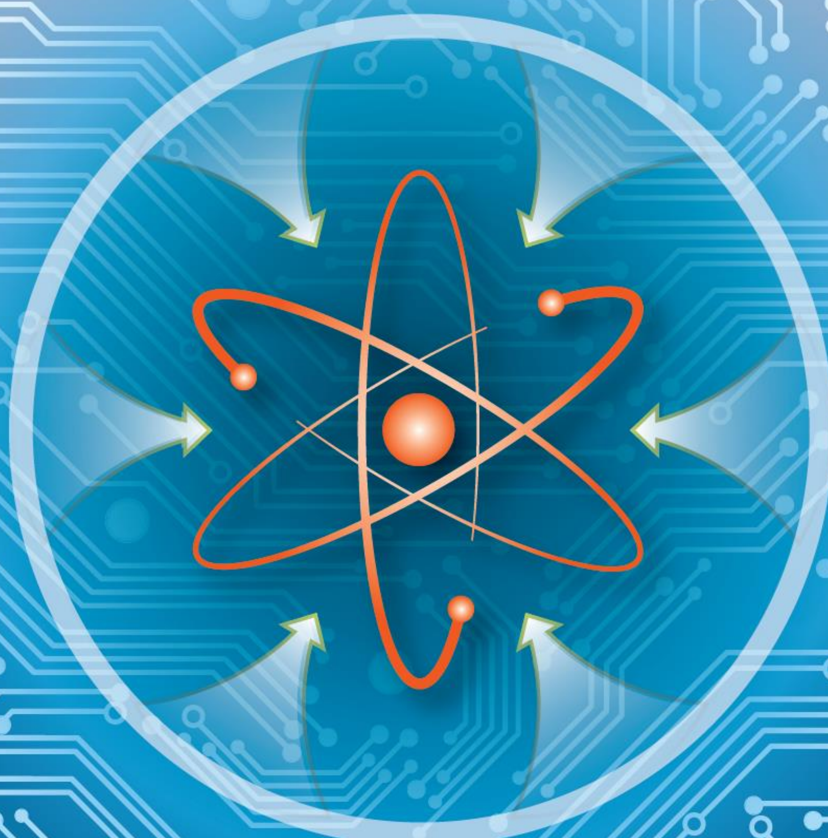
Office of Nuclear Energy

Advanced Sensors and Instrumentation Award Summaries



Nuclear Energy Enabling Technologies - Advanced Sensors and Instrumentation

June 2017

INTRODUCTION

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

In 2012, the Nuclear Energy Enabling Technologies (NEET) Program was initiated by the Department of Energy's Office of Nuclear Energy (NE) to conduct research, development, and demonstration (RD&D) in crosscutting technologies that directly support and enable the development of new and advanced reactor designs and fuel cycle technologies. Advanced Sensors and Instrumentation (ASI) is one program element of NEET Crosscutting Technology Development that is being carried out to foster the research and development required to develop and deploy innovative and advanced instrumentation and control capabilities for future nuclear energy systems, and to enable the advanced I&C technologies essential to NE's R&D efforts needed to realize mission goals.

The NEET ASI program has the following roles:

To coordinate crosscutting I&C research among NE programs to avoid duplication and focus I&C R&D in support of advances in reactor and fuel cycle system designs and performance.

To develop enabling capabilities to address I&C technology gaps common across NE's R&D programs. The NEET ASI program has identified four strategic I&C areas of research that represent key capabilities for nuclear energy systems, fuel cycle facilities, and that are needed to support materials test reactor irradiation-based research. These strategic areas are:

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

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

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

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

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

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

In FY 2012, ten projects, totaling $7,622,000, were initiated to address a range of common and crosscutting needs identified by the Office of Nuclear Energy 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 design of a 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 competevily in the area of nuclear plant communication.

Since FY 2011, NEET-ASI has funded 27 projects for a total of $21,117,565.

These projects are successful in advancing the state of the art for measuring, controlling, and broadly managing nuclear energy systems being developed by the DOE Office of Nuclear Energy. 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 Office of Nuclear Energy R&D programs, the nuclear energy industry, and other power generation sectors as well. As these research projects progress, the interest from stakeholders and industry has also increased, as are the number of individual technology deployments and partnerships.

FY 2014 NEET-ASI Research Summaries

In FY 2014, the NEET-ASI program selected six 3-year projects under the following solicited topics:

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

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

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

2. **Recalibration Methodology for Transmitters and Instrumentation**

   This program element focuses on development and demonstration of online calibration methodologies for transmitter and instrumentation calibration interval extensions.

   - Develop a methodology to provide virtual sensor estimates and high-confidence signal validation, and provide the capability to integrate with uncertainty quantification methodologies
   - Evaluate the impact of emerging sensors and digital instrumentation on the proposed recalibration methodology(ies)
   - Demonstrate the candidate recalibration methodology(ies) in an appropriate testbed or facility.

3. **Design for Fault Tolerance and Resilience**

   This program element focuses on development and demonstration of control system technologies that are resilient to anticipated faults and transients and can achieve high plant and system availability and lead to improvements in safety.

   - Develop and test fault-diagnosis algorithms for current and next generation plant components
   - Develop computer-enabled implementation of control algorithms for a simulator-based test
   - Develop a fully integrated operator-support system for demonstration including fault detection, fault diagnosis, and control actions to mitigate fault(s)
   - Perform full-scale simulator shakedown tests of integrated fault diagnosis and automated control for a thorough spectrum of faults
   - Develop technical requirements for broad application of the operator support technology across multiple plant systems.

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

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

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

5. **High-Temperature Fission Chamber**

- This program element focuses on fabrication and characterization of high-temperature fission chambers that provide high-sensitivity, high-temperature neutron flux monitoring technology.
- Fabricate and test a high-temperature fission chamber capable of operating from start-up to full power at 800°C Design and fabricate a fission chamber followed by characterization at high temperature in a reactor that demonstrates sensitivity; demonstrates mechanical/thermal robustness; and enables path to safe high-temperature reactors.

6. **Advanced Measurement Sensor Technology**

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

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

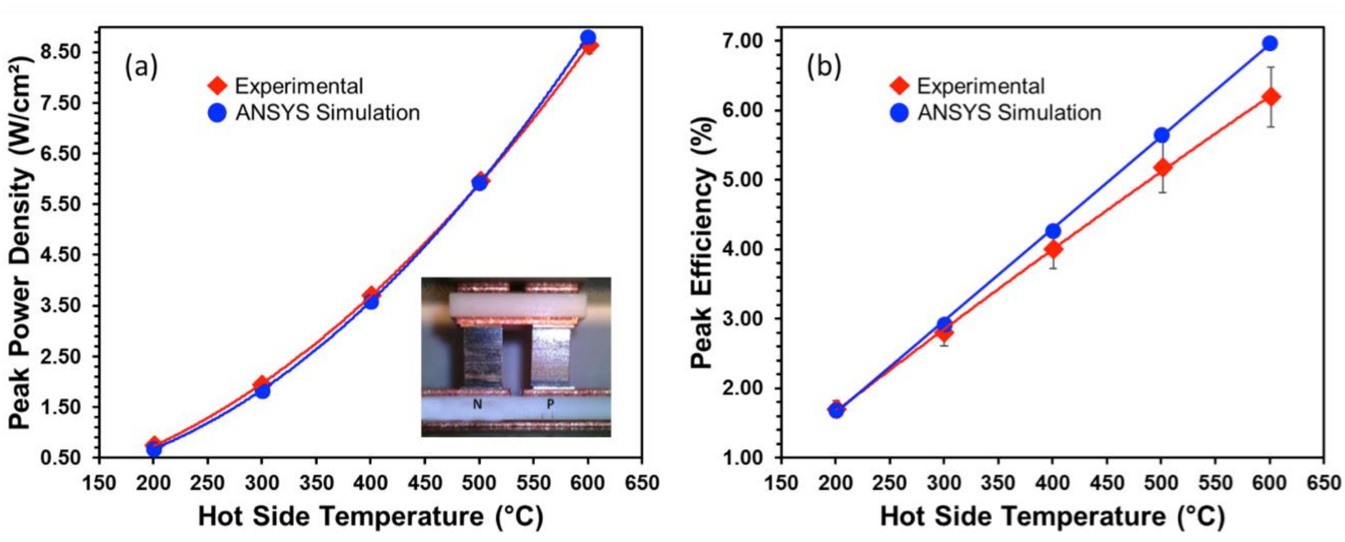
Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks

Yanliang Zhang and Brian Jaques, Boise State University;
Vivek Agarwal, Idaho National Laboratory
Zhifeng Ren, University of Houston
Funding: $980,804 (01/01/2015–12/31/2017)

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

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

Recent results and highlights: The team has designed and fabricated a fully optimized thermoelectric device using our high-efficiency nanostructured bulk (nanobulk) half-Heuslers thermoelectric materials that enable direct heat-to-electricity conversion over a wide temperature range. The figures show the peak power density and peak efficiency of the device tested under various hot-side temperatures while the cold side is maintained at 30°C. The measured peak power density of the device increased from 0.75 W/cm^2 at a ΔT of 170°C to 8.6 W/cm^2 at a ΔT of 570°C, which is among the highest in all the reported values. The measured heat-to-electricity efficiency increased from 1.7% at a ΔT of 170°C to 6.2% at a ΔT of 570°C.



(a) Peak electric power density, and (b) heat-to-electricity efficiency as a function of the hot-side temperature of a nanobulk half-Heusler thermoelectric device when the cold side is maintained at a constant temperature of 30°C.

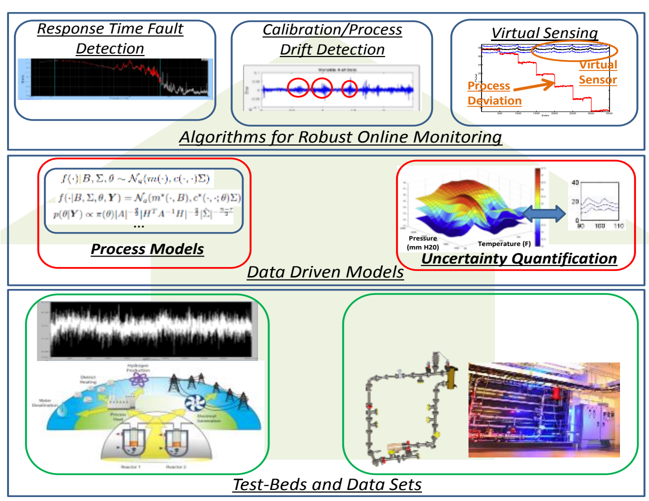
Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation

P Ramuhalli, Pacific Northwest National Laboratory
J. Coble, University of Tennessee Knoxville
B. Shumaker and H. Hashemian, Analysis and Measurement Services Corporation
Funding $1,000,000 (10/01/14–09/30-17)

Description of project: The goal of this research is to develop the next generation of online monitoring (OLM) technologies for sensor calibration interval extension and signal validation in nuclear systems through the development of advanced algorithms for monitoring sensor/system performance and the use of plant data to derive information that currently cannot be measured. Specific objectives are: (1) apply methods for data-driven uncertainty quantification to develop methodologies for high-confidence signal validation; (2) develop robust virtual sensor technology to derive plant information that currently cannot be measured (due to sensor failure or lack of sensors); and (3) develop a framework for OLM of both calibration and response time assessment for current and future sensors and instrumentation.

Impact and value to nuclear applications: Outcomes of this project will lay the groundwork for wider deployment of advanced OLM in U.S. nuclear facilities by developing a methodology to: (1) support the regulatory basis for OLM-based calibration assessment, (2) provide the high-confidence levels needed for signal validation, (3) provide virtual sensor estimates with meaningful confidence, (4) integrate response time testing of pressure transmitters with the OLM framework, and (5) evaluate the efficacy of these techniques for new sensor systems. These advances will provide a complete picture of health, reliability, accuracy, and speed of response of process instrumentation in legacy and future nuclear facilities, and are expected to improve safety, reliability, and economics of current and planned nuclear energy systems by enabling targeted instrumentation maintenance actions during planned outages.

Recent results and highlights: The focus of research is on OLM of process instrumentation used for controlling the plant and monitoring its safety. During operation, these sensors may degrade due to age, environmental exposure, and maintenance interventions and result in anomalies, such as signal drift and response time changes, and challenge the ability to reliably identify plant or subsystem performance deviations. Data-driven uncertainty quantification methods are at the core of the technology being developed. These models have been coupled with models of sensor dependencies to develop algorithms for robust OLM. These algorithms enable the detection of sensor calibration drift (including drift in sensor response times) in an automated fashion, and the calculation of corrected sensor measurements using virtual sensors. Critical to the use of virtual sensors is the ability to distinguish between sensor faults and process drift. Advances in diagnosing the source of an anomalous sensor measurement have been made in the project, resulting in an initial approach for sensor fault and drift detection. Results using experimental data from a variety of testbeds and data sets (including data from operating plants) indicate the potential of the method for robust OLM. Ongoing research focus is on integrating and testing of the algorithms with additional, complex data sets that include sensor drift and degradation (such as plugging or heat exchanger fouling) leading to process changes.



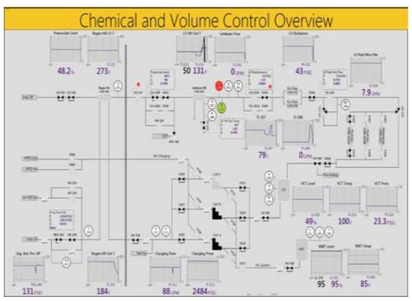
Data-driven robust OLM enables fault detection and virtual sensing. The examples use data from instrumented flow loops and steam generators in operating plants.

Operator Support Technologies for Fault Tolerance and Resilience

Richard B. Vilim, Argonne National Laboratory,
Kenneth Thomas and Ron Boring, Idaho National Laboratory
Funding: $995,000 (10/01/14–09/30/17)

Description of project: The objective of this project is to develop and demonstrate technologies needed to realize a computerized operator support system (COSS) that can assist operators in monitoring overall plant conditions, in making timely and informed decisions about needed actions and interventions, and in guiding the selection of appropriate control actions, even under conditions of uncertainty.

Impact and value to nuclear applications: Operator support technologies have the potential to significantly enhance operator response to time-critical component faults, resulting in fewer nuclear safety challenges and higher plant capacity factors. Certain complex or masked fault conditions at nuclear power plants may hinder the operators' ability to quickly diagnose the cause of a component fault or system failure and determine required actions. This is due to the limitations of current plant instrumentation.



Chemical and volume control system large overview display.

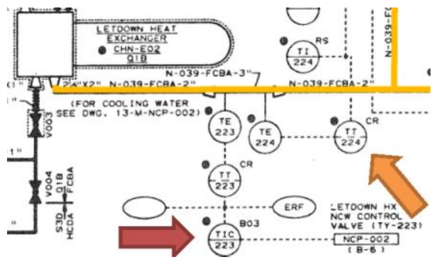


Diagram showing failed sensor (red) and good sensor (orange).

Operators operating COSS from the boards.

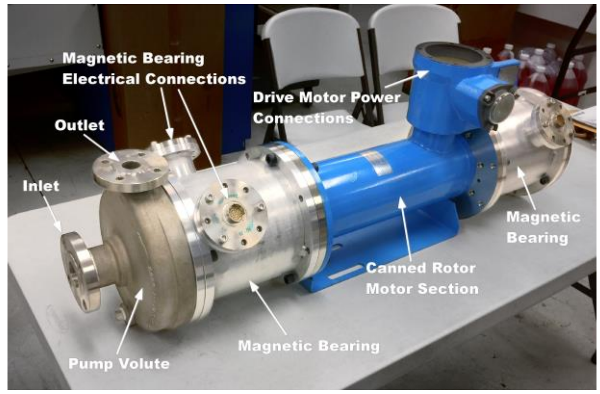
Recent results and highlights: The prototypic COSS underwent a first evaluation workshop conducted with licensed operators from a partner plant. The workshop provided an opportunity for operators to interact with the COSS prototype in real-time. The operators were tasked with diagnosing the fault and mitigating any issues. The operators performed the scenario using the traditional analog board layout and a COSS integrated layout. First the operators used the traditional board layout to benchmark their performance. The operators also used the COSS interface displayed within the chemical and volume control system board. A number of different measures were collected during each scenario completion. Simulator logs, eye tracking, and audio logs were taken in real time while the operators completed the scenario. Following the scenario, the operators completed a series of subjective questionnaires. The implementation and evaluation of COSS for the chemical and volume control system using a representative nuclear power plant demonstrated the effectiveness of an intelligent operator support system to aid operators in monitoring and controlling the plant. Additional work is required to continue the COSS development to make it available for nuclear industry use.

Embedded I&C for Extreme Environments

Roger Kisner, Alex Melin, and David Fugate, Oak Ridge National Laboratory

Funding: $1,000,000 (10/1/14–09/30/17)

Description of Project: This project functionally embeds instrumentation and control (I&C) technologies in nuclear power plant equipment to demonstrate potential performance gains under extreme environments. Extreme environments, which particularly apply to the advanced reactor types under development, include high temperature, radiation, high pressure, high vibration, and high EMI conditions. Performance gains from embedded I&C arise from moment-to-moment sensing of local variables and the immediate application of local feedback control. Such embedded control permits wider operating ranges and advantageous changes to the basic design of systems resulting in lower cost, higher reliability, and improved performance. Planning for embedding I&C starts early in the system design phases, which contrasts with a traditional, serial design approach that incorporates minimal I&C after mechanical and electrical design is completed. The embedded I&C demonstration comprises development and real-time control of a novel, motor-pump design that operates within a fluid environment, eliminating the need for rotating seals. Actively controlled magnetic bearings replace failure-prone mechanical contact bearings that typically suspend rotating components. This design, made possible by the embedded I&C, has the potential to positively change the architecture and behavior of pumping systems.



Assembled loop-scale magnetically suspended, canned rotor pump ready for connection to the embedded I&C system. This system will be installed in a water loop for demonstration.

Impact and Value to Nuclear Applications: This project develops crosscutting sensor and control technologies for nuclear reactors, and a loop-scale embedded I&C testbed and demonstration platform for future research into embedded instrumentation and control technologies for extreme environments. Performance testing at the bench-scale and loop-scale is producing performance improvements due to embedded I&C. Embedded sensors and controls enable features, performance, and reliability that are not possible with legacy approaches. Advanced nuclear power plant reactor concepts include elevated temperatures and other extreme environmental factors that challenge materials and component designs. Embedding sensors and controls in nuclear power plant components, as demonstrated in other industries, increases their performance and reliability. Embedded I&C methods represent a transition in component design and functionality from a static mechanical design to a flexible dynamic electromechanical system that adapts to changing environmental conditions. A great complementary benefit is diagnostic and prognostic capability that increases component lifetime and reduces operating costs. Component design margins can be safely reduced because of tight coupling between sensors and control, resulting in lower mass and, hence, lower costs.

Recent Results and Highlights: A loop-scale pump with canned rotor and magnetic bearings has been fabricated and assembled. The motor-pump system provides a demonstration environment for the real application of embedded I&C. This demonstration is on a room-temperature water loop, which provides a step towards the eventual development of a 700°C pump capable of operating in a harsh environment, such as a liquid salt reactor. The water system will allow for the development of advanced control algorithms and a sensorless position indication. Specifically, for the magnetically levitated, canned-rotor fluid pump, a motor design will emerge that prevents physical contact between moving parts (except the coolant itself). The design eliminates the need for lubrication and eliminates bearing and seal wear. Being a canned rotor design, the pump and motor are submerged in the coolant stream, which permits greater flow path design flexibility. The potential of this design type is high reliability and low maintenance. Elimination of lubrication and bearing and rotating seal structures also makes lower cost manufacturing possible. Already several pump manufacturers have expressed interest in collaborating for future work.

Enhanced Micro Pocket Fission Detector for High Temperature Reactors

Troy Unruh, Idaho National Laboratory (INL)
Douglas McGregor, Kansas State University (KSU)
Jean-Francois Villard, Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA)
Funding: $1,000,000 (10/1/14–9/30/17)

Description of project: The focus of this project is the research, development, demonstration, and deployment of High Temperature Micro-Pocket Fission Detectors (HT MPFD), which are compact fission chambers capable of simultaneously measuring thermal neutron flux, fast neutron flux, and temperature within a single package for temperatures up to 800°C.

HT MPFD under construction (left) and completed X-ray (right).

Impact and value to nuclear applications: The small size, tunable sensitivity, and increased accuracy of HT MPFDs represent a revolutionary improvement in flux characterization over current non-real-time methods used to support irradiations in U.S. material test reactors. Several test reactors are already requesting HT MPFDs to be included in their irradiation experiments. Various university reactors have already deployed MPFDs, and the Accident Tolerant Fuels irradiation test program will deploy the HT MPFD technology in steady-state and transient conditions in the Advanced Test Reactor and the Transient Reactor Test Facility. In addition, the Advanced Gas Reactor 5/6/7 irradiation test program will deploy a HT MPFD as part of a long-duration irradiation test in the Advanced Test Reactor.

Recent results and highlights: Current research efforts have focused on fabricating and testing HT MPFDs in laboratory and reactor environments. Activities in support of deployment include procurement of HT MPFD electronics, development of drawings for installation, and independent characterizations of the fissile depositing for device calibration. In addition, a U.S./Korea I-NERI project, "Radiation Hardened Readout Circuit Design for High Temperature Micro-Pocket Fission Detectors Operating in Harsh Environments," was awarded to support future deployments.


HT MPFD electronics.

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

Kevin P. Chen, University of Pittsburgh

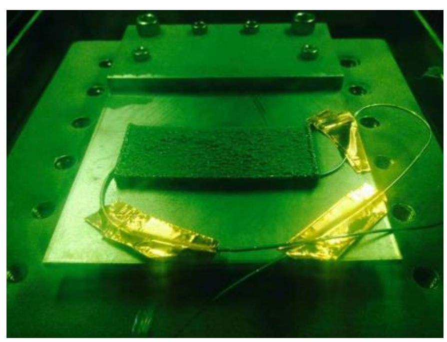
Funding: $987,676 (10/1/14–9/30/17)

Description of project: This project develops multi-functional, remotely activated, and distributed fiber optical sensor networks to monitor parameters critical to the safety of nuclear power systems with high-spatial resolutions. These objective will be achieved through the invention of new multi-function optical fibers as sensor platforms suitable for radiation environments, developments novel sensory materials for distributed chemical measurements (e.g., H_2), inventions of new active fiber-sensing schemes, and manufacturing of sensor-enabled smart components for high-spatial resolution measurements.

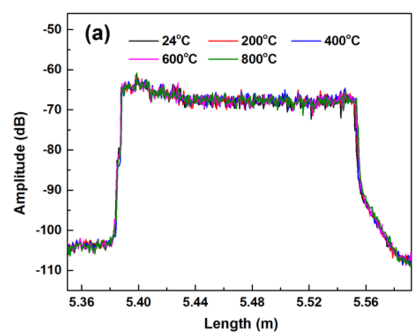
Impact and value to nuclear applications: The new distributed fiber-sensing capabilities, new radiation-hard multi-functional fibers, and new smart components developed by this program will address critical technology gaps for monitoring advanced reactors and fuel cycle systems under both normal operation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

Recent results and highlights: The project uses an integrated approach to develop distributed fiber sensors for nuclear energy. Working with Corning Inc., multi-core optical fibers have been designed for multi-parameter distributed measurements. Using multi-functional optical fiber as distributed sensing devices, this researchers invented smart electric cable that can perform temperature, strain, chemical, and radiation measurements with 1-cm spatial resolution. To improve high-temperature resilience of the distributed fiber sensors, this researchers use the ultrafast laser processing technique to enhance Rayleigh scattering of radiation-harden fibers. This innovation enable fiber sensors to function at extreme high temperatures (up to 800°C) to perform distributed measurements with 5-mm spatial resolution in radiation environments. Using additive manufacturing schemes, distributed optical fiber sensors were successfully incorporated into stainless steel and titanium parts. These sensor-fused parts can be integrated with reactor and fuel cycle systems to perform real-time, high-spatial resolution measurements at high temperatures. Results from this project led to several provisional/pending patents; Carnegie Science Awards for energy innovation and advanced manufacturing; and multiple publications.

Fiber sensor-enabled smart electrical cable.



Fiber sensor-fused smart part via 3D printing.



Laser-enhanced distributed high-T fiber sensor.

FY 2015 NEET-ASI RESEARCH SUMMARIES

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

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

- Proof of acceptable software operational reliability;
- Comprehensive non-destructive testability;
- U.S. NRC regulatory requirements;
- Ability to detect defects introduced through the entire supply chain;
- Ability to qualify commercial-grade devices dedicated for safety-related usage; and
- Cost-effective and broadly applicable to multiple small plant component.

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

Matt Gibson, Electric Power Research Institute (EPRI)
Dr. Gary Atkinson, Virginia Commonwealth University (VCU)
Dr. Carl Elks, Virginia Commonwealth University (VCU)
Funding: $991,000 (10/01/2015–09/30/2018)

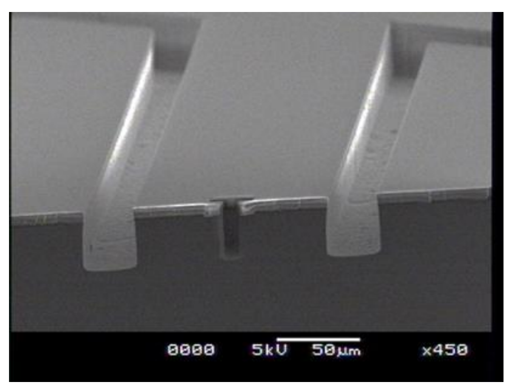
Description of project: An alternate approach to mitigate the unpredictable nature of software faults in safety-related instrumentation and control systems due to the unbounded and general-purpose nature of Von-Neumann architecture central processing units (CPUs) commonly used in these devices is being explored. This approach will identify and develop embedded digital components that can be demonstrated to contain no additional capabilities or characteristics other than that specially required to meet functional objectives. These verifiable and deterministic devices should have no hidden fabrication or infrastructure to complicate the straightforward analysis and validation. Configurable hardware logic will be used to investigate state-driven architectures that are deterministic in nature by eliminating fabrication, infrastructure, and application-level constructs that cannot be deterministically analyzed.

National Instruments cRIO platform

Two technologies are being pursued:

- Hardware-based sequencer architecture that can execute the IEC-61131 language directly in hardware, which can potentially be field reconfigurable while still providing formal verifiability. This technology is now ready for prototyping.
- Micro electro-mechanical systems (MEMS) technology to design and construct an emergency diesel generator module with one-time configurable logic that does not involve electronics or software for the main logic functions. This technology has been delayed due to technical issues with the MEMS etcher, but it is expected to recover and build prototypes this year.

Impact and value to nuclear applications: Successful demonstration of these alternate architectures will allow the deployment of deterministically verified systems in nuclear and other safety-related applications at a fraction of the current total installed cost and with less technical and regulatory risk.



DRIE Etch target with TRION Etcher

Recent results and highlights: Using MathWorks and Simulink Design Verifier, the research team has achieved a formally verifiable SymPle architecture that is suitable for prototyping. The Simulink Design Verifier model checker exhaustively searches using a mathematical k-induction on the state space of the model. The team will use a National Instruments cRIO platform to demonstrate the prototype SymPle Architecture. The cRIO is an Field Programmble Gate Array-based device that can host the new SymPle architecture and will allow exploration of practical input/output interfaces and communications.

MEMS design has concentrated on standing up, commissioning the MEMS etching machine, and working out the remaining fabrication challenges. Fabrication of the shadow mask process and a prototype relays will move forward as soon as the MEMS etcher is fully operational. The prototype target will demonstrate functional Boolean logic using electromechanical relays.

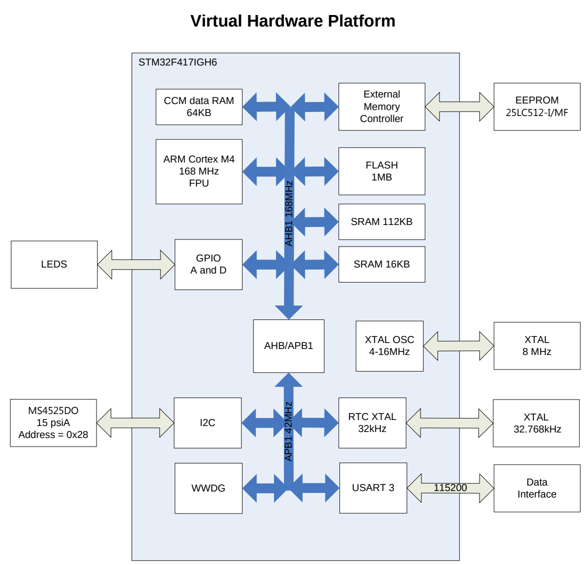
Development of Model Based Assessment Process for Qualification of Embedded Digital Devices in NPP Applications

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

Description of project: This project involves development and demonstration of a systematic approach to assess whether instrumentation with an embedded digital device is subject to software common–cause failure (CCF). The assessment of CCF resistance begins by classifying those devices according to the nature of their role in performing the instrument's function as the basis for a graded qualification approach. An essential element of the qualification approach is a suite of model-based testing (MBT) methods. The research will develop these MBT methods and evaluate their efficacy through experimental demonstration using representative test subject(s).

Impact and value to nuclear applications: Application of advanced instrumentation is constrained by nuclear regulatory concerns about CCF in embedded digital devices. Research will advance state of the art for qualification by (1) developing novel methods to demonstrate proof of operational reliability, (2) applying the developed methods to representative embedded digital devices to ascertain the effectiveness of the methodology, and (3) establishing a cost-effective qualification framework that is compliant to existing guidance and standards. Through the successful development and demonstration of this qualification methodology, impediments to advanced technology use can be eliminated to the benefit all reactor types.

Recent results and highlights: Recent research activities have focused on definition of a classification scheme for embedded digital devices (EDDs) to facilitate a graded approach to their qualification, develop and extend model-based testing methods to enable effective demonstration of whether devices are subject to CCF, establish a cost-effective testing framework, and select a target device for demonstration of the method. For the classification activity, an initial graded approach was developed to support systematic evaluation of prospective CCF vulnerabilities for equipment with an EDD. This approach was shared with industry for application in a diversity and defense-in-depth analysis for an international advanced reactor design. For the model-based testing method activity, the mutation testing methodology was extended to address potential fault types from the requirements and design phases of software life cycles. The results include classification of defects and definition of the corresponding mutation operators. In addition, an approach was developed for executing mutation test cases and determining the necessary and sufficient conditions to kill a mutant. For the demonstration activity, a prototype smart sensor was adopted as the baseline device to support development of the testing framework and serve as an initial, well-characterized target for applying the MBT methodology. To date, the smart sensor hardware has been emulated using a commercial simulation package. The virtual platform emulator serves as a foundational element of an automated testing framework by providing a transparent representation of the device hardware and the capability for accurate instruction execution of the device software.



FY 2016 NEET-ASI RESEARCH SUMMARIES

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

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

Research objectives:

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

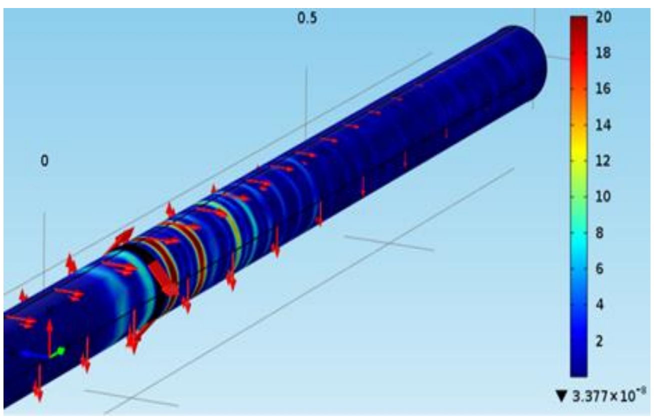
Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities

Richard B. Vilim, Argonne National Laboratory

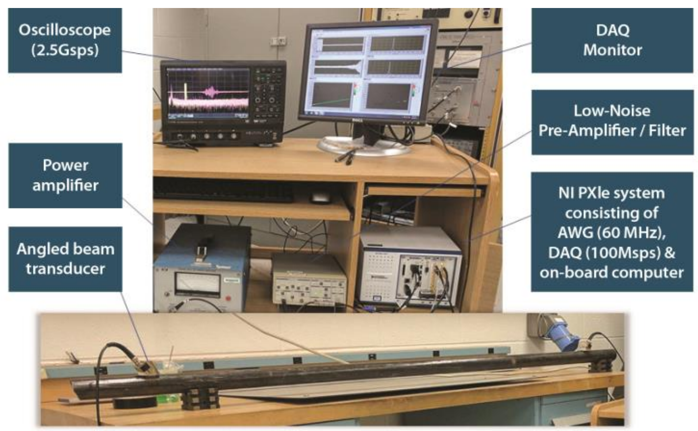
Funding: $1,000,000 (10/01/16–09/30/19)

Description of project: The objective of this project is to develop and demonstrate methods for transmission of information in nuclear facilities by acoustic means along existing in-place metal infrastructure (e.g., piping). Acoustic communication (AC) hardware and network protocols for efficient and secure transfer of data are being developed with experimental demonstration of a prototype AC system to be performed in a representative environment. Pipes are omnipresent in a nuclear facility and will serve as conduits for signals launched as acoustic surface waves.

Impact and value to nuclear applications: This innovative means of transmitting information overcomes physics hurdles that beset conventional communication methods (both wired and radio frequency wireless). It provides a crosscutting (applicable to multiple nuclear facility platforms) solution for those areas in the plant where wired or wireless communication is not feasible (presence of barriers), not reliable (lack of resilience under accident conditions), or not secure (prone to interception). Use of metallic pathways for transmission of information provides an additional level of protection for securing and protecting data streams.



Simulation results showing attenuation of an acoustic signal launched down a metal pipe.



Benchtop facility for measurement of acoustic signal bandwidth/attenuation along metal pipe.

Recent results and highlights: Initial research efforts have focused on identifying appropriate transducers and coupling mechanism for transmission and reception of acoustic signals along metal pathways. The transducers will ultimately be integrated into the communication system that will be developed later in this project. The main components of the current system setup include a waveform generator and power amplifier on the transmission side and a low-noise amplifier, filter, and data acquisition system on the receiver side. The focus of experimental activities to date has been on assessing piezoelectric transducers. Alternative transducers based on EMAT technology are also being evaluated in this project.

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

Jorge Carvajal and Michael Heibel, Westinghouse Electric Company

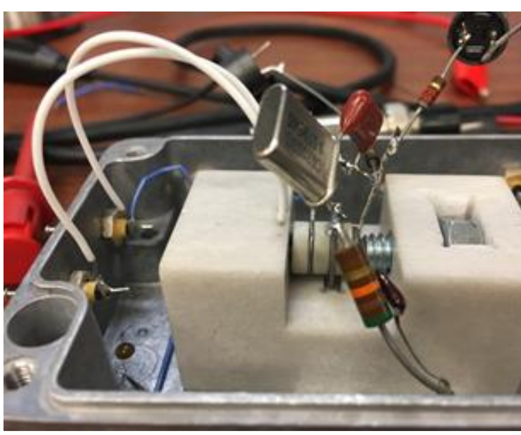
Dr. Kenan Unlu, Dr. James Turso, Pennsylvania State University Radiation Science and Engineering Center (RSEC)

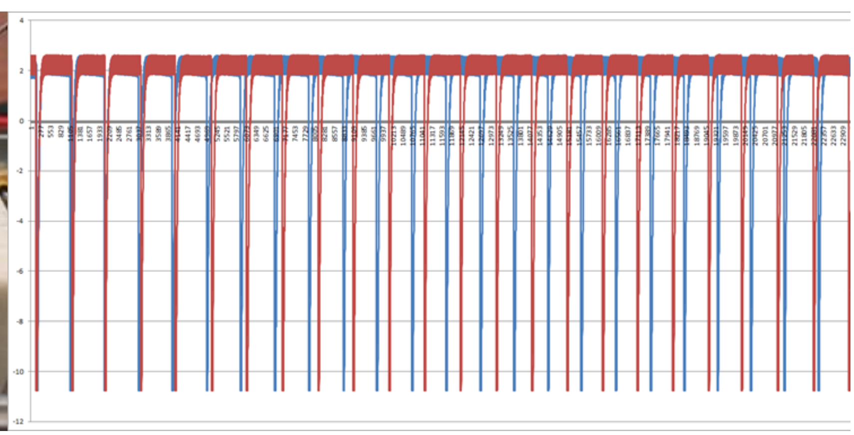
Funding $986,535 (10/1/2016–9/30/2019)

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

Impact and Value to Nuclear Applications: Power distribution measurements currently utilize Self-Powered Neutron Detectors axially located within approximately 33% of the fuel assemblies. The proposed project would enable 100% of fuel assemblies to be instrumented by placing a VME wireless transmitter in the top nozzle of each fuel assembly. It is expected that this technology would enable the plant to increase reactor operating margins 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 additional penetrations in the reactor coolant system boundary. From a safety standpoint, this is particularly beneficial for all light-water reactors. In addition, not having penetrations and cabling is a design simplification, which is always desirable.

Recent Results and Highlights: Sparkgap amplitude modulated VME oscillator was the first prototype built and tested. Data analysis is ongoing to determine repeatability and accuracy. VME oscillator with sparkgap modulator was exposed to the Co-60 source to determine the gamma radiation effect. Transmission of the radio frequency signal in demineralized water was tested. Results show minimal attenuation at transmission frequency.

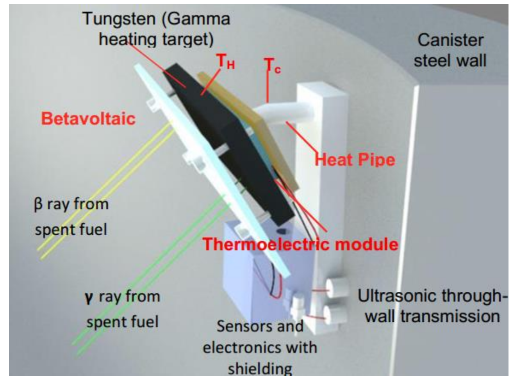




Modulated VME oscillator Modulated VME hot cell test (irradiated in blue, no irradiated in red)

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

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

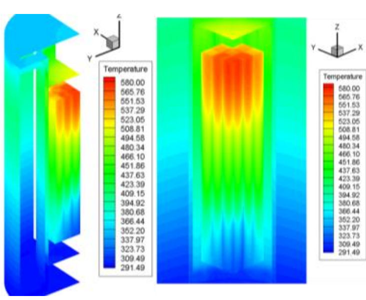


Description of project: Monitoring temperature, pressure, radiation, humidity, etc., inside enclosed storage vessels is crucial to ensure reactor safe operation and fuel security. However, the physical boundaries constructed of metal enclosures and thick concrete present huge challenges to sensing and data communications because these enclosures shield radio-frequency (RF) signals and obstruct the wiring of power supplies and communications. To combat these challenges, researchers will develop and demonstrate an enabling technology for the data communications for nuclear reactors and fuel cycle facilities using radiation and thermal energy harvester, through-wall ultrasound communication, and harsh environment electronics. The project will enable transmitting a great amount of data through the physical boundaries in the harsh nuclear environment in a self-powered manner.

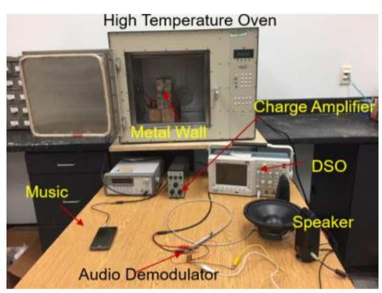
Impact and value to nuclear applications: The expected impacts and benefits include: 1) Energy harvesting from nuclear radiation where no other energy sources are available; 2) Validating the proposed electronics system incorporating energy harvesting and advanced communications through dense barriers as is needed in nuclear environments; and 3) Developing and reporting a detailed strategy for full realization of a high-temperature, radiation-tolerant electronics, and data communication platform for nuclear environments.

Recent results and highlights:

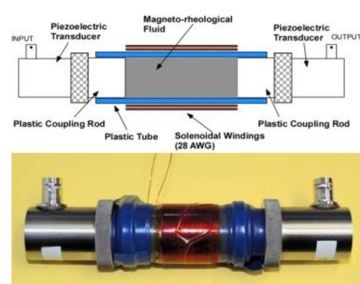
Simulated gamma heating in a tungsten plate placed above the assemblies, and to the side of the assemblies using the MCNP software. Simulated the temperature and flow field in the within/out an MPC-32 canister and validated the results with experimental data, which can be used to guide our TE materials selection and energy harvester design. Successfully verified progress in this phase of the project in high-temperature through-wall data communication: (1) high-temperature audio signal communication through thick metal (3 inch), and (2) Successfully demonstrated the ultrasound through-wall audio transmission in high temperature (100°C). Made progress on an experiment with magnetorheological fluid as an ultrasonic modulator. The second experiment was run to confirm the modulation capability of magnetorheological fluid. Magnetorheological fluids use ferromagnetic solids having diameters from 5 to 50 microns. Ferromagnetic fluids are exactly the same but use particles from 10 to 50 nanometers. The next experiments will be performed with ferromagnetic fluid.



Thermal analysis of the canister system (@VT).



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



MR Fluid as Ultrasonic Modulator (@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: www.energy.gov/ne.

FY 2011

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

FY 2012

- NEET In-Pile Ultrasonic Sensor Enablement, Idaho National Laboratory, $1,000,000 (03/01/12–09/30/14)
- Micro Pocket Fission Detectors, Idaho National Laboratory, $1,015,000 (03/01/12–09/30/14)
- High-Temperature Fission Chamber, Oak Ridge National Laboratory, $574,000 (03/01/12–03/30/14)
- Recalibration Methodology for Transmitters and Instrumentation, Pacific Northwest National Laboratory, $529,000 (03/01/12–04/30/14)
- Digital Technology Qualification, Oak Ridge National Laboratory, $1,269,000 (03/01/12–06/30/15)
- Embedded Instrumentation and Controls for Extreme Environments, Oak Ridge National Laboratory, $770,000 (03/01/12–03/30/14)
- Sensor Degradation Control Systems, Argonne National Laboratory, $360,000 (03/01/12–02/28/14)
- Design for Fault Tolerance and Resilience, Argonne National Laboratory, $900,000 (03/01/12–03/30/14)
- Power Harvesting Technologies for Sensor Networks, Oak Ridge National Laboratory, $380,000 (03/01/12–06/30/14)
- Development of Human Factors Guidance for Human-System Interface Technology Selection and Implementation for advanced NPP Control Rooms and Fuel Cycle Installations, Idaho National Laboratory, $825,000 (03/01/12–02/28/14)

FY 2013

- Radiation-Hardened Circuitry using Mask-Programmable Analog Arrays, Oak Ridge National Laboratory, $400,000 (10/01/13–09/30/15)
- Radiation Hardened Electronics Destined for Severe Nuclear Reactor Environments, Arizona State University,$399,674 (12/16/13–12/15/15)
- A Method for Quantifying the Dependability Attributes of Software-Based Safety Critical Instrumentation and Control Systems in Nuclear Power Plants, The Ohio State University, $399,990 (12/26/13–12/25/15)