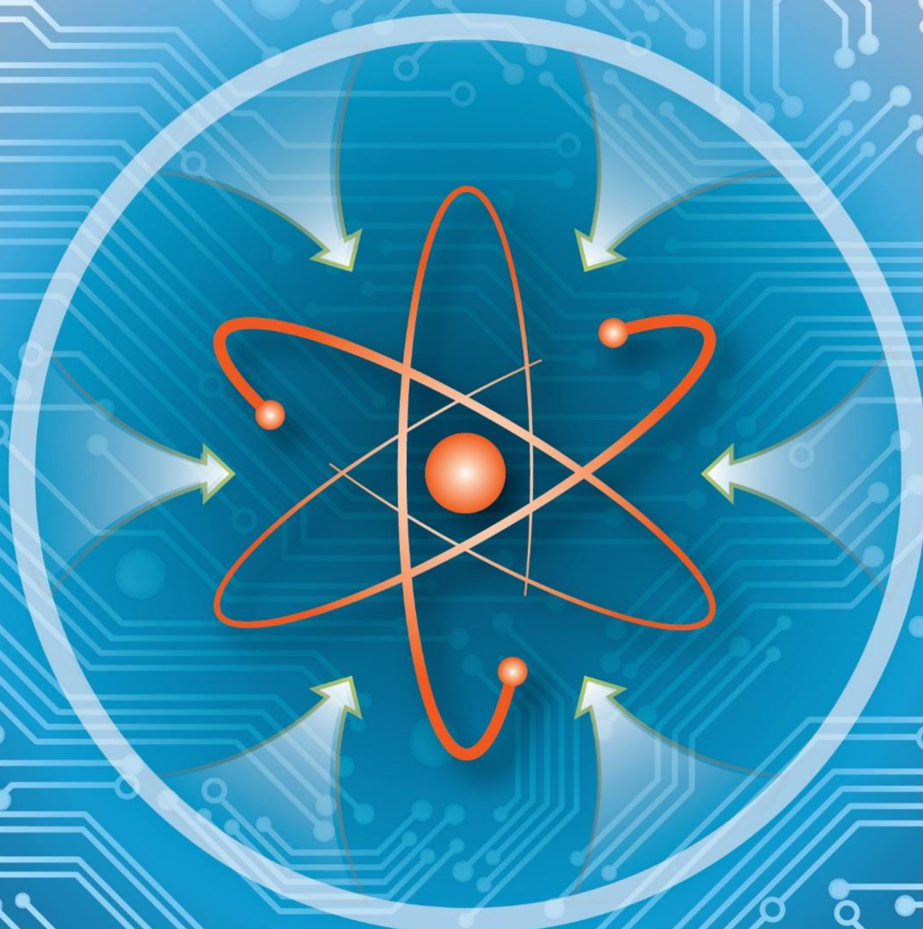
OFFICE OF NUCLEAR ENERGY

Advanced Sensors and Instrumentation Award Summaries



Nuclear Energy Enabling Technologies - Advanced Sensors and Instrumentation

June 2018

INTRODUCTION

Instrumentation and controls are used in commercial nuclear energy and fuel cycle systems to measure important system parameters, provide control input to components that maintain systems within desired and safe limits, and provide owners and operators with the needed awareness of plant conditions to plan and safely manage operational evolutions. In a sense, instrumentation and control (I&C) systems function as the nervous system of a nuclear power plant and other nuclear system applications. They monitor all aspects of the plant's behavior and provide automatic responses 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 that are used to develop and qualify new fuels and materials for future nuclear energy systems.

In 2012, the Nuclear Energy Enabling Technologies (NEET) Program was initiated by the Department of Energy's Office of Nuclear Energy (NE) 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 Crosscutting Technology Development that is being carried out to foster the research and development required to develop and deploy innovative and advanced instrumentation and control capabilities for future nuclear energy systems, and to enable the advanced I&C technologies essential to NE's research and development (R&D) efforts needed to realize mission goals.

Roles

The NEET ASI Program has the following roles:

- To coordinate crosscutting I&C research among NE programs to avoid duplication and focus I&C R&D in support of advances in reactor and fuel cycle system designs and performance.
- To develop enabling capabilities to address I&C technology gaps common across NE's R&D programs.

The NEET ASI program has identified four strategic I&C areas of research that represent key capabilities for nuclear energy systems, fuel cycle facilities, and that are needed to support materials test reactor irradiation-based research. These strategic areas are:

Advanced Sensors. Developing and qualifying new sensor capabilities and methods to detect and monitor behavior of reactor and fuel cycle systems and of desired parameters in integral tests to achieve needed accuracy and minimize measurement uncertainty.

Digital Monitoring and Control. Enhancing the monitoring of process variables and implementation of control actions that increase system reliability, availability, and resilience.

Nuclear Plant Communication. Researching and developing communications technologies needed to support greater data generation and transmission demands expected to accompany advancements in digital sensor, measurement, and control technologies while maintaining reliability, resiliency, and data security.

Advanced Concepts of Operation. Developing and testing advanced concepts of operation for future nuclear energy systems designed to achieve highly automated control, where new human and system interaction is defined. These areas correspond directly to the needed capabilities of future I&C technologies and systems, are familiar to the stakeholder community, and are largely recognized by the vendor community.

As the timeframe for payoff on NEET ASI R&D investments becomes longer, new strategic areas may be added.

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

In FY 2012, ten 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. Three of these projects were completed in 2017 and the remaining three will be completed in 2018.

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.

Since FY 2011, NEET-ASI has funded 31 projects for a total of $25,006,253.

These projects are 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, and other power generation sectors as well. As these research projects progress, the interest from stakeholders and industry has also increased, as has the number of individual technology deployments and partnerships.

FY 2014 NEET-ASI Research Summaries

In FY 2014, the NEET-ASI program selected six 3-year projects for award. Three of these project were completed last year and the remaining three will conclude their research this year. The solicited topics for the last three projects were as follows:

1. **Power Harvesting Technologies for Sensor Networks**

This program element focuses on development and demonstration of power harvesting technologies to power sensor networks in a nuclear environment and includes:

- Develop sensor requirements and sensor simulator to test and demonstrate concepts prior to full development
- Develop, design, and fabricate power efficient solid-state devices
- Demonstrate that conceptual system design is capable of surviving in the intended environments representative of nuclear power plants.

2. **Embedded Instrumentation and Controls for Extreme Environments**

This program element focuses on development and demonstration of embedded instrumentation and control technologies in major nuclear system actuation components (e.g., pumps, valves) that can achieve substantial gains in reliability and availability while exposed to harsh environments.

- Employ a multidisciplinary research effort to integrate sensors, controls, software, materials, mechanical, and electrical design elements to develop highly embedded I&C in major component design
- Construct and demonstrate a bench-scale and a loop-scale component with embedded controls
- Develop methods and metrics for assessing resulting system performance enhancements and demonstrate fault-tolerant control, high efficiency, and reliability in a testbed or representative facility environment.

3. **Advanced Measurement Sensor Technology**

This program element focuses on development and fabrication of advanced sensors for improved performance measurement technology that provides revolutionary gains in sensing key parameters in reactor and fuel cycle systems. These new sensor technologies should be applied to multiple reactor or fuel cycle concepts and address the following technical challenges:

- Greater accuracy and resolution
- Detailed time-space, and/or energy spectrum dependent measurements
- Reduced size
- Long-term performance under harsh environments.

High Spatial Resolution Distributed Fiber-Optic Sensor Networks for Reactors and Fuel Cycle Systems

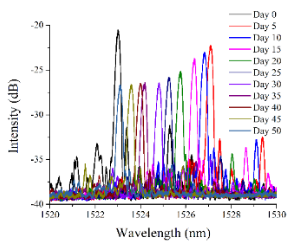
Kevin P. Chen, University of Pittsburgh

Funding: $987,676 (10/1/14–4/30/18)

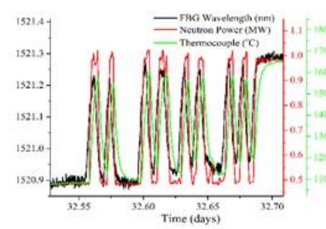
Project Description: The objectives of this project are to develop multi-functional, remotely activated, and distributed fiber optical sensor networks to monitor parameters critical to the safety of nuclear power systems with high spatial resolutions. These objectives will be achieved through the invention of new multi-function optical fibers as sensor platforms suitable for radiation environments, the development of novel sensory materials for distributed chemical measurements (e.g., H2), inventions of new active fiber sensing schemes, and manufacturing of sensor-enabled smart components for high spatial resolution measurements.

Impact and Value to Nuclear Applications: The new distributed fiber sensing capabilities, new radiation-hardened multi-functional fibers, and new smart components developed by this program will address critical technology gaps for monitoring advanced reactors and fuel cycle systems under both normal operation and in post-accident scenarios.

Fiber sensor lowered into the test react



FBG peak shift in the reactor from Day 0 to Day 50 for specially design radiation-harden fibers



FBG in (black) response to neutron power change (red) compared with thermocouple measurements (green).

Recent Results and Highlights: The project uses an integrated approach to developing distributed fiber sensors for nuclear energy. Multi-core optical fibers have been designed for multi-parameter distributed measurements. Using multi-functional optical fiber as distributed sensing devices, this project invented smart electric cable that can perform temperature, strain, chemical, and radiation measurements with 1-cm spatial resolution. To improve high-temperature resilience of the distributed fiber sensors, this project used the ultrafast laser processing technique to enhance Rayleigh scattering of radiation-hardened fibers. This innovation enables fiber sensors to function at extreme high temperatures (up to 800°C) to perform distributed measurements with 5-mm spatial resolution.

Through integrated efforts of specialty fiber design, radiation-hardened material development, fiber fabrication, and ultrafast laser fabrication of radiation-hardened fiber sensors, both fiber Bragg grating (FBG) sensors (Figure 1) and distributed fiber sensors have been successfully developed. In Year 3, fiber sensors were tested in the Massachusetts Institute of Technology reactor subject to the average testing temperature occurred at 620°C with fast neutron (>1MeV) flux at 1.2×10^{14} n/s/cm^2 neutron. Overall, radiation-induced FBG peak degradation was at 0.125 dB/day. It stabilized after 30 days as shown in Figure 1b. Fifty five-day tests of FBG sensors showed less than 6 dB reduction in FBG peak strength after over 1×10^{20} n/cm^2 of accumulated fast neutron dose. To our best knowledge, this is the best performance of any fiber sensors under neutron flux.

This project demonstrates that when silica fibers are properly developed and suitable laser fabrication techniques are implemented, both distributed and FBG sensors can survive extreme environments of the nuclear reactor cores under intense gamma and neutron irradiation at high temperatures. Results gathered and technology developed by this project reveal that temperature-stable fiber sensors (both FBG and distributed) fabricated in radiation-hardened fibers could be used as sensors to perform in-pile measurements, to improve safety and efficiency of existing and next generation nuclear reactors.

Embedded Instrumentation and Controls for Extreme Environments

Roger Kisner, Alexander Melin, Oak Ridge National Laboratory

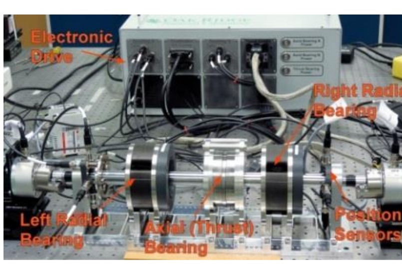
Funding: $1,000,000 (10/01/14–03/30/18)

Project Description: Oak Ridge National Laboratory (ORNL) is researching advanced instrumentation and controls (I&C) concepts for extreme environments. Advanced reactor components must survive environmental challenges such as high radiation, corrosive liquids, high-temperatures, and sometimes high pressures that operate reliably and safely for long periods. Many commercially available sensors, actuators, and controls do not operate at salt reactor temperatures, and existing solutions are expensive and inefficient. ORNL's research focuses on bridging specific technical gaps for I&C in extreme environments.

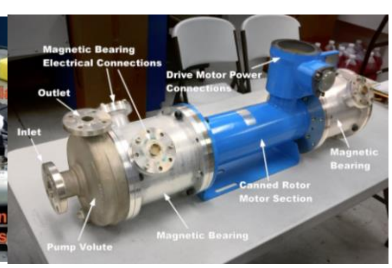
The project demonstrates embedded I&C for a magnetically suspended, canned rotor pump that will be eventually adapted to the high-temperatures of molten salt. Fluid pumps have wide applicability to nuclear reactors, solar collection systems, and other high-temperature applications. Challenges of these difficult environments are overcome by developing high-temperature electromagnetic sensors and actuators and advanced control algorithms. This successful technology development crosscuts a wide range of industrial applications by significantly raising the maximum operating temperature of those electromagnetic devices. Active sensing and control of the magnetic bearing enables a degree of shaft vibration mitigation. Shaft vibration can diminish seal and bearing reliability—both established operational issues.

Impact and Value to Nuclear Applications: ORNL has produced cross-cutting sensor and control technologies for high-temperature nuclear reactors. The research resulted in multi-disciplinary design integration techniques and a bench-scale and a loop-scale embedded I&C testbed and demonstration platform for future research in embedded I&C for extreme environments. Additionally, performance testing at the bench-scale and loop-scale has produced quantifiable performance improvements due to embedded I&C. This work has established a pathway to active measurement and control of behaviors that have operational impacts—seal elimination, horizontal shaft orientation, and cost reduction. Importantly, several commercial manufacturers has partnered with ORNL to propose development and testing of a full-temperature salt reactor pump using this technology. The private companies believe that resulting technology will become the standard pump design for high-temperature power reactor systems.

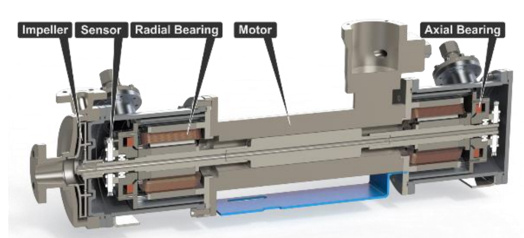
Recent Results and Highlights: Bench-scale and a loop-scale test beds are available. Extensive simulation and equipment testing are accomplished. Planned water loop installation has not yet been accomplished. The final report is available. The next phase of work to develop a 700°C pump has been proposed with commercial manufacturing partners.



Bench-Scale Magnetic Bearing Test Bed.



Loop-Scale Magnetic Bearing Test Bed.



Cross-Section of 10 hp Magnetically Suspended Canned Rotor Motor.

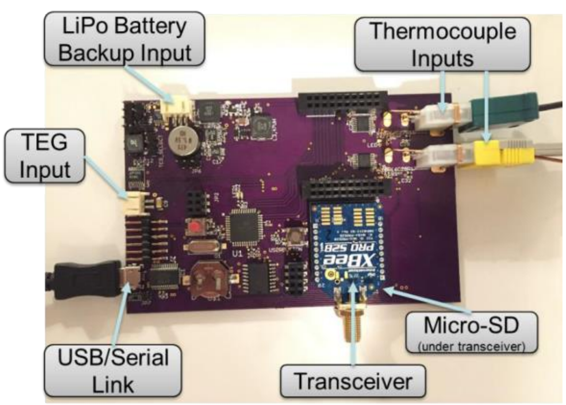
Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks

Yanliang Zhang, University of Notre Dame
Brian Jaques, Boise State University;
Vivek Agarwal, Idaho National Laboratory
Zhifeng Ren, University of Houston
Funding: $980,804 (01/01/2015–6/30/2018)

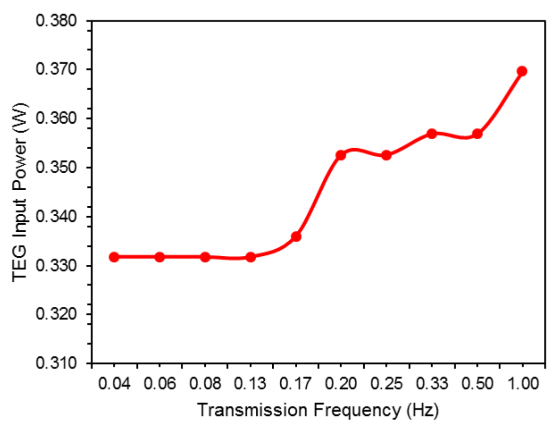
Project Description: The objective of this project is to develop high-efficiency and reliable thermoelectric generators (TEGs) for self-powered wireless sensors nodes (WSNs) utilizing thermal energy from nuclear reactors or fuel cycle. The project is based on the high-performance nanostructured bulk thermoelectric materials that the team has recently developed.

Impact and Value to Nuclear Applications: The power harvesting technology has crosscutting significance to address critical technology gaps in monitoring nuclear reactors and fuel cycle. The outcomes of the proposed research will lead to significant advancement in sensors and instrumentation technology, reducing cost, improving monitoring reliability, which enhances safety. The self-powered wireless sensor networks could support the long-term safe and economical operation of all the reactor designs and fuel cycle concepts, as well as spent fuel storage and many other nuclear science and engineering applications.

Recent Results and Highlights: The team has designed and built a TEG-powered WSN. The figure shows the prototype of the TEG-powered WSN board developed and tested in this project. The WSN system include the wireless transceiver, sensor, energy storage unit, data storage unit, and the input for TEG power. The entire WSN system consumes less than 0.4-W TEG power input during active data transmission.



Thermoelectric generator powered wireless sensor node prototype.



TEG input power versus frequency of data transmission.

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

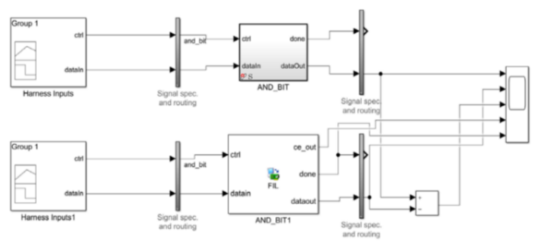
An embedded digital device is an electronic sub-component of a plant component (e.g., instrument or circuit breaker) which uses software or software-developed logic for some aspect of its operation. The qualification method will demonstrate a cost-effective means of ensuring that the device is not subject 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 (EPRI)
Dr. Carl Elks, Virginia Commonwealth University (VCU)
Funding: $991,000 (10/01/2015–03/30/2019)

Project Description: This project explores an alternate approach to mitigate the unpredictable nature of software faults in safety-related instrumentation and control (I&C) systems due to the unbounded and general-purpose nature of Von-Neumann architecture CPUs commonly used in these devices. This approach will identify and develop embedded digital components that can be demonstrated to contain no additional capabilities or characteristics other than that 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, which allows effective use of formal verification tools to create a high-fidelity verification. These methods will be applicable to both the platform and the application-level configuration.

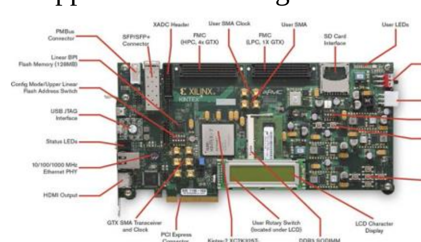


SymPle 1131 hardware-based sequencer architecture.

To achieve these objectives, the research team has developed a hardware-based sequencer architecture that can execute deterministic hardware function blocks that replicate IEC-61131 function block constructs directly in hardware. Called SymPle 1131, this architecture can be field reconfigurable while still providing formal verifiability. This technology is now ready for prototyping in an FPGA (field programmable gate array) environment. The team has also evaluated the architecture for compliance with IEC-61508, "Functional Safety," and has added self-checking and diagnostic features to more fully address commercialization requirements. While an FPGA environment will be used for prototyping, other construction modes can be used as well, such as ASIC's (application specific integrated circuit) and full custom silicon.

Impact and Value to Nuclear Applications: Successful demonstration of an alternate architecture will allow the 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 architecture has progressed through formal verification using MathWorks and Simulink Design Verifier. Although suitable for prototyping, the team has added Fault Aware Function block features to add resistance to random failures to compliment the architecture's intrinsic resistance to systematic failures. Prototyping is proceeding using the Xilinx Kintex 7 hardware platform. The application will be selected as a function subset of an actual nuclear control system from a full scope plant simulation using the Generic Pressured Water Reactor simulator by GSE, Inc. Work to select the functional application and design the hardware-in-the-loop test harness is underway. The SymPle prototype replaces a selected simulation function and demonstrates its ability to control a high-fidelity plant simulation. Additional work has also been done to allow the prototype to be the target of a mock Commercial Grade Dedication using IEC 61508 criterial as dedication specifications. This will give insight into how a commercialized SymPle 1131 would be provisioned under current 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.



Xilinx Kintex 7 hardware platform.

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

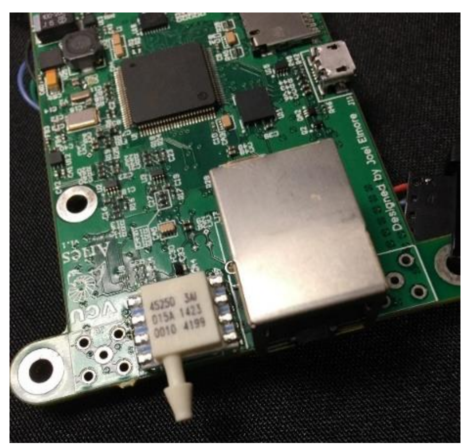
Richard Wood, The University of Tennessee,
Carl Elks, Virginia Commonwealth University
Brent Shumaker and Hash Hashemian, Analysis and Measurement Services Corporation
Carol Smidts, The Ohio State University
Funding: $988,000 (10/01/2015–09/30/2018)

Project Description: 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. Research will advance state of the art for qualification of digital devices by (1) developing novel methods to demonstrate proof of operational reliability, (2) applying the developed methods to representative embedded digital devices to ascertain the effectiveness of the methodology, and (3) establishing a cost-effective qualification framework that is 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 common-cause failure in embedded digital devices. Without development of cost effective qualification methods to satisfy regulatory requirements and address the potential for common-cause failure vulnerability associated with embedded digital devices, the nuclear power industry may not be able to realize the benefits of digital technology achieved by other industries. The research will develop an approach to ensure that qualification testing covers the full range of postulated systematic faults. Through the successful demonstration of this qualification methodology, impediments to advanced technology use can be eliminated to the benefit all reactor types.

Recent Results and Highlights: Recent research activities have focused on development of an MBT methodology to provide science-based evidence that qualification testing of a smart instrument covers the full range of postulated systematic faults and on establishment of a representative instrument with an embedded digital device to serve as a demonstration subject. The basis for the MBT approach is an extended mutation testing method that addresses potential fault types from the requirements and design phases of a software life cycle in addition to coding faults. The primary objective of the MBT approach is to define a suite of qualification tests that can detect instances (or mutants) corresponding to each of the postulated faults.

The application of MBT involves executing mutation test cases and determining the necessary and sufficient conditions to kill a mutant. The method for generating the test cases follows two steps: (1) for each postulated mutant, generate the logic expression that indicates the execution path that will kill the mutant; and (2) solve the logic expressions to obtain the suite of test cases that kill all mutants. For the demonstration activity, a prototype smart sensor (see figure) was selected and assembled for testing. The demonstration target is a prototype smart sensor based on a pressure/temperature sensor originally developed as a research device for aerospace applications. An automated testing framework has been developed for MBT demonstration. The testing results for the MBT demonstration will be compared against black-box baseline testing of the same device to show the effectiveness and efficiency of the MBT approach.



Prototype smart sensor.

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.

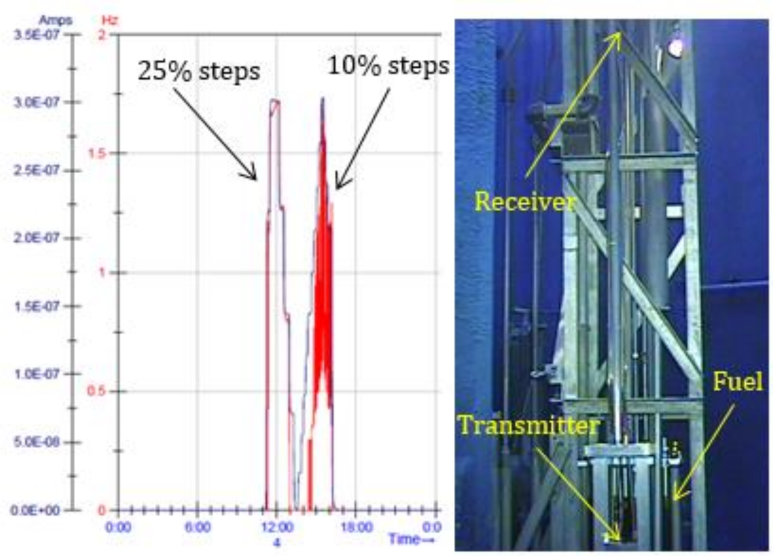
Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature-Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply

Jorge Carvajal, and Michael Heibel, Westinghouse Electric Company
Dr. Kenan Unlu, and Dr. James Turso
Pennsylvania State University Radiation Science and Engineering Center (RSEC)
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. This novel power distribution measurement 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. The temperature and radiation sensitivity performance of the VME device, which is the key component of the system, will be evaluated 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 axially located 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 the top nozzle of each fuel assembly. It is expected that this technology would enable the plant to increase reactor operating margin due to improved fuel usage knowledge. 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: An amplitude-modulated wireless transmitter has been installed at the Penn State Breazeale Reactor capable of processing a Rhodium (Rh) Self-Powered Detector (SPD) signal. The blue trace in the graph below represents the Rh SPD signal as recorded by a picoammeter, while the red trace represents the transmitted signal in response to the same Rh SPD signal. At 25% reactor power steps, the transmitted signal closely matches the Rh SPD signal, while at 10% reactor power steps some noise is evident due to the modulation scheme used, which will be improved. The transmitter has been irradiated to approximately 3×10^{18} n/cm^2.



Amplitude-modulated wireless transmitter.

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

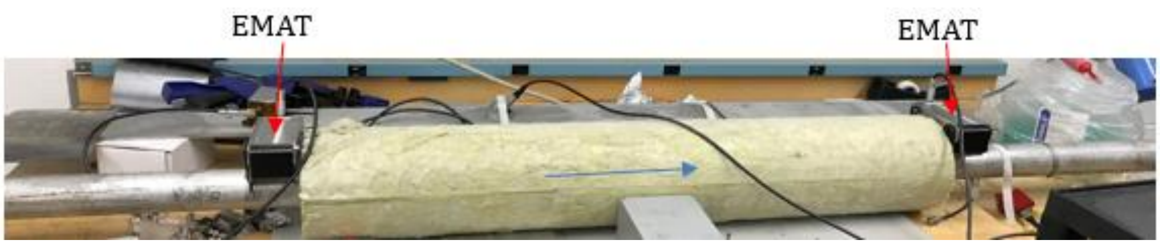
Richard B. Vilim, Alexander Heifetz, Argonne National Laboratory

Funding: $1,000,000 (10/01/16–09/30/19)

Project Description: The objective of this project is to develop and demonstrate methods for communication across physical barriers in nuclear facilities using acoustic/elastic waves as carriers of information along existing in-place metal piping infrastructure. Acoustic communication (AC) hardware and network protocols for efficient and secure transfer of data are being developed and with experimental demonstration of a prototype AC system to be performed in a representative environment.

Impact and Value to Nuclear Applications: This innovative means of transmitting information overcomes physics hurdles that beset conventional communication methods (both wired and radio frequency wireless). In particular, AC provides the only viable option to transmit information in and out of the containment building in post-accident scenario when there is complete loss of electrical power at the facility. The outcome of this project will improve safety, accident response, and recovery capabilities at nuclear facilities.

Recent Results and Highlights: Most common nuclear power plant designs include chemical and volume control system pipes, which penetrate through containment building walls through special tunnels. The pipes are physically not in contact in concrete, and held in place with welds to plates bolted to a concrete wall. An acoustic signal transmission on a stainless steel schedule-160 pipe has been demonstrated using Lamb Wave EMAT (electromagnetic acoustic transducer) transmitter and receiver.



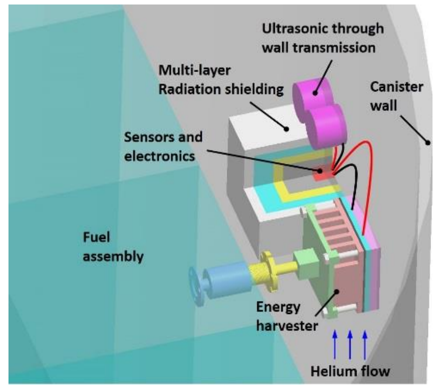
Setup of Lamb Wave EMAT to EMAT signal transmission along a stainless steel schedule-160 pipe with thermal insulation.

The pipe material and dimensions, as well as 2-in.-thick mineral wool thermal insulation, are similar to those found in most common chemical and volume control system heat exchanger charging lines. The distance between transmitter and receiver is 1.2 m, which is the same as typical containment wall thickness. Information was transmitted as on-off keying with bit rate of 5 kbps at carrier frequency of 417 kHz. Because of wideband characteristics of EMAT, achieving higher data transmission rate with EMAT compared to narrowband piezoelectric transducer could be possible.

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

Lei Zuo (PI) and Dong Ha, Virginia Tech
Haifeng Zhang, University of North Texas
Roger Kisner and Nance Ericson, Oak Ridge National Laboratory
Funding: $1,000,000 (10/01/16–9/30/2019)

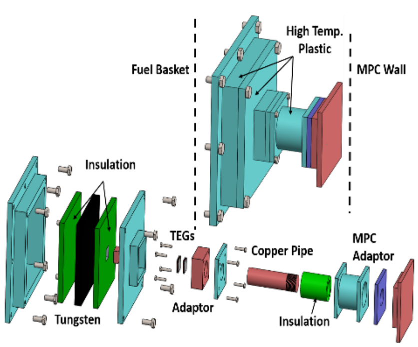
Project Description: Monitoring temperature, pressure, radiation, humidity, etc., inside enclosed storage vessels is crucial to ensure reactor safe operation and fuel security. However, the physical boundaries constructed of metal enclosures and thick concrete present huge challenges to sensing and data communications because these enclosures shield radio-frequency signals and obstruct the wiring of 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 harvester, through-wall ultrasound communication, and harsh environment electronics. The project will enable transmitting a great amount of data through the physical boundaries in the harsh nuclear environment in a self-powered manner.



Energy harvesting for sensing and communicating system powering.

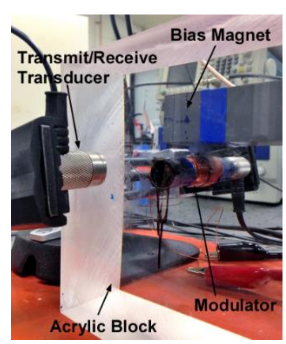
Impact and Value to Nuclear Applications: The expected impacts and benefits include: (1) pulling enough electrical energy from the radiation and thermal environment in the spent fuel canister for electronics powering, (2) validating the proposed advanced wireless communications through enclosed thick metal wall barriers as is needed in nuclear environments; and (3) developing high-temperature and radiation-tolerant electronics for data communication in nuclear environment.

Recent Results and Highlights: In this phase, (1) two energy harvesters, a gamma-radiation energy harvester, and a thermal energy harvester were built to power wireless through-wall communication for in-situ monitoring of interior conditions in nuclear canisters. Their performance over 50 years of service in the canister was analyzed using radiation and thermal modeling of the canister. (2) The ultrasonic TEXT transmission at temperature ranging from 20°C to 100°C using one to one transducer configurations communication method were successfully verified. (3) A possible method of directly modulating an ultrasonic wave using a low-power input was demonstrated.



The gamma radiation energy harvester design

The experiment setup for through-wall communication at 300°C.



Dual element transducer system tested on the 4 inch acrylic block.

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.

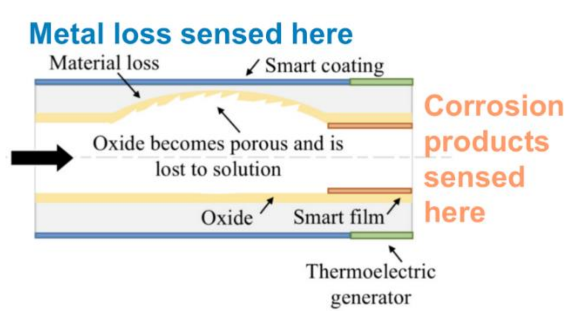
3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics, and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures

Douglas Adams, Kane Jennings, and Sankaran Mahadevan (Vanderbilt University)
Yanliang Zhang (University of Notre Dame)
Vivek Agarwal (Idaho National Laboratory)
Funding: $1,000,000 (10/01/17-09/30/20)

Project Description: This project is developing an automated sensing technology coupled with advanced data analytics for assessing the health of pipes in nuclear power plants as the pipe material degrades due to corrosion that grows from the inside out. The interdisciplinary technology combines innovations in materials for sensing both chemical and mechanical degradation with statistical algorithms based on Bayesian modeling. The 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, to continuously certify that nuclear power plants are safe to operate, workers must inspect them during planned outages. One critical type of degradation that is difficult for workers to find is corrosion in pipes. It is especially difficult to detect and monitor this type of corrosion because the chemical environment that causes 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 the inspections 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, the aim of this project is to enable operators to reduce maintenance costs and outages.

Results and Highlights:
In the area of sensing, two new types of smart polymer films have been developed that can capture metal ions with the goal of sensitively monitoring the onset of corrosion on the inner surface of the pipe. For the pNBDAC hydroxamic acid modified film, the concentration of ions in the film was shown to be 10,000 times greater than in solution meaning that the film will be highly sensitive to small changes in corrosion of the pipe. This film's stability is so strong that a negative pH was needed to release the metal ions. On the outer surface of the pipe, mechanoluminscent smart coatings are being developed for detecting changes in the vibro-acoustic response of the pipe wall due to corrosion-induced thinning of the metal or changes in the ions absorbed by the smart polymer film. A metal specimen was fabricated to emulate changes in the thickness of a pipe wall due to corrosion, and the dynamic response on the surface of the specimen was shown to be correlated to the thickness along the specimen using both a finite element model and laser vibrometer data. In the area of energy harvesting, a thermoelectric generator model was developed to guide the design of ink jet printed thermal devices. An Aerosol Jet printer was installed and utilized to print a thermoelectric film using an ink that was custom made. The thermoelectric bulk material was shown to be highly porous providing a high thermal conductivity and will be designed to harvest thermal energy on the outer surface of the pipe for powering sensors that monitor the smart coating. To prepare to demonstrate these sensing technologies, a cooling circuit testbed has been designed using a 1-D fluid flow model to select a 30 GPM pump to achieve a flow rate of 0.9 m/sec with a 5 cm diameter pipe. The graphic to the right illustrates the overall sensing strategy this project is taking to three-dimensionally map and monitor corrosion processes in pipe structures.



Sensing strategy.

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

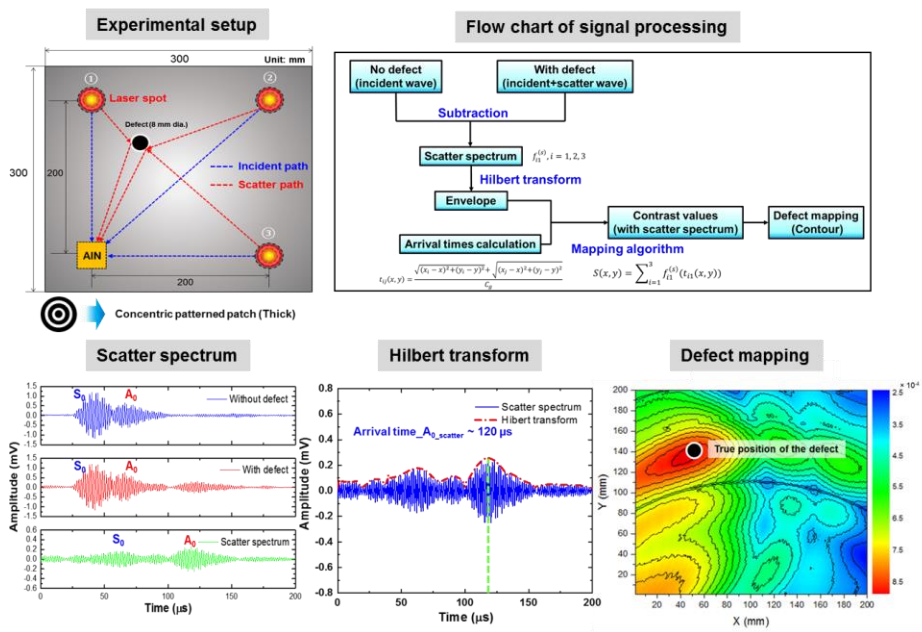
Dr. Xiaoning Jiang, Dr. Mohamed Bourham, Dr. Mo-Yuen Chow, and Dr. Leigh Winfrey, NC State

Funding: $999,688 (10/01/17-09/30/20)

Project Description: Advanced sensors and instruments are in critical need for monitoring of nuclear power plants. 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 of 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 the human operator from the vicinity of high temperature and radiation hazards.

Recent Results and Highlights: Piezo samples were prepared for preliminary irradiation tests. Wireless communication was reviewed for the proposed HiTEIS application. Photoacoustic Lamb wave non-destructive testing technique with candle soot/polydimethylsiloxane patches was successfully demonstrated (see the figure below).



Photoacoustic Lamb wave non-destructive testing technique with candle soot/PDMS patches.

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 (10/01/17 – 09/30/20)

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 applying combination of photonic properties of radiation-hardened waveguides and temperature progress of the properties of chalcogenide glasses (ChG), specifically their crystallization. This sensor is typically suitable for the monitoring of 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 (for example, when non-volatile memory is necessary to be introduced based also on the phase changes in the ChG) in the nuclear facilities since the chalcogenide glasses are radiation-hardened materials. Once the development of first sensor is accomplished and tested, it can be applied to multiple components through access of the Gateway for Accelerated Innovation in Nuclear (GAIN) program.

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 is addressing nuclear materials quantification and tracking. Delivery of a novel hybrid plasmonic sensor that is easier and less costly to manufacture, and which will continue to function properly after radiation exposure, is expected. The sensor can be quickly and easily reset and reused for a subsequent measurement.

Recent Results and Highlights: All necessary glasses for the project from the Ge-Se and Ge-S systems are synthesized. Differential scanning calorimetry analysis has been started to find out their characterization temperatures. The refractive indexes of thin films of these glasses has been measured at different temperatures to support the simulations of devices. Synthesis of three component heterogeneous glasses started in order to get devices with several characteristic temperatures. Simulation of the structure of the devices is performed with three different devices structures, each with metal on top, surrounded with an insulating film and Si wave guide, which is surrounded with chalcogenide glass as is expected when printing the devices. In all cases, formation of plasmonic mode was found, which will allow proper functioning of the devices.

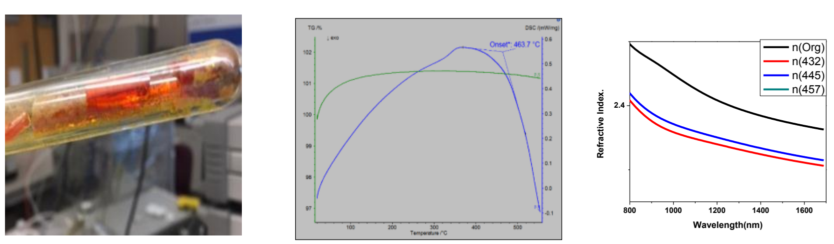


Figure 1. Ampoule with $Ge_{30}Se_{70}$ glass; Differential scanning calorimetry and refractive index data.

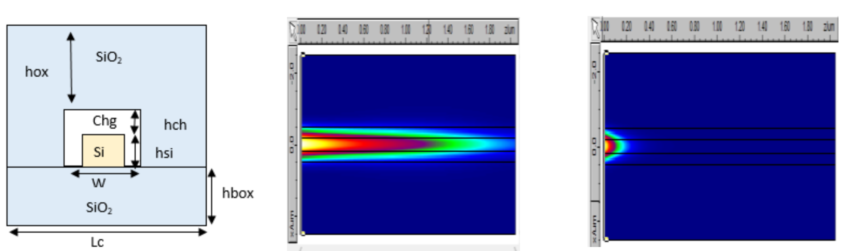


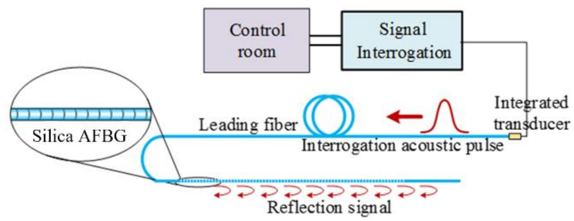
Figure 2. Device structure; light propagation in amorphous and crystalline states.

Work on ink preparation has begun. Students received clean room training as a result of working on this project.

Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring

Gary Pickrell and Anbo Wang, Virginia Tech
Denise Lee, Oak Ridge National Laboratory
Brian Risch, Prysmian Group
Funding: $1,000,000 (10/01/17-09/31/2020)

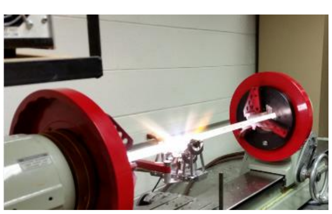
Project Description: The objective of this research is to develop an acoustic-based sensing system that will be able to monitor phenomena such as strain, temperature, pressure, and material corrosion in real-time to better evaluate the aging and degradation of relevant structural components in nuclear facilities. 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 resistant fused silica and single crystal sapphire fibers. Laboratory testing of prototype systems will be performed and benchmarked against commercially available fiber optic sensors.



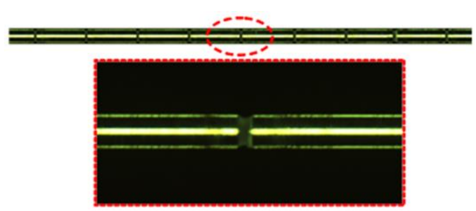
Schematic of AFBG sensing system.

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 base sensing technologies will fill the gap between low cost electronic sensors and high-performance fiber optic sensors and provide a first-of-a-kind, low-cost, fully-distributed, multi-parameter sensing platform that can operate reliably in a nuclear and high-temperature environment, and be integrated with three-dimensional network monitoring solutions.

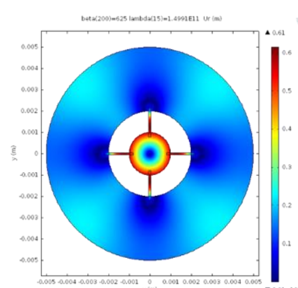
Recent Results and Highlights: Acoustic fiber waveguide (AFW) designs have been optimized via comprehensive theoretical modeling and simulation. An acoustic excitation and detection system has been designed and constructed for the testing of selected AFW designs and materials, as well as to provide the basis for a single-ended sensing system. Preliminary experimentation demonstrated the AFBG-based sensing technology for temperature, pressure, and corrosion sensing.



Automated glass working lathe for fused silica AFW fabrication



Optical micrograph of silica AFBG array.



Simulation of optimized AFW design.

COMPLETED PROJECTS

Projects listed below have been completed and summaries can be found in previous ASI Award Summaries available on the DOE/NE Website: www.energy.gov/ne

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

- 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).
- Enhanced Micro Pocket Fission Detector for High Temperature Reactors, Idaho National Laboratory, $1,000,000 (10/1/14-09/30/17).