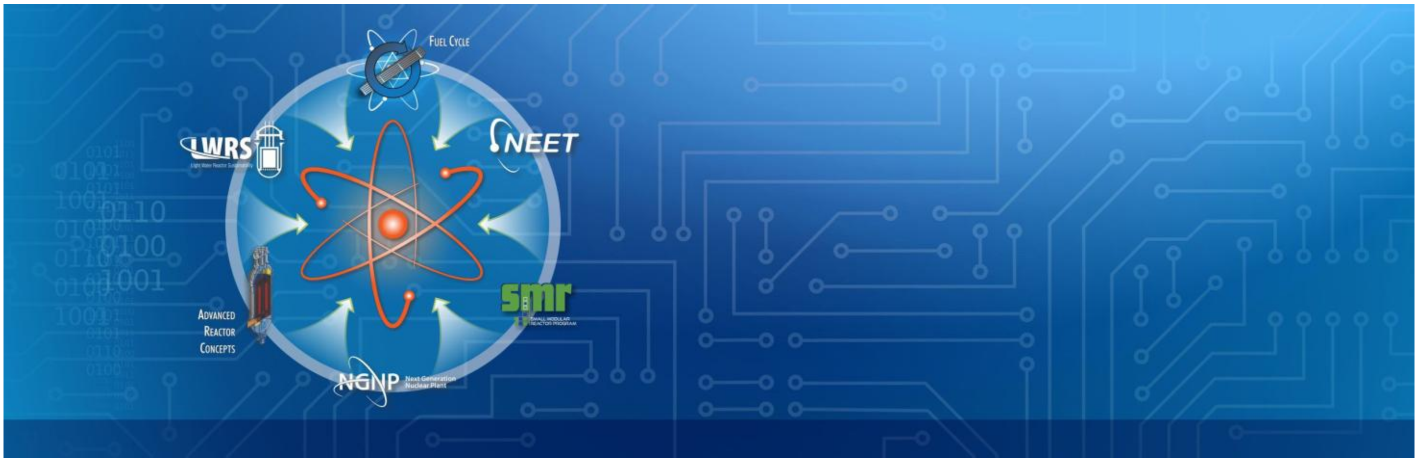


Advanced Sensors and Instrumentation 2013 ANNUAL PROJECT REVIEW MEETING SUMMARY

Germantown, MD
May 21-22, 2013

Introduction

The Advanced Sensors and Instrumentation (ASI) element of the Nuclear Energy Enabling Technologies (NEET) Program conducted its first Annual Project Review Meeting on May 21-22, 2013 in Germantown, Maryland with video links to other Department of Energy (DOE) National Laboratory sites. The purpose of the meeting was to review the 10 on-going ASI projects with presentations made by the research principal investigators. The presentations addressed the objectives and expected outcomes of research, and summarized technical performance and accomplishments since project inception. The presenters emphasized the enabling aspects of the research being performed to benefit the Office of Nuclear Energy (NE) research and development (R&D) programs. Representatives of DOE-NE's Nuclear Reactor Technologies, Fuel Cycle Technologies, and Advanced Modeling and Simulation programs participated in the meeting, as well as a representative from the U.S. Nuclear Regulatory Commission. Feedback from the programs regarding these projects will help ASI planning for next year.

In FY 2014, the ASI program is transitioning to a competitive research approach that will produce innovative and transformative research for the future. Areas of research will be selected based on NE R&D priorities, including feedback on the projects presented in this meeting. The meeting provided important input to NEET ASI on plans and priorities of the NE R&D programs that participated as well as a regulatory perspective of new instrumentation and controls related technologies being developed through the NEET ASI program. The review also served as an important engagement mechanism for NEET ASI to ensure that the results and plans for research address the needs of multiple NE R&D programs and to ensure the greatest leveraging of benefits.

Background

NUCLEAR ENERGY ENABLING TECHNOLOGIES

In FY 2012, the NEET program was initiated 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. Focusing RD&D on enabling technologies under one program increases the long-term impact of individual program expenditures by resolving problematic technical, cost, safety, security, and regulatory issues. This will be done in an optimal manner at an early phase rather than late in the development process with great cost escalation, in an ad hoc fashion, which has often been the case for the nuclear industry. These crosscutting technologies will advance the state of nuclear technology; thereby improving its competitiveness, and promoting continued contribution by nuclear power to meeting the nation's energy and environmental challenges.

The NEET program has the lead in coordinating the research activities undertaken that address enabling technologies by providing a mechanism for pursuing broadly applicable RD&D in areas that may ultimately benefit specific reactor or nuclear fuel cycle concepts. NEET will ensure that its activities are coordinated with individual program goals and needs to avoid redundancy and to contribute to cost-effective resolution of outstanding needs and challenges.

The NEET program includes four elements that contribute to a wide variety of existing and developing reactor and fuel cycle technologies: (1) Crosscutting Technology Development, (2) Energy Innovation Hub for Modeling and Simulation (Hub), (3) Nuclear Energy Advanced Modeling and Simulation, and (4) Advanced Test Reactor National Scientific User Facility.

The NEET Crosscutting Technology Development element has three technology areas (subprograms) that address critical technology gaps that span the DOE-NE R&D objectives: (1) Reactor Materials, (2) Advanced Sensors and Instrumentation, and (3) Advanced Methods for Manufacturing.

ADVANCED SENSORS AND INSTRUMENTATION

The primary goals of the NEET ASI program are to:

1. Enable the advanced Instrumentations and Controls (I&C) technologies essential to the DOE-NE R&D efforts to realize their mission goals.
2. Foster the research and development required to identify and deploy innovative and advanced I&C capabilities that address the limitations of current I&C systems.

The NEET ASI program has two distinctive roles:

1. Coordination of I&C research among DOE-NE programs to avoid duplication and focus the I&C R&D in support of advances in reactor designs and performance.
2. Development of enabling capabilities to address common I&C technologies gaps and needs across the DOE-NE R&D programs.

The NEET ASI program has identified four strategic I&C areas of 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.

Projects Summary

2012 ASI Projects

The 10 ASI projects presented during the Annual Project Review meeting are summarized below and grouped by each of the four strategic areas previously described. The project outcomes are directed at development of technologies, methods, and strategies that support multiple programs, and reactor or fuel cycle implementations. The meeting Agenda with links to the presentation is included as Attachment 1.

Advanced Sensors

High-Temperature Fission Chamber

The objective of this project is to develop a high-temperature fission chamber for in-core service, capable of operating from start-up to full power at 800°C, to monitor a fission reactor's neutron flux, which is a key safety and performance measurement. Neutron flux can peak sharply within the core and the peaking has both safety and performance implications. This fission chamber will improve spatial resolution of neutron flux measurement and may enable the reduction of the operating margin currently required due to the masking of the local flux variations by the intervening distance to ex-core neutron flux sensors. The High-Temperature Fission Chamber project supports the Advanced Small Modular Reactor, High Temperature Gas-cooled Reactor, and Advanced Reactor Concepts programs.

Accomplishments

In FY 2012 the properties of materials and components were evaluated against the likely requirements for in-core use in molten FLiBe (lithium fluoride-beryllium fluoride) and the high temperature gas-cooled reactor helium coolant flow. Report ORNL/LTR-2012/331, "Materials Selection for a High-Temperature Fission Chamber" summarizes these efforts. The report summarizes the properties and operation of a fission chamber - absorption of neutrons, transport of fission fragments through the fill gas, electronic signal generation - and the special requirements imposed by the design goals of 1 count/sec/unit flux, operation at 800 °C, immersion in helium or FLiBe, and operation at fluxes up to 10^{13} neutrons/cm^2/s. The report also addresses the protection that the chamber will require from the reactor coolant, how the interior must be constructed, how electrodes and insulators can be fabricated, electroplating of uranium onto electrodes, joining of metals and insulators, and the thermodynamics of radiation, convective, and conductive heating. An initial design for the chamber was produced that uses alumina insulators, high-temperature brazing, and nickel or nickel alloy metal sheathing and electrodes.

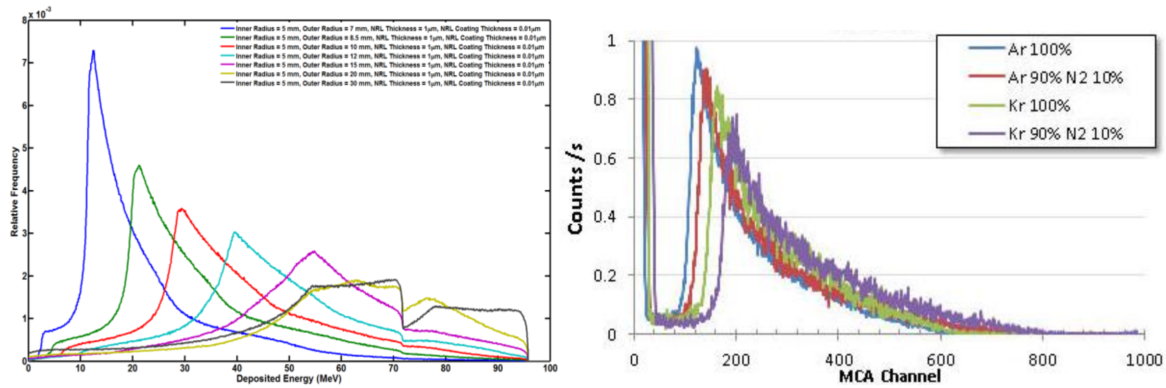


Figure 1. Computer modeling and physical experiments are used to study the energy deposition distribution of charged particles in the design of a new high temperature fission chamber for advanced nuclear reactors.

In FY 2013 experiments were performed to verify and validate information, assumptions, and conclusions related to electroplating uranium onto nickel and brazing alumina components together. Although electroplating experiments showed that the conversion from UO_2 to UN (a preferred material because of phase changes in the oxide with variations of temperature) caused some embrittlement of the nickel substrate, the rigidity of the alumina structure will prevent flexing and mitigates this potential issue. Experiments with Pd/Ni brazes have demonstrated that good butt joints can be formed between alumina tubes when the ends are first coated with titanium metal.

Micro-Pocket Fission Detectors (MPFDs)

The objective of this project is to develop a robust, compact, multipurpose sensor for measuring fast and thermal flux and temperature in real-time, with higher fidelity, and increased accuracy and resolution from smaller compact sensors that are less intrusive. The high temperature,[1] compact micro-pocket fission detectors developed from this project will benefit ongoing research and development activities in new fuels and materials in the Fuel Cycle Research and Development, Light Water Reactor Sustainability, Next Generation Nuclear Plant, Advanced Test Reactor National Scientific User Facility, and Advanced Reactor Concepts programs. By simultaneously measuring fast and thermal flux and temperature, MPFDs will provide higher resolution and higher accuracy information on temperature and flux distributions. Such information is particularly beneficial to on-going efforts to qualify new fuels and high temperature alloys and to validate new multi-physics models used in advanced code development programs.

<u>Accomplishments</u>

During FY 2012 MPFD development focused on enhancing the MPFD design to accommodate High Temperature Irradiation Resistant Thermocouples (HTIR-TCs) and to improve robustness for higher temperature, long-duration high flux irradiations. After the design was finalized, materials were procured for fabrication of a prototype MPFD; and fabrication procedures were developed to build the prototype. MPFD development activities at Kansas State University (KSU) focused on fissile deposition techniques to determine the optimal methods for fissile deposit characterization. In addition, KSU designed, assembled and tested a first-generation MPFD amplifier board in the KSU TRIGA reactor. All FY 2012 activities are summarized in “NEET Micro-Pocket Fission Detector – FY 2012 Status Report,” INL/EXT-12-27274, issued September 2012.

[1] The current effort is limited to evaluations of temperatures up to 600 °C; however, components have been selected to withstand temperatures above 1000 °C.

During FY 2013, development activities focused on refining MPFD construction techniques to finish prototype construction that is suitable for evaluations and characterization in high temperature, high pressure and radiation environments. In addition, INL initiated patent paperwork, Invention Disclosure Report IDR-2291. KSU research focused on performing fissile deposit evaluations to accurately characterize the fissile deposit and authored the paper, "Micro Pocket Fission Detectors (MPFD) for Fuel Assembly Analysis", describing potential use of MPFDs in radiation waste management at the ASME International Conference on Environmental Remediation and Radioactive Waste Management (ICEM), September 8-12 2013 in Brussels.

Planned activities for the remainder of FY 2013 include completing high temperature and high pressure evaluations, performing neutron and gamma response testing, and completing the report, "NEET Micro-Pocket Fission Detector – FY 2013 Status Report," INL/EXT-13-29346, which will be issued in September 2013. In addition, the KSU student will present the paper, "Micro Pocket Fission Detectors (MPFD) for Fuel Assembly Analysis", at the ASME ICEM conference. Activities for FY 2014 will use input from previous evaluations to refine the MPFD design (as needed) and perform more high temperature, high pressure and radiation response characterizations. It is planned to include testing of MPFDs in a nuclear reactor. All work will be summarized in a final program report to be issued at the program's completion in September 2014.

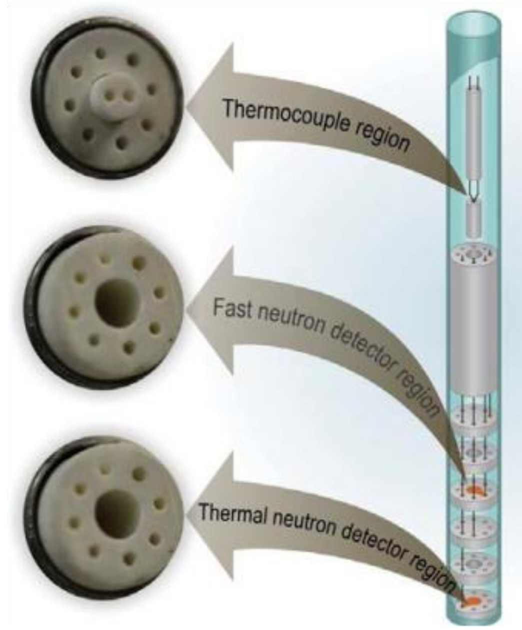


Figure 2. A new micro pocket fission detector combines sensors for fast neutrons, thermal neutrons, and temperature measurement in a compact size to provide improved resolution of key measurements during in-pile irradiations.

Irradiation Testing of Ultrasonic Transducers

The objectives of this project are to develop fundamental data on ultrasonic transducer performance under irradiation and to address gaps in signal analysis capabilities that limit the use of automated tools for advanced ultrasonic tests. The ultrasonic transducer irradiation performance data and enhanced ultrasonic signal processing techniques developed from this project will enable deployment of ultrasonic sensors with higher reliability, accuracy and resolution that benefit multiple DOE-NE programs [Fuel Cycle Research And Development, Advanced Reactor Concepts, Light Water Reactor Sustainability, Next Generation Nuclear Plant, and the Advanced Test Reactor National Scientific User Facility (ATR NSUF)] directly and indirectly. In particular, the use of radiation resistant high-performance ultrasonic transducers and improved signal processing techniques will enable the development of enhanced in-pile sensors for real-time or near-real-time measurement of a number of parameters (e.g., geometry changes, temperature, crack initiation and growth, gas pressure and composition, and microstructural changes). For example, in the case of ultrasonic thermometers, a single small diameter (~1 mm) probe can be used to obtain a temperature profile in materials heated up to over 2500 °C).

<u>Accomplishments</u>

The research involves collaboration between a Pennsylvania State University-led irradiation funded by the ATR NSUF at the Massachusetts Institute of Technology Research Reactor (MITR) and this NEET-ASI project. In FY 2012 the primary task, with regards to the irradiation, was identification of the most promising magnetostrictive and piezoelectric transducer materials for inclusion in the test. Activities were initiated to design a test capsule and select components (i.e. sensors, instrumentation, etc.). Input was gathered from cognizant DOE-NE R&D program leads (i.e., Advanced Fuel Cycle Technologies and Nuclear Reactor Technologies) about the parameters they want to monitor during irradiation testing in materials test reactors and the desired accuracy of these measurements. The ultrasonic signal characteristics of these parameters and hardware requirements for integrated signal processing system were determined. Finally, a report "NEET In-Pile Ultrasonic Sensor Enablement-FY 2012 Status Report", INL/EXT-12-27233, was issued that summarizes these efforts.

During FY 2013, the team continued capsule and transducer design and component selection activities for the irradiation test, and developed an irradiation test plan. This irradiation test plan describes the sensors selected for inclusion in the test, anticipated irradiation test conditions (e.g., temperature, power ascension, flux, and duration), and post-irradiation examination (PIE) activities. The paper, "Irradiation Testing of Ultrasonic Transducers" which describes this planned irradiation, was accepted as an invited paper for 2013 International Conference on Advancements in Nuclear Instrumentation, Measurement Methods, and their Applications (ANIMMA) conference.

Planned work for the remainder of FY 2103 includes completing transducer fabrication and transmitting these transducers and other components (e.g., cabling, instrumentation, etc.) to the Massachusetts Institute of Technology for irradiation in their reactor prior to the planned test startup date (August 2013). The status report "NEET In-Pile Ultrasonic Sensor Enablement-FY 2013 Status Report," INL/EXT-13-29144, will be issued in September 2013. In FY 2104, the team will complete evaluations of transducers, validate data from the transducer irradiation, and support PIE evaluations and data interpretation. Signal processing work will be a major focus of FY 2014 and will include development of enhanced signal processing algorithms for selected parameters, benchmarking of the developed algorithms with representative experimental data, and issuance of the final program report.

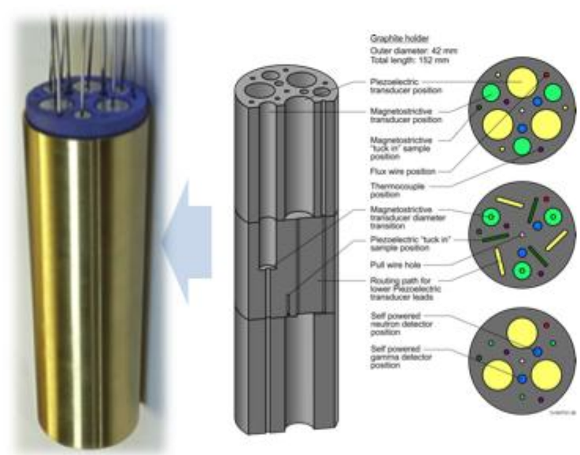


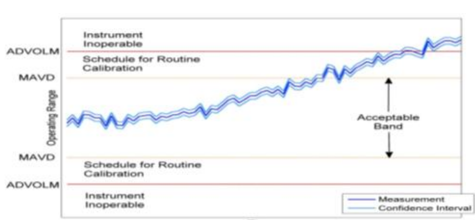
Figure 3. A three-year project to address transducer irradiation survivability and signal processing may pave the way for ultrasound-based sensors to measure numerous parameters during in-pile irradiations that are not available through current measurement technologies.

Recalibration Methodology for Transmitters and Instrumentation

The objective of this research is to develop online monitoring technologies for sensor calibration interval extension and signal validation in existing and new reactors. The Recalibration Methodology research project directly supports the needs of the Light Water Reactor Sustainability, Advanced Small Modular Reactor, Next Generation Nuclear Plant and Advanced Reactor Concepts programs, through the development of advanced algorithms for monitoring sensor and system performance and enabling the use of plant data to derive information that currently is not measured. These advances are expected to improve the safety and reliability of nuclear power systems as a result of greater accuracy and improved reliability of sensors used to monitor key parameters. This project will assess methods for improved uncertainty quantification in online monitoring, and use the results to develop robust virtual sensor technology and formal methods for signal validation.

Accomplishments

In FY 2012 this project reviewed relevant literature to assess the current state of the art and identify technical gaps that limit the potential of online monitoring for sensor calibration assessment and signal validation. The technical gaps identified include: (1) understanding the impacts of sensor degradation on measurements for both conventional and emerging sensors, (2) quantification of uncertainty for online recalibration assessments, (3) development of acceptance criteria to determine if a sensor is performing within calibration, (4) quantification of the effect of acceptance criteria variability on system performance, (5) a methodology to provide virtual sensor estimates to replace faulty sensor readings, (6) on-line monitoring needs for emerging sensor suites, and (7) impact of digital instrumentation and controls on on-line monitoring. The gaps assessment findings were published in a technical report (PNNL-21687). In FY 2013, research is ongoing to addresses the accurate quantification of uncertainty for online monitoring systems. Sources of uncertainty in typical on-line monitoring systems were identified, as were methods for model-neutral uncertainty quantification. Simulation and experimental data sets are planned for use in evaluation of uncertainty quantification methods. A simulation model of an instrumented heat exchanger was completed. Planning for measurement data acquisition from a laboratory-scale instrumented flow loop was also completed, along with a test plan for measurement data. Ongoing activities include exercising the simulation model to generate a set of measurements that encompass normal and off-normal conditions. Measurement data acquisition from the laboratory-scale flow loop will be conducted. These will be followed by an evaluation of uncertainty quantification methodologies and documentation in technical reports.



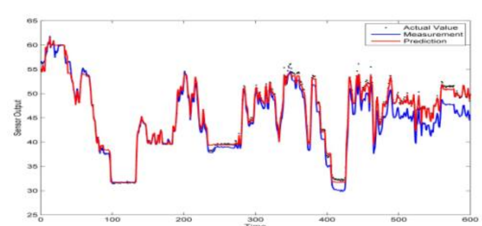


Figure 4. Signal validation and virtual sensors can be used to assess the performance of sensors and monitor the state of important plant parameters even when potential sensor drift and failures occur. This ensures reliable and accurate information is provided to plant operators and decision makers.

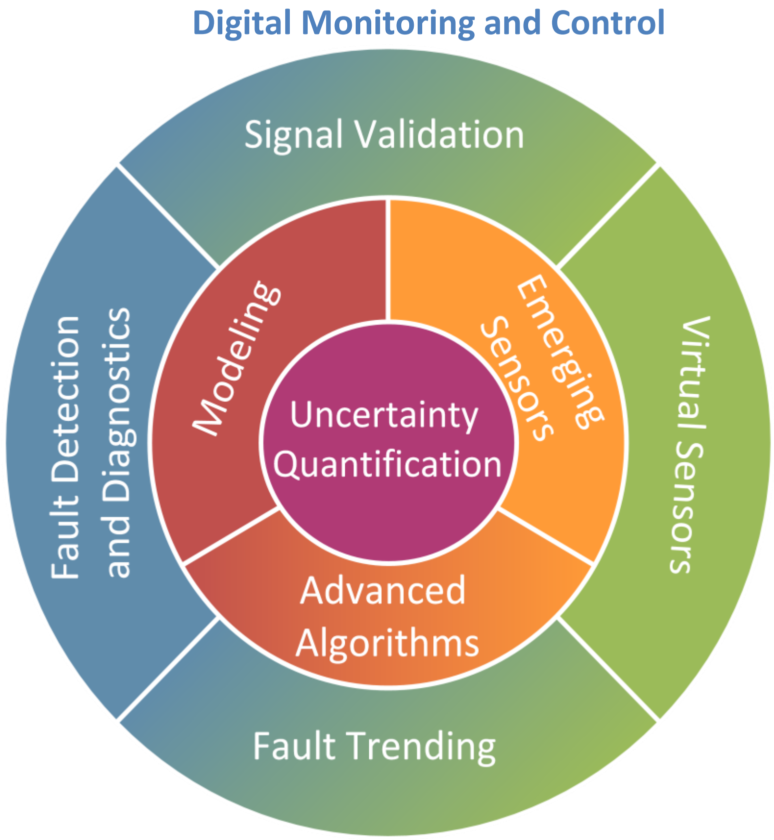


Figure 5. Advances in sensors and controls technologies vital to nuclear reactor and fuel cycle system safety depend on advances in interdependent fields of science and technology that are the focus of NEET ASI research.

Digital Technology Qualification

The objective of this project is to provide the basis for implementing fully digital instrumentation and control systems in nuclear power application by developing methods to resolve the potential susceptibility of digital technology to common-cause failure. By enabling the use of modern digital instrumentation and control technologies, the Digital Technology Qualification research project supports the goals of the Light Water Reactor Sustainability, Advanced Small Modular Reactor, Next Generation Nuclear Plant, and Advanced Reactor Concepts programs. The demonstration of digital measurement and actuation technologies facilitates the transition from dated, burdensome equipment to implementation of fully digital systems that are reliable, accurate, and more-readily maintainable. In addition, the development of a fundamentally sound approach to resolve common-cause failure vulnerability enables optimal instrumentation and control architectures with a well-defined safety basis, less imposed complexity, and, potentially, reduced life-cycle costs.

Accomplishments

A study was conducted into key challenges and impediments to qualification of digital technology for more extensive use in nuclear power plants (NPP). The findings from this study established the foundation for research to identify and demonstrate digital field devices suitable for replacing aging analog equipment and to provide objective criteria to resolve concerns about common-cause failure (CCF) vulnerability associated with digital I&C systems. The study identified digital alternatives to analog sensors, local control loops, and actuators that can meet the availability, reliability, and qualification requirements of safety-significant instrumentation and control systems. This study considered the major analog sensor and actuator technologies that are being incorporated into new plant designs (as well as perpetuated in current operating NPPs), why they are still being used rather than the new digital alternatives, and the likely impact on long-term operations in the form of process inaccuracies and excessive maintenance demands. The results of the study were published in a report entitled *Digital Technology Qualification Task 2 – Suitability of Digital Alternatives to Analog Sensors and Actuators* (INL/EXT 12-27215). An investigation of common-cause failure mitigation practices in nuclear and non-nuclear industries was also conducted. This investigation involved capture of common-cause failure experience, review of existing guidance on common-cause failure mitigation, identification of applied mitigation approaches, evaluation of prior common-cause failure research by the nuclear power industry, and analysis of knowledge gaps in the treatment of common-cause failure mitigation. The findings of this investigation were published in a report entitled *Common-Cause Failure Mitigation Practices and Knowledge Gaps* (NEET/ASI/ORNL/TR-2012/01). Research is proceeding into strategies for common-cause failure mitigation to establish digital technology alternatives to analog field devices. Based on initial findings, a taxonomy for common-cause failure mitigation is being developed to capture key characteristics of common-cause failure vulnerabilities and categorize mitigation approaches. An investigation is underway of the quantified performance characteristics of analog sensors in terms of quality, accuracy, reliability, maintainability, and qualification limitations. Digital replacements are similarly being evaluated against the same performance characteristics to determine the potential performance improvement afforded by these digital alternatives. Additional technical reports will be issued to document key outcomes of the research.

Design for Fault Tolerance and Resilience

The objective of this project is to develop fault tolerant control and protection system technologies for nuclear energy and associated fuel cycle system technologies. This project supports the Light Water Reactor Sustainability, Advanced Small Modular Reactor, and Next Generation Nuclear Plant programs by leveraging experience in the development of equipment fault detection and identification algorithms to the design of control and protection systems. By developing technologies that provide early detection and identification of incipient challenges or degradation, this research will result in more informed operator responses that can minimize fault effects and produce more resilient plant response.

<u>Accomplishments</u>

In FY 2012, a study was completed to identify NPP equipment faults that could be better managed with less risk of tripping the reactor through enhanced control automation in lieu of procedure-based operator actions. The study identified the Chemical and Volume Control System as a system that involved significant manual operator actions during transients involving this system. The study also investigated the merits of improving the NPP response to a loss-of-load transient and determined that there are opportunities for enhance control automation in lieu of operator actions to avoid reactor trips for these types of transients. This work was published in a report entitled Design to Achieve Fault Tolerance and Resilience (INL/EXT-12-27205).

In FY 2013, an approach was developed to provide a power plant operator with improved plant status information to better manage the outcome of equipment failures. Improved operator response to upset events can reduce the mechanical stress on a plant and the likelihood that the plant will be taken off-line which results in lost production and potentially destabilizes the electric grid. Rigorous methods were developed for detecting equipment failures more quickly and with greater sensitivity by tracking readings and relating them to equipment condition. This information will be used to automate control actions that in the past have been performed manually by plant staff and are subject to delayed manual response. Steps were begun to apply these technologies to a full-scale simulator for assessing and demonstrating the methods. We are investigating faults in the Chemical and Volume Control System using a full scale simulation of a commercial light water reactor to determine how operator performance can be improved compared to present methods for handling such events. This includes a human factors analysis which is paramount for assessing how operator performance will be improved or otherwise affected. Work was published in a report entitled Description of Fault Detection and Identification Algorithms for Sensor and Equipment Failures and Preliminary Tests Using Simulations (ANL/NE-12/57).

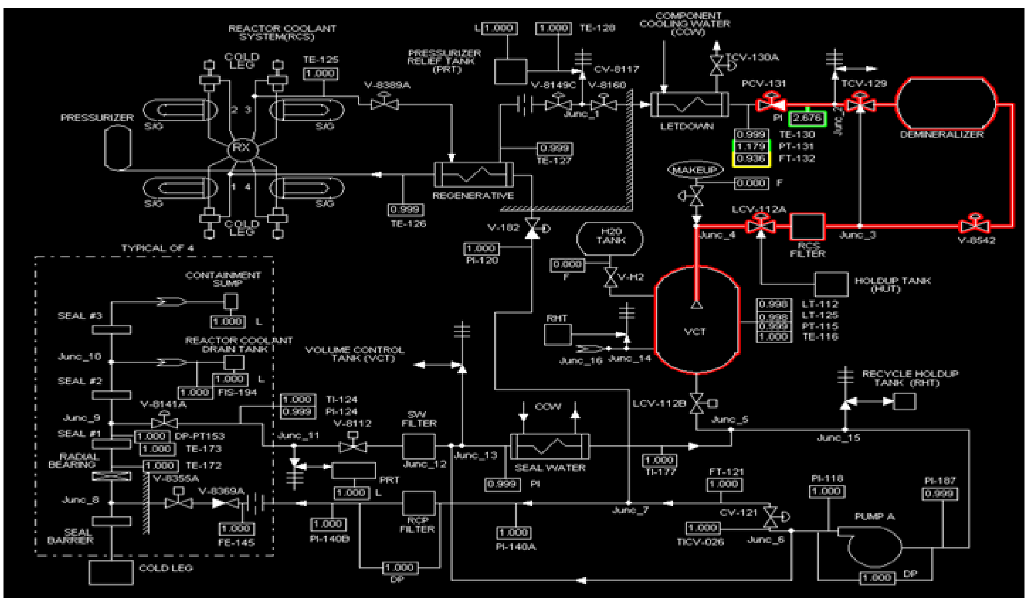


Figure 6. One goal of designing for fault tolerance and resilience is to enable diagnosis of impending equipment faults before annunciation by alarms. This will support timely response by plant personnel and avoid equipment challenges and plant shutdowns.

Sensor Degradation Control Systems

The objective of this project is to investigate new approaches for mitigating the effect of power plant sensor degradation and ensuring that nuclear energy systems achieve improved performance through advances in sensor reliability and accuracy. The technologies developed by this project directly support the goals of the Light Water Reactor Sustainability, Next Generation Nuclear Plant, Advanced Reactor Concepts and Advanced Small Modular Reactor programs. The research results from the Sensor Degradation Control Systems project will provide a technology base for obtaining more reliable sensor readings in the presence of sensor degradation mechanisms. The increased reliable sensor readings obtained from this research will enable increased sensor service life, self-calibration to counter sensor degradation mechanisms, and improved prediction of sensor failures.

Accomplishments

In the early stages of this project the benefits of treating sensor degradation from both an intra-sensor perspective (a single sensor) and an inter-sensor perspective (a network of sensors) were identified. An intra-sensor approach takes into account the local environment as it effects and shapes degradation processes. As an example, the rate of corrosion in the sheath of a resistance temperature detector (RTD) is affected by the dissolved oxygen concentration and temperature, which in a power plant can change in time and differ by plant equipment. The material science literature was reviewed and it was concluded that sufficiently accessible semi-empirical methods exist for modeling degradation as a function of the local environment. A start was made by identifying through numerical simulations the degradation mechanisms that most strongly effect RTD performance. That work has set the stage for more detailed investigation, the modeling of "crud" deposition and its affect on RTD performance. With respect to the inter-sensor approach, which considers how degraded sensors can be detected and identified within a network of sensors, we developed the Algorithm for Transient Multivariable Sensor Estimation (AFTR-MSET). This algorithm addresses the high false-alarm rate of existing data-driven methods, a result of their inability to treat plant transient data and to extrapolate beyond observed measurements.

Proof-of-principle tests were conducted using numerical simulations of nuclear plant equipment operating with failing sensors. The properties expected of AFTR-MSET from theory were verified in these simulations. Plans are being developed in collaboration with a nuclear utility to test AFTR-MSET in an application where an existing monitoring capability is producing unacceptably high false-alarm rates.

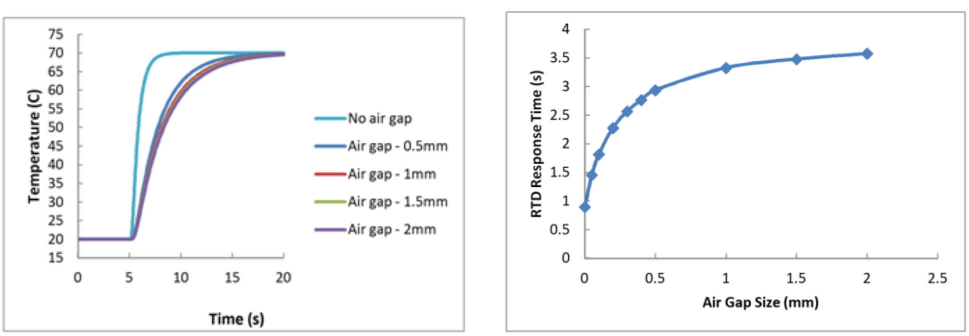


Figure 7. Modeling the degradation mechanisms that cause sensor drift and failure may lead to improved knowledge of sensor health, sensor-reading accuracy, and improved health monitoring of sensors in inaccessible locations during operations.

Embedded I&C for Extreme Environments

The objective of this project is to investigate embedded instrumentation and controls for nuclear power components and systems to demonstrate performance and reliability improvements that are possible in major components when sensors and controls are deeply integrated. Deeply embedding sensing and controls technologies within reactor components make possible designs, performance, and reliability that are otherwise unachievable. Results from the Embedded I&C in Extreme Environments project directly benefit the Next Generation Nuclear Plant, Advanced Reactor Concepts, and Advanced Small Modular Reactor programs. The combination of modeling, simulation, fabrication of physical systems, and subsequent characterization and testing in this project will demonstrate the viability of the embedded instrumentation and controls approach. A specific motor-pump type has been selected to demonstrate the embedding concept.

Accomplishments

Several notable results have been accomplished since the start of the project in FY2012. At the project outset, motor performance requirements were established. These requirements became the stimulus for a conceptual design that displayed embedded sensors, controls, and the related physical mechanisms of a demonstration motor and pump system. A reluctance drive was selected after a preliminary modeling effort and consideration of alternative motor types. The motor would be a canned rotor design with no rotating fluid seals and no sensor penetrations. The motor would be fully submerged in the cooling media and therefore need to operate at extreme temperatures. Rotor would be magnetically suspended so that there is no contact (or wear) with the stationary parts of the motor or pump volute.

A failure modes and effects analysis (FMEA) was conducted on a preliminary systems design. Significant motor sensor technologies that can operate at extreme temperatures were identified including a sensorless approach that utilizes the magnetic drive and suspension coils as position and rotation sensors. Additionally, a control strategy for the system was developed. Several engineering issues related to deploying the embedded concept for motor-pump applications were identified: (1) need for control of coupled response between motor torque and forces on magnetic bearings, (2) need for control of natural oscillatory modes and frequency response of sensors and control components, (3) consideration for magnetic materials in high-temperature environments, (4) design methods for minimizing the magnetic gap, and (5) development of insulation for high temperatures. These findings, their design basis, and additional backup information were published in a report[2] available from the Office of Scientific and Technical Information (OSTI). Subsequent to the report publication, a more detailed modeling and simulation effort has begun with the goal of preparing for the design and eventual fabrication of motor-pump system to demonstrate the effectiveness of the embedded approach. Modeling of the mechanical, thermal, and magnetic aspects of the motor using finite element methods has been done. Currently, the dynamics of magnetic suspension bearings is being simulated. A paper has recently been published as the lead article in the June issue of IEEE Instrumentation and Measurement Magazine.[3] The article discusses the challenges of sensor design and embedded instrumentation and controls for extreme environments such as for a liquid fluoride salt pump.

---

[2] R. Kisner et al., “Embedded Sensors and Controls to Improve Component Performance and Reliability,” ORNL/TM-2012/433, Sept. 2012.

[3] A. Melin, R. Kisner, and D. Fugate, “Advanced Instrumentation for Extreme Environments,” IEEE I&M Magazine, Vol.16, No. 3, June 2013.

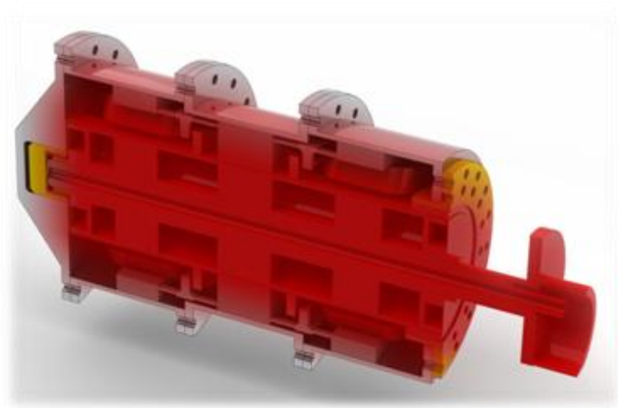


Figure 8. New components for advanced nuclear energy systems require highly embedded instrumentation and controls for real-time control and to function reliably for longer duty cycles in more extreme service environments than conventional components used today.

Nuclear Plant Communication

Power Harvesting for Sensor Networks

Instruments in nuclear power plants (NPPs) and many industrial environments typically are served by at least two sets of wires; one set carries data and control signals and the other provides instrument power. Wireless communication devices are beginning to appear in a limited number of non-safety-related NPP applications and wireless sensor networks have proven to be less expensive, more flexible, and more reliable in industrial settings than their wired counterparts. The objective of this project is to investigate methods of power harvesting techniques that can be reliably applied in a nuclear power plant environment. The Power Harvesting Networks project directly benefits the Light Water Reactor Sustainability, Advanced Small Modular Reactor, Advanced Reactor Concepts, and Next Generation Nuclear Plant programs and indirectly benefits the Fuel Cycle Research And Development program by minimizing the need for many of the power cables to sensors, enabling cost-effective deployment of larger numbers of sensors that can improve the redundancy, security, and safety of nuclear reactors and fuel cycle systems. This project will assess the viability of deploying power harvesting methods, developing tools to optimize the circuits for low power dissipation, designing solid state electronics that minimize power losses, and designing data transmission protocols that are adaptive, robust, and require little power while still maintaining the necessary amount of information flow.

<u>Accomplishments</u>

The current state of the practice in power harvesting has been investigated and various potential energy sources were examined for use in a NPP environment. These energy sources include kinetic (vibration, acoustic, mechanical, and fluid flow), thermal (thermoelectric and pyroelectric), and radiant (light and radio frequency). Knowledge gaps in power harvesting technologies were documented in ORNL/ TM-2012-442. Researchers concluded that thermal energy harvesting is an excellent choice for deployment in a NPP environment owing to a suitable number of environmental energy sources and significant energy density for power harvesting. Consequently, future R&D activities will emphasize thermal energy harvesting – either thermoelectric or pyroelectric. A baseline power estimate for a hypothetical sensor node that includes signal conditioning and digitization electronics for four thermocouples, a small microprocessor, and a radio transceiver that consumes twice as much power during the transmit cycle as the most efficient available commercial transceivers has been developed. Local energy storage, probably in a supercapacitor, will allow periodic, short-duration periods of elevated power consumption. If environmental conditions limit the amount of power that is available for prolonged periods, the frequency of data transmissions can be dynamically adjusted to reduce power consumption.

To arrive at the optimal wireless sensor network architecture, the current state of the practice in sensor networks has been investigated including Wireless HART and ISA100.11a commercial technologies.

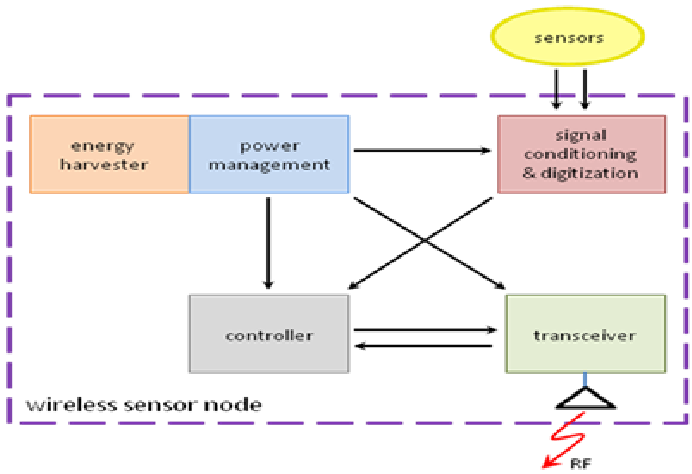


Figure 9. Power harvesting research for nuclear plant sensors will lead to less need for cables and the ability to easily add sensors to plant sensor networks using heat and other energy sources that are present in abundance in the environment.

Advanced Concepts of Operations

Advanced Human-System Interfaces

The objective of this project is investigate the role that advanced human-machine interface technologies will play in establishing a resilient control system that enhances human performance and limits the occurrence and effects of human error. The emphasis of the RD&D activities will be on improving operational safety and efficiency and improvement of human performance. This will produce a coherent framework and guidance for the development of new operating concepts that would add significantly to the ability of future system designers to reduce operating and maintenance costs. The advances from this project will benefit Light Water Reactor Sustainability, Advanced Small Modular Reactor, Advanced Reactor Concepts, Next Generation Nuclear Plant, and Fuel Cycle Research and Development programs. State-of-the-art of Human System Interface technologies will be evaluated for their ability to support operating crews in achieving error-tolerant and resilient operation and optimal task performance. The research will promote methods to use advanced technologies to allocate functions appropriately to humans and systems and to present plant process and state information to the operator for efficient and safe operations. This effort will ensure that the most suitable technologies are available to be deployed in nuclear power plants and new fuel cycle facilities.

Figure 10. New human system interface technologies can be used to enhance operator performance to support safe and reliable human performance in nuclear plant activities, a key objective of nuclear energy research in the NEET-ASI program.

Accomplishments

Research in this effort has produced a classification of Advanced Human-System Interfaces (HSIs) for current and future generations of nuclear energy systems. This classification characterizes human performance in relation to the effective, efficient, safe and error-resistant use of advanced technologies in terms of the *context of use*, that is, the actual conditions under which a given HSI technology is likely to be used by nuclear plant personnel in work situations and their use environments. The characterization included definitions of operational scenarios, a taxonomy of input, output and hybrid devices used for human-system interactions, and human performance characteristics. This characterization will be used to establish the technical basis for the future design and selection of advanced HSIs. The results to date demonstrate a method to classify advanced HSIs using three dimensions:

- The work environment where the device is used, also called the *work domain context.*
- The condition of the plant or system at the time when a specific task has to be performed, also called the *operational context*.
- The nature of the device used to perform a task and its suitability for the task at hand, which includes the characteristics of human mental and physical performance requirements in specific operating situations, also called the *human-system interaction context*.

These results will serve as input to a gap analysis of the current state of technologies in the nuclear industry, compared to current best practice in other industries, with special emphasis on the development of technology selection criteria to best support human performance in advanced concepts of nuclear e3nergy system operations.

Contact

For more information about the NEET ASI program or to learn about future funding opportunities, please contact:

Suibel Schuppner (email: Suibel.schuppner@nuclear.energy.gov)

Bruce Hallbert (email: bruce.hallbert@inl.gov)

Attachment 1

Agenda

Advanced Sensors and Instrumentation

2013 ANNUAL PROJECT REVIEW MEETING
May 21-22, 2013
Germantown, MD
Germantown (B-432)
INL (ESL\B-102), ORNL (4500N\K-221), ANL (A-138), PNNL (White Room)

Tuesday, May 21, 2013

9:00 am	Opening Remarks (Shane Johnson/Suibel Schuppner)
9:15 am	Overview (Suibel Schuppner/ Bruce Hallbert)
	Sensors:
9:30 am	High Temperature Fission Chambers (Zane Bell) [NGNP, ARC, SMR, LWRS]
10:15 am	Micro-Pocket Fission Detectors (Troy Unruh) [FCR&D, NGNP, ARC, LWRS]
11:00 am	Irradiation Testing of Ultrasonic Transducers (Joshua Daw) [FCR&D, NGNP, ARC, LWRS]
11:45 am	Recalibration Methodology for Transmitters and Instrumentation (Pradeep Ramuhalli) [LWRS, NGNP, ARC, SMR, FCR&D]
12:30 pm	***Lunch Break***
	Digital Monitoring and Control:
1:30 pm	Digital Technology Qualification (Richard Wood/Ken Thomas) [LWRS, SMR, NGNP, ARC]
2:15 pm	Design for Fault Tolerance and Resilience (Rick Vilim/Ken Thomas) [LWRS, SMR, NGNP, ARC]
3:00 pm	Sensor Degradation Control Systems (Rick Vilim) [LWRS, NGNP, ARC, SMR, FCR&D]
3:45 pm	Embedded I&C for Extreme Environments (Roger Kisner) [SMR, NGNP, ARC, MPACT]
5:30pm	***Adjourn***

Wednesday, May 22, 2013

9:00 am	Opening Remarks (Suibel Schuppner/ Bruce Hallbert)
	Nuclear Plant Communication:
9:15 am	Power Harvesting for Sensor Networks (Dwight Clayton) [LWRS, SMR, UNFD, NGNP, ARC, MPACT]
	Advanced Concepts of Operation:
10:00 am	Advanced Human-System Interfaces (Jacques Hugo) [LWRS, SMR, NGNP, ARC, MPACT]
10:45 am	Feedback/Discussion (Bruce Hallbert)
11:45 am	Concluding Remarks (Suibel Schuppner)
12:00pm	***Adjourn***