Advanced Sensors and Instrumentation

Issue 8 • March 2018

Program Update

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U.S. Department of Energy

The Advanced Sensors and Instrumentation (ASI) program, on its sixth fiscal year, continues to address key gaps within the nuclear community regarding instrumentation and control capabilities for future nuclear energy systems, and to enable the advanced instrumentation and control (I&C) technologies essential to the Office of Nuclear Energy's research and development (R&D) efforts needed to realize mission goals. Since its inception, the ASI program has funded 27 projects, most of them through the Consolidated Innovative Nuclear Research (CINR) funding opportunity announcement (FOA) to national laboratories, universities, and industry collaboration teams. Information on our projects can be found in our ASI annual awards summaries, annual review webinars, and newsletters posted in the Office of Nuclear Energy website (energy.gov/ne).

A new initiative, the In-Pile Instrumentation initiative, was started late in FY 2017. This initiative's vision is to provide real-time, accurate, and spatially resolved information regarding performance of fuels and materials. The goal is to develop unique in-pile sensors and instrumentation to characterize the behavior of fuels and materials during irradiation tests. More details on this initiative are included in the next article.

This year, we are planning a Digital Environment for Advanced Reactor Workshop on June 5-6, 2018 at the Argonne National Laboratory in Chicago. The purpose is to gather input from stakeholders related to advanced sensors, monitoring, control and human automation interaction technologies needed to support the development of advanced reactors. Information obtained from this workshop will be used to identify gaps between existing and needed capabilities, by the advanced reactor community, and to establish funding priorities by our office. This will include planned solicitations for future funding opportunities, cost shared R&D, and pilot projects through private-public partnerships.

As the ASI program moves forward in FY 2018, two FOAs are available for new awards: the CINR and a new industry-focused solicitation titled, "U.S. Industry Opportunities for Advanced Nuclear Technology Development." Information on both can be found at neup.gov.

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U.S. DEPARTMENT OF ENERGY

Characterizing the Behavior of Fuels and Materials during Irradiation Tests

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The In-Pile Instrumentation Initiative was established in fiscal year 2017 to conduct research needed to develop and deploy unique instruments that characterize the behavior of fuels and materials during irradiation tests conducted by the Nuclear Energy (NE) programs. This initiative, also referred as I3, falls under the Advanced Sensors and Instrumentation subprogram within the Nuclear Energy Enabling Technologies Crosscutting Technology program. The vision of I3 is to provide real-time, accurate, spatially resolved information regarding performance of fuels and materials that can be directly tied to microstructure. This vision is reflected in the research direction of several NE programs that have identified a need to correlate material performance with evolving microstructure. Currently, these relationships can only be inferred through examination of materials in a post-irradiation environment.

Realization of this vision will require technical breakthroughs in several key areas, including materials science, modeling and simulation, advanced manufacturing, and instrument development and deployment. Insights gained from this initiative will be critical for advancing a number of NE objectives. Examples include expediting the development of accident-tolerant fuels, providing a deep understanding of materials suitable for the extreme environments associated with new reactor technologies, and providing unparalleled validation metrics for new science-based fuel performance codes.

Approach

New in-core instrumentation capability will require a paradigm-shifting methodology that connects sensor development and performance, material innovation, and modeling and simulation. Reaching this objective will involve combining advanced manufacturing with high throughput combinatorial material science to develop radiation-resistant materials and create disruptive sensor designs. Advanced manufacturing will facilitate enhanced current in core sensor technologies and will enable the development of new, miniaturized sensors that are capable of multimodal measurement.

Instrument development is driven by measurement needs that have been identified by NE programs. Measurements of temperature, pressure, and neutron flux can be performed with passive sensors and are the most straightforward measurements to make. Additionally, measurements of these field variables can be used to directly validate current modeling and simulation work. Measurement of materials properties will require active sensors and represent the next level of complication. The ultimate goal of this initiative is to develop the ability to connect measured properties to chemistry and microstructure.

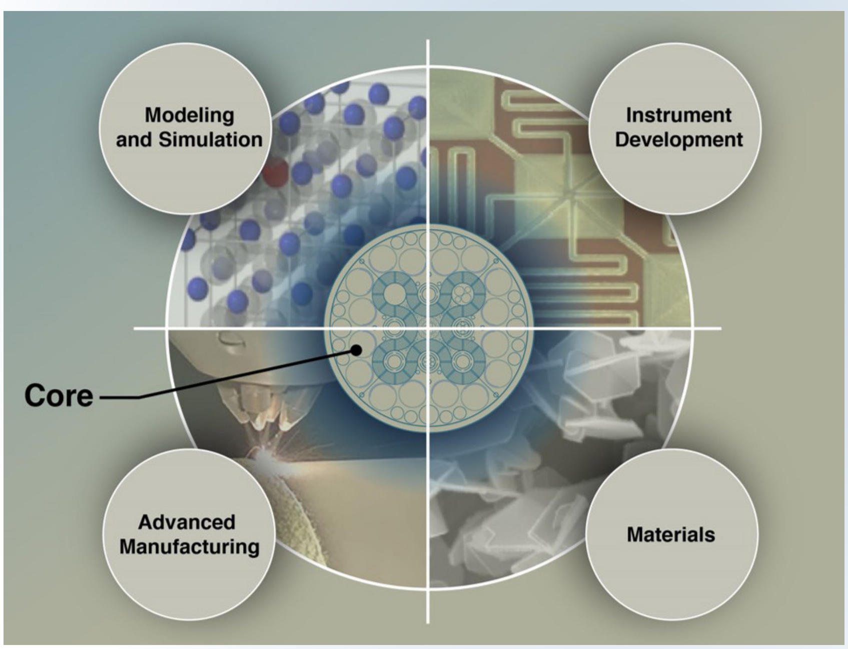

Figure 1. The In-pile Instrumentation Initiative contains four scientific thrust areas.

Organization

This initiative is unique in that it will conduct research to address critical gaps in technologies related to characterization of fuels and materials during irradiation testing. It does so through a new model of instrument development based on strong interdisciplinary scientific collaboration. This collaborative effort will be divided into four science based thrusts:

1) **The Materials Science Thrust** will use traditional and combinatorial high-throughput materials development to rapidly screen application-specific sensor materials.

2) **The Advanced Manufacturing Thrust** will develop additive and micro-manufacturing techniques that enable integration of sensors onto fuels and materials.

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3) **The Instrument Deployment Thrust** serves as a focal point for transitioning prototypes into instruments ready for installation.

4) **The Advanced Modeling and Simulation Thrust** will develop tools and capabilities to predict the in-pile behavior of sensors and sensor materials.

The resulting in-pile instruments will provide essential information regarding evolution of the structure property relationships, resulting in a more-direct measurement of key phenomena, fewer uncertainties, and greater access to real-time data. Critical outcomes of this Initiative will include the following:

- Reduced development lifecycle for new in-reactor instrumentation
- Sensors that employ multiple methodologies (multimode) to improve data quality
- Smaller length scale data that will provide insights into radiation-induced property evolution
- Access to in-pile material behavior that cannot be captured in a post-irradiation environment.

Individually, these advances are important; collectively, they represent a step change in capability over current in-pile instruments. They are also responsive to the complex, in-pile measurement objectives identified by NE. By providing technologies that can be developed rapidly and customized to suit the needs of individual irradiation tests, this initiative assists in addressing the needs for reactor and fuel cycle technologies. It will also provide a key element to the Gateway for Accelerated Innovation in Nuclear (GAIN) program by providing the nuclear energy industry with access to new monitoring technology and advanced validation of modeling and simulation.

Research and Development Activities

The research direction of I3 addresses a coordinated set of needs that have been identified through engagement with stakeholders from the NE research and development (R&D) programs. I3 also integrates public private partnership requirements into the overall set of R&D activities performed. The foundation of I3 is based on the four thrusts mentioned above. While each thrust addresses key technological questions, the overarching structure of the Initiative encourages strong engagement between thrusts. In addition to the four thrusts, there are three broadly defined R&D activities, discussed below, that have been identified by stakeholders from NE programs. A key example is given under each R&D activity that highlights the utility of the instrument being developed.

1 - Measurement of field properties: Field properties are defined by scalar (e.g., temperature), vector (e.g., neutron flux) and tensor (e.g., pressure) fields. Accurate measurement of field properties is required for assessing the effects of neutron damage, monitoring fission gas pressure buildup, and understanding the evolution of microstructure with temperature. A practical example discussed in this section is the application of melt wires to measure the peak temperature field. Researchers at INL in collaboration with researchers at Boise State University have fabricated an array of melt wires using aerosol jet printing (Figure 2). The wires are interrogated in a post-irradiation environment to determine the peak temperature experienced during the irradiation test. These miniaturized sensors represent a significant change in capability over the current melt wire technologies in that they provide spatially resolved information about peak temperature. Future work in this area will involve applying combinatorial material science methods to produce melt wires of varying composition that more completely cover the range of temperatures experienced during normal and off-normal operating conditions.

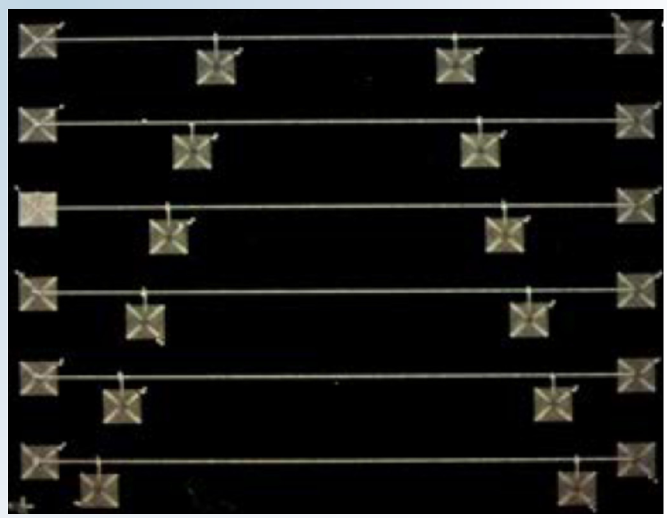

Figure 2. Passive Temperature Melt Array. Four-point structure of iron printed on titanium coated sapphire (wire to wire distance ~ 1mm).

2 - Measurement of materials properties: Thermal and mechanical properties of nuclear fuel and materials play an important role in determining the operation characteristics of fuel assemblies during normal operation and are crucial to understanding the response of fuel during accident conditions. For example, the cladding that surrounds the fuel prevents radioactive fission fragments from escaping into the coolant. The cladding must remain ductile and corrosion resistant while maintaining a low-absorption cross section for neutrons. In the fuel meat, thermal conductivity is intimately related to energy conversion

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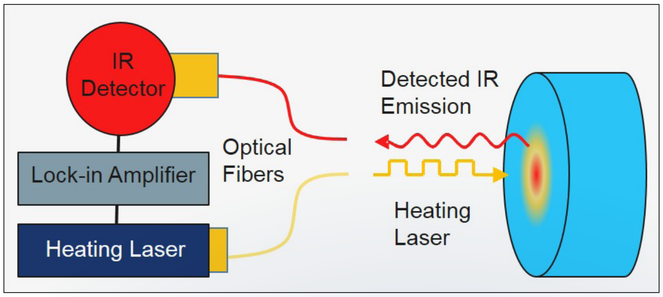

Figure 3. Photothermal radiometry used to measure thermal diffusivity of nuclear fuel.

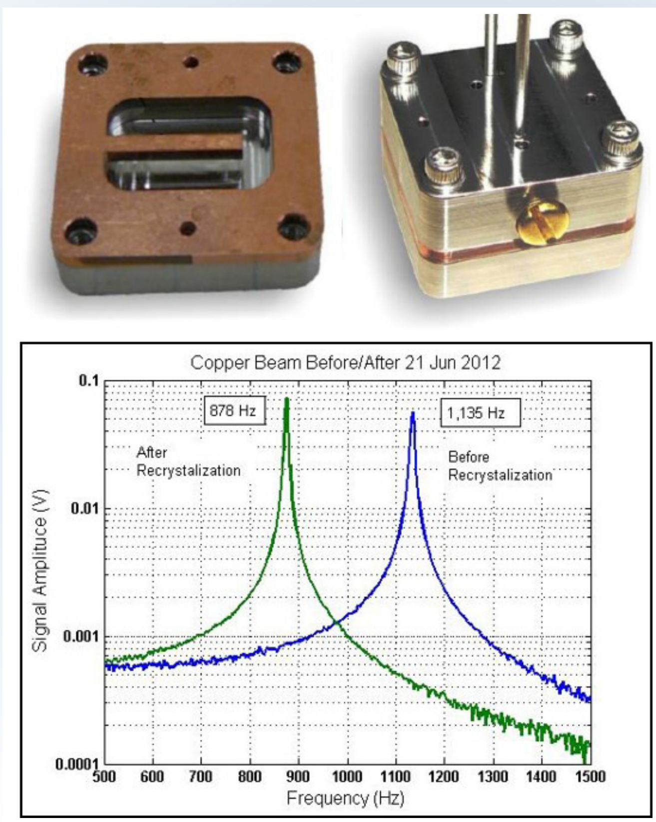

Figure 4. Laser ultrasonics is used to monitor grain restructuring in cantilever samples made from metallic fuel surrogates.

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efficiency as well as reactor safety and is arguably one of the most important material properties. An important area of research under this activity, being pursued by researchers at INL and The Ohio State University, involves measurement of the thermal diffusivity of fuels in the TREAT reactor using fiber-based photothermal radiometry. This choice of test reactor is significant because fiber darkening due to irradiation damage will not come into play for transient and/or short-lived steady-state tests. A schematic of this approach is shown in Figure 3. An intensity-modulated fiber-coupled laser will be used to heat the sample locally. Modulated blackbody radiation from the sample will be collected with the same fiber and used to measure the temperature evolution. A continuum-based theory is then used to extract thermal properties.

3 - Measuring Chemistry and Structure: Changes in chemistry and structure over the lifetime of the fuel are closely tied to fission gas buildup, cladding embrittlement, and excessive corrosion, grain restructuring, and crack formation, all of which lead to fuel failure. Monitoring changes in structure and chemistry of nuclear fuel and materials pose significant technological challenges. Few lab-based methods that directly image structure and chemistry can be extended to an in-pile environment. A notable area of research being conducted by researchers at INL and Purdue University involves using ultrasonic methods to indirectly measure grain restructuring in nuclear fuels. A prototype of this instrument is shown in Figure 4. Lasers for ultrasonic generation and detection are routed through fibers incased in long metal rods. The measurement involves monitoring changes in the resonant frequencies of a cantilever bar during recrystallization and relating this information to grain macrostructure.

Look Ahead

Advancements in measurement and characterization capabilities will support a variety of needs shared by a number of NE programs. Instrumentation development will initiate observations of real-time behavior of fuel and materials, provide the opportunity to improve measurements of material behavior during irradiation, and improve sensor coverage in irradiation experiments. In addition, advanced manufacturing capability developed under this program will enable the gathering of smaller length scale data that can be used to understand microstructure-mediated changes to materials properties caused by irradiation.

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

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This research is developing and demonstrating methods for the transmission of information in nuclear facilities by acoustic means along existing in-place metal infrastructure (e.g., piping). This innovative means of transmitting information overcomes physics hurdles that beset conventional communication methods (both wired and radio frequency [RF] wireless). This project provides a cross-cutting solution (applicable to multiple nuclear facility platforms) for those areas in the plant where wired or wireless RF communication is not feasible (presence of barriers), not reliable (lack of resilience under accident conditions), or not secure (prone to interception). Use of metallic pathways for transmission of information provides an additional level of protection for securing and protecting data streams by eliminating the broadcasting of RF signals. The authors of this article are developing the acoustic communication (AC) hardware and network protocols for efficient and secure transfer of data with the objective of providing a preliminary experimental demonstration of the AC system prototype in a representative environment.

While the use of wireless RF signals for the transmission and reception of data in nuclear facilities provides, in principle, greater data transfer rate per unit cost, the presence of physical boundaries presents a major challenge to actual implementation. The typical nuclear facility for safety reasons (e.g., confinement of radiation and radionuclides) is heavily partitioned and equipment-packed resulting in transmission paths that are highly attenuating for electromagnetic waves. Primary barriers include a containment building's thick reinforced high-strength concrete walls, which in most plant designs have liners (steel plates) on the interior side. Additional security-related concerns related to use of RF exist because of long-distance propagation of the RF signal outside of nuclear facility boundaries.

In our approach to this problem, the backbone of the physical layer of the AC system consists of metal process-fluid conduits. Pipes are omnipresent in a nuclear facility given their role of transferring mass and energy between the outside world and the inner workings of the facility. In our method, piping networks serve as conduits for signals launched as guided acoustic surface waves. Acoustic transducers compatible with harsh operating environments are being combined with efficient digital and analog data communication protocols.

In a first step, candidate metallic pathways that hold promise for transmission of information by acoustic means through the reactor containment wall were identified. Upon review of the various containment penetrations in a commercial nuclear power plant (NPP) design, the charging line of the chemical and volume control system (CVCS) emerged as a promising location for the application of an acoustic transmission device.

A benchtop experiment facility has been assembled to study the transmission characteristics of a representative section of charging line piping. The length of the pipe (5 feet) represents the minimum distance required for transmission of signals through the penetration in the reactor containment wall. The main components of the current experimental acoustic system setup are a waveform generator and power amplifier on the transmission side, and a low-noise amplifier, a filter, and data acquisition system on the receiver side. The transmitting and receiving piezoelectric transducers are coupled to the test piece using angle wedges that allow for adjustment of the beam angle. The utility of electromagnetic acoustic transducers (EMATs) are also being evaluated as couplant-free transmitter and receiver elements. The laboratory apparatus showing various components of the acoustic communication system is displayed in Figure 1.

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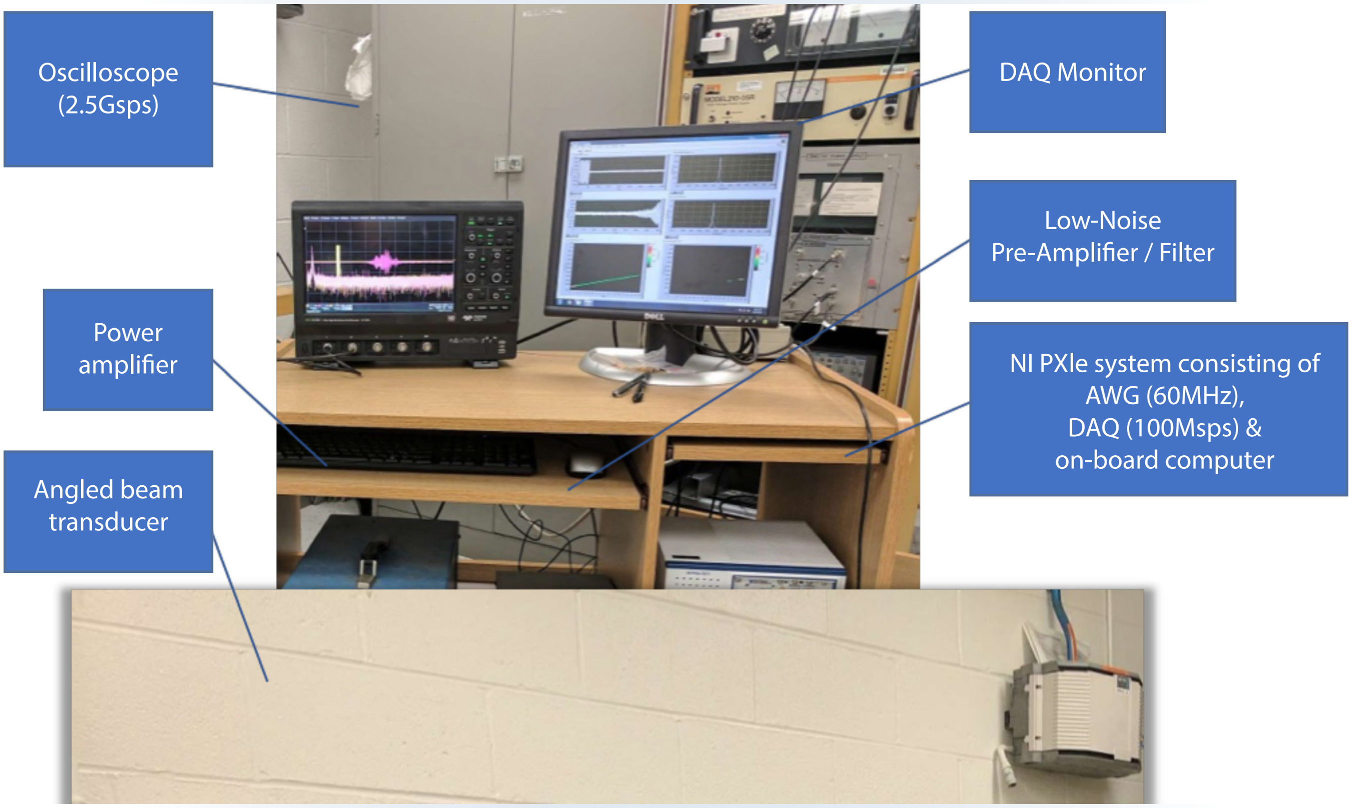

Figure 1. Benchtop setup showing various components of the acoustic communication system. Displayed at the bottom is the pipe mounted with angled transducers.

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Multi-physics simulations studies are being performed to better understand the wave propagation characteristics of ultrasonic waves in pipe-like structures. These simulations permit the parameter space to be investigated more thoroughly compared to laboratory experiments yielding better insight into performance limits of acoustic signal transmission over complex geometries, including dispersion, absorption, and scattering in different metallic media. The pipe properties that most influence the ultrasonic wave propagation are thickness, diameter, material properties, surrounding and internal materials, pipe elbows, and the presence of dissimilar materials. These modeling simulations permit the optimization of the design parameters in a more cost-effective manner. The ultimate objective of these simulations is to increase the acoustic transmission distance through the metal pathway by proper selection of operating frequency and excitation mode.

Communication channel capacity requirements for sensory data transmission with acoustic means are being assessed. A survey of the literature was performed to identify a minimal set of process parameters, the values of which would be needed to characterize post-accident conditions in containment. Sensor time constants and the number of data bits to encode their values lead to the estimate of the minimum required bit rate.

Preliminary experimental investigations of channel capacity and signal encoding schemes have been performed with the objective of determining the optimal modulation scheme for transmission of signal under the constraint of limited signal generator power. To date, the on-off keying (OOK) protocol appears most promising. In Figure 2, the results of transmission and reception of a train of 50-μs duration OOK pulses are displayed. Based on the

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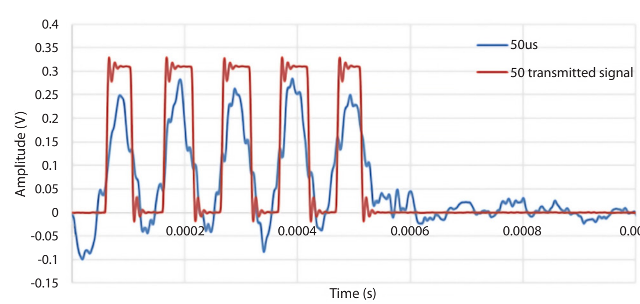

Figure 2. Transmission and reception of a train of 50-μs duration OOK pulses.

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preliminary results, we conclude that the OOK scheme with a low bit error rate can be achieved using 50-μs duration pulses. This is equivalent to a 20-kbs data transmission rate, which is significantly greater than what would be required for envisioned sensor data transmission rates.

The minimum data rates required for the containment challenge problem are being assessed. The researchers once again performed a literature search to identify process parameters needed to characterize post-accident conditions in containment. Knowing these parameters, the required updating frequency and number of data bits to encode their values lead to the minimum required bit rate. These data are summarized in Table 1.

Next steps will involve demonstration of sensory data transmission along the pipe using two field-programmable gate array (FPGA) boards.

Variable	Sensor	Time Constant (s)	Signal Range	Variable Range	No. Bits
Control Rod Position	Linear transducer	-	-	-	16
Cold Leg Temperature	TC (K-type)	3	0–78 mV	0–1250°C	16
Core Exit Temperature	TC	3	0–78 mV	0–1250°C	16
RCS Pressure	Strain pressure transducer	0.25	0–20 mA	0–500 Pa	16
RCS Inventory	Differential pressure transducer	<1	0–20 mA	0–500 Pa	16
Containment Sump Water Level	Differential pressure transducer	<1	0–20 mA	0–500 Pa	16
Containment Pressure	Strain pressure transducer	0.25	0–20 mA	0–500 Pa	16
Containment Isolation Valve Position	Potentiometer	<1	0–5 V	0–359 degrees	16
Hydrogen Concentration	Electrochemical Galvanic cell	30	-	–	16
SG Level	Differential pressure transducer	<1	0–20 mA	0–500 Pa	16
SG Pressure	Strain pressure transducer	0.25	0–20 mA	0–500 Pa	16

Table 1. List of post-accident monitored variables and associated data specification.

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

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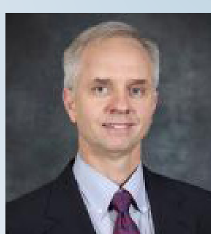

In the nuclear industry many vital components, such as spent fuel storage canisters and nuclear reactor pressure vessels (RPV), are entirely enclosed by metal and surrounded by thick concrete walls that manage the potentially harmful radiation and prevent release to the environment. For example, after removing dry casks from the reactors and cooling the casks in spent fuel pools, the spent nuclear fuel assemblies will be stored (and transported) inside leak-tight canisters of 1/2-in. to 5/8-in-thick stainless steel surrounded by concrete walls, which provide the front line of protection with a service life of 50 years or longer. Due to the casks' long storage, monitoring temperature, pressure, radiation, humidity, structural health, etc., within these enclosed vessels is crucial to ensure the fuel containment safety and security. Because of the potentially volatile nature of the spent fuel, wiring through the metal walls for power and data is undesirable and largely unfeasible in most nuclear environments. This poses a great challenge for the sensing of and communicating with the internal canister monitoring.

Project Overview

In the United States, typically one-third of the nuclear fuel elements in the reactors are replaced every 18 months, and the U.S. Nuclear Regulatory Commission (NRC) estimates that 70,000 metric tons of uranium (MTU) are contained in spent fuel. In the U.S. alone there are 2,100 loaded dry casks, and the number increases by 200 each year. However, there is currently no internal sensing and instrumentation system that can provide direct measurements of the critical conditions because (1) there is no long-lasting electricity power supply for sensors inside the enclosed canisters, (2) data cannot be transferred out of the enclosed steel canister using wires or RF wireless, and (3) the harsh high-temperature (150–175°C on the wall surface) and high-radiation environment inside the enclosed vessel create challenges for electronics and sensors. Similar sensing and communication needs and challenges exist for the nuclear reactor vessels of boiling water reactors (BWRs) and pressurized water reactors (PWRs).

The research for this project addresses these issues to provide the self-powered data communications for nuclear reactors and fuel cycle facilities using local environment energy harvesting, through-wall ultrasound communication, and harsh environment electronics. The specific objectives are (1) directly harvest electrical energy from the gamma rays using the gamma heating and thermo-electrics, and from the beta particles using betavoltaic cells; (2) transmit a large amount of sensing data through the metal wall and thick concrete via ultrasound based on "mode conversion" principle; and (3) creatively design, develop, and deploy electronics for the demonstration of the complete system, and provide a design, fabrication, and shielding strategy for future realization of high-temperature and radiation-hardened electronics circuits and communication systems for use inside the enclosed nuclear vessels.

The whole package (Figure 1) includes: (1) a radiation energy harvester with power management; (2) ultrasound wireless communication using high-temperature piezoelectric transducers; (3) electronics modules for harvesting, sensing, and data transmission; and (4) radiation shielding for electronics and sensors. The package is able to harvest tens to hundreds of mW power from nuclear canister environment directly. The energy will be stored and used to power sensors and ultrasound data transmission inside the vessels.

This article provides a summary of the key findings during the collaborated research activities among two universities and one national laboratory, and describes the current status of the project.

Energy Harvesting for the Nuclear Environment

Energy harvesting and wireless communication provide a promising opportunity to revolutionize nuclear sensors

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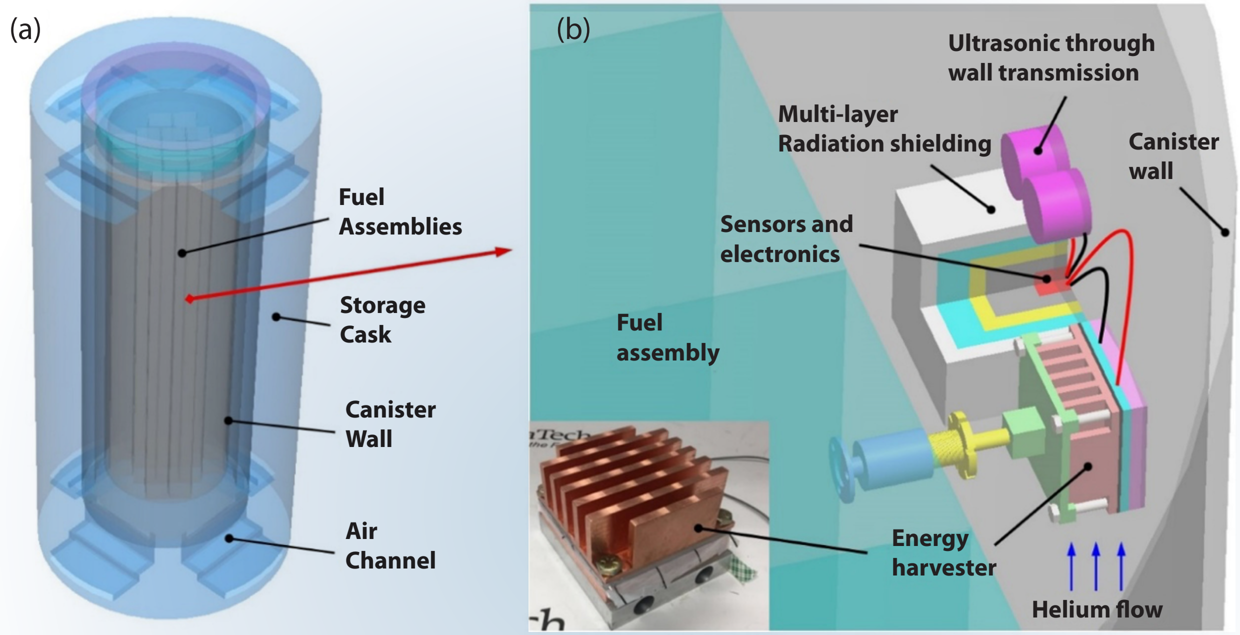

Figure 1. System illustration of gamma heating thermoelectric energy harvesting and ultrasonic through-wall data communication for enclosed nuclear canisters.

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and instrumentations, and to benefit reactor design and fuel cycle facilities by reducing the cost of power, wiring, and signal transmission or eliminating battery replacement. More importantly, when a severe accident or massive loss of grid power happens, the energy harvester can still provide self-sustainable power to monitor the critical parameters of the nuclear power plant or fuel cycle facilities. Actually, to power a 1.0-W sensing and data transmission system for 3 seconds, the system only needs 10-mW of continuous energy harvesting every 5 minutes.

In a canister, spent nuclear fuel emits alpha, beta, neutron, and gamma rays as radioactive decay, which provide abundant energy sources for energy harvesting. The neutron and gamma rays are the two main radiation particles within the canister. The gamma rays are extremely high-frequency photons with energy of 100 keV–1 MeV and a very high penetration capability. Most of the radiation energy is emitted as gamma rays. Another important radiation particle in the spent fuel is the neutron rays (averaged ~1.5 MeV). However, the decay heat from a neutron deposition is several orders lower than that from gamma. The decay heat generated within the dry cask storage is highly dependent on the fuel makeup and its operation within the reactor. According to the simulation result using SCALE, the initial decay heat in a multi-purpose canister (MPC)-32 canister is as high as 38.44 kW after storage for 5 years in the pool and decreases to 10.67 kW after another 50 years of storage.

Because of the decay heat generated by the gamma and neutron rays' deposition, the peak temperature within the canister can be as high as 620 K. To accelerate the dissipation rate of the decay heat into the ambient environment, the canister is backfilled by the helium gas with a pressure of 3.3 atm. The concrete overpack is made to house the MPC and has inner channels to allow airflow between the concrete and MPC, cooling the canister by taking advantage of buoyancy force. The strong convective heat transfer processes inside and outside the MPC create a large temperature drop near the canister wall, making it an ideal place for thermoelectric energy harvesting. Our previous calculation found that the temperature drop near the canister wall can be as high as 70 K when it was initially restored in the canister. The temperature difference decreases to 13 K when it is stored in the canister for another 50 years.

Noticing these, we built a gamma heating energy harvester that can effectively use the gamma heating in the tungsten plate. The power output of this energy harvester with a matched load resistor is 17.8 mW when the nuclear waste is initially stored in the canister—a bit higher than the necessary 10 mW as announced. However, because of the huge tungsten plate size and a large volume of thermal isolation material, the final energy harvester is very heavy and cumbersome. With times going on, the voltage and power outputs of the energy harvester reduce quickly as result of significant decrease in gamma deposited heat. For the Year 55 case, the energy harvester can provide less than 1.0 mW energy, which is far less than the target goal of 10 mW.

Considering that the power output of the gamma radiation energy harvester can hardly meet the power demand (~10 mW) for the wireless communication system, a more applicable energy harvester for the existing temperature gradient near the canister wall was designed (Figure 1). The overall size of the TEG energy harvester is about

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$8 \times 8 \times 6$ cm^3, making it compact and easy to install in the canister. To achieve the best performance, the finned array is optimized based on the flow condition along the canister wall. Simulations found that the maximum power output of the energy harvester was about 44.1 mW, which was more than enough for electronics powering. To verify the performance of the thermoelectric energy harvester in a real situation, the hydraulic oil circulation loop is used to simulate the helium environment in the canister. The maximum power output of the TEG energy harvester is around 6.4 mW in the previous tests, which is a bit less than 10 mW needed for electronics powering. The performance of the thermal TEG energy harvester is poorer than the simulation results because the thermal contact resistances are too high in the energy harvester assembly. To meet the energy demand, we replaced the TEG module (Hz-2) with another model (TEG1-1263-4.3) and improved the thermal contact. A recent test gave a voltage of triple the old result and a power output of four times the old result (~60 mW).

As the energy harvester and the electronics work in the nuclear canister for more than 50 years, how to protect the energy harvester from high temperatures and high gamma- and neutron-radiation environments is extremely important to ensure its long-term performance. Generally, the gamma rays are better absorbed by materials with high atomic numbers and high density, although neither effect is important compared to the total mass per area in the path of the gamma ray. Lead is widely used for gamma shielding due to its higher density. The higher the energy of the gamma rays, the thicker the shielding made from the same shielding material is required. Traditional neutron-absorbing materials, such as cadmium materials, boron plastics, and boron steel, can all satisfy the requirements for neutron-radiation shielding. High abundance of B makes B_4C suitable for the ideal neutron-radiation shielding materials. However, it is difficult to fabricate uniform B_4C thin plates due to its brittleness. Using Al or other metal as the matrix, it is possible to fabricate neutron-shielding material with desired properties, including light weight, good toughness, and low fabrication cost. High-temperature 3-D printing technologies, such as selective laser melting (SLM), should be a good choice to fabricate these multi-layer shielding layers for the energy harvester and electronics.

Ultrasound Through-wall Data Communications

Many new technologies have emerged that make data exchange possible through a metal wall. In this project, the amplitude modulation (AM) of ultrasonic waves inside a metal wall was developed to exchange information via ultrasonic wave produced by the piezoelectric transducers. The main advantage of such a solution is that it is highly useful in a high-temperature nuclear environment. As a breakthrough, we have experimentally demonstrated the ultrasonic TEXT communication up to 300°C using a one-to-one transducer configuration.

To realize the above concept, the schematic diagram shown in Figure 2 is used to design the text transmission system. Two PZT Piezo transducers are bonded coaxially on either side of the metal wall. The entire system (metal wall with piezo transducer) is placed inside the high temperature oven and the temperature is varied linearly from 20°C to 300°C. The text data generated from the computer is converted into serial binary output by utilizing Arduino Uno board. The baud rate used for this data communication is fixed as 1200 bits per second. The proposed system can also be operated up to 9600 baud rate, which depends on the metal wall thickness and Piezo properties. The serial binary output from the Arduino is given as a modulating signal to an Amplitude Modulator (AM) system (for this application we have used the Agilent 33220A function generator as an AM modulator). The carrier frequency of the AM circuit is fixed as 126 KHz, which basically depends on the metal wall and Piezo transducer acoustic resonance frequency. The modulated signal with binary output is given to a transmitter Piezo ceramic. The transmitter Piezo transmits

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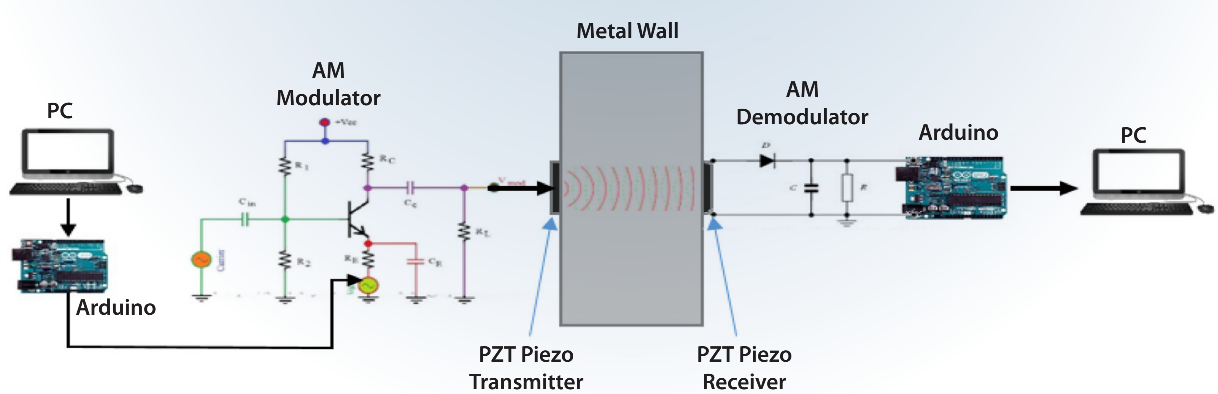

Figure 2. Schematic of ultrasound text transmission system

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a binary signal from one end to the other end of the metal wall, which is received by the receiver Piezo ceramic. After the amplification process, the received signal is given to the demodulator circuit. The demodulated binary signal is fed to the Arduino receiver board and the received text is monitored in a computer.

The photograph of experimental setup is shown in Figure 3. The high-temperature ceramic glue (Respond - 989 Ceramic) is used to attach the transducer to the high-temperature wall. For a test, the Text "Hello World" is successfully transferred from one side of the metal wall to other side at 300°C.

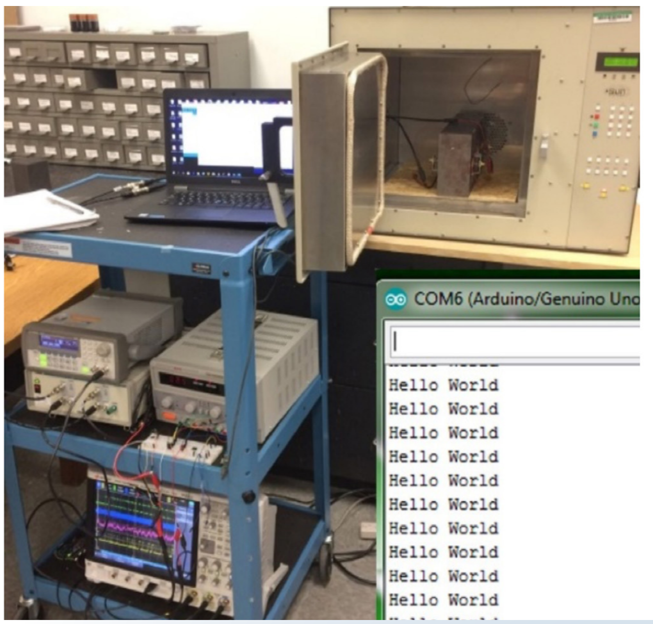

Figure 3. Photograph of the experiment setup for through-wall communication at 300°C.

Ferrofluid Modulation for Through-Cask Data Communications

A ferrofluid modulation technique was investigated using three possible topologies: through fluid, reflection with a dual element transducer, and reflection with two transducers. All topologies employ a bias magnet and a coil-wrapped ferrofluid chamber for modulation. A block diagram for signal flow in the once-through design is shown in Figure 4. The device amplitude modulates ultrasonic signals between send and receive transducers. This topology was used for testing the principles of the ferrofluid modulation-demodulation. In Block 1, a compressional transducer sends a 2.25-MHz ultrasonic carrier wave through the ferrofluid chamber, which is received and amplified in Block 2. Block 3 is the power amplifier providing the modulation signal across the coil to modulate the ultrasonic wave with the ferrofluid response. The lock-in amplifier is depicted in Block 4.

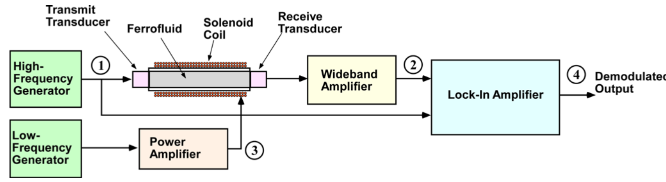

Figure 4. Block diagram of the through fluid measurement characterization system

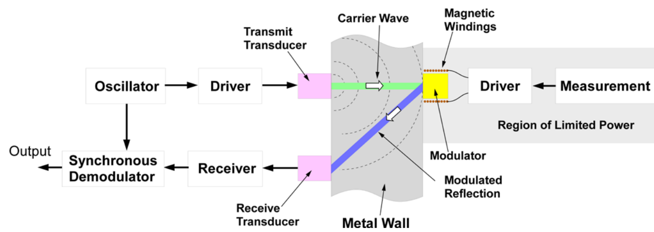

Figure 5. Transducer reflection topology. One transducer transmits the carrier through the wall media. The ferrofluid transducer modulates the magnitude of the carrier, which is received at the receiving transducer. This signal is demodulated with a lock-in amplifier.

A realistic implementation is shown in Figure 5 in which ultrasonic waves are bounced off the ferrofluid-filled modulating transducer. A separation of the transmit and receive transducers reduces crosstalk. Laboratory tests indicated that the magnitude response is influenced by the position and orientation of the bias magnet. Orientations of the field were tested at both parallel and orthogonal fields with respect to the field through the coil. The optimal orientation of the magnet was with parallel field lines to that of the solenoid. It was also discovered that the optimal position of the magnet was centrally aligned to the coil at about 10 mm above the coil—a distance determined by magnet field strength. The through-fluid topology led to favorable results for communication. The magnitude response of the through-fluid topology (Figure 6) is not flat as would be ideal and the bandwidth is fairly low in

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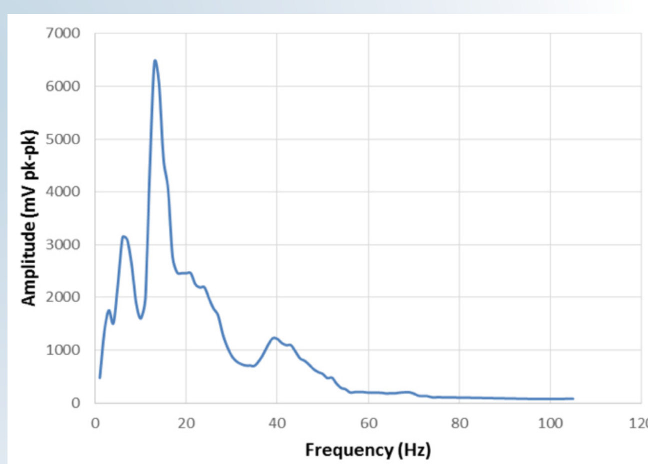

Figure 6. Ferrofluid magnitude response of through-fluid communication system.

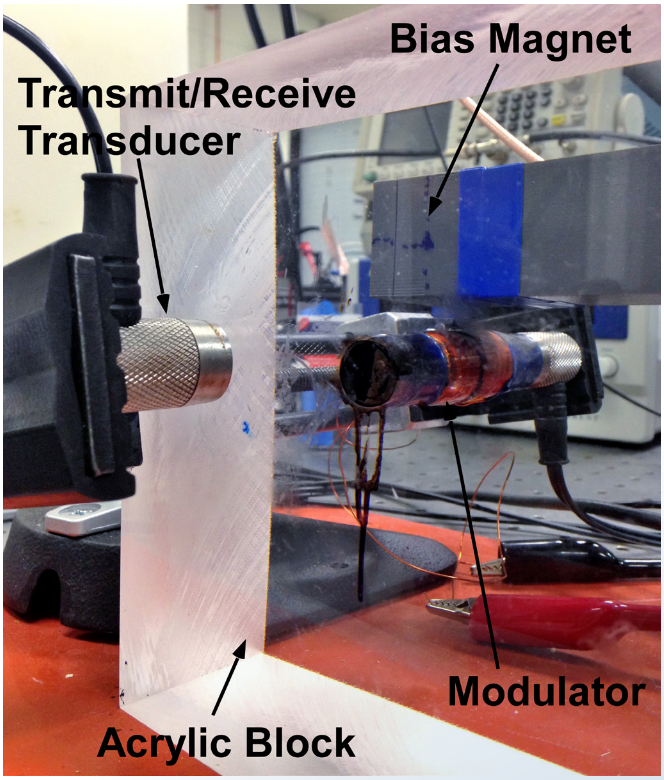

Figure 7. Dual element transducer system tested on the 4-in. acrylic block.

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frequency. Although not suitable for voice transmission, this transfer function can be used for low-frequency discrete signals. The through-wall demodulation permitted system set-up to optimize placement and orientation of the bias magnet. A system was constructed that reflects ultrasonic energy off a modulating transducer through a 4-in. wall. We tested the dual element transducer topology through a 4-in. block of acrylic (Figure 7).

Lab testing of the ferrofluid modulated reflection technique produced good results. The addition and optimal placement of a bias magnet will enable lower power operation, but a power study has not been fully performed. The bandwidth of the signal is small, but should be sufficient for the limited monitoring requirements of this application. This result is extensible to other materials, such as stainless steel. Successful application of this technique to scenarios having thicker walls is probable but will require further investigation of the two transducer techniques.

Temperature and Radiation-Hardened Electronics for In-Cask Sensor Interfacing and Communications (ORNL)

Electronics and sensors located within the fuel casks will be exposed to very high levels of radiation and elevated temperatures over the anticipated monitoring lifetime. Studies have been initiated to estimate the in-cask, position-dependent radiation dose expected over the

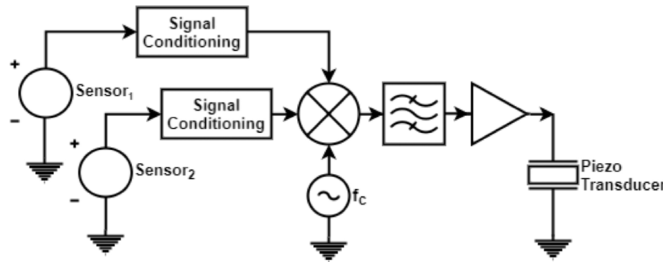

Figure 8. Direct sensor modulation with a carrier waveform of frequency fc.

50-year operating life of the monitoring system. In addition, published in-cask temperature modeling data predicts temperatures approaching 300°C at the onset of the cask monitoring. With these requirements in mind, various electronic topologies have been investigated based on different classes of components, including single- and double-sideband analog modulation, on-off keying, and other forms of digital communication. Figure 8 shows the most direct approach based on multi-sensor direct modulation of a carrier waveform. Further work this year will involve designing and simulating a prototype sensor interface and modulation circuit, and prototyping and testing using off-the-shelf components in a laboratory environment. Results of these studies will inform a selection of technologies to meet the radiation and temperature requirements of in-cask monitoring. Tradeoffs to be considered will include device technologies such as Metal Oxide Semiconductor (MOS), bipolar, and vacuum-state active devices.

Conclusions

Two energy harvesters were designed to power the electronics for the wireless through-wall data communication in nuclear environments. Simulation and lab tests were conducted with dimensionless setup and verified that ~60 mW can be achieved from an MPC-32 canister at 50 years of service life. The ultrasonic TEXT transmission at temperatures up to 300°C using a one-to-one transducer configuration has been verified. An alternative method of directly modulating an ultrasonic wave using a ferrofluid modulation has been demonstrated. We are working on the design of radiation-tolerant circuitry for the internal electronics for the fuel cask. Gamma and neutron shielding design for the electronics and thermoelectric generator will also be conducted.

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Assessing the EMI/RFI Risks of Wireless Devices Using a Cognitive Radio System

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The benefits of wireless technology in nuclear power plants are well known and established. The application of wireless sensors for condition monitoring [1], tablet devices for the mobile work force when performing operator rounds and electronic work packages [2], radiation dose reduction using real-time wireless dosimetry, and the general efficiencies and improvements that can be gained through the use of cell phones, wireless cameras, and other wireless devices are significant driving forces within the industry. These benefits have become even more necessary with the recent initiative, "Delivering the Nuclear Promise," which drives nuclear power plants to reduce operating and maintenance costs to keep nuclear power competitive with other forms of power generation, while increasing efficiency and maintaining the same level of safety.

Today, nuclear facilities use wireless technology by defining specific or generic "exclusion zones" where wireless devices cannot be used. For example, a U.S. nuclear power plant has imposed the following generic stipulation for the use of wireless technology: "as a general rule, radio units should not be used within 15 feet of panels and instrument racks housing sensitive electrical/electronic equipment." Most other plants are not as restrictive and have defined more specific exclusion zones based on the type of wireless devices that may be used in the sensitive areas of the plant. However, in a study of typical exclusion zones, it was determined that exclusion distances in almost all nuclear power plants are still overly conservative, which severely limit the use of wireless devices in most areas of the plant. This level of conservatism may arise from the fact that most plants have historically used walkie-talkie devices for wireless communications, which have a history of emitting strong and interfering signals. This is evident in the data shown in Table 1 where exclusion zones are compared for some of the commonly used wireless devices in nuclear power plants.

Wireless Device	Distance (Feet)
iPad	8
Cell Phone	9
Laptop Computer	3
Wireless Dosimeter	1
Wireless Vibration Sensor	2
Walkie Talkie	13

Table 1. Examples of exclusion distances in nuclear power plants.

Analysis and Measurement Services Corporation (AMS) is conducting a Small Business Innovation Research (SBIR) project to assist the nuclear industry with the successful implementation of wireless devices and addressing the overly conservative exclusion distances. The project titled, "Strategy for Implementation of Fixed and Mobile Wireless Technologies in Crowded and Confined EMI Environments of Nuclear Power Plants," is currently in a Phase II effort. The project was successfully commercialized through collaboration with a nuclear power plant as it deployed a wireless network for voice, data, and sensor communications.

During the Phase I project, research was conducted to evaluate nuclear power plant equipment for vulnerabilities to wireless signals and to determine mitigation techniques when necessary. First, Electromagnetic Compatibility (EMC) standards from other industries were evaluated to determine the optimal methods for performing in-situ high-frequency radiated susceptibility testing of plant equipment. Laboratory experiments were conducted on representative plant equipment to identify specific vulnerabilities to wireless signals at certain radio frequencies, modulation schemes, and signal bandwidths. Next, Electromagnetic and Radio Frequency Interference (EMI/RFI) mitigation practices were implemented during these experiments to address any vulnerabilities. These efforts culminated in the conceptual design of a Cognitive Radio System (CRS) with the capability to perform radiated immunity and wireless coexistence testing in a nuclear power plant environment. These methods and procedures that were developed serve as the initial steps of standardizing the in-situ EMI/RFI testing of plant equipment.

Many exclusion zones can be reduced significantly through the use of in-situ testing of representative plant equipment [3]. For example, most exclusion zones in nuclear power plants are defined based on the power output of wireless

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signals and do not account for the effect of frequency. In fact, the research conducted during this project has demonstrated through in-plant and laboratory testing that the susceptibility or vulnerability of a majority of plant equipment diminishes significantly at higher frequencies as illustrated in Figure 1. This implies that the higher frequencies from devices using Wi-Fi and Bluetooth (e.g., 2.4 GHz) may not pose a significant risk to power plant equipment when in close proximity even though the calculated exclusion distance may be 8 feet or more.

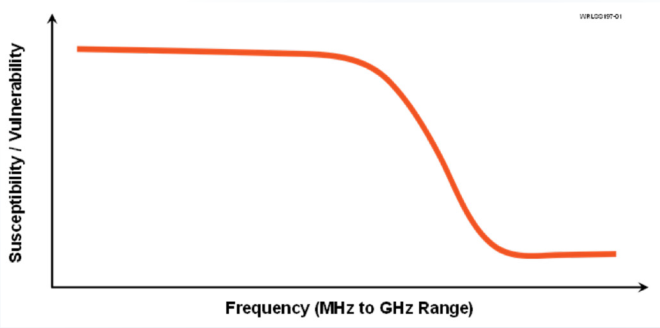

Figure 1. Illustration of susceptibility of plant equipment versus frequency of wireless signals.

Figure 2. Photograph of the Cognitive Radio System.

Description Of Cognitive Radio System

The CRS was developed as a tool to assist nuclear power plants in reducing the exclusion zones to appropriate and acceptable distances without the wireless devices posing a significant risk to plant operation. The CRS is capable of performing passive electromagnetic site surveys as well as subjecting plant equipment to signals representative of wireless devices through intrusive testing. The system consists of a vector signal analyzer and generator operating in the frequency range of 65 MHz to 6 GHz. The CRS module can be connected to amplifiers and antennas to record the RF spectrum and characterize the electromagnetic environment in a nuclear power plant. The system also has the ability to reproduce the recorded RF spectrum in a laboratory setting to simulate the nuclear environment. Finally, the CRS can generate desired wireless signals such as Wi-Fi, Bluetooth, Long Term Evolution (LTE), etc., and verify the immunity or vulnerability of plant equipment to these wireless signals. Figure 2 is a picture of the CRS with the amplifier and antenna used for in-situ immunity testing.

Modifying Existing RF Test Methods

For radiated RF susceptibility testing in the nuclear industry, the guidance from NRC Regulatory Guide 1.180 Revision 1 [4] and EPRI TR-102323 Revision 4 [5] state that two testing standards meet the requirement for testing equipment to radio frequency signals. The standard test methods are MIL-STD-461 RS103 and IEC 61000-4-3. The modulation schemes that are used for these tests are pulse modulation and amplitude modulation, respectively. The modulation schemes were developed to provide a worst-case signal to identify the greatest level of wireless vulnerabilities. The tests are performed for a frequency range of 30 MHz to 10 GHz using an electric field strength of 10 V/m.

While these test standards are an acceptable method for testing the overall vulnerability of plant equipment, the signals that are produced during the test are significantly different from those produced by modern wireless devices. The primary differences are the modulation technique and the bandwidth of the output signal. Newer wireless technologies use modulation schemes such as quadrature amplitude modulation, binary phase shift keying, and others. Figure 3 is a plot of a pulse-modulated signal used by the MIL-STD-461 RS103 test method, and Figure 4 shows the spectrum of an LTE Cellular Signal. The pulse-modulated signal contains the fundamental output frequency and its harmonics. The LTE signal covers a much wider and uniform bandwidth.

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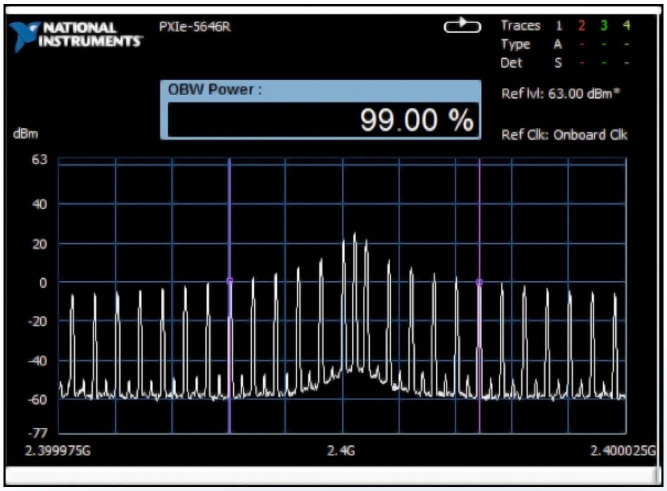

Figure 3. Spectral plot of a pulse-modulated signal.

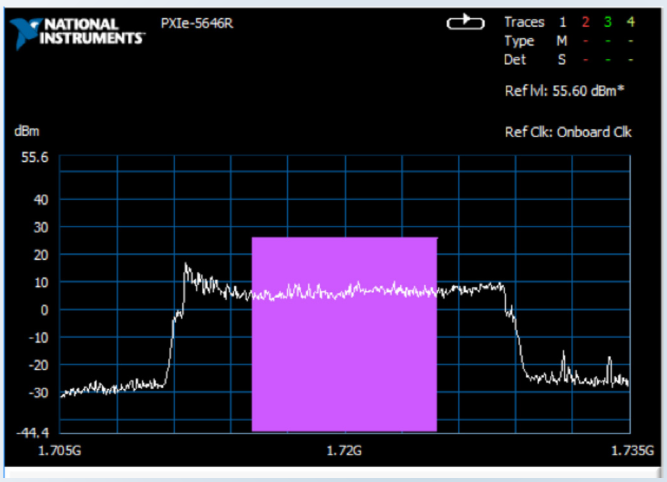

Figure 4. Spectral plot of an LTE signal.

Signal Type	Bandwidth	Power Output
Pulse Modulation	22 kHz	10 V/m
AM Modulation	2 kHz	10 V/m
LTE	20 MHz	29 dBm*
Wi-Fi	20 MHz	36 dBm*

*Maximum Power Output of a Typical Device

Table 2. Comparison of signal bandwidths and power levels for standard signals and wireless protocols.

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Table 2 shows the comparison of the bandwidth used by the standard test signals and modern wireless standards. The table also includes a description of the field strength generated by the test standards and the maximum power outputs of several wireless protocols.

By exploiting the differences between the standard test signals and the actual wireless protocols coupled with accounting for higher frequencies and testing to levels exceeding the 10 V/m standard test level, this R&D effort has shown that the exclusion distances for wireless devices can be significantly reduced.

Nuclear Power Plant Implementation

Nine Mile Point Nuclear Station, a General Electric Boiling Water Reactor (BWR) plant, is currently implementing a Wi-Fi and distributed antenna system (DAS) in both Unit 1 and Unit 2. Both systems will enable plant personnel to use cellular and Wi-Fi devices in the plant to increase efficiency during operator rounds and maintenance activities, as well as allow them to implement wireless sensors for condition monitoring purposes. To ensure plant personnel can use these wireless devices in close proximity to existing plant system without causing EMI/RFI, a collaboration project was initiated to establish objective exclusion zones.

The project was two-fold and included both laboratory measurements as well as onsite evaluations and testing. For EMC laboratory testing, an Apple iPad® with Verizon cellular capabilities and a Samsung Galaxy S8® phone using AT&T® cellular services were selected. Data was measured for all three transmitters (cellular, Wi-Fi, and Bluetooth) built into the devices. The results provide the typical emissions that can be expected from the wireless devices in an environment with adequate signal strength while performing high-data transmission-intensive applications.

In conjunction with the laboratory testing, several activities were being performed onsite with the support of plant personnel. The three main activities consisted of walking down existing plant systems to identify potentially vulnerable equipment, conducting EMI/RFI site surveys to understand the plant's electromagnetic environment, and performing susceptibility testing of selected plant equipment using the CRS.

The walkdown established the basis for developing a comprehensive test plan for the onsite work. During the walkdown, equipment installations were evaluated based upon the system characteristics identified during the Phase I SBIR effort to identify any observed deviations from good EMC practices, such as inadequate grounding, missing shielding, cable tray discontinuity, etc., that may make the equipment vulnerable to wireless signals.

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The next activity was to perform passive wireless EMI/RFI site surveys to locate and identify signal sources and frequencies that may compete with wireless devices and/or indicate vulnerabilities of existing equipment. The frequency spectrum for 22 locations in Unit 1 and Unit 2 of Nine Mile Point were recorded during the evaluation.

The most informative activity was the performance of onsite immunity testing of selected plant equipment to determine if they are vulnerable to wireless signals. The modified test methods and procedures developed during the SBIR project were performed onsite in a plant training facility. In addition to the standard EMC test method, actual wireless signals for LTE and Wi-Fi were generated and subjected to the representative plant equipment at levels consistent with the maximum power levels allowed by the protocols. All of these signals were generated using the CRS tool. Six different pieces of equipment were selected for the immunity testing. Each piece of equipment was subjected to the various frequencies of wireless devices between 430 MHz and 6 GHz. A photograph of the test setup is shown in Figure 5. Only one piece of equipment, a controller, exhibited vulnerability to the wireless signals in the frequency range of 475 to 960 MHz. The vulnerability was successfully mitigated through the use of additional shielding.

Figure 5. Test setup for Immunity Testing in a laboratory at Nine Mile Point.

Conclusions

One of the barriers to the implementation of wireless sensors and communication devices in nuclear power plants is the concern for EMI/RFI of the wireless signals with existing plant equipment. Through the approach developed during this SBIR project, the risks associated with wireless devices can be successfully mitigated. A majority of the plant equipment is immune to the frequencies and levels associated with modern wireless devices. When vulnerabilities are identified, they can be managed through administrative procedures or through equipment modifications to harden the equipment against EMI/RFI.

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Managing Human Factors Engineering in I&C System Modifications

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Managing Human Factors Engineering (HFE) in Instrumentation and Control (I&C) system modifications is one aspect of a complex and interrelated set of issues that must be addressed for nuclear utilities to move forward with modernization. Other issues include the business case, licensing process burden, technical qualification, cyber security, and implementation schedules compatible with short refueling outages.

A number of nuclear industry organizations are now engaged in developing a viable path for modernizing I&C systems at nuclear power electrical generating stations. These include the nuclear utilities, Nuclear Energy Institute (NEI), Electric Power Research Institute (EPRI), Institute of Nuclear Power Operations (INPO), and the nuclear component supplier community. In addition, the United States (U.S.) Nuclear Regulatory Commission (NRC) has developed an Integrated Action Plan (IAP) to modernize the digital I&C regulatory infrastructure as a means of addressing regulatory barriers for digital upgrades.

The U.S. Department of Energy Light Water Reactor Sustainability (LWRS) Program is also engaged with several nuclear utilities to assist with the modernization of their control room instrumentation. In late 2017, an LWRS HFE project team conducted an operator-in-the-loop workshop with a central-U.S. commercial nuclear power electrical generating station at their control room simulator.

Workshop Summary

The purpose of the workshop was to conduct an operator-in-the-loop HFE assessment of the planned control room upgrades that will be integrated into the modernization of the I&C systems in this commercial nuclear power electrical generating station. The objective was to identify potential HFE issues with the planned upgrades.

The operator-in-the-loop workshop entailed direct observation and assessment of key interactions of licensed operators with the new human-machine interfaces (HMIs) across a number of normal, abnormal, and emergency scenarios. The scenarios were designed to evaluate the functional and human factors aspects of the upgraded I&C systems for the control board, with particular emphasis on the ability of the new and modified components to support operators' cognitive processes and their ability to perform the correct control actions.

Human factors researchers and operationally experienced monitors observed the station's operators who performed actions in the scenarios using relevant procedures (see Figure 1). Observations focused on operator interactions that were affected by the upgraded controls and indicators. Changes in time available for operator action, as well as information availability, were identified by observers during the scenarios.

The assessment strategy focused on assessing overall "human-system" performance. As such, measures of usability, workload, and situational awareness were collected during

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Figure 1. Human factors researchers observing station operators.

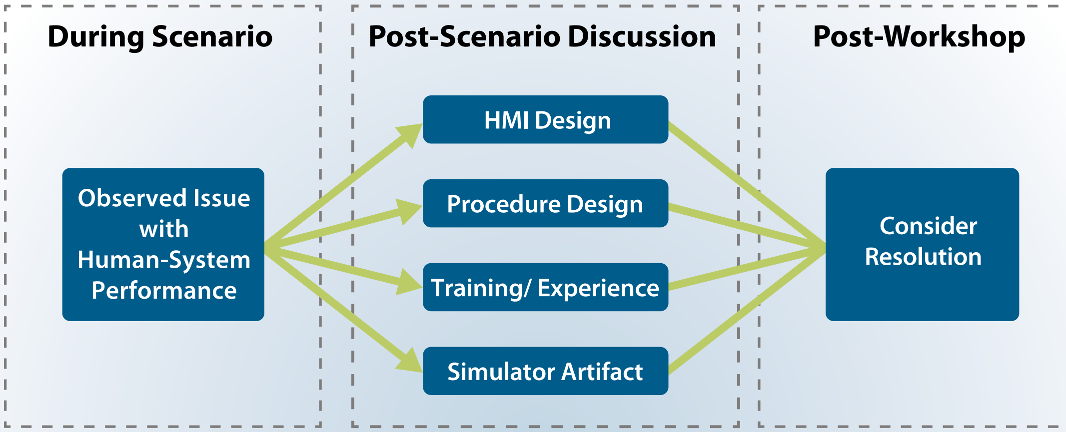

Figure 2. Comparison of a typical narrowband signal with a UWB pulse in both time and frequency domains (left) narrowband, continuous waveform (right) ultra-wideband, pulse based.

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select scenarios to evaluate the suitability of the new HMIs in an operational context (see Figure 2). During each scenario, the evaluation team also identified key information that determined the success or failure of the new HMIs exhibited in the scenario. If any potential deviations or difficulties were identified, then the LWRS HFE project team held a post-scenario discussion with the operators to identify potential contributors (HMI design issues, procedure issues, training/ experience, simulator artifacts, etc.) so that appropriate actions could be taken.

Workshop Results

Overall, the operator-in-the-loop workshop demonstrated that the upgraded HMIs support operators in emergency operation tasks in that they did not adversely affect operator performance in highly complex scenarios where the operators' responses to transients and casualties that challenges the safety of the plant are important. For normal and abnormal operating conditions, the operators were mostly able to successfully complete the tasks correctly, completely, and without confusion or misunderstandings using the upgraded HMIs. The operators were sufficiently alerted, provided with usable controls, and received adequate feedback from the system interfaces. That is, while observations and analyses of the scenarios identified a few medium and low level human factors issues, the performance issues observed here can and will be addressed satisfactorily with training and revised procedures.

The results also showed a number of operational improvements that will be realized with the successful installation of the Ovation system. The most apparent example of this is in how Ovation has an automatic median select function instead of manual channel selector switches, which therefore eliminates any potential operator errors in failing to correctly diagnose that a transmitter or sensor has failed. Overall, in the context of evaluating "human-system" performance, the control room operator teams appear to be sufficiently supported by upgraded HMIs, operating procedures, and their training to safely control the plant with the upgraded HMIs.

Issues identified will be summarized in a LWRS HFE project team report provided to the utility management, after the conclusion of the assessment and an adequate period of time to evaluate the recorded observations against industry standards. Based on the discussions held with the utility management at the end of the workshop, it appeared that virtually all of the human factors issues identified were ones they were interested in correcting before the upgrade is installed in the main control room.

Conclusion

Results from this workshop informed the utility management of any HFE issues that should be addressed prior to being integrated in the main control room. Results from this workshop will also serve as a resource for future modernization efforts in the remaining utility control rooms.

Overall, this workshop furthered Department of Energy's objective to support the long-term sustainability of the light water reactor fleet by conducting research and development that addresses reliability and obsolescence issues of legacy analog control rooms, and by demonstrating and documenting the human factors processes that utilities should undertake to perform control room modernization for a fleet of nuclear power plants operating in a merchant market.

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