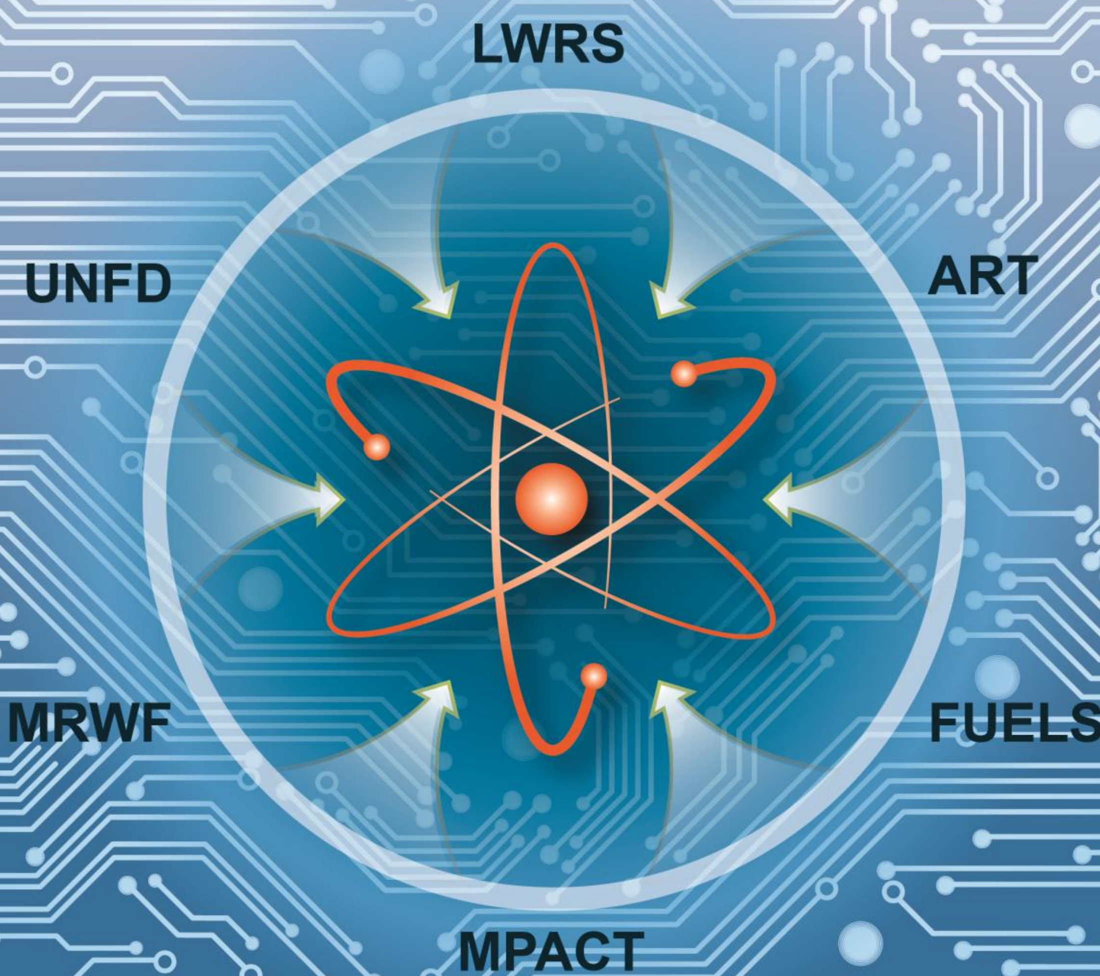
OFFICE OF NUCLEAR ENERGY

Advanced Sensors and Instrumentation Award Summaries



Nuclear Energy Enabling Technologies - Advanced Sensors and Instrumentation

May 2016

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:

1. *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.
2. *Digital Monitoring and Control*. To enhance monitoring of process variables and implementation of control actions that increase system reliability, availability, and resilience.
3. *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.
4. *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, totally $1,979,000, were awarded competitively in the areas of digital monitoring and controls.

Since FY 2011, NEET-ASI has funded 24 projects for a total of $18,131,030.

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 2013 NEET-ASI Research Summaries

In FY 2013, the NEET-ASI program selected three 2-year projects under the following solicited topics:

1. Design a custom radiation-tolerant electronics system, using the best available commercial or near-commercial technologies necessary for operation in a severe nuclear environment. The proposed system will be tested in a radiation-tolerant multi-functional robot to overcome implementation challenges as well as to provide observable evidence of the technology capabilities.
2. Methods to quantify software dependability characteristics can facilitate the resolution of factors that inhibit expanded use of modern digital technology by the nuclear power industry. The current reliance of process-oriented software quality assurance programs and the resultant subjective evaluation of digital system safety drive the nuclear industry to choose between maintaining legacy technologies that have proven licensable or embarking on costly, non-optimum implementations that are constrained to pose the least amount of licensing risk. Development of an objective technical basis for evaluating the suitability for software-based instrumentation and control (I&C) systems in safety applications at nuclear power plants would enable a science-based safety case to be demonstrated, thus reducing regulatory uncertainty. Measures, metrics, and methods are sought to permit quantification of the safety, quality, dependability, and reliability characteristics of software-based I&C systems.
3. Develop and demonstrate a general-purpose data acquisition system built from commercial or near-commercial radiation-hard analog arrays and digital arrays that will be the building blocks of a family of future fieldable radiation-hard systems. As the recent accident at Fukushima Daiichi so vividly demonstrated, telerobotic technologies capable of withstanding high-radiation environments need to be readily available to enable operations, repair, and recovery under severe accident scenarios where human entry is extremely dangerous or not possible. Telerobotic technologies that enable remote operation in high dose-rate environments have undergone revolutionary improvement over the past few decades. However, much of this technology cannot be employed in nuclear power environments due the radiation sensitivity of the electronics and the organic insulator materials currently in use. Therefore, radiation-tolerant electronics are one of the major limiting technologies preventing effective telerobotic application to high-radiation environments present under severe accident conditions or in support of fuel reprocessing. Moreover, the electronics, once developed, are a low-cost-enabling frequent replacement when used under high dose-rate conditions.

These projects were the first three NEET ASI program to transition to the fully competitive solicitation and selection process. They have concluded in 2015.

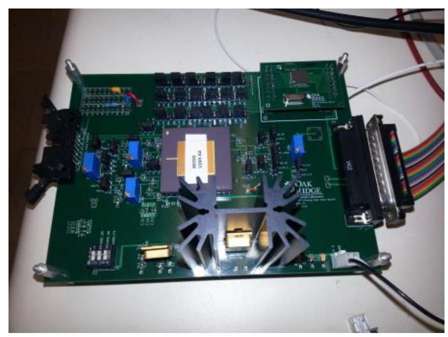
Radiation-Hardened Circuitry using Mask-Programmable Analog Arrays

Chuck Britton, Jacob Shelton, Nance Ericson, Oak Ridge National Laboratory,
Benjamin Blalock, The University of Tennessee
Funding: $400,000 (10/01/13–09/30/15)

Description of project: This project developed and demonstrated a general-purpose data acquisition system built from commercial or near-commercial radiation-hard analog and digital arrays that could be the building blocks of a family of future fieldable radiation-hard systems. As the recent accident at Fukushima Daiichi demonstrated, telerobotic technologies capable of withstanding high-radiation environments need to be readily available to enable operations, repair, and recovery in the event of a severe accident where human access to equipment and systems may be limited if even possible. Telerobotic technologies that allow for remote operation in high dose-rate environments have undergone revolutionary improvement over the past few decades. However, much of this technology may be currently limited for use in nuclear power environments due to its reliance on electronics and organic insulator materials that exhibit radiation sensitivity. The absence of radiation-tolerant electronics is one of the major barriers to effective telerobotic application in support of fuel reprocessing or in post-accident environments. Such electronics, once developed, could be low cost, allowing for frequent replacement when used in high-dose-rate conditions.

Impact and value to nuclear applications: This research produced a prototype radiation-hard data acquisition system that was constructed and tested to demonstrate functionality and radiation hardness of the identified commercial or near-commercial technology for use in a nuclear reactor environment. The system prototype was tested with functional metrics for both pre- and post-radiation scenarios. In addition to success/fail results, the measured degradation observed in each of the circuit functions were also summarized to provide insights into the degree of radiation hardness of each system component following a 200 krad or greater total integrated dose.

Recent results and highlights: A suite of tests developed during this project permitted evaluation of hardware before and after irradiation and during exposure to elevated temperature. The radiation exposure facility, a laboratory at Arizona State University, was selected in the early phase of the project. Radiation exposure consisted of total integrated dose above 200 krad with several intermediate doses during the test. With a target of 30 krad/h, dose rates were selected in various ranges determined by the radiation exposure facility staff. Complete systems were tested for performance at intermediate doses during this task. Extended temperature testing was performed up to the limit of the commercial sensors (typically 125°C).



Radiation-Hard Analog Array Board.

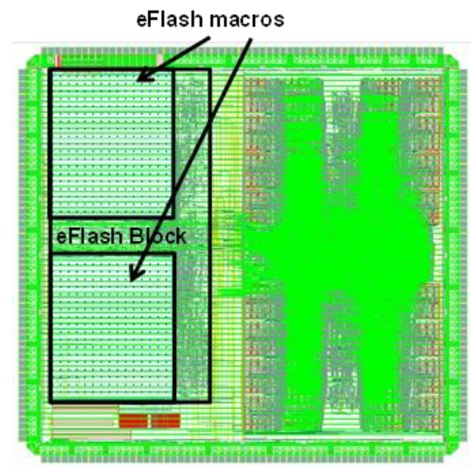
Radiation Hardened Electronics Destined for Severe Nuclear Reactor Environments

Keith E. Holbert, Arizona State University,
Lawrence T. Clark, Arizona State University
Funding: $399,674 (12/16/13–12/15/15)

Description of project: Severe accident conditions at a commercial nuclear power facility represent a harsh environment for electronics. This research project developed radiation hardened by design (RHBD) electronics using commercially available technology employing commercial off-the-shelf (COTS) devices and presents generation circuit fabrication techniques to improve the total ionizing dose (TID) hardness of electronics.

Impact and value to nuclear applications: Ionizing radiation is intrinsic to the entire nuclear energy fuel cycle and is found in differing levels of concentration under normal operating conditions throughout nuclear energy generation and fuel cycle facilities. The pervasive use of electronic systems demands devices that can withstand significant radiation exposure. The nuclear power industry may benefit from the advancements in the semiconductor industry that have led to low-cost ubiquitous devices. This project is investigating the deployment of state-of-the-art electronics that are needed for data acquisition, processing, and communication for important functions during normal and off –normal conditions, including potential accident conditions. These capabilities will contribute to the the reliability and safety of the current fleet of power reactors as well as provide new capabilities needed for future nuclear energy and fuel cycle facilities.

Recent results and highlights: This research has taken a two-pronged approach: specifically, the development of both board and application-specific integrated circuit (ASIC) level RHBD techniques. The former path has focused on total ionizing dose testing of representative microcontroller integrated circuits with embedded flash (eFlash) memory, as well as standalone flash devices that utilize the same fabrication technologies. The standalone flash devices are less complicated, allowing better understanding of the TID response of the crucial circuits. TID experiments utilized biased components that were in-situ tested, and in full operation during irradiation. A potential pitfall in the qualification of memory circuits is the lack of rigorous testing of the possible memory states. For this reason, the tests employed test patterns that included all ones, all zeros, a checkerboard of zeros and ones, an inverse checkerboard, and random data. With experimental evidence of improved radiation response for unbiased versus biased conditions, a demonstration-level board using the COTS devices was constructed. Through a combination of redundancy and power gating, the demonstration board exhibited radiation resilience to over 200 krad. Furthermore, the ASIC microprocessor using RHBD techniques was shown to be fully functional after an exposure of 2.5 Mrad whereas the COTS microcontroller units failed catastrophically at <100 krad.



Application-specific integrated circuit test die.

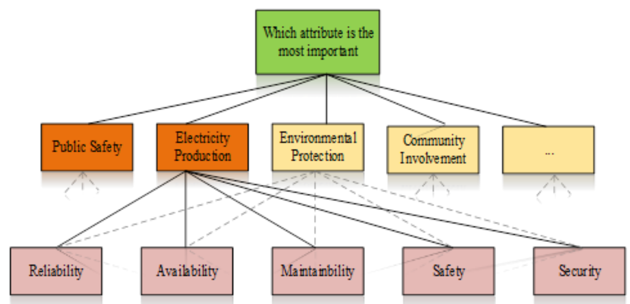
A Method for Quantifying the Dependability Attributes of Software-Based Safety Critical Instrumentation and Control Systems in Nuclear Power Plants

Carol Smidts, The Ohio State University,
Ted Quinn, Technology Resources
Funding: $399,990 (12/26/13–12/25/15)

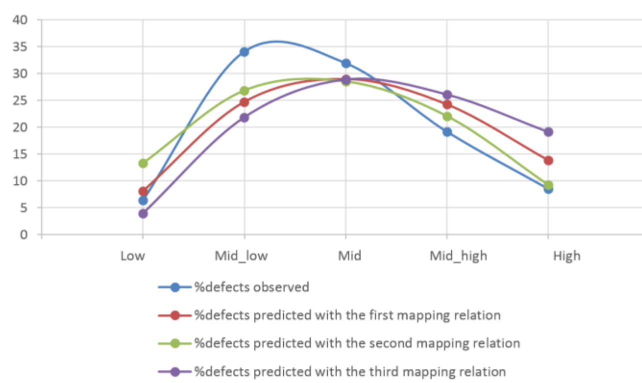
Description of Project: With the current transition from analog to digital instrumentation and control systems in commercial nuclear power plants, the number and variety of software-based systems being considered for control applications have significantly increased. The sophisticated nature and complexity of software raises trust in these systems as a significant challenge for acquisition by owner-operators, and by regulators. The trust placed in a software system is termed software dependability. Software dependability analysis faces uncommon challenges since software systems' characteristics differ from those of hardware systems. The lack of systematic science-based methods for quantifying the dependability attributes in software-based instrumentation as well as control systems in safety critical applications has proved to be a significant inhibitor to the expanded use of modern digital technology in the nuclear industry.

Impact and Value to Nuclear Applications: To address the need for quantification of software dependability and give a more objective basis to the review process of software-based instrumentation and control systems—therefore, reducing regulatory uncertainty—measures and methods are needed to assess dependability attributes early on, as well as throughout the life-cycle process of software development.

Recent Results and Highlights: 20 semi-structured questionnaires were designed, 77 experts were invited and 41 responses were received. A new notation system, Causal Mechanism Graphing (CMG), was developed for expert opinion elicitation. The CMGs were merged to obtain a representation of the consensus knowledge about software dependability attributes shared by domain experts. A total of 50 entity classes, 265 measures and 141 measurement approaches were identified. The ranking of dependability attributes were obtained from nuclear stakeholders. A detailed quantification model for safety in the requirements phase was developed and a preliminary control gate for balancing the time spent in the requirements phase was proposed. The safety quantification model was applied to two case studies. These case studies show that our quantification model can be used to predict software safety in the requirements phase and at the reactor protection system channel level. Based on the CMGs and measures, detailed quantification models for other dependability attributes can be built to improve software dependability design, guide software dependability risk management, and reduce dependability risks of the Software Based Safety Critical Instrumentation and Control Systems in Nuclear Power Plants.



AHP Structure for the Ranking of Dependability Goals.



Distribution of requirements defects predicted and requirements defects actually observed.

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

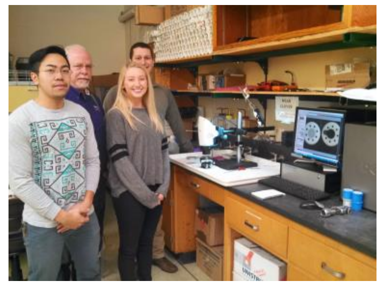
This program element focuses on development and fabrication of advanced sensors for improved performance measurement technology that provides revolutionary gains in sensing key parameters in reactor and fuel cycle systems. These new sensor technologies should be applied to multiple reactor or fuel cycle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

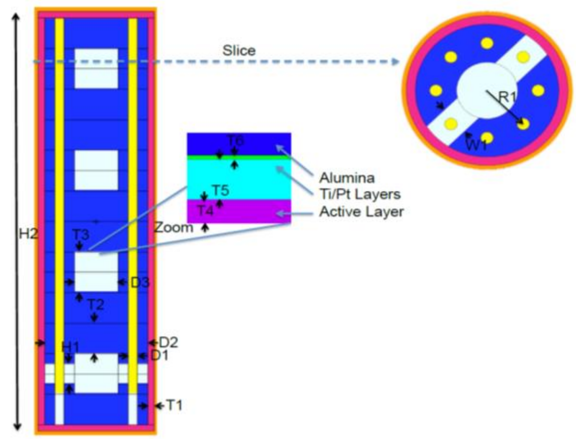
Enhanced Micro-Pocket Fission Detector (MPFD) for High-Temperature Reactors

Troy Unruh, Idaho National Laboratory,
Phillip Ugorowski, Kansas State University,
Jean-Francois Villard, Commissariat à l'Énergie Atomique et aux Energies Alternatives
Funding: $1,000,000 (10/01/14-09/30/17)

Description of project: This project is being conducted to research, develop, demonstrate, and deploy High Temperature Micro-Pocket Fission Detectors (HT MPFDs), 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. The project team consists of U.S. researchers from Idaho National Laboratory (INL) and Kansas State University (KSU). In addition, the French Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA) participates in the research at their own expense through an agreement with CEA.



KSU HT MPFD Researchers



ATF-3 funded computer model of HT MPFD for TREAT irradiation

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 DOE-NE irradiation programs are already requesting HT MPFDs to be included in their irradiation tests. The Accident Tolerant Fuels (ATF) irradiation test program will deploy the HT MPFD technology in steady-state and transient conditions in the ATF-2 and ATF-3 irradiation tests in the Advanced Test Reactor (ATR) and the Transient Reactor Test Facility (TREAT). 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 ATR.

Recent results and highlights: High-temperature compatibility research efforts have focused on improvements in fission chamber geometry, construction, and material selection to allow for stable operation in a wide range of temperatures during the harsh conditions encountered in steady-state and transient irradiation tests. Accurate characterization of the fissile deposits is required to assure the MPFDs behave as expected during irradiation; supplementary methods to further characterize the fissile deposits are being developed that will aid in resolving the relationship between detector response and neutron flux. In addition, the development of a HT MPFD computer model is ongoing to further understand operational characteristics so that the signal response can be used to accurately predict irradiation conditions in both steady-state and transient irradiations.

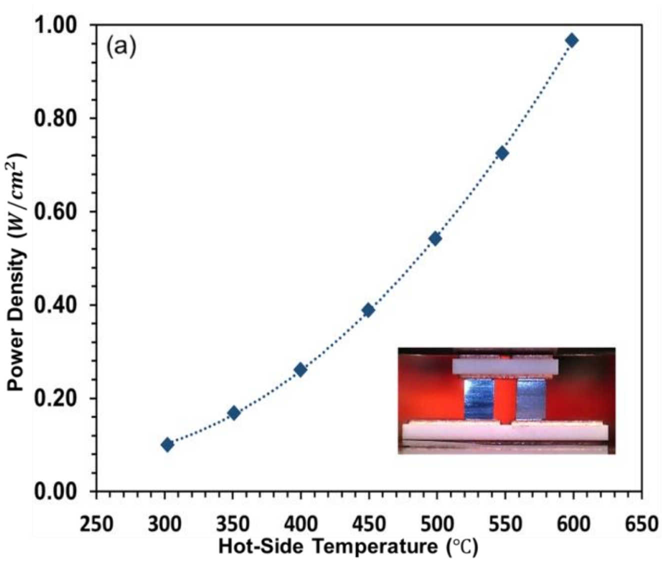
Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks

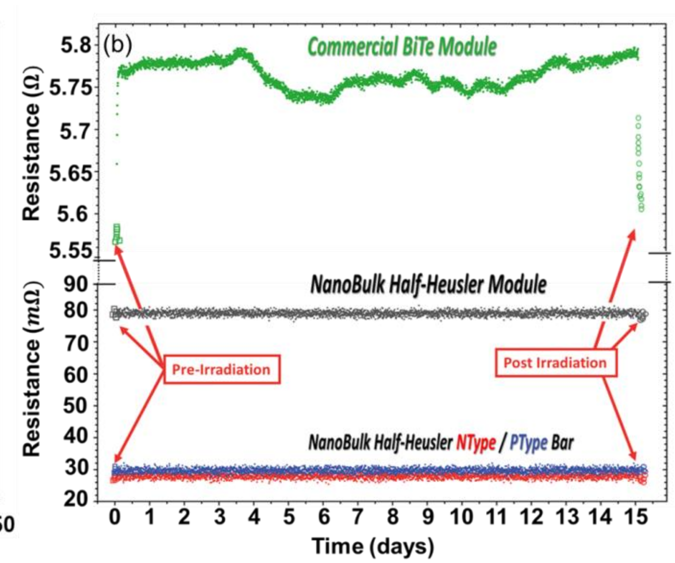
Yanliang Zhang and Darryl P. Butt, Boise State University,
Vivek Agarwal, Idaho National Laboratory, Zhifeng Ren, University of Houston
Funding: $980,804 (01/01/2015–12/31/2017)

Description of project: The objective of this project is to develop high-efficiency and reliable thermoelectric generators (TEGs) for self-powered wireless sensors nodes (WSNs) utilizing residual or 'waste' thermal energy from process systems found throughout nuclear reactors or fuel cycle facilities. The project is based on the design of high-performance nanostructured bulk thermoelectric materials recently developed by the team.

Impact and value to nuclear applications: This power harvesting technology has crosscutting significance to address critical technology gaps in monitoring nuclear reactors and fuel cycle facilities. The outcomes of the proposed research are intended to lead to significant advancements in sensors and instrumentation technologies, reducing costs, improving monitoring reliability, both of which will enhance plant safety. Self-powered wireless sensor networks could support the long-term safe and economical operation of all the reactor designs and fuel cycle concepts, as well as spent fuel storage and many other nuclear science and engineering applications. They provide a capability to reduce the amount of current and future cabling required to both power sensors and associated instruments used throughout plant systems, as well as reduce cabling associated with data transmission, so long as wireless communications technologies are feasible for the intended application.

Recent results and highlights: The team has designed and fabricated an initial unoptimized thermoelectric unicouple device using our nanostructured bulk (nanobulk) half-Heuslers thermoelectric materials that enable direct heat-to-electricity conversion over a wide temperature range. Figure (a) shows the power density of the unicouple device tested under various hot-side temperatures while the cold side is maintained at 100°C. We also investigated the effect of Gamma radiation on the electrical resistance of our nanobulk devices and a commercial device. Figure (b) shows that our nanobulk devices demonstrate no changes before, during, and after radiation, whereas the commercial device shows noticeable increases in electrical resistance.





(a) Electric power density versus hot-side temperature of a nanobulk half-Heusler unicouple device at a constant cold-side temperature of 100°C. (b) Gamma radiation effect on the electric resistances of the nanobulk half-Heusler devices and a commercial BiTe device.

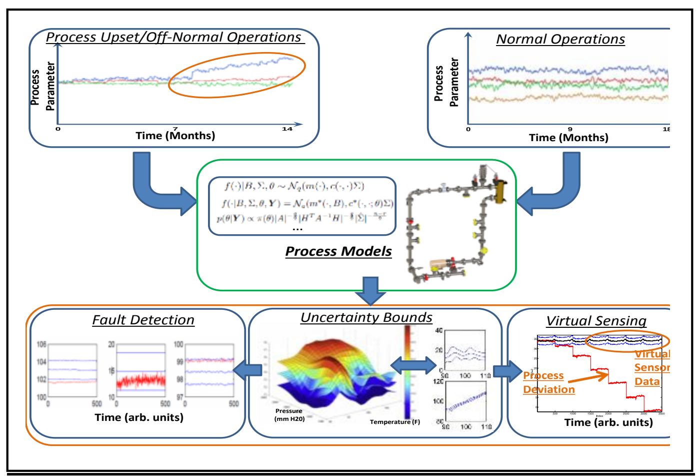
Robust Online Monitoring Technology for Recalibration Assessment of Transmitters and Instrumentation

Pradeep Ramuhalli, Pacific Northwest National Laboratory, Jamie Coble, University of Tennessee,
Brent Shumaker and Hash 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 online monitoring (OLM) technologies that can be used for sensor calibration interval extension and to validate sensor signals 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 to (1) apply methods for data-driven uncertainty quantification (UQ) to develop methodologies for high-confidence signal validation; (2) develop a 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 US nuclear facilities by developing a methodology to (1) support the regulatory basis for OLM-based calibration assessment, (2) improve the confidence 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 more 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.

Recent results and highlights: The focus of this research is on OLM of process instrumentation used for control of the plant and monitoring of its safety. During operation, these sensors may degrade due to age, environmental exposure, and maintenance interventions; result in anomalies such as signal drift and response time changes; and challenge the ability to reliably identify plant or subsystem performance deviations. A Gaussian process (GP) representation was developed for uncertainty quantification and was adapted to address the fault detection and virtual sensor problems. GP representation of residuals from an Autoassociative Kernel Regression model was applied to high-confidence signal validation, resulting in an initial approach for sensor fault and drift detection. A GP model of dependencies between sensors was applied for predicting virtual sensor readings with confidence bounds. Results in both cases using experimental data indicate the potential of the method in robust OLM. However, additional evaluations are ongoing with larger and more complex data sets. A framework for sensor response time assessment using noise analysis was evaluated on measurements from a flow loop as well as available data from plant operations. The approach shows promise; however, several hurdles exist to adapting this approach to automated, online assessment of response time, which includes automating the building of models from noise analysis data. These challenges are being addressed in ongoing research.



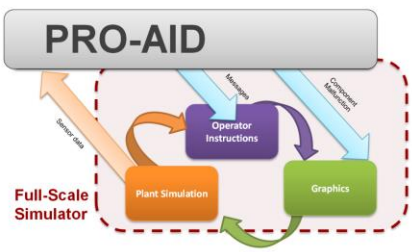
Data-driven robust OLM enables fault detection and virtual sensing. The example uses data from an instrumented flow loop.

Operator Support Technologies for Fault Tolerance and Resilience

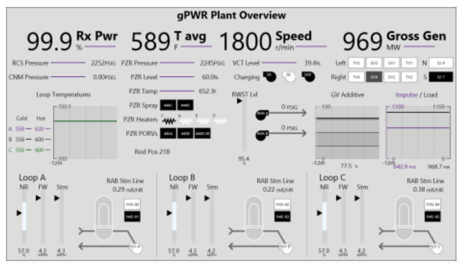
Richard B. Vilim, Argonne National Laboratory,
Kenneth Thomas and Ron Boring, Idaho National Laboratory
Funding: $995,000 (10/01/14–09/30/17)

<u>Description of project</u>: 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.

<u>Impact and value to nuclear applications</u>: 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.



Coupling between PRO-AID and the HSSL and COSS



Screenshot of COSS plant overview display.

Photograph of COSS integrated into HSSL.

<u>Recent results and highlights</u>: Fault diagnosis algorithms were tested using computer simulations of 20 different faults introduced into the chemical and volume control system (CVCS) of a pressurized water reactor (PWR). The testing approach followed accepted procedures for verifying and validating software. The software (PRO-AID: <u>P</u>arameter-Free <u>R</u>easoning <u>O</u>perator for <u>A</u>utomated <u>I</u>dentification and <u>D</u>iagnosis) satisfies its functional requirement, which is to accept sensor information, identify process variable trends based on this sensor information, and then to return an accurate diagnosis based on chains of rules related to these trends. The validation and verification exercise made use of a one-dimensional systems code for simulation of CVCS operation. Plant components were failed and the systems code generated the resulting plant response. Parametric studies with respect to the severity of the fault, the richness of the plant sensor set, and the accuracy of sensors were performed as part of the validation exercise. The results of these tests demonstrated robustness of the underlying code and methods development for diagnosing a broad range of faults that would be difficult for human operators to diagnose except through painstaking troubleshooting procedures today.

The research is also being used to evaluate aspects of the human-system interface – the portion of the system that provides information to control room operators about the analysis and results from the COSS that can be used to take appropriate control actions to minimize the impact of simulated faults from plant components. Development work on the COSS has focused on optimizing the presentation of fault information to maximize the operators' situation awareness. The COSS is integrated into the Human Systems Simulation Laboratory (HSSL), a full-scope glass-top simulator facility at the Idaho National Laboratory. The HSSL is used to conduct operator-in-the-loop studies to maximize safety and operator performance for new digital technologies introduced into nuclear power plant control rooms. The COSS is fully integrated into a high-fidelity simulation of an existing plant. The COSS provides the operator interface while bridging the plant model and the PRO-AID prognostic software. By using COSS in the HSSL, it has been possible to validate visualization methods for presenting fault information to operators. Additionally, through COSS demonstrations in the HSSL, nuclear utilities have been able to see the advantages of PRO-AID in providing early fault detection and helping operators mitigate those faults successfully and quickly.

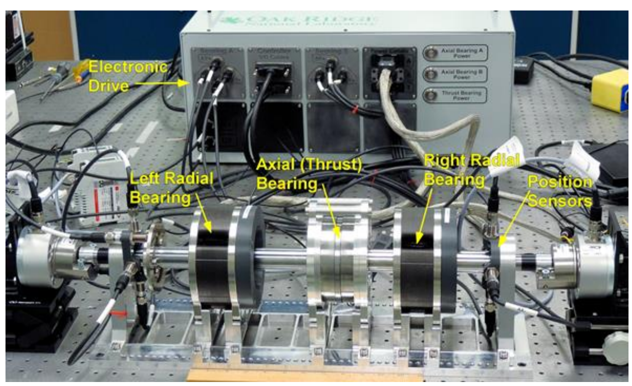
Embedded Instrumentation and Controls for Extreme Environments

Roger Kisner, Oak Ridge National Laboratory
Funding: $1,000,000 (10/01/14–09/30/17)

Description of project: This project uses embedded instrumentation and control (I&C) technologies to demonstrate potential performance gains of nuclear power plant components in extreme environments, such as high-temperature, radiation, high-pressure, high-vibration, and high-electro-magnetic interference conditions. For extreme environments, performance gains arise from moment-to-moment sensing of local variables and immediate application of local feedback control. Planning for embedding I&C during early system design phases contrasts with the traditional, serial design approach that incorporates minimal I&C after mechanical and electrical design is complete. The demonstration application involves the development and control of a novel, proof-of-concept motor/pump design. The motor and pump combination operate within the fluid environment, eliminating the need for rotating seals. Actively controlled magnetic bearings also replace failure-prone mechanical contact bearings that typically suspend rotating components. As such, the design has the potential to significantly enhance the reliability and life of the pumping system, which would not be possible without embedded I&C.

Impact and value to nuclear applications: This project will yield 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. Additionally, performance testing at the bench-scale and loop-scale will yield quantifiable measures of the performance improvements due to embedded I&C. Embedded sensors and controls can enable features, performance, and reliability not possible with legacy approaches. Future 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 is expected to increase their performance and reliability. A transition of component design and functionality from a static mechanical design to a flexible dynamic electromechanical system with embedded sensors and controls can realize components that can adapt in real-time to changing environmental conditions while sensors provide diagnostic and prognostic capabilities that increase component lifetime and reduce operating costs. Component design margins can be reduced because of tight coupling between sensors and controls, resulting in lower mass and, hence, lower costs.

Recent results and highlights: A bench-scale testbed has been fabricated, including magnetic bearings, custom-designed switched reluctance motors, sensors and real-time control hardware. The testbed provides an implementation environment for the remaining I&C tasks, such as the development of advanced control algorithms and a sensorless position indication. A detailed design for a submerged loop pump system has also been completed. These results and further results over the next year are expected to show the path to improve crucial performance and reliability factors using deep embedding. 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 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 possible lower cost manufacturing.



Bench scale test device incorporating shaft, magnetic bearings, and sensors shown with electronic drive. This system will be combined with a commercial canned-rotor pump for water-loop demonstration.

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

Kevin P. Chen, University of Pittsburgh
Funding: $987,676 (10/01/14–09/30/17)

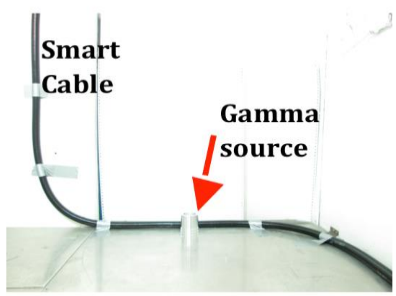
Description of project: The objective of this project is to develop multi-functional, remotely activated, and distributed fiber optical sensor networks to monitor parameters critical to the safety of nuclear power systems with high spatial resolutions. This objective will be achieved through the invention of new multi-function optical fibers as sensor platforms for radiation environments, development of novel sensory materials for harsh environment chemical measurements, invention 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 during both normal operating conditions and during accident and post-accident conditions.

Recent results and highlights: In Year 1, this project developed new multi-core optical fibers that can perform simultaneous physical parameter measurements with high spatial resolution. Fiber sensing technology enabled by these fibers will provide information in radioactive environments. Using multi-functional optical fiber as distributed sensing devices, this project invented a smart electric cable that can perform temperature, strain, chemical, and radiation measurements with 1-cm spatial resolution. The deployment of a smart electric cable may be able to self-monitor some aging parameters of the cable itself in service environments. This will reduce the amount of inspection activities that ultimately must be devoted to performing material condition assessments of these cables when in service. It is also being designed to spatially locate and measure environmental anomalies such as elevated radiation, abnormal temperature, and the presence of hydrogen for containment condition monitoring. 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 up to 700°C.

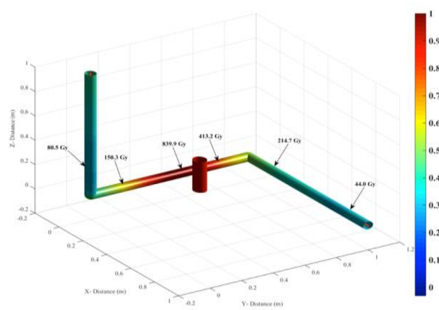
Fiber sensor enabled smart electrical cable

(a)



Testing of smart cable using gamma source

(b)



Smart electrical cable detection of radiation (1-cm resolution).

(c)

FY 2015 NEET-ASI Research Summaries

In FY 2015, the NEET-ASI program selected two 3-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:

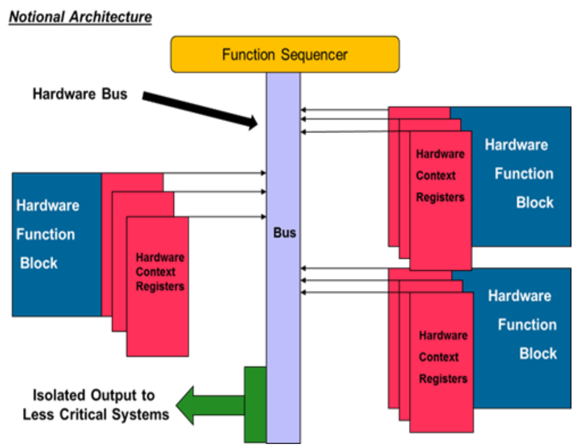
- Proof of acceptable software operational reliability;
- Comprehensive non-destructive testability;
- U.S. NRC regulatory requirements;
- Ability to detect defects introduced through the entire supply chain;
- Ability to qualify commercial-grade devices dedicated for safety-related usage; and
- Cost-effective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

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

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

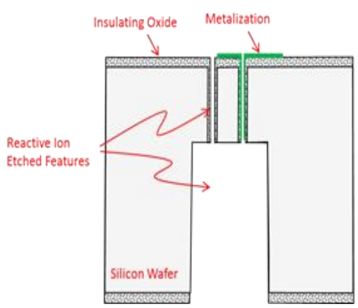
Description of project: An alternate approached to mitigate the unpredictable nature of software faults in safety-related instrumentation and control (I&C) systems due to the unbounded and general-purpose nature of Von-Neumann architecture CPUs commonly used in these devices is being explored. This approach 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 straightforward analysis and validation.

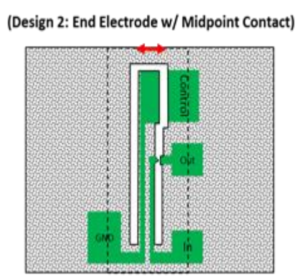
Programmable hardware logic will be used to investigate state-driven architectures that are deterministic in nature by minimizing fabrication, infrastructure, and application-level constructs that cannot be deterministically analyzed.



Two technologies will be 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.
- 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.





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.

Recent results and highlights: Early progress has been made in developing effective formal verification methods and processes using MathWorks® Simulink Design Verifier (SLDV) that provides the underpinning of the deterministic verification methods used for specific architecture features. The SLDV model checker exhaustively searches using a mathematical k-induction on the state space of the model. This contrasts with simulation or input vector testing methods, that are not exhaustive or one hundred percent. MEMS design has progressed to the development of an innovative shadow mask process for fabrication. This process allows confidence that the voltage and current needed for the design can be obtained on the selected silicon wafer material, and a preliminary design of the basic electromechanical relay that will be used to construct prototype devices. Design and physical validation of the relay primitive will continue as well as work on establishing the efficacy of the new shadow mask process.

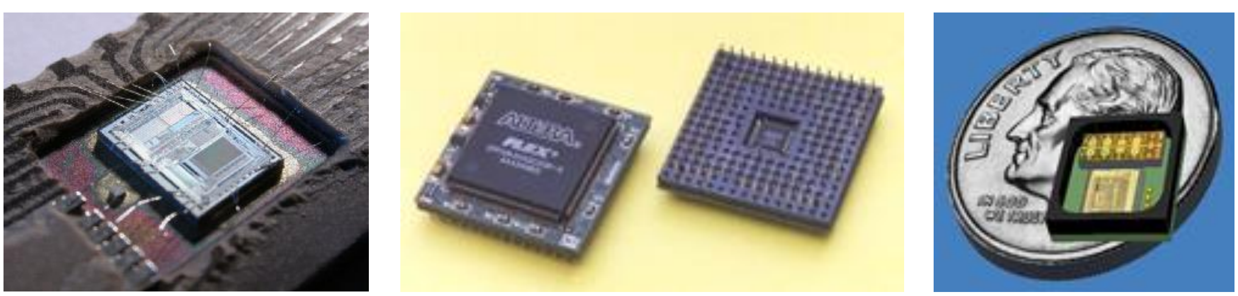
Development of Model Based Assessment Process for Qualification of Embedded Digital Devices in NPP Applications

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).

Recent results and highlights: The research approach involves assessing the regulatory context for treatment of CCF vulnerability in embedded digital devices, defining a classification scheme for embedded digital devices to characterize their functional impact and facilitate a graded approach to their qualification, developing and extending model-based testing methods to enable effective demonstration of whether devices are subject to CCF, establishing a cost-effective testing framework that incorporates automation and test scenario prioritization, and demonstrating the qualification approach through selection and testing of candidate digital device(s). Initial research activities focus on investigating approaches to the qualification of instruments with embedded digital devices. A workshop was held in March 2016 to capture insights from industry stakeholders. Extensive participation by regulators, vendors, and utilities, as well as domestic and international research organizations, enabled dialog on emerging regulatory positions and early efforts to resolve technical issues.

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.



Technology supporting embedded digital devices

Completed Projects

Projects listed below have been completed and summaries can be found in previous ASI Award Summaries available on the DOE-NE Website. The final summaries for the FY 2013 projects are included in the front of this document.

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)