Office of Nuclear Energy

Advanced Sensors and Instrumentation Project Summaries

Nuclear Energy Enabling Technologies - Advanced Sensors and Instrumentation

June 2020

INTRODUCTION

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

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

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

RESEARCH AREAS

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

These research areas are as follows:

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

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

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

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

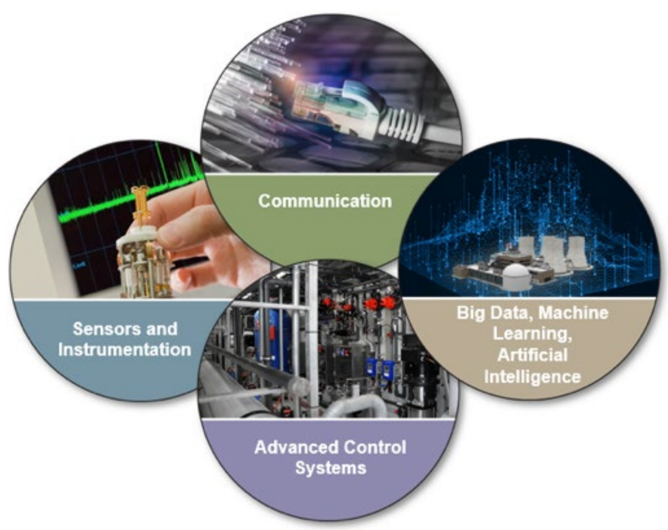


Figure 1. NEET ASI Research Areas

ROLES

The NEET ASI Program has the following roles:

- Coordinate crosscutting research among NE programs to avoid duplication; focus R&D in support of advances in reactor and fuel cycle system designs and performance.
- Develop enabling capabilities addressing technology gaps across the four research areas common in all NE's R&D programs.
- Advance technology readiness levels across the four research areas in order to support transition of research first to NE's R&D programs, then to commercialization.

SUMMARY

Since fiscal year (FY) 2011, NEET-ASI has funded 41 projects competitively for a total of $34,563,523. These projects have been successful in advancing the state of the art for measuring, controlling, and broadly managing nuclear energy systems being developed by the DOE-NE. Some of these technologies have the potential to impact systems and technologies beyond nuclear energy. They all address critical needs and gaps in current capabilities and are aimed at many of the highest priorities shared by different R&D programs. They include participation from a number of laboratories, universities, and industry. The eventual goal for this research is the deployment of these technologies in a manner that most benefits individual DOE-NE R&D programs, the nuclear energy industry, as well as other power generation sectors. As these research projects progress, the interest from stakeholders and industry has also increased, as have the number of individual technology deployments.

Since FY 2017, NEET-ASI has funded directed In-Pile Instrumentation (I2) research for a total of $20,300,000 under the Sensors and Instrumentation technical area organized as follows:

- Nuclear instrumentation
- Sensor fabrication by advanced manufacturing
- Measurement systems for nuclear materials properties characterization
- Instrument deployment

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

This 2020 ASI report includes summaries of the current on-going projects. A list of completed projects is included at the end of this report and summaries can be found in previous issues saved in the ASI documents page: https://www.energy.gov/ne/advanced-sensors-and-instrumentation-asi-program-documents-resources

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

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

In FY 2012, 10 projects totaling $7,622,000, were initiated to address a range of common and crosscutting needs identified by the DOE-NE R&D programs. These projects were concluded in FY 2014 when the NEET ASI program transitioned to a fully competitive solicitation and selection process.

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

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

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

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

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

In FY 2018, five 3-year projects totaling $5,000,000, were awarded competitively in the area of sensors, big data analytics, and application of additive manufacturing. Additionally, direct funded research were continued under I2 for a total of $5,300,000.

In FY 2019, five 3-year projects totaling $4,500,000, were awarded competitively in the area of sensors, digital monitoring, and nuclear plant communication. Also, in FY 2018, the program funded a 2-year project totaling $1,500,000 to advance research in printed sensor capability. Additionally, direct funding research was continued under I2 for a total of $5,500,000.

In FY 2020, 17 directed projects were funded to continue work under the I2 areas for a total of $4,500,000 and one new project on risk-informed predictive analytics was direct funded for a total of $300,000.

A one-page summary for each of the current projects, are organized from newest to oldest, and are listed in the following pages. A list of completed projects is included at the end of the summary document.

FY 2020 NEET-ASI Research Summaries

1. The Nuclear Instrumentation technical area implements research and development activities to develop nuclear instrumentation that addresses critical technology gaps for monitoring and controlling existing and advanced reactors and supporting fuel cycle development. Instrumentation is used to measure process parameters, such as temperature, flux, displacement, pressure, independently of the experiment, component, or process in which it is deployed. Summaries for the following projects are presented in this section:
   - Thermocouples
   - Neutron flux sensors
   - Passive monitors
   - Acoustic sensors
   - Optical fiber-based sensors
2. The Sensor Fabrication by Advanced Manufacturing area implements research and development activities to develop additive, micro, and nano manufacturing techniques for the fabrication of sensors to be used for innovative nuclear instrumentation. Once the feasibility of the fabrication process is validated, advanced manufactured sensors will be deployed as innovative instrumentation as part of the Nuclear Instrumentation area. Summaries for the following projects are presented in this section:
   - Process Control and Sensor Fabrication
   - Feedstock Development
   - Combinatorial Material Science for Sensor Development
3. The Measurement Systems for Nuclear Materials Properties Characterization area implements research and development activities to develop measurement systems that can characterize relevant material properties of nuclear materials in support of the design of advanced reactors and the development of innovative fuel cycle technologies. In contrast to the Nuclear Instrumentation area, Measurement Systems are typically highly intrusive and normally designed for the specific purpose of the measurement rather than deployed in existing experiments or plant systems. Summaries for the following projects are presented in this section:
   - Mechanical Properties
   - Photothermal Radiometry
   - Line Source Method
   - Resonant Ultrasound Spectroscopy
   - Electrochemical Measurements
4. The Instrumentation Deployment area enables the demonstration of sensor technologies in conditions relevant to nuclear power system by testing in facilities available as part of Department of Energy Office of Nuclear Energy research and development program capabilities. This is an essential step towards the development of instruments that are qualified, validated, and ready to be adapted by the nuclear industry. Summaries for the following projects are presented in this section:
   - Flowing autoclave system
   - Mock-up Fuel Re-Instrumentation Facility
   - Irradiation testing
   - Wireless communication
5. Develop Methods and Tools using Nuclear Science User Facilities Data to Support Risk-informed Predictive Maintenance

   Develop a risk-informed predictive analytics capability that would enable optimization of test reactors operation and maintenance. To develop methods and tools to enable risk-informed predictive analytics, acoustic and other data from nuclear science user facilities (NSUF), specifically from advanced test reactor (ATR), will be leveraged.

Nuclear Instrumentation - Thermocouples

PI: Richard Skifton, Collaborators: Lance Hone, Joe Palmer, David Swank, David Cottle – Idaho National Laboratory

Lan Li, Brian Jaques, Scott Riley, Ember Sikorski – Boise State University

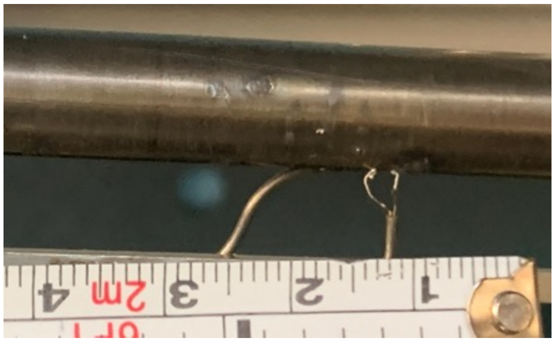
Funding: $278,000 (FY 2020)

Project Description: Addressing the performance of specialized low-drift thermocouples for operation in high-neutron flux environments, the High-Temperature Irradiation Resistant Thermocouples (HTIR-TCs) and their iterations are being tested in prototypic conditions to reactor and fuel surrogates. In addition, specialized thermocouples and welding processes are being developed to measure surface temperature of advanced fuel claddings. Specific FY 2020 scope includes long-term furnace testing of optimized HTIR-TCs, testing traditional HTIRs in flowing autoclave for mechanical reliability assessment under pressurized water reactor conditions, and modeling and simulation for predictive performance assessment.

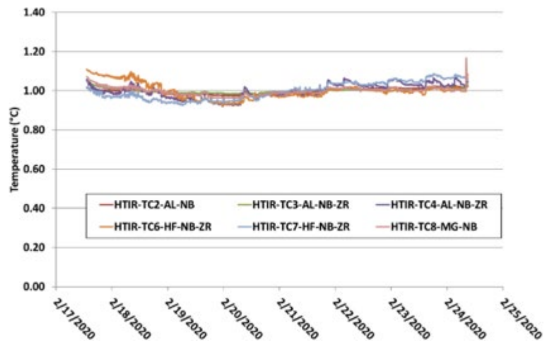
Impact and Value to Nuclear Applications: Real-time temperature measurements are arguably the most imperative observation of irradiation experiments. The HTIR-TC pushes the limit to 1650°C or more, making direct fuel temperature readings achievable during irradiation testing of Generation IV, small modular reactor, and micro-fuel and reactor designs. Further, having an HTIR-TC in place to monitor any potential post-accident condition is advantageous for all reactor operation conditions.

Recent Results and Highlights: The optimized HTIR-TC, or HTIR-Demicouple (DC), has reduced materials and processes to bring down cost and points of failure. The HTIR-DC is being tested at 1250°C in a temperature-controlled furnace over the next 12+ months. Surface cladding junctions―either exposed or intrinsic―are being tested on Zircoloy-4 cladding material.

R&D 100 Award winning, 6-meter-long HTIR-TCs manufactured and ready for deployment.



Intrinsic thermocouple junctions on Zircoloy-4 cladding.



Result of optimized HTIR-TCs in a temperature-controlled furnace. Normalized by average temperature.

Nuclear Instrumentation - Neutron Flux Sensors

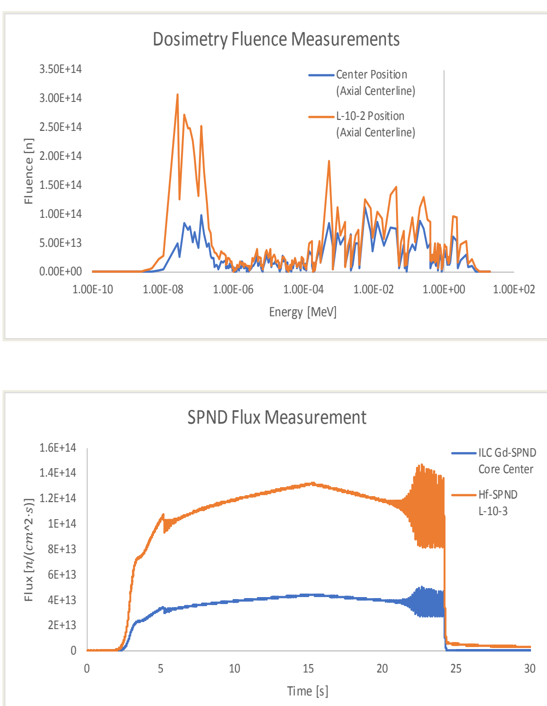
PI: Kevin Tsai, Collaborators: Troy Unruh – Idaho National Laboratory
Brian Jaques – Boise State University
Funding: $770,000 (FY 2020)

Project Description: The neutron flux sensor tasks are to develop, demonstrate, and qualify neutron flux sensors for experimental and operational support. Present activities focus on demonstration and qualification of Self-Powered Neutron Detectors (SPNDs) given its high-technology readiness level. Secondary activities are performing innovative research in radiation-resistant hardware and providing fission chamber fabrication support.

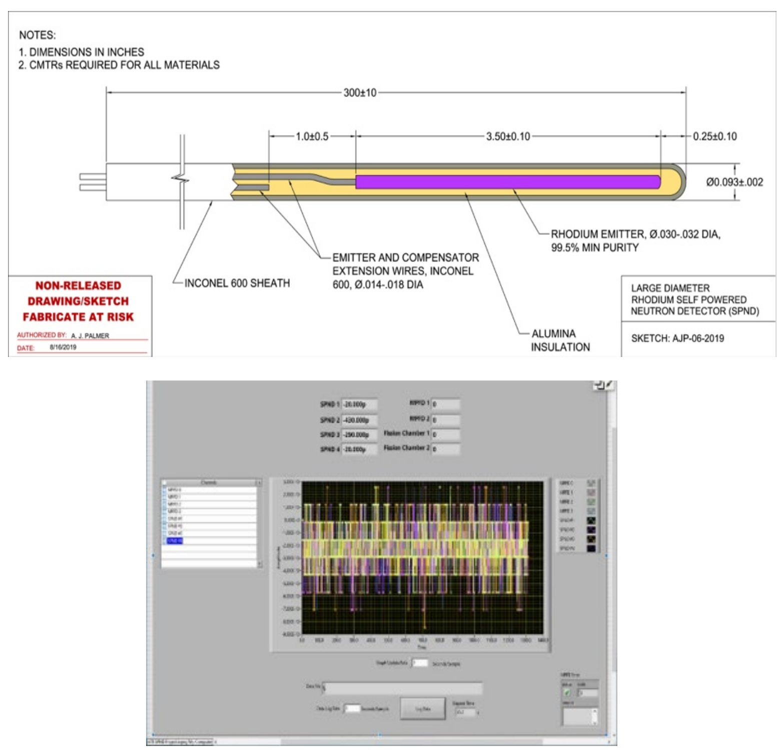
Impact and Value to Nuclear Applications: Development and qualification of neutron flux sensors will provide real-time measurements that improve the standard methods of determining spatially resolved neutron flux beyond reactor dosimetry. Qualified neutron sensors can provide exact flux measurements at key locations in-core that are more reliable than standard ex-core power monitors. Similarly applied to experiments, reliable, localized flux measurements near specimens undergoing irradiation testing are crucial to qualifying new fuels.

Recent Results and Highlights:

Continuing the FY 2019 deployment of Gd-SPNDs in the Transient Reactor Test Facility (TREAT), SPND irradiations were performed concurrently with standard dosimetry in two reactor locations (as shown in the figures on the left])—this is a crucial step toward qualifying the Gd-SPNDs. Additional effort is put toward reproducing the same demonstration in a steady-state reactor with Rh-SPNDs, as shown in the figures on the right.



SPND and dosimetry measurement comparison in TREAT.



Rh-SPND design and measurement software development.

Nuclear Instrumentation - Passive Monitors

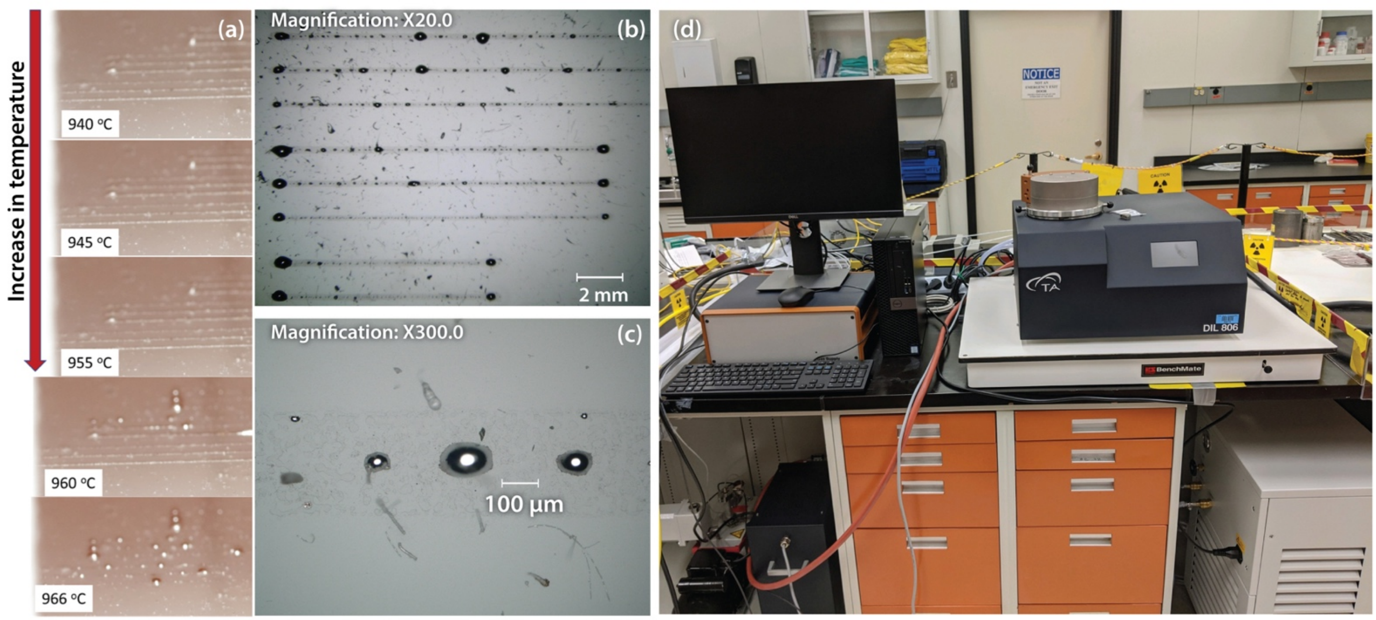
PI: Malwina Wilding; Collaborators: Kurt Davis, Lance Hone, Kiyo Fujimoto, Kunal Mondal, Michael McMurtrey and Troy Unruh – Idaho National Laboratory

Funding: $236,000 (FY 2020)

Project Description: Passive monitors for peak temperature and neutron fluence are needed for when real-time sensors are not practical or economical to install in irradiation testing experiments. This task supports the fabrication of quartz encapsulated melt wire assemblies and flux wires for irradiation testing. The second task that focuses on the use of silicon carbide (SiC) peak temperature monitors (in rodlet and disc shape) is being investigated to provide a more accurate and reliable method to measure averaged, local peak irradiation temperature. A third task is targeted at assessing the use of advanced manufactured passive monitors to improve performance as well as to overcome difficulties with fabrication, deployment, and post-irradiation examination.

Impact and Value to Nuclear Applications: Passive monitors provide a practical, reliable, and robust approach to measure peak irradiation temperature and neutron fluence during post-irradiation examination while complementing the current more-complex real-time temperature and flux sensors.

Recent Results and Highlights: SiC Peak Temperature Monitors were successfully installed and tested high-resolution dilatometer (DIL-806) to 1400°C under inert gas (argon) and vacuum conditions, as shown in Figure 1d. Advance manufactured melt wire arrays of silver (Ag) were heated for initial evaluations of their relative melting temperatures using a high-temperature furnace, as shown in the figure (a–c).



Initial melting testing of printed silver melt wire shown in (a), (b), and (c);
dilatometer fully installed shown in (d).

Nuclear Instrumentation - Acoustic Sensors

PI: Joshua Daw, Collaborators: Lance Hone – Idaho National Laboratory, Dan Deng, David Estrada, Takoda Bingham, Shane Palmer – Boise State University.

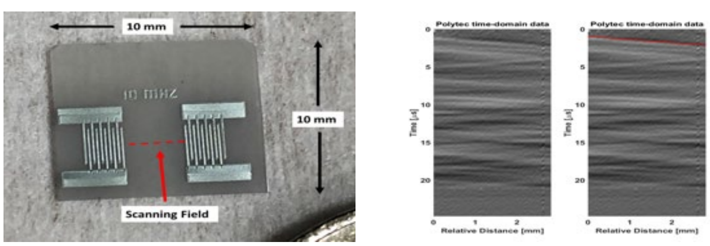
Funding: $729,000 (FY 2020)

Project Description: This project focuses on maturing various acoustic and ultrasonic sensors to a level at which they are routinely deployable for in-pile experiments. Acoustic and ultrasonic methods can be used in numerous sensors measuring a multitude of parameters, including temperature, gas pressure, vibration, etc.

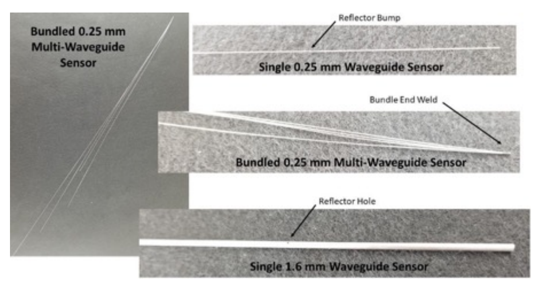
Impact and Value to Nuclear Applications: This project has three primary components: testing of an Idaho National Laboratory (INL)-developed ultrasonic thermometer to determine envelope of use, additive manufacturing of surface acoustic wave (SAW) devices, and identification of sensors/technologies for measuring fission gas pressure and fuel rod vibration in-situ. Given the ability of some ultrasonic sensors to make multiple, spatially resolved and multiplexed measurements, sometimes without direct access to the sample to be measured, development of these sensors will have increasingly relevant impact for given the push to develop new reactor designs.

Recent Results and Highlights:

Efforts to date have involved fabrication of test samples and sensor modeling. Shown in the figure on the left, SAW devices with printed electrodes were fabricated and analyzed with a laser doppler vibrometer. Modeling of a waveguide base ultrasonic thermometer (UT) has begun and is being compared to the performance results of a UT. UTs have been fabricated for "envelope" testing to find the limits of temperature and pressure in which they may be used. To date, UTs for high-temperature testing have been fabricated using stainless steel, zircaloy-4, molybdenum, and tungsten. Different waveguide configurations (as seen in the figure on the right) have been fabricated from stainless steel and molybdenum.



SAW device printed on LiNbO.



Several prototype UT waveguide configurations.

Nuclear Instrumentation – Optical Fiber-based Sensors: Temperature and Pressure

PI: Austin Fleming, Collaborators: Kelly McCary, Pattrick Calderoni – Idaho National Laboratory, Nirmala Kandadai, Harish Subbaraman Sohel Rana – Boise State University, Kevin Chen – University of Pittsburgh

Funding: $912,000 (FY 2020)

Project Description: Optical fibers have the potential to greatly impact the instrumentation used in the nuclear industry. This is largely to their small size, immunity to electromagnetic noise, multi-modal capacity, and high-speed measurement capability. These benefits have made them common-place in other industries with similar demanding measurement applications, such as down-hole and aerospace applications. This multi-faceted project addresses specific challenges that are unique to fiber-optic instrumentation in the nuclear industry. These include, but are not limited to, the radiation-induced effects (attenuation, compaction, emission), high-pressure high-temperature feed throughs, and extending the operating envelope of fiber-optic sensors.

Impact and Value to Nuclear Applications: This project qualifies and adapts fiber-optic sensor instrumentation technologies for use in nuclear applications. The focus of these efforts is on technologies with high-potential impact to the nuclear industry and those with a high-technology readiness level. Some examples include fabry-perot pressure sensors and intrinsic temperature sensors (Rayleigh scattering and Fiber Bragg Gratings).

Enabling the use of fiber optics in the nuclear industry for instrumentation purposes has the potential to revolutionize data density in a variety of measurements. A wide range of nuclear applications include research and development irradiation testing experiments, structural health monitoring, advanced reactor demonstrations, and spent fuel storage monitoring.

Recent Results and Highlights: Recent advances have begun, including in-pile testing of intrinsic fiber-optic temperature measurements using Fiber Bragg Gratings and Rayleigh scatting in radiation-hardened optical fiber. Additionally, a modular extrinsic fabry-perot pressure sensor is actively under development. This pressure sensor has the potential to be easily reconfigured for a variety of pressure ranges to accommodate many measurement needs.

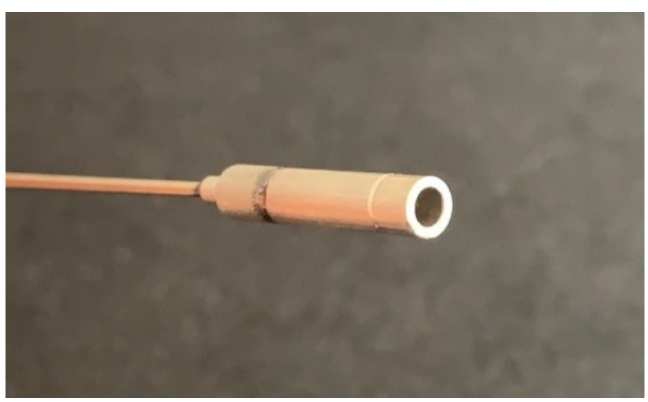


Image of prototype extrinsic fiber-optic pressure sensor.

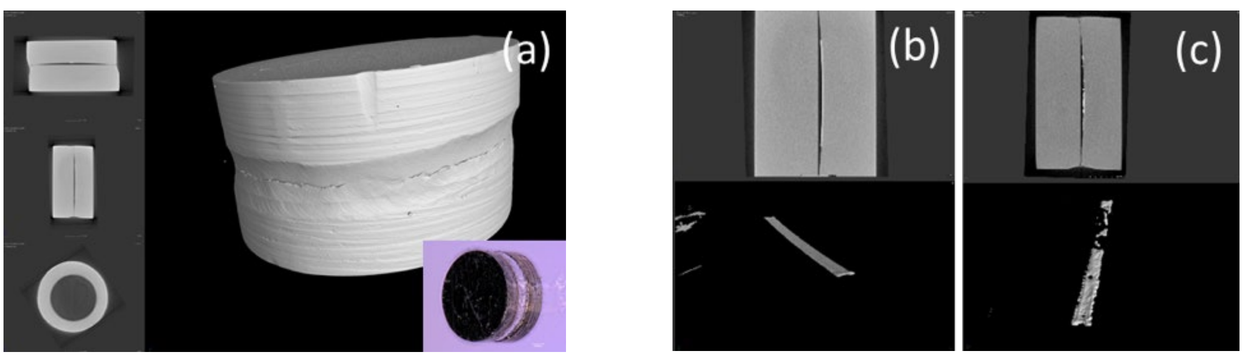
Sensor Fabrication by Advanced Manufacturing – Process Control and Sensor Fabrication

PI: Michael McMurtrey, Collaborators: Kunal Mondal,
Kiyo Fujimoto, Idaho National Laboratory
Funding: $483K, (FY 2020)

Project Description: Direct-write (DW) techniques have been identified as tools with significant promise towards application in a large range of sensor types. DW can create complex 2-D designs while utilizing a growing list of materials (inks). These benefits provide for the development of advanced, innovative in-pile instrumentation. The inks can then be used to form narrow (anywhere from tens to hundreds of micrometers wide) and thin (typically hundreds of nanometers thick) lines that are sintered to create the wires and films of active and passive sensors of use in nuclear test reactors.

Impact and Value to Nuclear Applications: Experiments in nuclear test reactors are expensive and advanced instrumentation will allow for additional information gathered during the irradiation rather than relying solely on post-irradiation examination. Although the highest impact is generally from active sensors, initial research tasks are focusing on passive sensors as they do not require feedthroughs and can easily be added to irradiation experiments. This allows for rapid irradiation testing to infer material survivability as well as to understand passive sensor performance in prototypic conditions.

Recent Results and Highlights: Printed melt wires, a sensor capable of monitoring peak temperature during an experiment, have been fabricated on a chip that is 2 millimeters in diameter and 1 millimeter thick. Furthermore, the melt mires are encapsulated to provide protection from the environments. X-ray-computed tomography (X-CT) is used to inspect the melt wires before and after the irradiation. Initial non-nuclear testing has been performed evaluate not only the manufacturing procedure, but also the ability to visualize the melted wires.



Characterization of printed melt wires: (a) X-ray computer tomography (CT scan) of the melt wire chip. Furnace test of the melt wire: (b) before heating, and (c) after heating at 1000°C confirms melting of the printed silver wire.

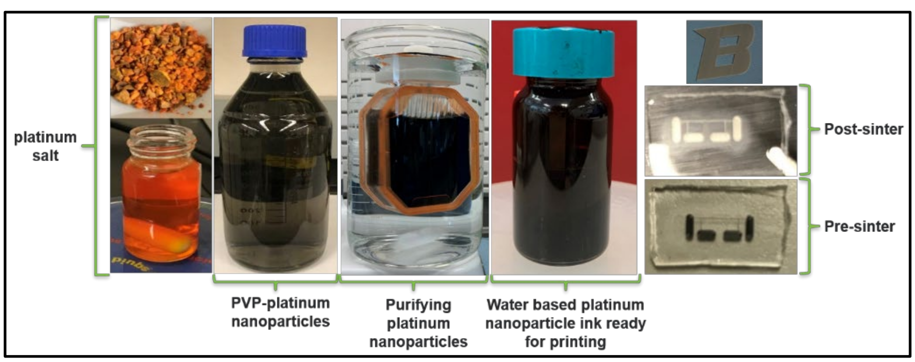
Sensor Fabrication by Advanced Manufacturing – Feedstock Development

PI: Michael McMurtrey, Collaborators: Kiyo Fujimoto – Idaho National Laboratory
David Estrada, Boise State University
Funding: $290K (FY 2020)

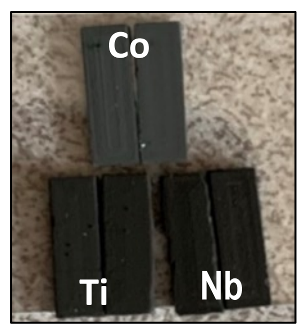
Project Description: This project aims to expand the current library of nanomaterial inks available for additive manufacturing (AM) technologies to encompass those materials that are considered nuclear relevant to facilitate the development of advanced nuclear instrumentation. Utilizing a variety of formulation techniques, nanomaterial inks will be developed that are compatible with several AM methods for the fabrication of in-pile passive sensors capable of inferring reactor peak temperature and neutron flux.

Impact and Value to Nuclear Applications: AM has emerged as the predominant enabler for innovation and design as it significantly expands the design envelope in terms of materials, form, and functionality. Additionally, these technologies enable rapid prototyping, reduced production cost, and reduced material waste in comparison to classical fabrication methods. For nuclear applications, the limiting factor of implementing AM for novel sensor design is the current selection of commercially available feedstock materials that are compatible with these technologies. Significantly expanding this library of materials to include those that are more nuclear relevant provides a necessary pathway towards incorporating these novel methods for nuclear energy applications, and it stands to revolutionize the development of in-pile nuclear sensors. Miniaturized sensors, high-density sensor arrays, and embedded sensors for nuclear applications are all expected to be high-impact-enabling technologies from this research task.

Recent Results and Highlights: The library of materials for additive manufacturing technologies of aerosol jet printing, plasma jet printing, and extrusion printing has been expanded to include Pt, Co, Ti, Fe, Nb, Mo, W, Sn, Zn, and Al_2O_3, as shown in the figure on the left for platinum. Prototypic melt wires and neutron dosimeters are shown in the figure on the right for peak temperature and neutron flux monitoring, respectively, which have been fabricated.



Platinum ink synthesis process.



Printed neutron dosimeter prototypes.

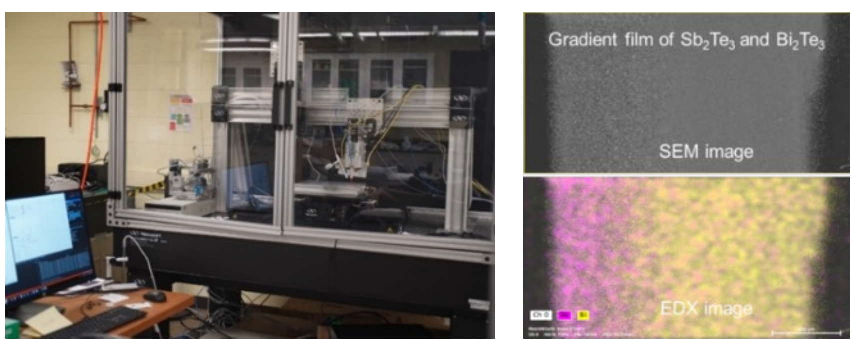
Sensor Fabrication by Advanced Manufacturing – Combinatorial Material Science

PI: Michael McMurtrey – Idaho National Laboratory; Collaborators:
Miles Bimrose, Minxiang Zeng, Nicholas Kempf, Yanliang Zhang, University of Notre Dame
Funding: $137K (FY 2020)

Project Description: While advanced manufacturing is used to produce novel sensor designs, the unique functions of some manufacturing techniques also allow it to be used as a research tool to discover and develop new materials for sensors and instrumentation. Through use of multi-feedstock (or ink), films with gradient compositions can be created for a combinatorial materials science based high-throughput testing to rapidly screen and optimize new material compositions.

Impact and Value to Nuclear Applications: Nuclear test reactors provide a significant challenge for sensor materials, which must retain integrity at high temperatures, potentially corrosive environments, and in the presence of neutron radiation, and must continue to reliably operate as a sensor. Combinatorial materials science provides a method to screen thousands of compositions within a single irradiation test, reducing time and expense when identifying optimal material compositions with desired sensor properties and radiation resistance.

Recent Results and Highlights: A custom built aerosol jet printer was recently completed at University of Notre Dame that mixes multiple inks during the build process. The printer was used to create a film of gradient composition by mixing two test inks. The next set of inks to be tested will be relevant to the high-temperature irradiation resistant thermocouple materials to optimize thermocouple properties and radiation resistance.



Multi-ink combinatorial printer (left) at Notre Dame used to create a gradient composition (right).

Nuclear Materials Properties Characterization - Mechanical Properties

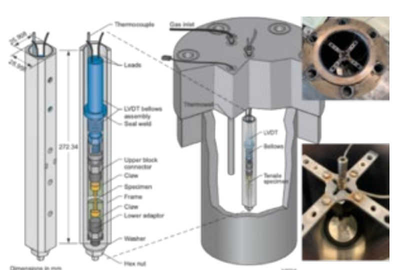
PI: Richard Skifton, Collaborators: Kurt Davis, Malwina Wilding, Anthony Crawford,
Austin Fleming - Idaho National Laboratory;
Brian Jaques David Estrada, Dan Deng, Tim Phero - Boise State University;
Kevin Chen - University of Pittsburg

Funding: $903,000 (FY 2020)

Project Description: Develop instruments to (1) measure mechanical properties of nuclear fuels and materials and (2) characterize the mechanical response of nuclear plant components in operation. In the first area, this project will address the key technological gaps associated with further developing Linear Variable Differential Transformers (LVDT) with the following tasks: establish a viable supply chain for Department of Energy research programs and the U.S. nuclear industry; develop less-intrusive LVDTs to enable application to advanced reactor tests and demonstration facilities; and reduce the cost of LVDT-based systems by demonstrating the compatibility of commercial data acquisition systems (DAS) with nuclear-grade sensors provided by Institute of Energy Technologies (IFE, *Institutt for Energiteknologier*). The near-term application of LVDTs is the creep test rig, which has been selected based on the maturity of the design and the need expressed by ASI program stakeholders. The second area will evaluate the performance of conventional and advanced manufactured strain gauges, optical fibers, and acoustic sensors to measure the response of core components, with near-term application to flow-induced vibrations for small modular reactors and core block characterization for microreactor technologies. In the long term, this project will begin demonstrating non-destructive examination systems for advanced reactors, focusing on acoustic and optical fiber technologies.

Impact and Value to Nuclear Applications: Through collaborative activities and direct procurement of equipment from IFE in Halden, Norway, this project supports the ASI program commitment to ensure continuity in the availability of instrumented irradiation experiments for the U.S. nuclear industry after the closure of the Halden Test Reactor. The characterization of nuclear components in operational environments is crucial to advanced reactor design demonstrations, while reliable non-destructive evaluation (NDE) techniques would enable advanced operation and maintenance processes with demonstrated cost effectiveness in other industrial sectors.

Recent Results and Highlights: (1) Creep test rigs based on LVDT technology have been fabricated and tested out of pile in static autoclaves. (2) Customized LVDTs have been procured from IFE and their operation has been evaluated with commercial DAS. (3) A test facility (Double Delta) for mechanical properties instruments has been designed and fabricated. *The Double Delta device employs two concentric-opposing 3-D motion delta platforms equipped with force/torque sensors to closely assimilate multi-physic (force, vibration, thermal, etc.), 3-D reactor environments while remaining extremely controllable and accessible. Most measurement systems in this field (e.g., Stewart Platform Configuration) are typically limited to one of these aspects and lack the breadth to study interactive phenomena, especially when also being driven by representative 3-D motions/loadings.*



Creep test rig incorporating LVDT sensors. The rig is placed in an autoclave environment.

Double Delta system for stress, strain, and radial deformation measurements.

Nuclear Materials Properties Characterization - Photothermal Radiometry

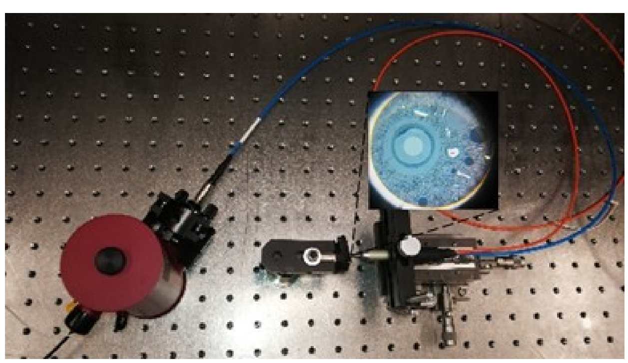
PI: Zilong Hua, Collaborators: Robert Schley, Zain Karriem, Zachery Thompson, Austin Fleming, David Hurley – Idaho National Laboratory

Funding: $400K (FY 2020)

Project Description: The goal of this project is the development of an optical fiber-based instrument to measure in-pile thermal conductivity of fuels and materials. This instrument is based on photothermal radiometry and involves locally heating a sample and measuring the temperature gradient by collecting black-body radiation. The sample conductivity is extract by comparing experimental results with continuum-based models. This contactless, remote measurement approach has numerous advantages over laser flash and modulated thermo-reflectance techniques. First, it is insensitive to the surface condition, thus no surface preparation is required. Second, measurement accuracy increases with increasing temperature making it ideally suited for high-temperature measurements. Third, this technique does not require access to the backside of the sample. Lastly, this approach can be used to measure friable spent fuel samples with irregular and/or poorly defined boundary conditions.

Impact and Value to Nuclear Applications: Thermal conductivity of nuclear fuels is a critical physical property that is directly related to reactor safety, reliability, and efficiency. Moreover, development of advanced fuels with higher thermal conductivities will enable operating fuels at lower temperatures. Low-temperature operation is desirable because fission gas transport is greatly reduced at lower temperatures. Understanding how thermal conductivity changes with irradiation is key to the development of high-conductivity fuels. Thermal transport in oxide and to a lesser extent in metallic fuels is influenced by radiation defects such as point defects, dislocation loops, small defect clusters. Researchers have speculated for years that the conductivity in-pile can be significantly different from that measured in a post-irradiation examination (PIE) environment. The reason for this is that point defects, which effectively scatter thermal carriers, anneal before PIE measurements can be performed. Having the ability to make accurate, in-pile measurements of fuel conductivity will greatly benefit advanced fuel performance codes and will aid in the development of high-conductivity fuels.

Recent Results and Highlights: A free-space photothermal radiometry system, (built in FY 2019) was used to gather data on several samples having conductivities that span the spectrum from high-conductivity fresh metallic fuels to low conductivity spent oxide fuels. A continuum-based model was used to define a measurement envelop that produces accurate/reproducible results. This work helps identify and isolate measurement artifacts associated with white-light diffraction and transfer function nonlinearities. Current efforts are aimed at heating and infrared collection using fiber optics.



Proof of concept system using a fiber-optic to collect black-body irradiation associated with transient laser heating. The inset shows an optical micrograph of the fiber end facing the sample.

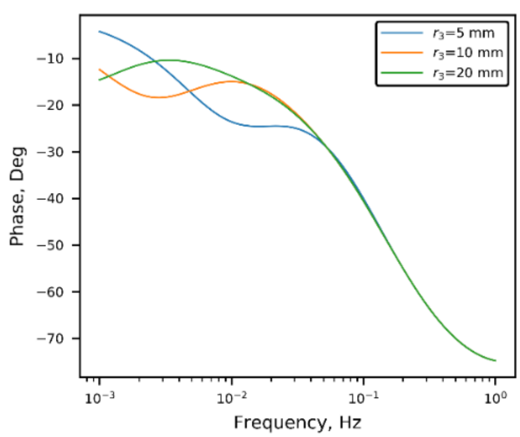
Nuclear Materials Properties Characterization – Line Source Method

PI: Austin Fleming, Collaborators: Kurt Davis – Idaho National Laboratory,
David Estrada, Katelyn Wada – Boise State University
Funding: $200,000 (FY 2020)

Project Description: Thermal conductivity of nuclear materials is of high interest and importance because of its impact on the ability of a nuclear reactor to efficiently transfer energy to its cooling system. The transient line source technique is a standard technique for measuring the thermal conductivity of semi-infinite materials, but it cannot account for finite sample sizes or for thermal contact resistance between the heat source and the specimen. This results in significant errors in the thermal property measurement; therefore, it requires a more-sophisticated technique. The FY 2020 tasks include the development of a frequency domain measurement technique for thermal conductivity. This approach draws on the advantages of the 3-omega technique and the transient line source method to enable probe miniaturization to allow higher measurement frequencies for greater spatial resolution. This improved spatial resolution helps account for finite specimen sizes and the thermal contact resistance.

Impact and Value to Nuclear Applications: The disruption of materials microstructure from irradiation damage has a significant impact on thermal properties of the material. This is especially true for nuclear fuel, which, in addition to the microstructure damage, accumulates fission products. Accurate values thermal properties of these nuclear materials are essential for the proper design and operation of power producing reactors. This complex relationship to irradiation damage and burnup makes in-pile thermal property measurements highly desirable.

Recent Results and Highlights: To establish this novel thermal property measurement technique, both analytic and finite element solutions have been developed for multi-layered conduction models to account for the probe properties, contact resistance, and finite sample sizes. These models are used to perform the inverse problem to extract the measured thermal properties. They also identify the appropriate measurement frequencies to enhance measurement sensitivity of the desired thermal property and minimize the impact of other factors. The following figure provides one of these results that demonstrates the frequency dependency of the sample radius.



Thermal conductivity probe frequency domain characterization.

Nuclear Materials Properties Characterization - Resonant Ultrasound Spectroscopy

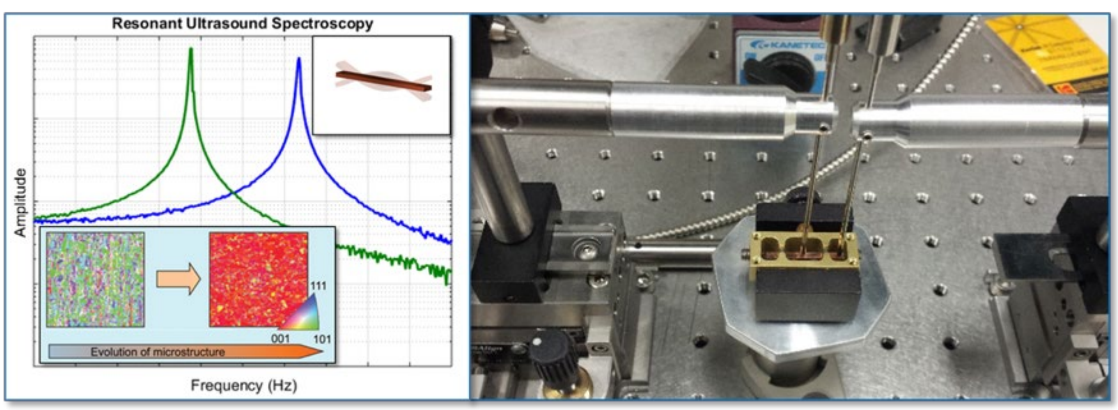
PI: Robert S. Schley, Collaborators: David H. Hurly, Zilong Hua – Idaho National Laboratory

Funding: $576,000 (FY 2020)

Project Description: The goal of this project is the development of an ultrasonic-based instrument for in-pile monitoring of microstructure evolution. The measurement approach involves optically exciting and detecting flexural waves in a thin sample beam. The resonant frequency of the vibrational modes can be indirectly tied to microstructure. Examples include relating changes in the polycrystalline elastic constants to changes in texture and connecting changes in acoustic attenuation to changes in dislocation density.

Impact and Value to Nuclear Applications: This technology will provide a new capability for monitoring microstructure evolution under irradiation that cannot be captured in a post-irradiation examination. By providing a better understanding of how microstructure changes under irradiation, this project supports the objectives of the In-pile Instrumentation (I2) program to develop instruments to aid in the development of advanced fuels and materials.

Recent Results and Highlights: An irradiation capsule for use with a cantilever beam was developed and tested in FY 2019. This work culminated in an irradiation test at the Idaho National Laboratory's Transient Reactor Test Facility (TREAT). This test was successful and has attracted attention from National Nuclear Security Administration-Department of Energy. Currently, the Low-Enriched Uranium (LEU) development program is funding a similar test to study a reduction in the phase transition temperature of U-10Mo under irradiation. FY 2020 work under the I2 program is focused on developing a free-free beam configuration that will eliminate the cantilever boundary condition. Meeting the cantilever boundary condition is difficult in practice and consequently introduces additional uncertainty. Moreover, the cantilever boundary condition precludes precise measurement of ultrasonic attenuation. A conceptual test capsule for a free-free beam geometry has been designed and is undergoing benchtop testing. The beam is held at nodal points for the first flexural mode and should minimize ultrasonic coupling to the environment. Higher sensitivity detections methods are also being investigated due to the smaller displacements in a free-free beam configuration. Initial testing has shown the ability to detect the first flexural mode of the beam as shown below.



Resonant ultrasound used to measure changes in microstructure. Left: monitoring high-temperature changes in grain microstructure associated with changes in texture. Right: Test capsule used to test new free-free beam geometry.

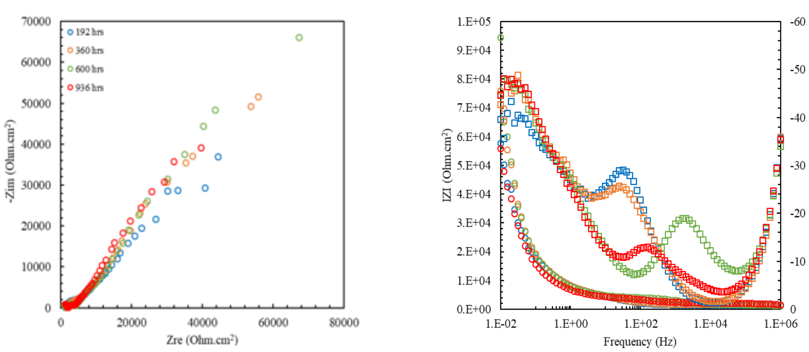
Nuclear Materials Properties Characterization - Electrochemical Measurements

PI: Hongqiang Hu, Collaborators: Ling Ding - Idaho National Laboratory,
Michael F. Hurley, Hui Xiong, Min Long, Corey Efaw, Michael Reynolds - Boise State University
Funding: $400,000 (FY 2020)

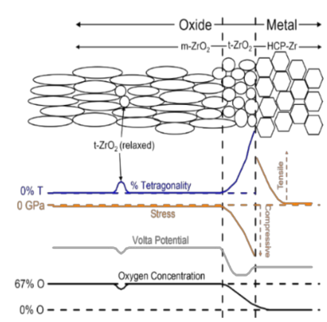
Project Description: This project will develop electrochemical impedance spectroscopic (EIS) instruments that will enable in-pile studies of changes in chemistry. Examples include monitoring changes in stoichiometry and measuring the growth of oxide and hydride layers in extreme irradiation and temperature environments. EIS-based instruments are well suited to measure changes in chemistry associated with several nuclear materials and under a variety of environmental conditions. To demonstrate the utility of EIS instruments, specific attention will be paid to monitoring changes in cladding hydride formation and cladding corrosion.

Impact and Value to Nuclear Applications: The primary contribution of this project will be the development of an EIS instrument capable of monitoring surface chemistries of cladding materials under conditions that mimic that of the pressurized primary coolant. Real-time information associated with changes in cladding materials that can be performed without interrupting reactor operations is an important advantage of EIS-based sensing. In the near-term, it is expected that this instrument will prove useful in the development and qualification of new alloys used in fuel cladding applications. In mid-term, this instrument or slightly modified versions of this instrument may be used in more demanding applications, including monitoring chemical redistribution and changes in stoichiometry under irradiation.

Recent Results and Highlights: Two EIS testing systems were designed: one for an air-environment for both fuel pellets and cladding materials, and another for aqueous conditions for cladding materials only. The impedance spectra for a sample Zircaloy-4 as a function of immersion time is demonstrated in the figure on the left. This data provides key information regarding near surface structural and chemical changes. Two scenarios are considered to understand the EIS reponse of this system. If a dense oxide is formed, one time constant is sufficient to model the impedance data. The frequency dispersion commonly observed could be attributed to surface roughness of the underlying metal and dielectric relaxation. If the oxide is composed of multiple layers with different properties, several time constants are needed to model the data. The changes observed are related to changes in the pore structure. Samples were characterized using various techniques. All metal/oxide parameters are summarized schematically in the figure on the right. The percent tetragonality, stress, Volta potential, and oxygen concentration are shown for different phases of zirconia and zirconium metal. Preliminary results of finite element FE modeling on hydride evolution and distribution show that hydrogen can penetrate the cladding surface at a rate of 0.5 mm per year.



EIS signal of Zircaloy-4, Nyquist (left) and Bode (right) plot.



Zirconia inter-phase.

Irradiation Deployment - Flowing Autoclave System

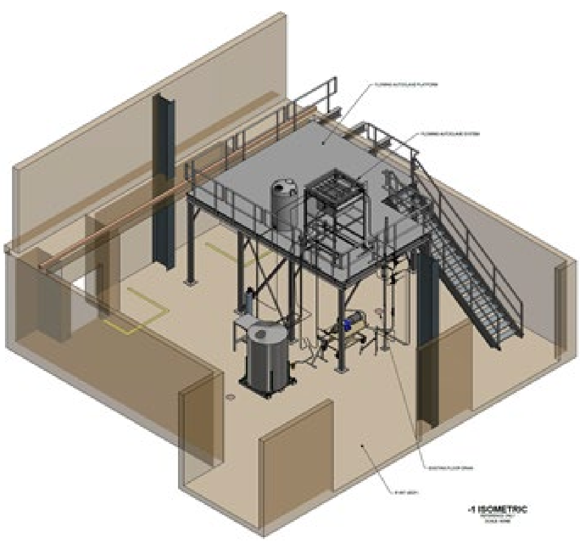
PI: Richard Skifton, Collaborators: Nate Oldham, Bryce Kelly,
Lisa Moore-McAteer – Idaho National Laboratory

Funding: $583,382 (FY 2020)

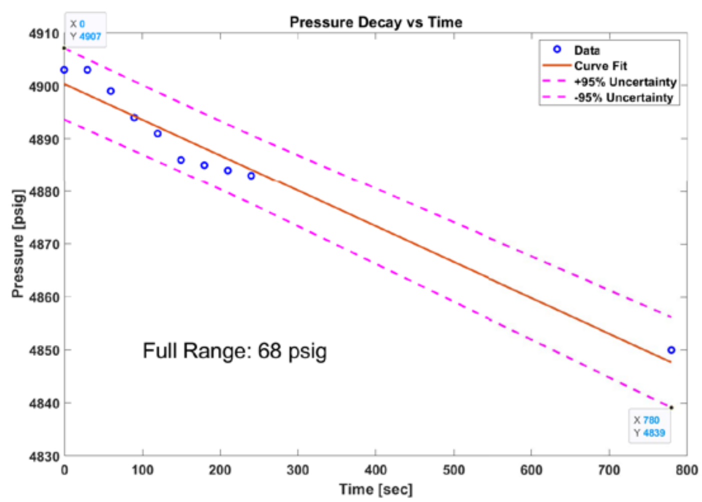
Project Description: A Flowing Autoclave System (FAS) is designed, fabricated, and assembled to provide non-nuclear prototypic flow and chemistry conditions for relevant test sections of the Idaho National Laboratory's (INL) Advanced Test Reactor (ATR). The FAS will be primarily used to demonstrate instrumentation performance in pressurized water reactor (PWR) prototypic conditions (thermocouples, linear variable differential transformer [LVDT], self-powered neutron detectors [SPND], etc.) as needed to support irradiation testing experiments prior to insertion into ATR.

Impact and Value to Nuclear Applications: The FAS accurately prototypes reactor PWR conditions to serve as a testbed for instrumentation in irradiation testing experiments. By characterizing non-nuclear performance of in-pile instrumentation inside the FAS prior to insertion in the reactor, any points of failure can be readily fixed in a timely, cost-effective manner.

Recent Results and Highlights: The water Flowing Autoclave System is capable of controlled water chemistry, vibration measurements via accelerometers, and the following maximum conditions: 180 L/min [50 gal/min] flow rate (empty channel), 15 MPa [2200 psi], and 320°C [600°F]. The FAS was recently commissioned with a 10-min, over-pressurization test to 32.8 MPa (+1.7 MPA/-0 MPa) [4750 psi (+250 psi/-0 psi)]. The FAS is now available to test sensors, wiring feedthroughs, and other experiment design details in non-nuclear prototypic conditions of ATR.



An isoview of the FAS facility located at Idaho National Laboratory. The ATR relevant test section can be seen right of center just below the upper deck.



A pressure decay test at over-pressurization of the entire system was performed on the FAS for ~10 min. This was the last commissioning test before the FAS was fully operational.

Instrumentation Deployment - Mock-up Fuel Re-Instrumentation Facility

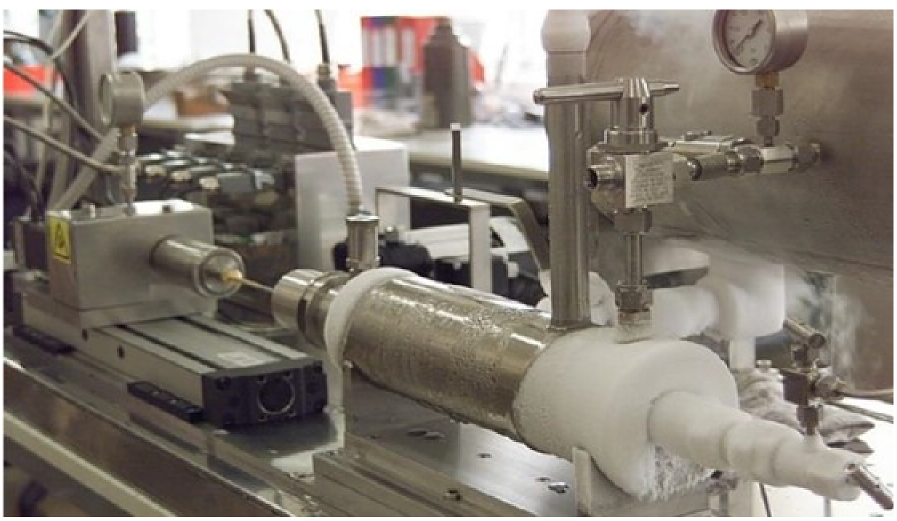
PI: Joe Palmer, Collaborators: Pattrick Calderoni and Malachi Nelson – Idaho National Laboratory

Funding: $948,000 (FY 2020)

Project Description: Develop specifications and procure a set of prototype equipment modules designed to "refabricate" previously irradiated commercial nuclear fuel into shorter lengths with integral instrumentation embedded, a process termed "re-instrumentation." The modules are to be procured from the Institute for Energy Technology (IFE) in Halden, Norway, previously also known as the Halden Reactor Project.

Impact and Value to Nuclear Applications: Nuclear fuel research has a multi-decade history of success in developing new technologies, decreasing the frequency of refueling outages in commercial reactors while producing more reliable fuel pin designs. The acknowledged leader in this field for light water reactor (LWR) fuel research has been the Halden Reactor Project in Norway. Both the U.S. Department of Energy and the commercial nuclear industry have relied upon Halden's expertise to refabricate and reinstrument previously irradiated fuel rods—the key technology to enable in-situ measurements in reactor. These techniques are no longer actively practiced at Halden since the 2018 decision by the institute that operates the reactor to terminate reactor operations. To preserve the capabilities developed by Halden engineers over decades of research and practice, a set of prototypical equipment modules is being procured. These equipment modules will be used not only to practice installing standard instrumentation, such as thermocouples, but also as a testbed to develop techniques for incorporating advanced fiber-optic and acoustic-based sensors into fuel pins. This activity is key to advancing critical research in modern LWR and advanced reactor fuels.

Recent Results and Highlights: In March 2020, a contract was issued to IFE to procure two of the three equipment modules required to reinstrument surrogate fuel rods. These modules are scheduled to be delivered to INL in FY 2020.



Example image of fuel rod being drilled in preparation for installation of a thermocouple. The fuel is frozen cryogenically to stabilize it during the drilling process.

Instrumentation Deployment - Irradiation Testing

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

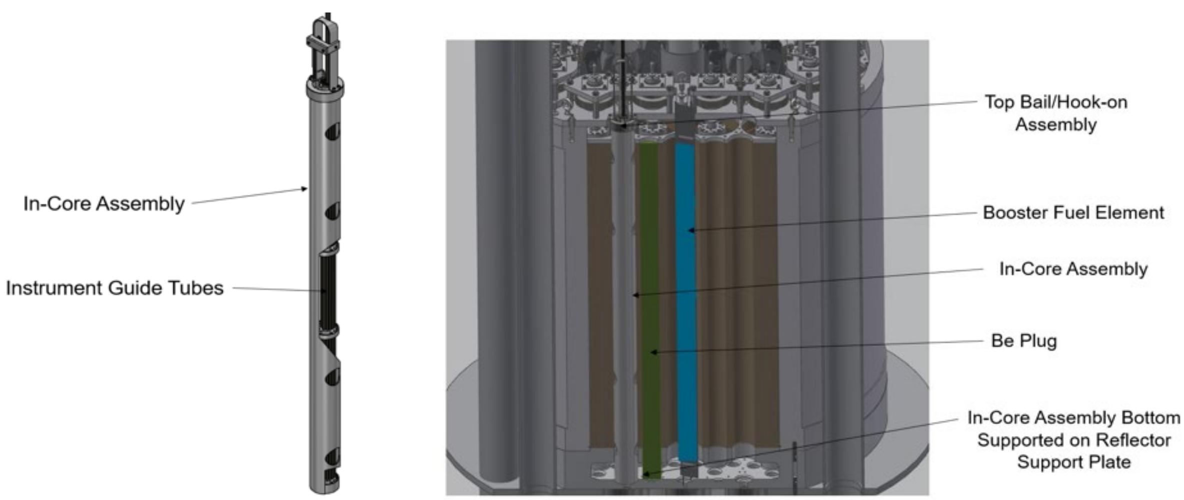
Funding: $675,000 (FY 2020)

Project Description: Develop capabilities to test and demonstrate in-pile instrumentation in conditions similar to those expected to be seen in irradiation testing experiments. This testing and demonstration will lead to the use of this instrumentation in the qualification of new fuels and materials as well as the eventual use in commercial nuclear reactors. The Irradiation Testing Activity provides this by focusing on three areas for FY 2020: (1) test neutron sensors in the Advanced Test Reactor Critical (ATRC) facility, (2) test transient instrumentation performance in the Transient Reactor Test Facility (TREAT) via concurrent testing and neutron-equivalent devices, and (3) deploy optical fiber probes in the High Dose Graphite-1 (HDG-1) experiment.

Impact and Value to Nuclear Applications: Successful completion of these activities will create new capabilities at the INL ATR and TREAT facilities that are crucial to support the development, demonstration, and deployment of advanced in-pile instrumentation. These instrumentation deployments will enable highly instrumented irradiation testing of nuclear fuels and materials in support of the U.S. advanced nuclear technology industry.

Recent Results and Highlights:

1. The design of the components needed for installation of the neutron flux test in the ATRC core is complete. The final design review is scheduled for mid-April.
2. The following ASI instruments have been deployed for test in TREAT: five SPNDs, one fiber-based pyrometer, one distributed temperature sensor fiber, one impedance sensor, one Micro-Pocket Fission Detector MPFD, and neutron dosimeters.
3. Fabrication of two optical fiber probes for deployment in the ATR HDG-1 experiment is complete.



In-core instrument holder assembly installed in ATRC.

Instrumentation Deployment – Wireless Communication

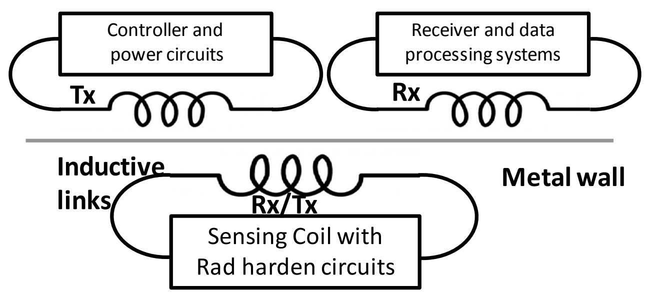
PI: Vivek Agarwal; Collaborator: James A. Smith – Idaho National Laboratory

Funding: $118,000 (FY 2020)

Project Description: The focus of this activity is to compile the state-of-the-art wireless communication technologies and their applications in nuclear environments to support development and deployment. This activity will advance the implementation of smart processes and structures by being able to cost effectively create a large network of sensors within and around nuclear reactors.

Impact and Value to Nuclear Applications: Wireless communication enables the ability to reliably and securely transmit data from a measuring location to another location for further processing without cables that can become prohibitively expensive to install and maintain. Advancements in wireless communication to support in-pile sensing and communication is expected to have a transformative impact on the nuclear industry as has already been seen in other industries. Traditional wireless communication approaches use radio frequency (RF) or passive methods to transfer data. One of the challenges with RF communication technologies is reliable operation of electronics when exposed to harsh environments. While in the case of passive communication, it is attenuation of the signal during transmission. This research is reviewing promising communication technologies that can ensure reliable transfer of sensor signals and develop an appropriate test plan to evaluate feasibility of the technology.

Recent Results and Highlights: Researchers at INL reviewed several wireless technologies that have the potential to support in-pile sensing and communication. In particular, inductive technology will be the focus going forward because of potential synergistic opportunities with future in-pile testing experiments.



A schematic representation of inductive sensing and communication.

Develop Methods and Tools using Nuclear Science User Facilities Data to Support Risk-informed Predictive Maintenance

Vivek Agarwal, Idaho National Laboratory

Funding: $300,000 (10/01/2019 – 09/30/2020)

Description of project: The project will develop a risk-informed predictive analytics capability that would enable optimization of test reactors operation and maintenance. To develop methods and tools to enable risk-informed predictive analytics, acoustic and other data from nuclear science user facilities (NSUF), specifically from advanced test reactor (ATR), will be leveraged.

Impact and value to nuclear applications: The research outcomes will lay the foundation for advanced reactors to influence their design process by including risk-informed knowledge to support salient measurements. This will allow then to achieve the maintenance by design concept and perform cost-benefit analysis. The approach developed as part this research can be extended to and utilized by other facilities under NSUF as they have similar data; thus, NSUF data are very important.

Recent results and highlights

Figure 1 illustrates the proposed research approach, highlighting the fact that predictive analytics outcome can be incorporated into traditional risk assessment techniques. Different available data, including ATR's primary coolant pump vibration and acoustic data collected as part of a Laboratory Directed Research and Development project, will be leveraged. This will allow stakeholders to update the risk profile of plant system with the time- and condition-based information. Initial data analysis of acoustic signals collected at primary coolant pumps (PCPs) is shown in Figure 2.

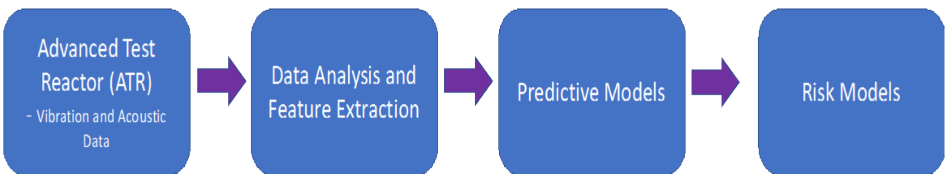


Figure 2. Proposed research approach.

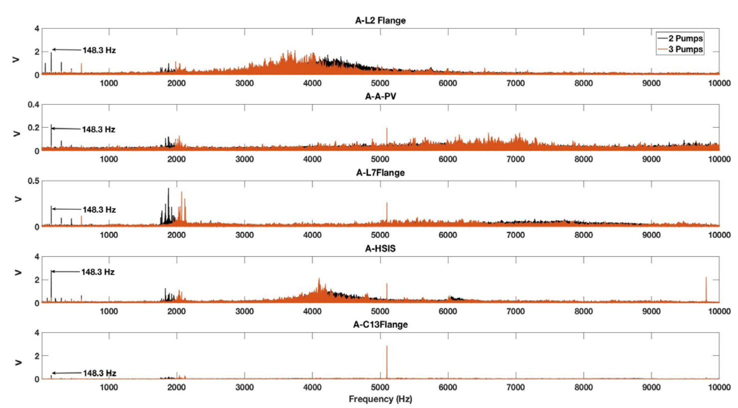


Figure 3. Fast Fourier Transformation of the acoustic signal shows when 2 PCPs and 3 PCPs are operated. PCP vane Frequency of 148.3 Hz is observed at all locations.

FY 2019 NEET-ASI Research Summaries

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

   Develop and demonstrate advanced online monitoring to better manage nuclear plant assets, operation, and maintenance.

2. Context-Aware Safety Information Display for Nuclear Field Workers

   Development of an "Intelligent Context-Aware Safety Information Display" (ICAD) for nuclear power plant (NPP) field workers.

3. Design of Risk-Informed Autonomous Operation for Advanced Reactors

   Develop and demonstrate artificial reasoning systems for operator decision support, aided by autonomous control technology, for advanced nuclear power reactors.

4. Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

   Improve the economic competitiveness of advanced reactors through the optimization of cost and plant performance, which can be achieved by coupling intelligent online monitoring with asset management decision-making.

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

   Develop an integrated sensor concept that enables simultaneous measurements of temperature, pressure, and gas composition using a single sensor platform, thereby limiting the number of penetrations in a reactor vessel that are needed.

6. Direct Digital Printing of Sensors for Nuclear Energy Applications

   Deploy a network of PWSTs at a location of interest to the nuclear industry. The network is comprised of novel digitally printed radio frequency (RF) surface acoustic wave (SAW) devices that act as a platform for a multitude of sensing modalities.

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

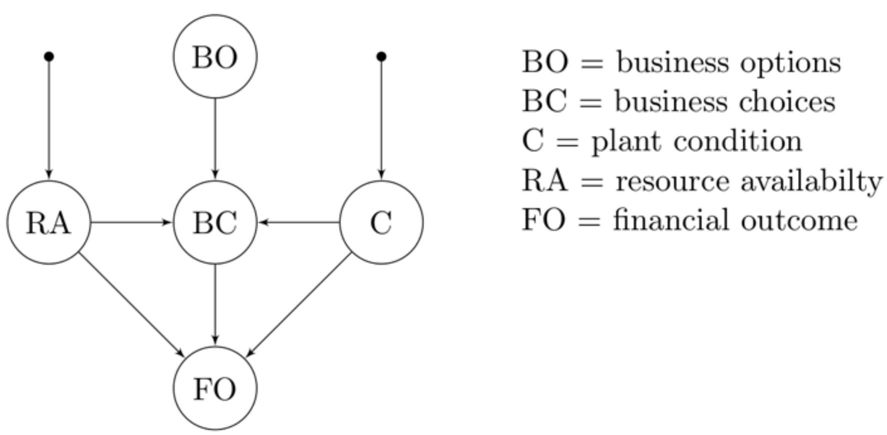
PI: Daniel G. Cole, University of Pittsburgh

Funding: $1,000,000 (10/1/2019 – 9/30/2022)

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

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

Recent Results and Highlights: Bayesian networks are the tool we use to integrate the disparate fields of supply chain reliability, condition monitoring, and business and financial decisions. We have been building Bayesian networks for the supply chain, using the Delphi method to collect expert opinion about resource availability and for system components to estimate condition.



An asset management model integrates the plant condition, the supply chain risk, and business options to determine the financial outcome of different decisions.

Context-Aware Safety Information Display for Nuclear Field Workers

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

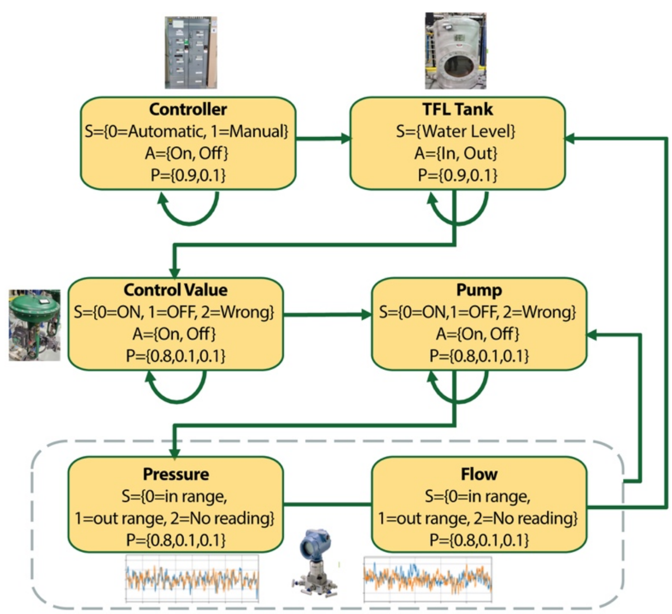
Funding: $500,000 (10/01/2019 – 09/30/2022)

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

Field: AR information display example.

Impact and Value to Nuclear Applications: This project will produce knowledge and technical approaches for supporting real-time safety information display to nuclear workers. About 80% of the undesirable events in the commercial nuclear industry are due to human factors. Real-time safety information display to nuclear workers can guide field workers to reduce errors that lead to incidents and accidents, thereby creating positive social, economic, and technical impacts for the nuclear industry.

Recent Results and Highlights: The project team worked on the following research activities in this reporting period: (1) conducted literature review of operations in NPPs with light water reactors and synthesized the most frequent operational errors and problematic processes that occurred in the field; (2) designed ontologies that represent the logical relationship among NPP-operation-related concepts, processes, and errors synthesized from the literature; and (3) established a process model based on a flow loop operation training process as a case study to find out how operational errors occur and propagate in this process and identify key actions, objects, and locations that are at high risks.



Operation process modeling.

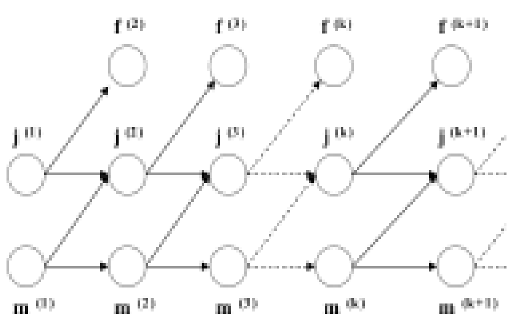
Design of Risk-Informed Autonomous Operation for Advanced Reactors

PI: Michael Golay, Massachusetts Institute of Technology
Hyun Gook Kang, Rensselaer Polytechnic Institute
Sacit M. Cetiner, Pradeep Ramuhalli, Oak Ridge National Laboratory
Jong Gyun Choi, KAERI, ROK
Funding: $1,000,000 (10/01/2019 – 09/30/2022)

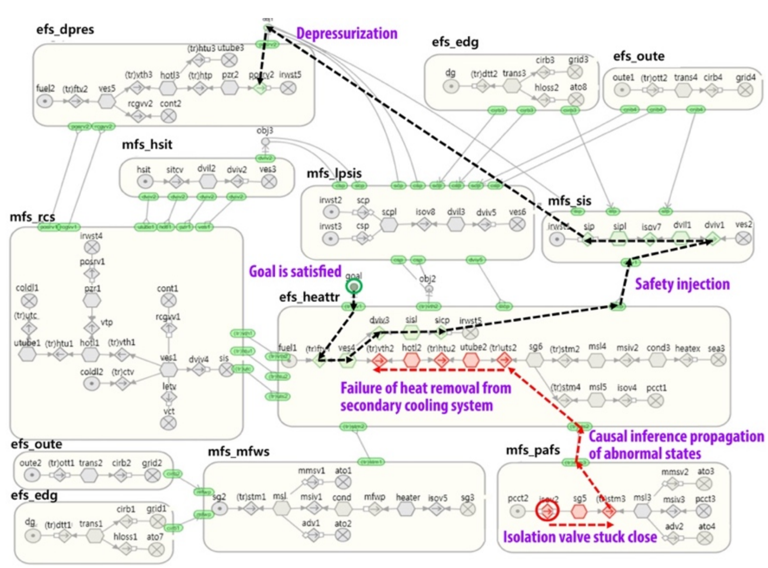
Project Description: The objective of this project is to develop and demonstrate artificial reasoning systems for operator decision support, aided by autonomous control technology, for advanced nuclear power reactors. A critical aspect of the operator decision support technology proposed here is the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

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

Recent Results and Highlights: The solution is under development to build an integrated framework of component diagnostics and plant prognostics for enhanced plant operation decision making based on the data analytic methods and the inference modeling. Empirical data and model-based data are under collection to be incorporated to produce the example inputs.



Markov modeling for system status categorization



Simplified causality model of a typical PWR accident

Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

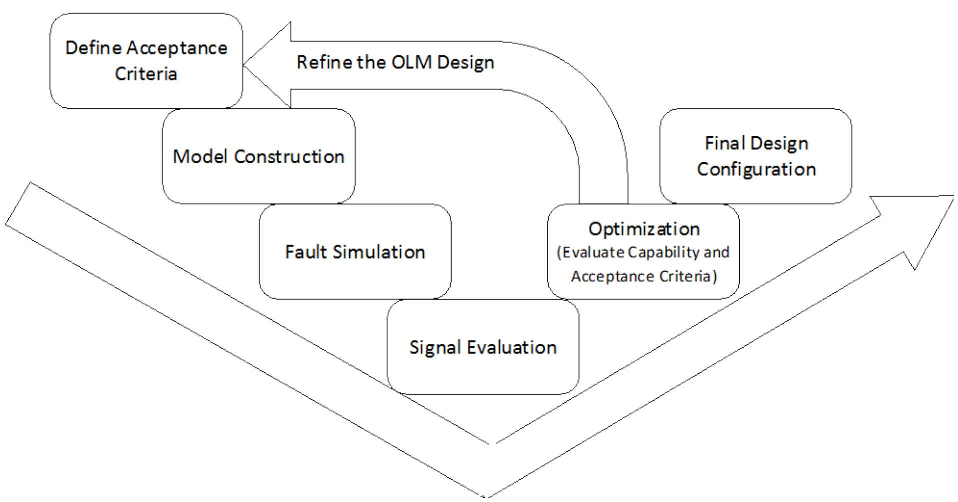
PI: David Grabaskas, Argonne National Laboratory
Carol Smidts, Ohio State University
Eric Helm, Framatome
Funding: $1,000,000 (10/01/2019 – 9/30/2022)

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

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

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

Recent Results and Highlights: Research is currently focused on the coupling of the sensor network design method with available tools for online monitoring and fault diagnostics during operation. In addition, methods for incorporating online diagnostic information into the real-time plant risk profile are also under review.

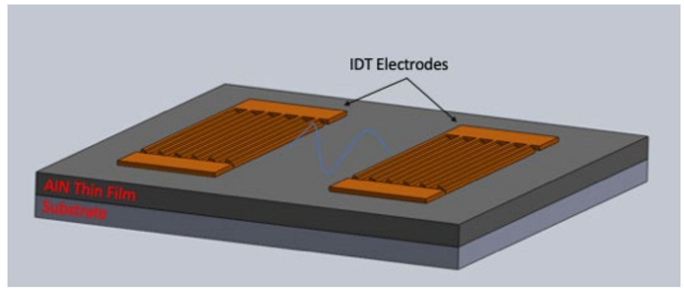


Methodology for Online Monitoring (OLM) system design with fault analysis.

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

PI: Mike Larche, Tiffany Kaspar, Morris Good, Pacific Northwest National Laboratory
Haifeng Zhang, Chen Zhang, University of North Texas
Funding: $1,000,000 (10/01/2019 – 9/30/2022)

Project Description: Advanced reactor environments, such as molten salt reactors, present a number of challenges for in-situ sensing, including elevated temperatures, radiation, and infrequent outages. New sensors capable of operating in these harsh conditions are needed for monitoring critical parameters, including temperature, flow, pressure, and fission gas composition, among other parameters. The Acousto-Optic Smart Multimodal Sensors project is developing an integrated sensor concept that enables simultaneous measurements of temperature, pressure, and gas composition using a single sensor platform, thereby limiting the number of penetrations in a reactor vessel that are needed. This sensor concept is based on the use of surface acoustic wave devices, and uses acousto-optic coupling for high-sensitivity, high-reliability measurements in a challenging environment.

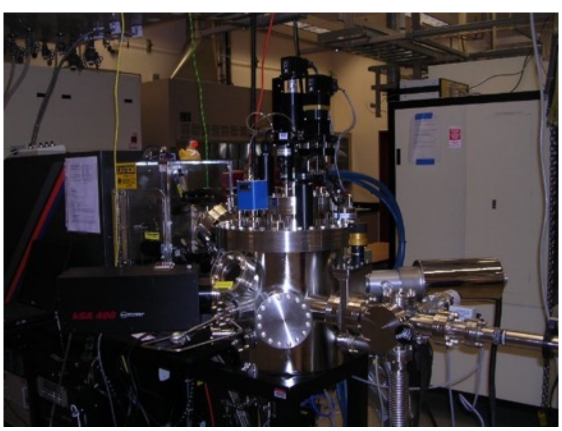


SAW device concept.

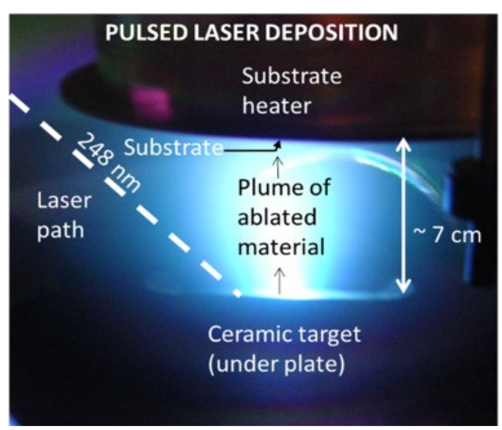
Impact and Value to Nuclear Applications: An integrated multimodal sensor platform will aid in the reduction of reactor pressure vessel penetrations. Appropriate materials selections consistent with high-temperature and harsh environments will also aid in filling gaps identified in available reactor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

Recent Results and Highlights: In the current stage of this project, the team is leveraging modeling and simulation tools for designing a temperature/pressure sensor concept. This preliminary surface acoustic wave sensor concept will be used as a starting point for the multimodal sensing concept and aid in the development of necessary thin-film deposition process optimization, interdigital electrode fabrication, and development of evaluation criteria for assessing the multimodal concepts.

Preparations for growing nitride films using the Pacific Northwest National Laboratory thin film deposition laboratory (shown below) are being made in parallel with modeling and simulation activities.



PNNL thin film deposition laboratory.



Pulsed laser deposition detailed view.

Direct Digital Printing of Sensors for Nuclear Energy Applications

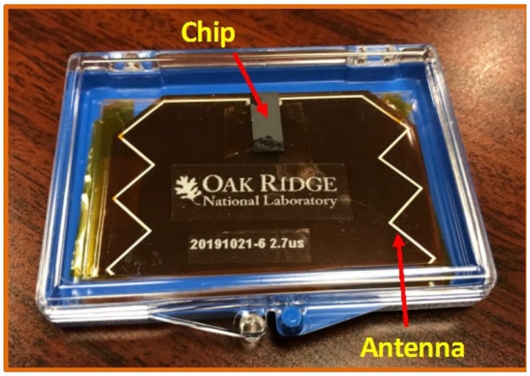
PI: Timothy J. McIntyre, Oak Ridge National Laboratory

Funding: $2,000,000 (10/01/2019 – 9/30/2020)

Project Description: Researchers at Oak Ridge National Laboratory (ORNL) are developing and demonstrating prototype passive wireless sensor technology (PWST). Our goal is to deploy a network of PWSTs at a location of interest to the nuclear industry. The network is comprised of novel digitally printed radio frequency (RF) surface acoustic wave (SAW) devices that act as a platform for a multitude of sensing modalities. Currently, several sensor types have been developed, including temperature, hydrogen gas, voltage, and current. The RF/SAW sensor platform is fabricated by state-of-the-art additive manufacturing (AM) technologies. RF/SAW functionalization, also being developed by ORNL, is done by depositing ultra-thin films into the acoustic wave propagation path, thereby altering the wave properties. The sensor platform is inherently temperature sensitive because the substrate is piezoelectric. Our functionalization methods additionally make the RF/SAW device responsive to hydrogen, voltage, current, and other stimuli as well.

Impact and Value to Nuclear Applications: Passive wireless RF/SAW sensors have no batteries, can be economically produced by AM, can sense physical parameters directly (temperature, strain, pressure, voltage, current, etc.), and can be functionalized (coatings on the SAW devices) to sense many things (moisture, H_2, CH_4, CO, CO_2, C_2H_2, etc.). Many more sensors can be deployed, which increases sensor network robustness and information quality by redundancy. Sensor degradation and failure can be rapidly identified by monitoring nearest neighbors. 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.

Collecting more reliable and accurate data streams will improve analytics. For example, Southern Company, Nuclear Division is developing remote, real-time monitoring capabilities for their electricity generation fleet. Enhanced data streams will feed new machine-learning algorithms to look for anomalies from normal operation. The ability to detect incipient failures in operating equipment enables improved preventative maintenance strategies that reduce human exposure to hazardous conditions. The types of sensors developing in this project include hydrogen sensors for both leak detection (<500 ppm) and hydrogen coolant inventory monitoring in gas turbines (<97%). Current, voltage, phase, and temperature measurements on power conductors that switch gear, breakers, generators, etc., are also of interest.



RF/SAW sensor and printed antenna.

Recent Results and Highlights: ORNL has developed and tested multiple sensor types, including temperature, hydrogen, voltage, and current. Additionally, simultaneous readout of multiple sensors (5+) and multiple sensor modalities (temperature, H_2, and voltage) has also been demonstrated. Further, successful communication with sensors over long distances (>100 ft) has been shown. Lastly, robust interrogator designs that reliably function outdoors for an extended period of time, can be constructed.

FY 2018 NEET-ASI Research Summaries

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

   Address a unique challenge in the area of digital monitoring (i.e., the application of advanced sensor technologies [particularly wireless sensor technologies] and data science-based analytic capabilities) to advance online monitoring and predictive maintenance in nuclear plants and improve plant performance.

2. Development of optical fiber-based gamma thermometer

   Build an optical fiber-based gamma thermometer (OFBGT) and test it in two University Research Reactors (URRs) of different in-core configurations. Develop methods to process the data that is produced by OFBGTs to produce estimates of the power density in the volume of the reactor that surrounds the OFBGTs.

3. Process-Constrained Data Analytics for Sensor Assignment and Calibration

   Develop and demonstrate data-analytic methods to address the problem how to assign a sensor set in a nuclear facility, or subsystem in the facility, such that (1) a requisite level of process monitoring capability is realized, and in turn, (2) the sensor set is sufficiently rich to allow analytics to determine the status of the individual sensors with respect to their need for calibration.

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

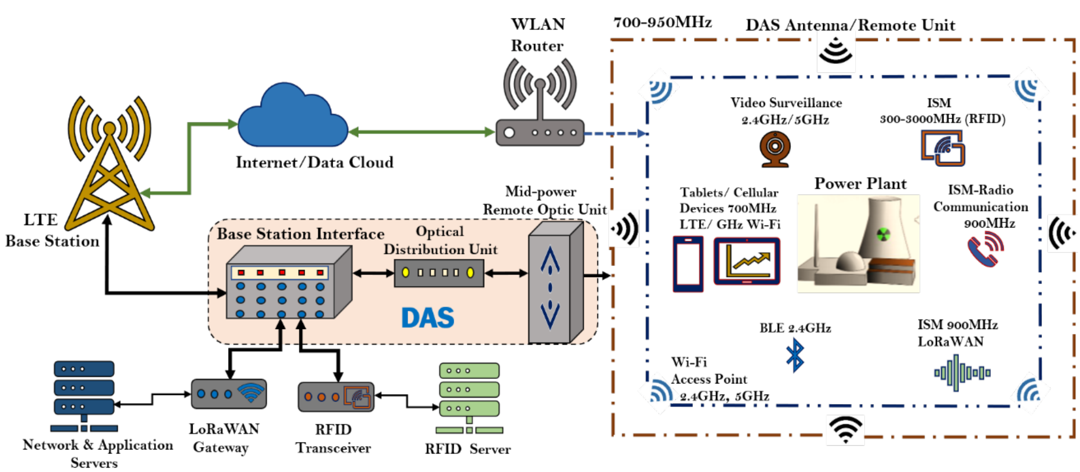
PI: Vivek Agarwal, Ahmad Al Rashdan, and Ronald Boring, Idaho National Laboratory
Pradeep Ramuhalli, Oak Ridge National Laboratory
Michael Taylor, Electric Power Research Institute
Scot A. Greenlee, Exelon Generation Company
Funding: $1,000,000 (10/01/2018 – 09/30/2021)

Project Description: The project will advance online monitoring and predictive maintenance in nuclear plants to enhance efficiency gain and economic competitiveness. Specific objectives are defined to achieve project goal. This includes: (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) scalable visualization algorithm.

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:

To attain automation, the nuclear industry is beginning to leverage wireless communication technologies. The proposed multi-band heterogeneous wireless network (Figure 1) would enable industrial applications that require low- to high-power, low- to high-frequency, and short- to long-range communication regimes. The TEA considered wireless local area network (WLAN) and distributed antenna system (DAS) as the backbone of the proposed network. The TEA showed that the number of DAS units required to achieve technical feasibility is less than WLAN units, but that DAS units are expensive even without taking into consideration industrial, scientific, and medical (ISM) band technologies. For both machine-to-machine and real-time video transmissions, the network performance of both DAS and WLAN networks are comparable.



Techno-economic analysis of a multi-band heterogeneous network.

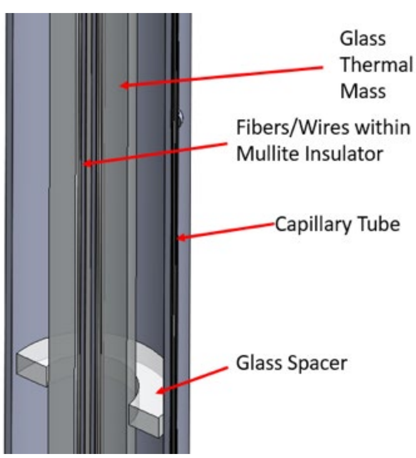
Development of an Optical Fiber Based Gamma Thermometer

PI: 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)

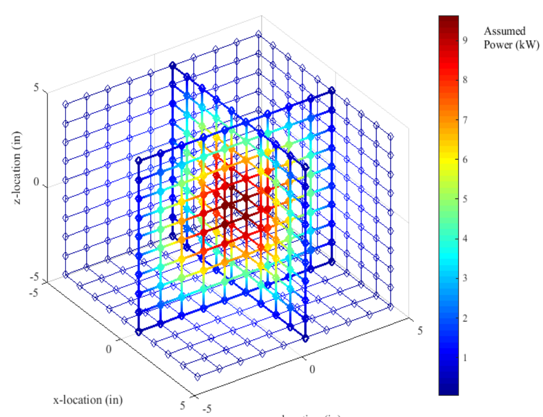
Project Description: The objective of this project is to develop an optical fiber-based gamma thermometer (OFBGT). A system of OFBGTs could be used to calibrate the power monitors in reactors. Also, utilizing data analytics, a system of OFBGTs could be used to determine the power distribution in a reactor directly. We are presently developing a silica-fiber OFBGT, and plan to develop a sapphire-fiber OFBGT (see Figure 1). We postulate that the sapphire-fiber OFBGT could withstand the extreme temperatures in next generation reactors. We are developing data analytic methods to obtain the power distribution from the OFBGTs, which fundamentally measure gamma-ray (and to a lesser extent, neutron) absorbed dose in the OFBGT thermal mass (see Figure 2). 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 enable a permanent system for calibration of power monitors, which would replace traversing in-core probes (TIPs), which are currently utilized in boiling water reactors. Also, an OFBGT can extend the entire length of an instrument tube, and acquire a distributed gamma-ray absorbed dose rate along its length. TIPs, or even thermocouple-based gamma thermometers, act as point sensors and do not possess such a capability. Therefore, OFBGTs are particularly useful regarding "big data" generation and enable a higher resolution measurement of the 3-D distribution of core power than can be obtained with ion chambers.

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



Cross-sectional internal view of OFBGT.



Testing of data analytic methodology.

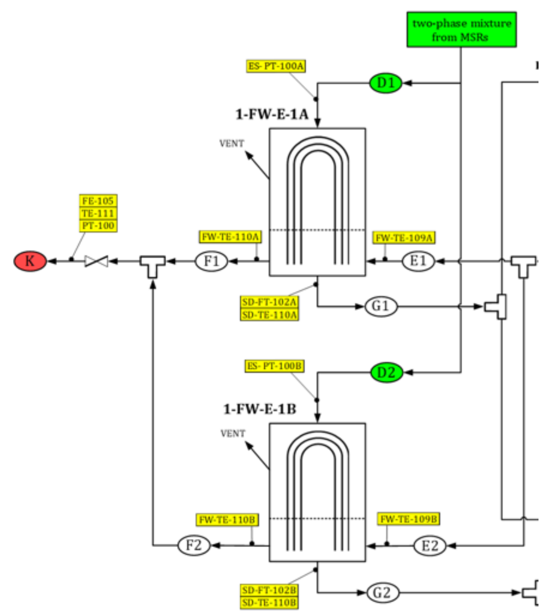
Process-Constrained Data Analytics for Sensor Assignment and Calibration

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

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

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

Recent Results and Highlights: The optimal sensor set problem suffers from the curse of dimensionality where computation time increases exponentially as the size of the system grows. To overcome this difficulty, a pre-conditioner algorithm was developed to find an approximate solution close to the actual solution. This serves as a seed for the full-blown algorithm and acts to constrain the space that must be searched. The solution algorithms have been implemented on a parallel computing platform. In a case under investigation with a collaborating utility partner, the sensor set upgrade needed to provide adequate coverage to infer that a sensor calibration status is being identified. Preliminary results indicate the value in approaching the sensor assignment problem at the system level rather than standalone component level.



A portion of the utility partner's High-Pressure Feedwater System being analyzed under the sensor assignment optimization study.

FY 2017 NEET-ASI Research Summaries

1. 3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics, and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures

   Develop 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.

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

   Develop high temperature embedded/integrated sensors (HiTEIS) and laser ultrasound transducers for remote monitoring of reactors and fuel cycle systems.

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

   Focused on the research and development of a new in-situ, reusable, and reversible sensor concept for integrated temperature monitoring applying combination of photonic properties of radiation-hardened waveguides and temperature progress of the properties of chalcogenide glasses (ChG), specifically their crystallization.

4. Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring

   Develop an acoustic-based sensing system that will be able to monitor phenomena such as strain, temperature, pressure, and material corrosion in real-time to better evaluate the aging and degradation of relevant structural components in nuclear facilities.

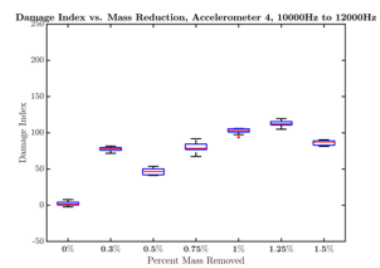
3-D Chemo-Mechanical Degradation State Monitoring, Diagnostics, and Prognostics of Corrosion Processes in Nuclear Power Plant Secondary Piping Structures

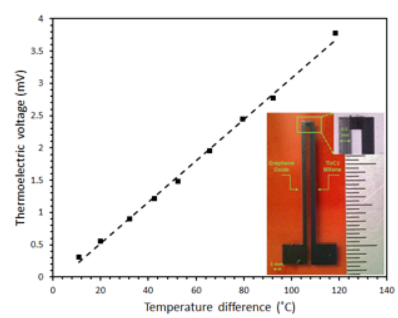
PI: Douglas Adams, Kane Jennings, and Sankaran Mahadevan, Vanderbilt University
Yanliang Zhang, University of Notre Dame
Vivek Agarwal, Idaho National Laboratory
Funding: $1,000,000 (10/1/2017 – 9/30/2020)

Project Description: This project develops an automated 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.

Recent Results and Highlights: Vanderbilt developed a measurement system for detecting mass loss using six accelerometers mounted on an elbow that is installed in the pipe rig. A damage index for quantifying changes in transmissibility was formulated using the weighted sum of relative transmissibility over the measured frequencies of the operational acceleration spectra collected on the pipe rig. The damage index increased at Accelerometer Location 4 as the mass was removed incrementally from the inside diameter of multiple pipe elbows. Additionally, Notre Dame printed the thermocouples on a flexible Kapton substrate using graphene oxide and Mxene films that showed good sensitivity of 32 uV/K and linear relationship between voltage and temperature. A matrix of thermocouples printed on pipes for monitoring temperature, used in conjunction with a pipe thermal model, could estimate mass loss due to corrosion.





Top plot of damage index developed using pipe vibration measurement showing increase in index as inner surface of pipe wall is removed causing a mass decrease. Bottom plot of voltage versus temperature for printed thermocouples on a flexible Kapton substrate showing high sensitivity of 32 uV/K.

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

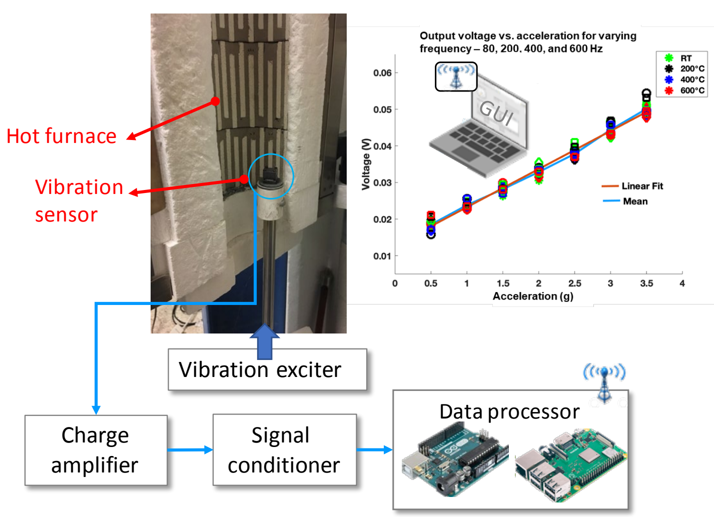
PI: Dr. Xiaoning Jiang, Dr. Mohamed Bourham, Dr. Mo-Yuen Chow, North Carolina State University
Dr. Leigh Winfrey, Pennsylvania State University
Funding: $999,688 (10/01/2017 – 09/30/2020)

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

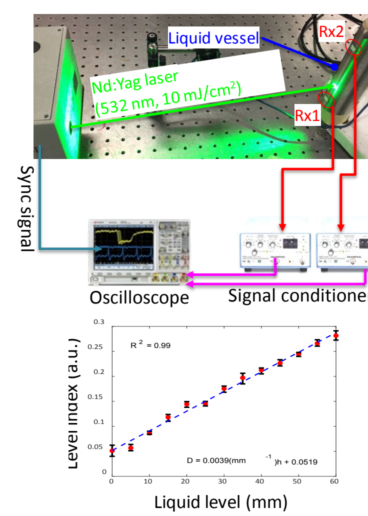
Impact and Value to Nuclear Applications: The development of HiTEIS will enable non-invasive sensing of operation parameters of nuclear power plant structures. Remote communication system will aid to monitor nuclear power plant system more frequently in reliable manners and removing human operators from the vicinity of high-temperature and radiation hazards.

Recent Results and Highlights:

AlN (aluminum nitride single crystal) vibration sensors were prototyped and validated under high-temperature (1000°C) and radiation (>10 kGy) conditions. A wireless communication system was tested for the remote sensing of vibration in a hot furnace (600°C). The laser-assisted liquid level sensor using leaky guided ultrasound waves was developed and tested. Radiation and corrosion resistance of sensing elements are currently being studied.



Remote vibration sensing using an AlN sensor under a high temperature condition.



Laser-assisted liquid level sensor and the validation.

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

PI: 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 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 in the nuclear facilities.

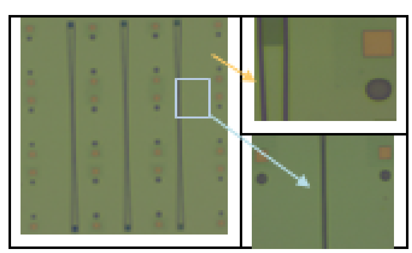
Impact and Value to Nuclear Applications: The sensor offers opportunity for nuclear safety, in particular—for facilities, their employees, and the public—by offering increased sensor system accuracy, real-time monitoring, reliability, and efficiency. The technology is addressing nuclear materials quantification and tracking. Delivery of a novel hybrid plasmonic sensor that is easier and less costly to manufacture, and which will continue to function after radiation exposure, is expected. The sensor can be quickly and easily reset and reused for subsequent measurements.

Recent Results and Highlights: In the recent development of the project, the prototypes of the temperature sensors were fabricated. They have been irradiated with ion fluxes with energies of 200, 600, and 1,000 keV, fluence 1014/cm^2 and dislocation per atom (dpa). Devices characteristics were measured before and after irradiation (the top figure shows stable performance and radiation hardness).

In parallel, the electron beam lithography (EBL) method for fabrication of waveguide based devices has been initiated. Optimization of the waveguide device structures and e-beam process has been performed, which will ensure high yield of successfully fabricated devices.

Further development of the work includes production of waveguide-based devices, as well as fiber tip type of devices, their employment for temperature measurement, and experiments in radiation environment for establishing their application in nuclear facility.

Prototype of the temperature sensor, working on a temperature switch by current application; devices in the irradiation plate; I-V characteristics of $Ge_{33}SE_{67}$ devices before and after variety of irradiation



SEM image of produced waveguide devices with enlarged grating coupler and tapper lines, as well as enlarged waveguide.

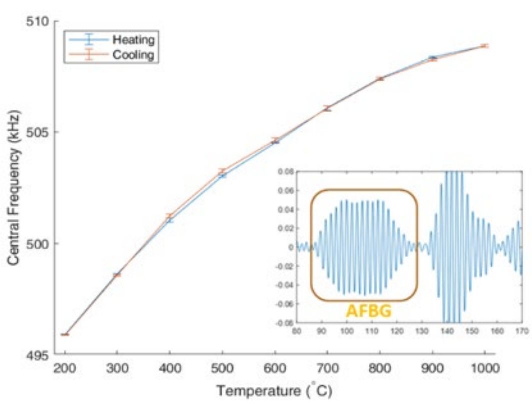
Versatile Acoustic and Optical Sensing Platforms for Passive Structural System Monitoring

PI: 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)

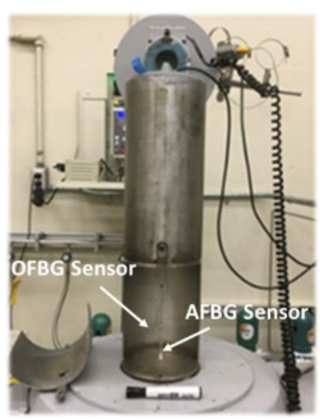
Project Description: The objective of this research program is to develop an acoustic-based sensing system that will be able to monitor phenomena such as temperature, pressure, and material corrosion in real time to better evaluate the aging and degradation of relevant structural components in nuclear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

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

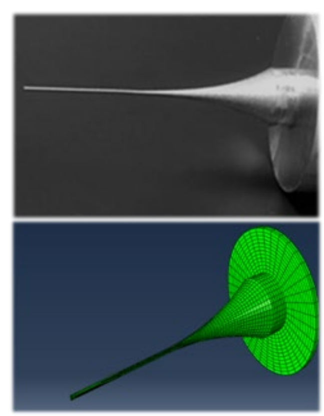
Recent Results and Highlights: A prototype all-fused silica acoustic fiber Bragg grating (AFBG) temperature sensing system was fully integrated, performance tested to a temperature of 1000°C (see figure on the left), and successfully deployed for gamma radiation exposure testing at Oak Ridge National Laboratory (see middle figure). A new "Coupled Mode" method was developed to describe the acoustic response of discontinuities in acoustic fiber waveguides (AFWs) for accurate AFBG sensor design. A micro-acoustic amplifier/horn was designed and optimized for coupling energy to the AFW (see figure on right). The successful demonstration of the AFBG sensing system provides the framework for integration of the technology with selected materials and multi-parameter sensing.



Performance testing of fused silica AFBG sensor up to 1000°C.



Radiation exposure testing of AFBG and OFBG sensors.



Aluminum micro-acoustic horn/amplifier.

FY 2016 NEET-ASI Research Summaries

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

   Develop the technology necessary for a wireless reactor power distribution measurement system.

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

   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.

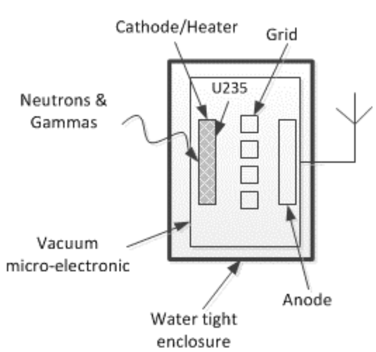
Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and a Gamma-Harvesting Power Supply

PI: Jorge Carvajal, Michael Heibel, Westinghouse Electric Company
Dr. Kenan Unlu, Pennsylvania State University Radiation Science and Engineering Center
Total Budget: $986,535 (10/1/2016 – 7/31/2020)

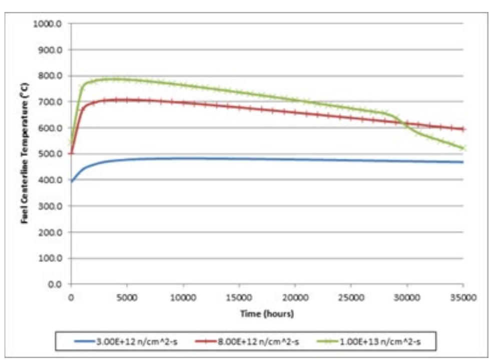
Project Description: The project is developing the technology necessary for a wireless reactor power distribution measurement system. This novel power distribution measurement system utilizes highly radiation- and temperature-resistant vacuum micro-electronics (VME) technology that continuously broadcasts 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 also includes 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 (SPND) 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.

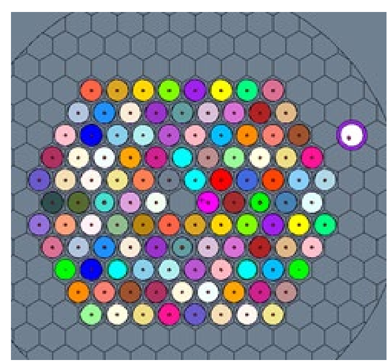
Recent Results and Highlights: Energy harvesting methods, such as using a fissionable material and a gamma heating element, have been investigated for the VME heater element with the goal of thermionically emitting electrons without the traditional electrical current. The figure on the left shows the simplified schematic of the VME. Predictions using fuel performance code PAD, shown in the middle figure, that temperatures above 700°C are possible. Monte Carlo N-Particle (MCNP) simulations using the gamma heating characteristics of tungsten as the heater element were also performed. The figure on the right shows the Penn State Breazeale Reactor core top view with a tungsten piece (dimensions representative of a real heater element) on the top right. MCNP results show that temperatures above 900°C are possible. The tungsten heating approach will be demonstrated at the Penn State Breazeale Reactor in FY 2020.



VME schematic.



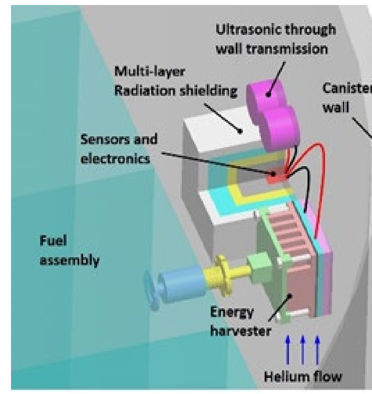
Fissionable material temperature.


MCNP tungsten.

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

PI: Lei Zuo, Virginia Tech, Haifeng Zhang, University of North Texas,
Nance Ericson, Oak Ridge National Laboratory
Funding: $1,000,000 (10/01/2016 – 9/30/2020)

Project Description: The objective of this project is to develop novel energy harvesting and wireless through-wall data communications technology for in-situ monitoring of interior conditions in enclosed metal vessels or thick concrete walls as found in dry storage canisters and nuclear reactor vessels. This objective is being achieved with the collaborative effort of two universities, a national laboratory, and a company through three innovations: (1) direct harvesting of electrical energy from gamma irradiation heating using thermoelectric devices, (2) transmitting sensor data through the metal wall using ultrasound, and (3) creatively designing and packing high-temperature electronics circuits with radiation hardening and/or shielding inside the enclosed nuclear vessels.



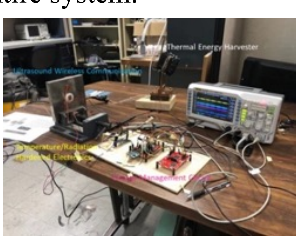
Energy harvester for powering sensing and communications.

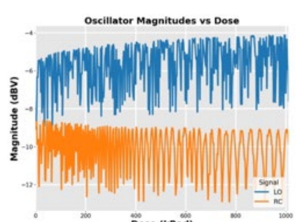
Impact and Value to Nuclear Applications: The expected impacts and benefits include:

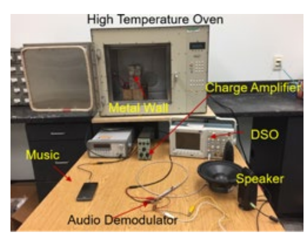
1. Energy harvesting from nuclear radiation where no other energy sources are available,
2. Validating the proposed electronics system incorporating energy harvesting and advanced communications through dense barriers, as is needed in nuclear environments,
3. Developing and reporting of a detailed strategy for full realization of a high-temperature, radiation-tolerant electronics and a through-wall data communication platform for nuclear environments.

Recent Results and Highlights:

1. Conducted gamma radiation testing on all system modules at the Westinghouse Astronuclear Laboratory (124 Mrad – energy harvesting and acoustic communication modules; 2 Mrad – sensor electronics).
2. Completed the energy harvesting module and circuit design and tested the prototypes in radiation and high-temperature environment.
3. Demonstrated the through-wall communication system and the system has passed the radiation test. The performance of the transducer and receiver were satisfactory under strong Gamma radiation.
4. The sensor circuit signal frequencies measured demonstrate a slight logarithmic frequency shift due to the dose while the data integrity remained consistent (2 Mrad gamma dose).
5. Completed the system integration testing of the three modules validating the feasibility and stability of the entire system.







System Integration Test Set-up (@VT).

High Temperature Through Wall Data Communication Set-up (@UNT).

Measured Oscillator Fundamental Frequency Magnitudes with Respect to Gamma Dose (@ORNL).

COMPLETED PROJECTS

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

FY 2011

- A High Temperature-tolerant and Radiation-resistant In-core Neutron Sensor for Advanced Reactors, The Ohio State University, $455,629 (9/29/2011–9/30/2014)
- High Temperature Transducers for Online Monitoring of Microstructure Evolution, Pennsylvania State University, $455,628 (10/12/2011–12/31/2014)
- NEUP: One-Dimensional Nanostructures for Neutron Detection, North Carolina State University, $455,629 (9/29/2011–9/30/2014)

FY 2012

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

FY 2013

- Radiation-Hardened Circuitry using Mask-Programmable Analog Arrays, Oak Ridge National Laboratory, $400,000 (10/01/2013–09/30/2015)
- Radiation Hardened Electronics Destined for Severe Nuclear Reactor Environments, Arizona State University, $399,674 (12/16/2013–12/15/2015)
- A Method for Quantifying the Dependability Attributes of Software-Based Safety Critical Instrumentation and Control Systems in Nuclear Power Plants, The Ohio State University, $399,990 (12/26/2013–12/25/2015)

FY 2014

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

FY 2015

- Nuclear Qualification Demonstration of a Cost Effective Common Cause Failure Mitigation in Embedded Digital Devices, Electric Power Research Institute, $991,000 (10/01/2015-06/30/2019)
- Development of Model Based Assessment Process for Qualification of Embedded Digital Devices in NPP Applications, University of Tennessee, $988,000 (10/01/2015-09/30/2018)

FY 2016

- Transmission of information by Acoustic Communication along Metal Pathways in Nuclear Facilities, Argonne National Laboratory, $1,000,000 (10/01/2016-09/30/2019)