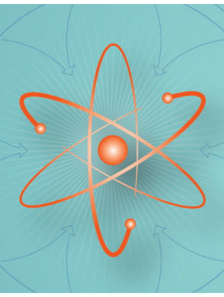

Advanced Sensors and Instrumentation

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ASI Program Update

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The Advanced Sensor and Instrumentation (ASI) program has entered its nineth year of implementation and continues to face the challenge of adapting to the conditions imposed by the response to the COVID-19 pandemic. The disruption has been particularly severe for the projects relying on experimental activities, particularly those impacted by delays in the operational schedule of research and material test reactors and other irradiation facilities. As organizations across the country adapted to the pandemic response, some of the delays have been recovered, but issues associated with supply chain have become more impactful as the pandemic continues. These include the availability of materials, stock components, and parts, as well as delays in shipping. However, researchers across the program have learned to make the best of this difficult situation, and progress and accomplishments have been remarkable despite the challenges.

The ASI program's Annual Review was held as virtual webinar on three consecutive weeks in the fall of 2020 (October 29, November 5, and November 12). It showcased 35 presentations, discussing the summary of accomplishment in Fiscal Year 2020 in the four research areas of the program: Sensors and Instrumentation, Nuclear Plant Communication, Advanced Controls and Big Data, and Machine Learning and Artificial Intelligence. The webinar attracted more than 120 attendees from industry, including nuclear system developers and instrumentation vendors, national laboratories from the Department of Energy (DOE) complex, universities, and government agencies. A few weeks earlier (October 13, 2021) the ASI program also provided technical coordination for the

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workshop on Sensor Technologies for Advanced Reactors, organized by the Gateway for Accelerated Innovation in Nuclear (GAIN), the Electric Power Research Institute (EPRI), and the Nuclear Energy Institute (NEI). The workshop discussed sensor needs for advanced reactor concepts and current national laboratory capabilities to identify gaps to inform the DOE research programs, with focus on receiving inputs from industrial collaborators.

The start of fiscal year (FY) 2021 has brought several changes to the ASI program management team. Melissa Bates has taken over Suibel Schuppner's responsibilities as the DOE Office of Nuclear Energy (NE) headquarters program manager. Bates is a native of the west, having grown up in southeast Idaho. She started her career with the DOE in 2003 in the DOE Idaho Operations Office (ID). Working on her degree in parallel, she graduated in 2009 from Idaho State University with a degree in mechanical engineering. During her time at DOE-ID, she supported programs like the Nuclear Hydrogen Initiative, the Used Fuel Disposition campaign, and the Nuclear Fuels Storage and Transportation Planning Project. In 2015, Bates relocated her family to the District of Columbia metropolitan area to take a job as the acting team lead for the Nuclear Fuels Storage and Transportation Planning Project where she worked to lay the groundwork for a future interim storage facility and large-scale transportation system for commercial spent nuclear fuel. In 2018, Bates changed positions within the DOE-NE to become the program manager for the Advanced Small Modular Reactor Research and Development program. Through this program, she worked with DOE's industry partners to bring light-water small modular reactor technologies to commercialization. Through these experiences, Bates has developed a technical expertise in the management of contracts and financial assistance agreements. As the program manager for the ASI program, Ms. Bates will be an ardent supporter of deploying new sensors and instrumentation for use by the nuclear industry. She believes that this work will be critical for the continued success of both the current reactor fleet and to support bringing future advanced reactors to commercialization. One of her main goals for the program is to close the technology gaps in raising the technology readiness level of the sensors and instrumentation currently under development in a way that can support the existing reactor fleet and the developers of new advanced reactor technologies. She is confident that with the support of those on the ASI team, they will be able to accomplish amazing things.

In addition to the federal manager, the start of FY 2021 has also seen the transition of the national technical director role from Craig Primer to Pattrick Calderoni. Calderoni is an Italian-born nuclear engineer who started his academic and research career at the University of Bologna and the European Joint Research Center (JRC) network of laboratories and completed it with a Ph.D. in mechanical engineering at the University of California, Los Angeles. The development of advanced instrumentation has been an integral part of his research activities from the earliest experiences at the High Flux Reactor (Petten, the Netherlands) to his current responsibilities as the Measurement Science Department Manager at Idaho National Laboratory. The 5 years of project management activities for ITER (a large-scale facility under construction in the south of France to demonstrate the viability of nuclear fusion as energy source) have consolidated his expertise, as he was responsible for the development of the instrumentation and control system of two complex Test Blanket Modules. Dr. Calderoni joined INL in 2006 and has more than 20 years' experience in the development of fission and fusion energy systems and testing of nuclear components. In addition to sensors, his technical expertise includes molten salt reactors and tritium technology.

Nuclear Applications for Radiation-Hard Electronics

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Introduction

Nuclear sensing and instrumentation play key roles in assuring safe operation of power reactors, research reactors, microreactors, and space reactors. However, due to the limitations in commercially available electronics for harsh environment applications (high radiation, elevated temperature), sensor deployment requires the use of long cable runs and connectors or penetrations that are susceptible to noise, degradation, and cyber-physical security issues. Installation of the front-end read-out electronics for pressure sensors, flow sensors, resistance temperature devices (RTDs), and neutron sensors as close as possible to the sensor greatly increases signal integrity and reliability. In addition, analog-to-digital conversion, encoding, and encryption could be performed at the sensor, prior to signal transmission, resulting in more accurate and robust sensor systems.

Systems of Interest

Sensors with integrated signal processing, digitization and communications interfaces are of significant interest for near-core and in-containment sensing, as well as robotic operations involving inspection, maintenance, and cleanup. Key technology advancements are needed to produce the enabling circuit functions required for reactor-sensor interfacing. Improvements in radiation resistance and temperature tolerance of common circuit functions, including sensor interface electronics, analog-to-digital converters (ADCs), signal processing, encoding and encryption, and antenna or cable driving amplifiers are needed for effective reactor application.

In addition to improvements signal conditioning near the sensing mechanism, the application of wireless communications to the reactor environment would greatly reduce the need and even eliminate cabling required to access nuclear sensor data. Plant-wide integration of wireless technology would advance the modernization of existing light water reactor technology by improving signal integrity and reducing noise susceptibility.

Beyond the electronics associated with sensing systems, integration of robots and remote operations would greatly reduce human exposure to radiation environments within nuclear reactors and spent fuel storage. These systems would increase the safety and reliability of reactors and provide similar benefits in other nuclear environments.

Radiation Effects on Electronics

Understanding the mechanisms by which radiation can affect electronic systems is critical to their robust design. Radiation effects are categorized into ionizing radiation damage and neutron displacement damage. Ionizing damage is further categorized into dose rate and total accumulated dose effects. Dose rate effects cause single-event upsets such as latchups and photon generated currents, which may cause device failure. Dose rate effects are a major concern for low-earth orbit applications, which dominate the commercial market. For example, high -ionizing dose rates result from random high-energy solar and cosmic events, such as solar flares. However, these applications do not see high total ionizing dose rates in comparison to terrestrial reactor applications.

Compared with space applications, terrestrial nuclear applications are limited by neutron displacement damage and total ionizing dose. Ionizing damage creates charge traps in insulation regions and layers, such as the silicon oxide gate insulators in metal-oxide-semiconductor field-effect transistors (MOSFETs) or the field oxides associated with all semiconductor integrated circuits including bipolar junction transistors (BJTs). Displacement damage removes atoms from the semiconductor lattice structure shortening the minority carrier lifetime resulting in decreased carrier mobility and increased noise. Displaced atoms from neutrons also create charge trapping centers.

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Table 1. Neutron displacement damage on active device technology.

Technology	Max fluence (n/cm^2)	Displacement effects
Diodes	10^{13}-10^{15}	Increased leakage currents; increased forward voltage threshold
LEDs	10^{12}-10^{14}	Reduced light intensity
BJTs	10^{13}	Current gain degradation (PNP devices are more sensitive than NPN devices)
JFETs	10^{14}	Increased channel resistivity; decreased carrier mobilities
SiC JFET	10^{16}	Increased channel resistivity; decreased carrier mobilities
MOSFETs	10^{15}	Increased channel resistivity; decreased carrier mobilities
CMOS	10^{15}	Increased channel resistivity; decreased carrier mobilities

Table 2. Gamma TID damage on active device technology.

Technology	TID (Gy)	TID effects
Photodiodes	10^4-10^6	Increased photocurrents
LEDs	10^5-10^6	0.25dB attenuation
BJTs	10^3-10^5	Current gain degradation and increased leakage currents
JFETs	$>10^6$	Minimal observable effects
SiC JFET	$>10^6$	Minimal observable effects
Si MOSFETs	10^4	Increasing threshold voltage and leakage currents
CMOS	10^6	Variations in the threshold voltage and leakage currents

Current State-of-the-Art

Understanding the limitations of devices and systems is critical for effective electronics design for terrestrial nuclear applications. Tables 1 and 2 summarize the neutron and total ionizing dose (TID) limits on semiconductor device technologies and associated effects.

Passive components are inherently rad-hard. However, components relying on dielectrics, including capacitors and cables, will experience capacitance variations due to radiation ionization resulting in bound charge changes and dielectric breakdowns from induced charge trapping, especially if organic compounds are used for the dielectrics.

Minority carrier devices such as diodes, light-emitting diodes (LEDs), and bipolar junction transistors (BJTs), are sensitive to neutron displacement damage, which increases leakage current and decreases electric current amplification gain values through the reduction of their minority carrier lifetime. When minority carrier devices are fabricated with field oxides, charge trapping occurs which also reduces the leakage current and decreases the electric current amplification gains.

Insulated gate field-effect transistors, such as MOSFETs, are more sensitive to charge trapping from ionizing radiation. As trapped charges accumulate in the gate insulation, electric fields that govern the operation of these devices increase, which cause variations in the device threshold voltage and create leakage currents. As modern complementary MOSFET (CMOS) processes decrease transistor dimensions, the chances of inducing a charge trap are lessened. Sub-micron CMOS technology is a promising candidate for reactor applications. Neutron displacement in MOSFET semiconductor technology degrades the semiconductor lattice structure of these

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devices. Increased semiconductor doping increases their neutron resistance, but Si-based devices have lower doping limits than wide bandgap materials.

Insulated gates are not present in junction field-effect transistors (JFETs) and, as a result, these devices are incredibly resistant to ionizing radiation. However, neutron displacement degrades the lattice structure of all semiconductors, which limits the lifetime of these devices. JFETs are rarely used in modern electronics design because the device gain matching required in complex analog and digital circuits is difficult to achieve during integrated circuit (IC) fabrication.

Vacuum devices are inherently resistant to radiation damage. However, their size, high voltage requirements, and inefficiencies reduce interest. Recent research into micro-vacuum tubes is promising, but as these devices become smaller, the effect of charge trapping on an individual device is exacerbated.

Operational amplifiers are analog components which are heavily used to process sensor signals; however, most commercially available rad-hard amplifiers are fabricated using silicon integrated circuit technology and only survive up to 0.3–1 Mrad (Si) total ionizing dose (TID). Wide bandgap materials, such as silicon carbide (SiC), gallium oxide (Ga_2O_3), and gallium nitride (GaN), will enable higher temperatures and typically provide a higher radiation resistance over silicon-based circuits. Rad-hard-by-design techniques implemented in silicon devices improve their radiation tolerance, but these devices are subject to significant temperature limitations (up to ~150°C).

Microcontrollers, like operational amplifiers, are typically fabricated using silicon-based processes. These units are very desirable for nuclear instrumentation due to their compact size, reconfigurability, and flexible functionality, including use as digital signal processors (DSPs). They These units are small computer systems that can be programmed to interface with analog and digital signals, and electromechanical components. When used as DSPs, these devices provide real-time signal processing and data analysis capabilities, which enable more rapid data operations and control responses.

Gaps and Future Directions

Understanding the performance limitations of devices and integrated circuits under irradiation is crucial for reactor electronics/instrumentation designers. The availability of more radiation tolerant technologies continues to grow in both the commercial and research sectors. Commercially available rad-hard or rad-tolerant circuits are presently only qualified for low-earth orbit and space flight applications. However, proper use of these devices may enable instrumentation placement in new and more extreme reactor environments and locations. Collecting these offerings into a single comprehensive database of standardized devices and their limitations would be beneficial to the development and implementation of instrumentation.

JFET semiconductor technology is incredibly resistant to radiation, but complex circuits designs which that take advantage of these devices are limited. Increasing the quantity of high-complexity JFET and sub-micron CMOS circuits will lead to the advancement of electronic circuits suitable for high-radiation environments. However, Si-based semiconductor technology is still limited to ~150°C. Transitioning circuits to wide bandgap materials, such as SiC or GaN, will increase the upper thermal limits of electronics and allow for increased doping, which increases neutron resistance.

Conclusions

Proper use of sensors and instrumentation in nuclear reactor applications will improve the safety and operational efficiency of nuclear reactors. As reactor technology advances, the operating temperatures used in these designs increases, heightening the need for more and better sensor technology. Understanding the harsh environment of reactors, the associated effects of temperature and radiation on modern electronics technologies, and the commercial offerings of harsh environment circuits are all key components enabling effective design of electronics for sensor interfacing, signal processing, and communications in nuclear reactors.

Advanced-Manufactured Sensors: Enabling Technologies

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Motivation and Background

Advanced manufacturing (AM) has emerged as the predominant enabler for innovation and design as it significantly expands the design envelope in terms of materials, form, and functionality. Additionally, these technologies enable rapid prototyping, reduced production cost, and reduced material waste in comparison to classical fabrication methods. As part of the AM focus of the Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation Program (NEET-ASI), Idaho National Laboratory has recently established in-house capabilities to develop, fabricate, and test new AM sensors, such as those for measuring peak irradiation temperature within a nuclear test reactor. The exploration of novel technologies allows for the development of unique sensors that are not achievable with conventional fabrication processes. The ability to produce miniature and robust sensors is made possible with additive-manufacturing techniques known as direct-write (DW) technologies, such as aerosol-jet printing, plasma jet printing, ink-jet printing, and micro-dispense printing, as they are capable of consistently producing device features from 10 to 25 µm [1]. These size ranges are advantageous for instances where miniaturization of sensors is required due to space limitations within an experiment.

Advanced Manufacturing Objectives

The limiting factor for implementing DW technologies in nuclear instrumentation fabrication is the current selection of commercially available feedstock materials that are compatible with those technologies. The database of materials available for DW technologies is rapidly expanding and benefitting greatly from emerging nanomaterials development. Significantly expanding this library of materials to include those that are more nuclear relevant provides the necessary path towards incorporating these novel methods for nuclear energy applications. Such material breakthroughs will revolutionize in-pile sensor development and deployment for the monitoring of nuclear fuel and material behavior during an irradiation experiment. To enable such an advance in sensor technology, current activities of the AM sensor work involve expanding the database of nuclear relevant feedstock available for DW technologies, and these initial efforts having been guided by the development of passive monitoring techniques, such as AM peak temperature sensors and advanced-manufactured neutron flux dosimeters.

Initial prototypes of both types of sensors are provided in Figure 1. From Figure 1.A, the deposition of aluminum, tin, and zinc melt wires were fabricated into a small dimple within a stainless steel disc (Figure 1.A1). The melt wires were then encapsulated by placing a second stainless steel disk on top and welding the two discs together (Figure 1. A2). Utilizing a non-transparent material for encapsulation requires that X-ray computed tomography be used to visualize the printed melt wires before and after heating, and an X-ray computed tomography of an initial prototype before heating is shown in Figure 1. A3. Regarding advanced-manufactured neutron flux dosimeters, materials capable of serving as neutron dosimeters of Ti, Co_2O_3, Ni, and Fe were deposited into a printed alumina capsule (Figure 1. B1, B2), and the full neutron dosimeter assembly with printed alumina dosimeter holder are shown in Figure 1.B3.

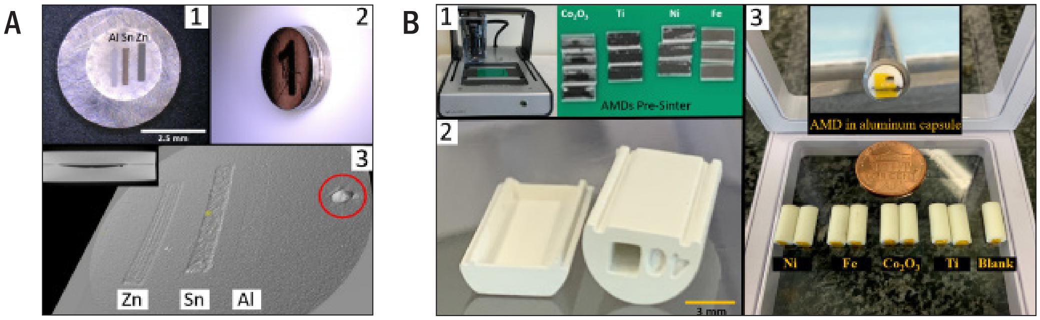

Figure 1. Initial prototypes of advanced manufactured melt wires (A) and neutron dosimeters (B). AM melt wires were fabricated within a small dimple pocket created in a stainless steel disc (A1), a second steel disk was placed on top and the two pieces were welded to encapsulate the printed melt wires (A2). X-ray computed tomography is then used to visualize the printed wires before and after heating (A3). A fully printed neutron dosimeter assembly and the alumina dosimeter holder was created via an additive technique.

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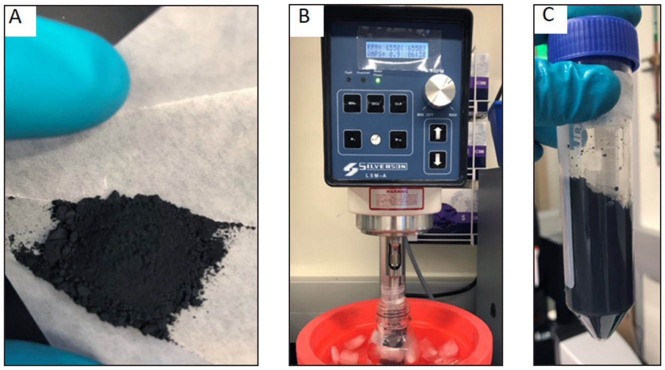

Figure 2. Schematic of the top-down ink synthesis method. The top-down method begins with a nano powder of the material of interest (A.) followed by shear mixing (B) to create an ink (C).

Utilizing additive-manufacturing techniques for sensor fabrication requires a substrate to serve as the surface that the print is built upon, and the application of printed devices is highly dependent upon the substrate used. With that, the interaction between the printed material and substrate is significant as it influences both print quality and device integrity. The ability to measure the adhesion strength between the printed sensor and substrate will ensure sensor quality and is critical for the successful deployment of these sensors. However, current approaches to assess the adhesion strength rely on peel tests that are destructive, and often unreliable [2, 3]. Additionally, these methods are not suitable for evaluating the adhesion strength of small device features. A non-destructive measurement method is currently being developed that involves the use of a laser ultrasonics-based non-contact and non-destructive technique to measure the film/substrate adhesion strength from the mechanical vibrations of the printed sensors.

Current Status

Feedstock Development. Methods for ink synthesis encompass both top-down and bottom-up methods. A schematic for the top-down approach is provided in Figure 2, and it begins with nanoparticles of the metal, ceramic or alloy of interest in the form of a powder or a dispersion. The key challenges of the top-down approach are found in obtaining a homogenous dispersion of functional material with a solvent system compatible with DW technologies, limited control over particle size, and large particle size distributions. On the other hand, bottom-up methods for metallic nanoparticles require the synthesis of nanoparticles from their metallic precursors. A capping agent, which induces a steric stabilization to agglomeration, is employed to enhance suspension stability. The bottom-up approach is the preferred method as it allows for greater control over particle size and size distribution, which are key properties of affecting the quality of the ink formulation. Key challenges associated with bottom-up methods includes the development of an appropriate synthesis method, isolation of desired particle shape, particle size and distribution, and identification of an appropriate capping agent.

Currently, the database of available ink materials has been expanded to 31 different materials that have been fabricated for use with a variety of DW technologies. Feedstock development is guided by sensor development and current efforts have been focused on AM melt wires and neutron dosimeters. To expand the temperature monitoring range and to provide a finer temperature resolution than traditional melt wires, bi-metallic alloys are being investigated, such as bismuth/platinum alloys. Initial efforts have started by demonstrating the ability to synthesize nanoparticles, from bottom-up methods, of both platinum and bismuth nanoparticles (Figure 3 and Figure 4). Successful synthesis of a variety of bismuth/platinum bi-metallics would enable peak temperature monitoring from 271°C to 1768°C with significant potential to fine tune temperature resolution by tailoring melt wire composition, which directly impacts passive peak temperature monitor performance.

The next steps include demonstrating the successful synthesis of a variety of compositions of bismuth/platinum melt wires. Once these compositions are printed, the melting point characterization of those nanoparticles will be evaluated for their suitability for developing passive peak temperature monitor melt wire arrays. These are expected to have better temperature resolution than classically manufactured passive peak temperature monitors fabricated from bulk metals.

Adhesion Strength Measurements. A laser ultrasonic method that utilizes a pulsed laser to excite vibrational modes via thermoelastic generation and an optical interferometer to detect the vibrational displacements, shown in Figure 5, is

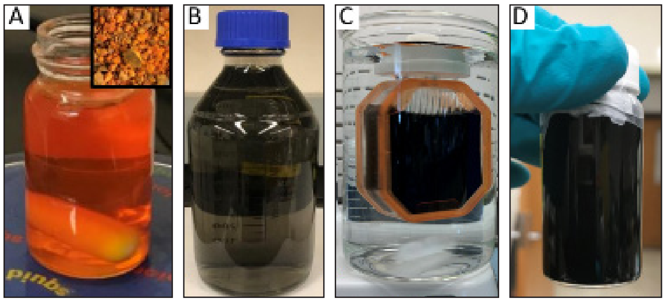

Figure 3. Schematic of the bottom-up ink synthesis method for platinum. Utilizing a platinum salt precursor (A) a reduction method was employed to produce polyvinylpyrrolidone capped platinum nanoparticles (B). Platinum nanoparticles are purified via diafiltration (C) and concentrated to about 20 wt.% for use in a wide range of DW technologies (D).

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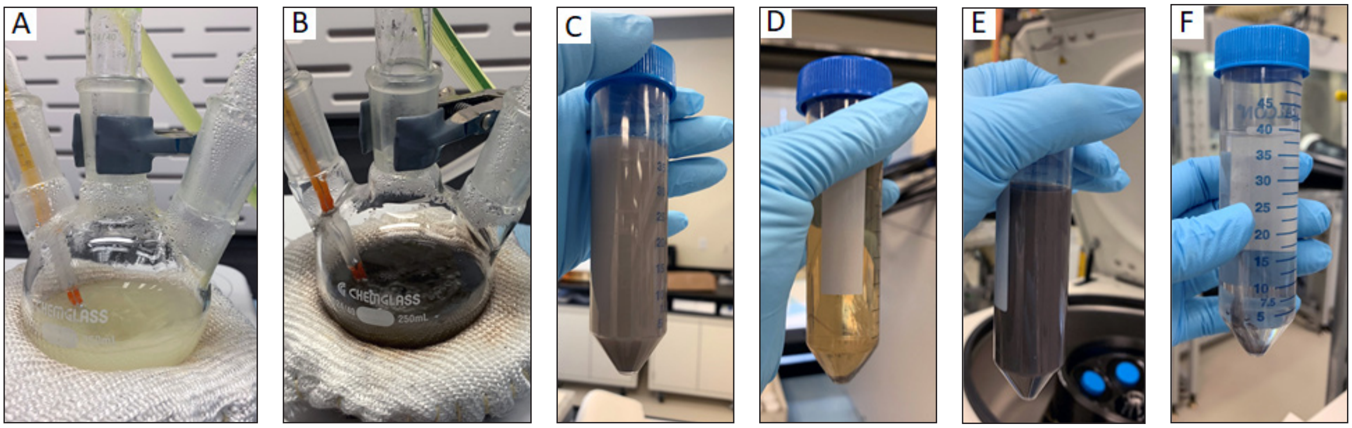

Figure 4. Schematic of the bottom-up ink synthesis method for bismuth. Utilizing a bismuth salt precursor (A) a reduction method was employed to produce polyvinylpyrrolidone capped platinum nanoparticles under reflux (B). Bismuth nanoparticles are purified via centrifugation where the clarity of the supernatant is shown with each subsequent "wash" (C-F)

being used as a non-contact tool for assessing the adhesion strength between the printed sensor and the substrate. The setup includes a 1064 nm pulsed laser used for ultrasonic excitation (shown in Figure 5A with red arrows), and a 532 nm laser interferometer beam is used for detection of vibrational displacements (shown in Figure 5A with green arrows). The fixed-free vibrational frequency of the sensor material is related to the contact stiffness between the printed sensor and the substrate. Preliminary laser ultrasonic measurements have been performed on silver printed on sapphire and glass substrates using aerosol jet printing.

Process control variables and experimental factors that could affect the quality of the printed sensor-substrate contact and the performance of the sensor were surveyed. A test matrix has been developed to systematically identify the effects of experimental factors using the laser ultrasonic approach. These factors include the substrate surface quality/roughness, substrate surface treatment, ink curing temperature, and duration. Currently, stainless steel substrates are being polished to varying degrees of surface roughness. The substrates will then be treated in oxygen plasma to alter their surface energy right before the sensors are fabricated using aerosol jet printing with silver nanoparticle inks.

Next steps include performing laser ultrasonic measurements of the sensors manufactured in the test matrix to determine the dominant combination of factors that significantly alter the ink-substrate adhesion. Therefore, the experimental methodology will enable a systematic post-fabrication process control that ensures the durability and robustness of the sensor to the substrate, particularly for harsh operating environments of coupled radiation and temperature extremes. Future directions will also include assessing process variables that influence the quality and adhesion strength of sensors fabricated using plasma jet printing to relevant substrates that may be of interest for nuclear fuels and materials testing.

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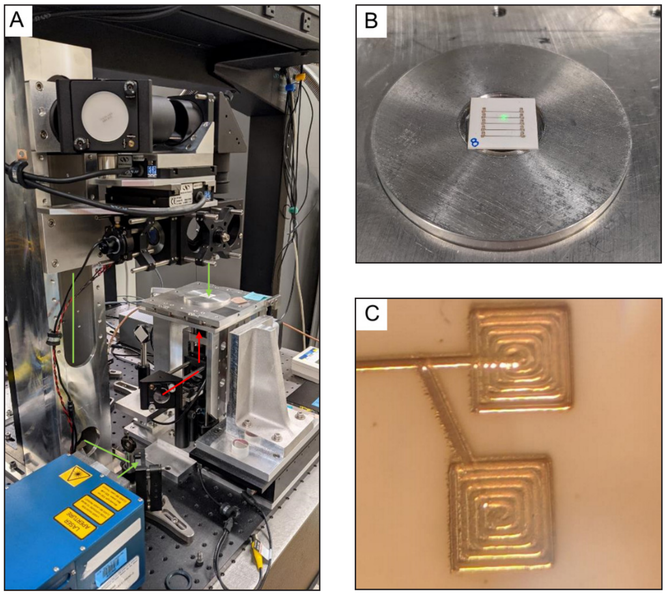

Figure 5. A.) Photograph of the laser ultrasonic experimental setup used to measure the adhesion of printed sensors on substrates. The red arrow represents the 1064 nm pulsed laser used for ultrasonic excitation, while the green arrow represents the 532 nm laser interferometer beam used for detection of the vibrational displacements. B.) View of a sample comprised of silver nanoparticle ink printed on an alumina substrate in the laser ultrasonic test setup. C.) Detailed view of the sensor pad observed under an optical microscope.

Electrochemical Sensors for Monitoring Cladding Degradation

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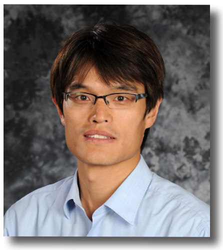

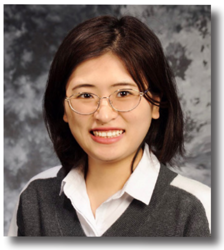

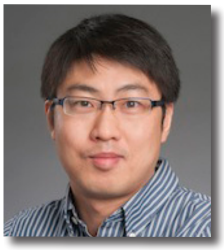

Introduction

Integrity of the nuclear fuel cladding is essential for maintaining safe and efficient reactor operation by providing a primary barrier between the fuel and coolant and ensuring containment of the fuel and fission products. Zirconium alloys are used for fuel cladding due to a low-neutron absorption cross section and strong corrosion resistance while in a pressurized water reactor core. Although the cladding is initially protected by a thin oxide film, during reactor operations, continued oxidation and hydride formation cause degradation of the cladding material and the extreme operating environment makes it difficult to predict or monitor cladding condition. Currently, chemical evolution over the lifetime of cladding can only be inferred using post-irradiation examination or by experiments mimicking the coolant-side conditions. Hence, real-time monitoring of the cladding condition is desired to support increased reactor performance and safety.

The objective of this project was to develop electrochemical impedance spectroscopy (EIS)-based techniques for in core measurements of structural changes to nuclear fuel cladding materials through a coordinated effort to connect experiments, model simulation, and materials characterization. This project involved the initial development of electrochemical sensing technologies for measuring spatial and time resolved changes in cladding structure, chemistry, and surface reactions with specific attention given to corrosion and monitoring changes in cladding hydride and oxide formation and deformation.

Electrochemical Impedance Sensor Development

Electrochemical impedance spectroscopy (EIS) is a well-established technique for determining interfacial phenomena and monitoring surface reactions such as corrosion and oxidation. EIS is a 2-electrode AC (alternating current) electrochemical technique in which the impedance response of the electrode is monitored over a range of frequencies and the technical barriers to implementing are comparatively low. Within the reactor core the cladding itself serves as one electrode and only electrical connections to the electrodes are needed.

To determine corrosion rate and oxide properties from EIS sensor response, the data is modeled with an equivalent electrical circuit and the circuit components can then be attributed to cladding material surface phenomena such as corrosion attack and oxide properties. Work for this report focused on EIS experimental work for investigating corrosion and hydride formation of Zr-4 samples at various conditions in a static autoclave reactor; development of equivalent circuit models to simulate the experimentally obtained EIS spectra; characterization of samples using scanning electron microscopy with energy-dispersive X-ray spectroscopy to provide interface structure of zirconium oxide and metal/oxide interface; and preliminary finite element (FE) modeling on the chemistry and structure change of cladding materials [1].

Experimental Testing and Modeling Results

Using previously reported sensor designs [2], Zr-4 samples were tested using EIS in aqueous solution with six pressurized water reactor-relevant conditions: pure water at 250°C/573 psi; 7 ppm LiOH solution at 250°C/573 psi and 250°C/1500 psi, respectively; 70 ppm LiOH solution at 250°C/1500 psi, 70 ppm LiOH solution at 250 °C/573 psi with 3% H_2; and 140 ppm LiOH solution at 250°C/573

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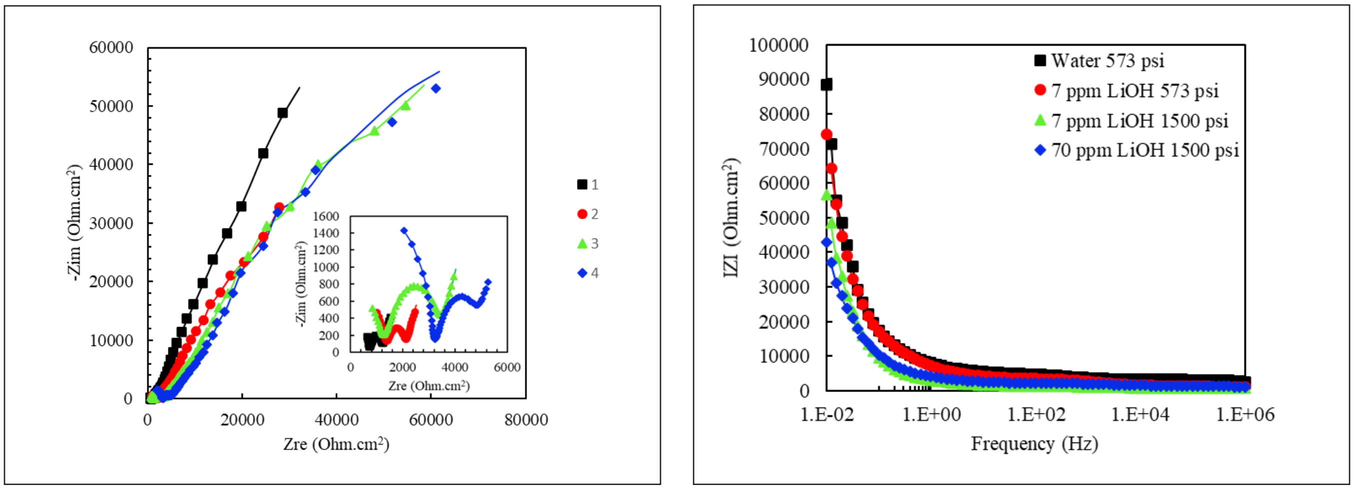

Figure 1. EIS spectra of Zr-4 ex-situ tests with different conditions at 250°C

psi with 3% H_2. Impedance measurements on samples in autoclaves were made as a function of time to follow the penetration of the electrolyte into the oxide pores. For most testing conditions, two time constants can be observed in the EIS results as shown in Figure 1; however, the frequency dispersion is quite large, indicating that the oxide is inhomogeneous. However, the interfacial capacitance at high frequencies remains constant with time, indicating that the oxide is fairly dense and protective.

EIS tests on all conditions both in-situ and ex-situ were also performed. As demonstrated in Figure 2, the spectra were fitted with equivalent circuit models consisting of two resistor-capacitor parallel circuits in series, except samples exposed to 3% H_2 where only one time constant was observed. Samples not exposed to H_2 initially developed an oxide film composed of a single layer. However, after about 1 week of exposure, two layers were apparent: an outer porous layer soaked with the electrolyte and inner dense layer. For specimens exposed to 3% H_2, no significant corrosion activity was observed. Similarly, oxide resistance was obtained from low-frequency impedance data and reflected instantaneous changes in corrosion rate and consequently the start and end of oxide growth rate transitions.

In addition to the experimental testing, we have successfully developed a Finite Element (FE) simulation model of coupled oxide and hydride evolutions in zircalloys, under various reactor-relevant conditions. The preliminary results of the FE model present a corrosion rate in conditions expected to be similar to the Advanced Test Reactor (ATR). FE simulations demonstrated that the hydride preferentially develops at a specific penetration depth from the coolant side, forming a circumferential “ring”-like structure. The

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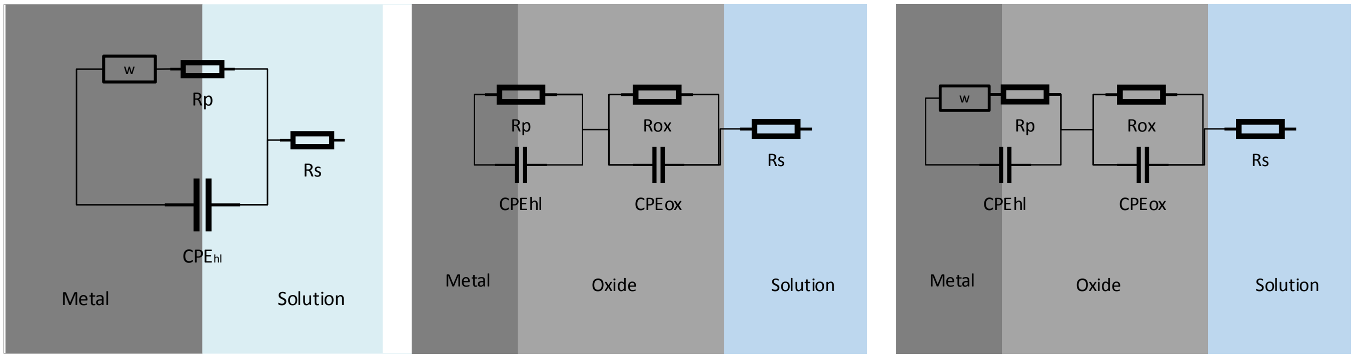

Figure 2. Models of equivalent circuits; Rs is the solution resistance, Rox is the oxide resistance, Rp is the polarization resistance, CPEox is the non-ideal oxide capacitance and CPEhl is non-ideal capacitance of the Helmholtz layer.

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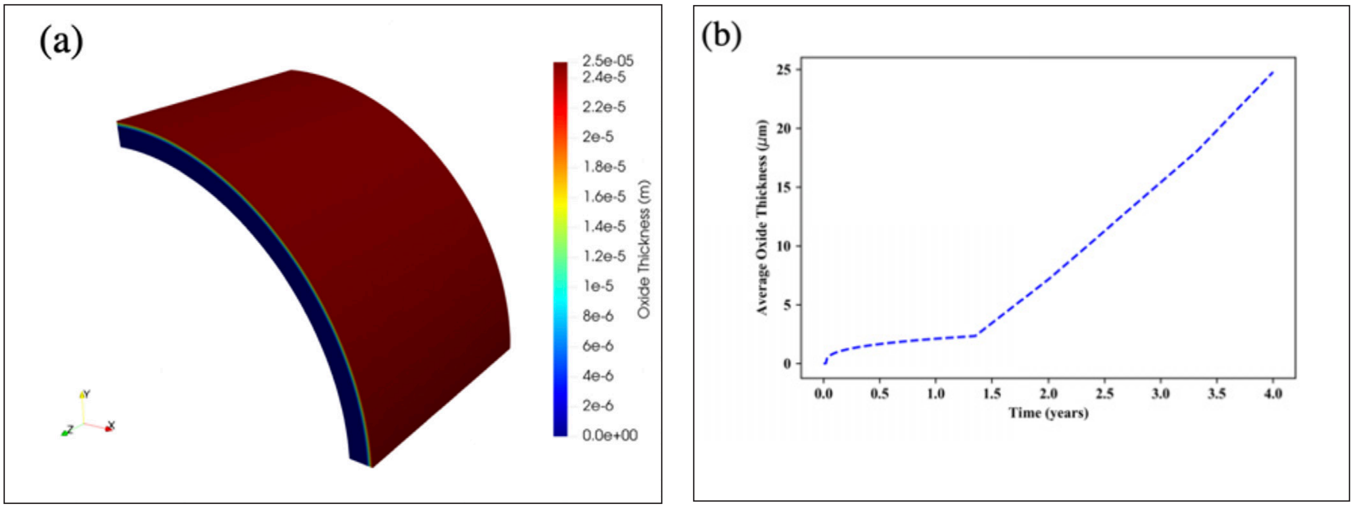

Figure 3. (a) The distributions of oxide thickness after 4 years. (b) The average oxide thickness growth. The average oxide thickness after 4 years is approximately 25.0 µm. It can be seen that the pre-transition process dominates before 1.4 years and post- transition process dominates the evolution after that.

average hydride concentration increased sharply during the first year (simulated), and then leveled off gradually. It was also observed that there were two phases for oxide growth, which were governed by pre-transition oxidation process and post-transition oxidation process, respectively. When the simulated oxides exceed a thickness of 2 µm, they will transform to a post-transition oxidation process evolution and thus have a faster growth rate (Figure 3). The oxide was evenly distributed on the cladding surface with an average thickness of 25 µm after 4 years.

Conclusions

Longitudinal data analysis from in-situ EIS sensor measurements to estimate cladding material service life has tremendous potential future benefits for cladding maintenance as well as the nuclear industry. Five key parameters for estimating cladding service life or cladding failure can be obtained from the EIS sensing and coupled modeling efforts developed herein, including oxide thickness, corrosion rate, oxide impedance, non-ideal oxide capacitance, and corrosion potential.

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Transmission of Information on Nuclear Facility Metallic Pipes with Ultrasonic Elastic Waves

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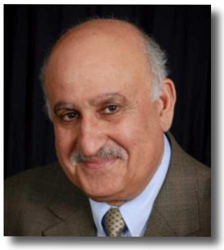

Introduction

Integration of advanced communication technologies into nuclear facility operation has the potential for enhancing safety and efficiency of the existing fleet of light water reactors, as well as those of advanced reactors under development. Recent research on nuclear facility communications has explored wireless options, which would allow for transmission of information in harsh environments without relying on physical cables, which can be damaged due to environmental degradation. Wireless radio frequency communication systems face implementation challenges at nuclear facilities due to the presence of physical barriers, such as thick reinforced concrete walls with steel liners of the containment building. Investigation of basic components of a wireless communication system for a nuclear facility, in which information is carried with ultrasonic elastic waves propagating on stainless steel pipes [1–16]. The objective is to develop an alternative capability to transmit high-volume data, such as images and video, out of the containment building. The ultrasonic communication system is intended for diversity of communication means in scenarios when conventional communication channels (wired or wireless) are disabled because of power outage or physical damage, which could occur because of a severe accident. A conceptual diagram of the ultrasonic communication system deployment at a nuclear facility is shown in Figure 1 [1]. Such communication system would take advantage of the existing piping infrastructure to transmit information in and out of containment building of a nuclear facility, as well as hard-to-reach places within the nuclear facility. Minimal hardware modification would be required because ultrasonic transducers, which are otherwise commonly used for nondestructive testing (NDT) of pipes, can be installed without modifying piping pressure boundaries. Because piping networks are omnipresent in the nuclear facility, essentially all critical locations of the nuclear facility can be reached using such communication system. Using a metallic pipe as a communication channel provides a layer of physical cybersecurity to the nuclear facility. The pipe is an analog information transmission channel, which is accessible only through direct physical contact. In addition, a stainless steel pipe is difficult to sever compared to conventional communication cables. Compared to ultrasonic transmission through other media, such as through thick concrete walls, transmission on pipes offers higher bitrate communication option.

A viable candidate for ultrasonic communication channel is a chemical volume control system (CVCS) stainless steel pipe, which penetrates through the containment building wall. Using typical dimensions of a CVCS pipe charging line, a laboratory test article for ultrasonic information transmission was developed. In the initial phase, an ultrasonic communication system

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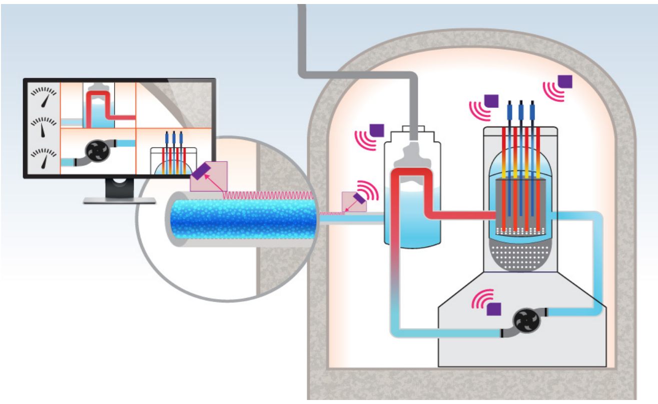

Figure 1. Proposed ultrasonic communication system at a nuclear facility would transmit information via elastic waves on steel pipes already in place for nuclear reactor operation. [1]

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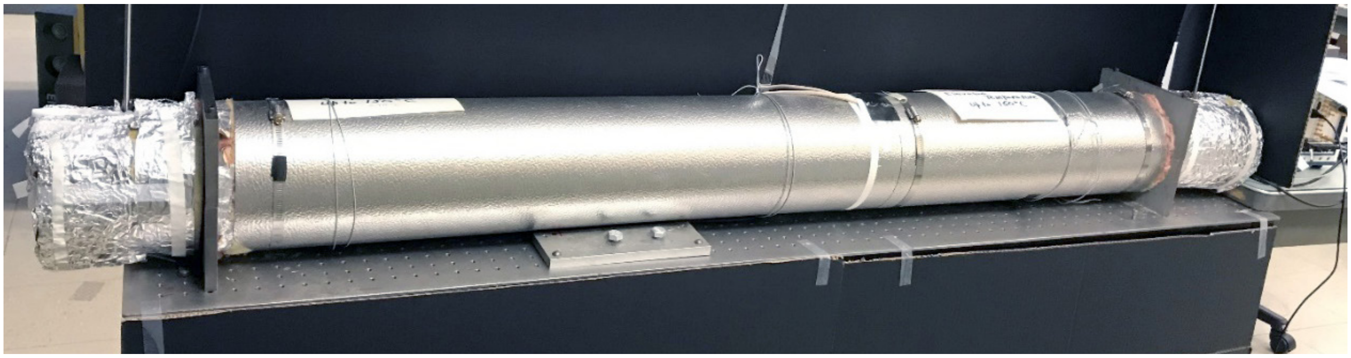

Figure 2. Laboratory setup for ultrasonic communication on a pipe at elevated temperature. [1]

for room temperature transmission of large volume of data, such as images, text files, and sound, using refracted shear waves generated with 2MHz paintbrush piezo electric transducers (PZT) [2] was designed. The advantage of using elastic shear waves as information carriers is that these types of ultrasonic waves do not couple into water, and hence presence or absence of water in the pipes would have no effect on information transmission. The ultrasonic communication system was shown to be resilient to low-frequency process noise. Amplitude shift keying (ASK) communication protocol, which is a variant of the on-off-keying protocol, was developed and implemented using GNU Radio software defined radio environment. A proof-of-principle demonstration consisted of transmitting a 32-KB image at 2-Kbps bitrate with bit error rate (BER) of 10^{-3} across straight 6 feet-long 304L stainless steel pipe at room temperature.

Subsequently, the focus of this study shifted to information transmission at elevated temperature using Lithium Niobate ($LiNbO_3$) ultrasonic transducers, which are resilient to high-temperature and ionizing radiation. A high-temperature test article was developed by installing heaters and temperature controllers

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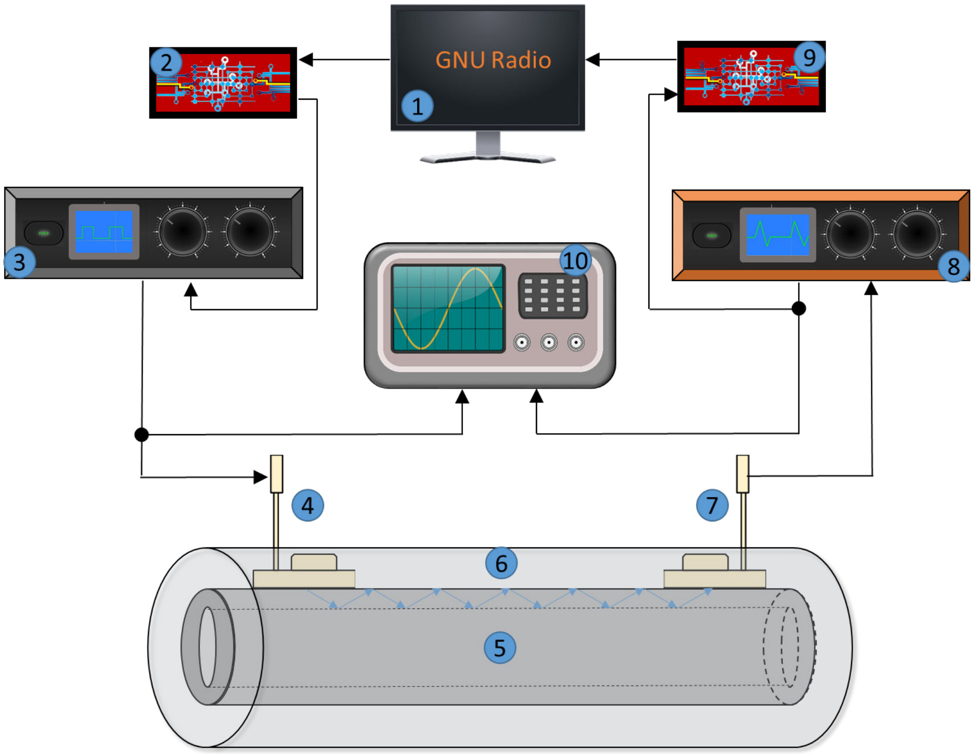

Figure 3. Hardware of ASK high-temperature ultrasonic communication system setup [1]. (1) Digital computer with GNU Radio software, (2) Red Pitaya transmitter board, (3) Power amplifier, (4) LiNbO3 ultrasonic transmitter, (5) Stainless steel pipe, (6) Thermal insulation layer, (7) $LiNbO_3$ ultrasonic receiver, (8) Low noise amplifier, (9) Red Pitaya receiver board, (10) Digital oscilloscope.

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on the laboratory pipe, to achieve steady-state pipe temperature of up to 230°C. The range of temperatures was chosen to represent communications during normal and post-accident environment at a nuclear facility. High-temperature LiNbO3 transducers were integrated into previously developed ASK acoustic communication system, implemented with Red Pitaya electronic boards and GNU Radio software. Ultrasonic transducer ringing following short temporal duration pulse generation, which led to inter-symbol interference (ISI), was determined to be one of the key factors limiting data transmission bit rate. A pulse shaping root-raised-cosine filter was implemented in software to suppress ISI. This allowed increasing communication data transfer rate to 10 Kbps with BER~10^{-3}. Proof-of-principle demonstration of ultrasonic communication on high-temperature included transmission of a 90-KB image at 10-Kbps bitrate on a straight stainless steel pipe heated to 230°C. Data transmission on heated pipes was demonstrated using a 90-KB image of Argonne logo (Figure 4) [1]. For eventual deployment at a nuclear power plant, we anticipate developing a communication system in which carriers of information are elastic shear waves on a metallic pipe.

Figure 4. GNURadio screen capture of a 90KB image file used in data transmission demonstration. Image was transmitted at 10Kbps with BER=10-3. [1]

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Versatile Acoustic and Optical Sensing Platforms for Passive Structural Systems Monitoring

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Introduction

Continuous health monitoring has become of paramount importance to the assessment and management of large-scale complex systems, such as nuclear power plants. The ability to monitor the performance of critical components, in real-time, enables operators to address the deterioration of the structural systems and implement the necessary strategies to avoid shutdowns in operation and/or minimize health and environmental risks.

Subsequently, there has been significant work dedicated to the integration of traditional sensing technologies into current and next generation nuclear power plants to assure operational safety and optimize performance. Although electronic sensors are available at relatively low-cost, fiber-optic sensors are receiving intense interest because of their relative tolerance to radiation exposure and elevated temperatures. Fiber-optic sensing technologies can also be configured to provide the distributed measurements necessary for 3D network monitoring solutions. Nonetheless, prevalent concerns related to reliability and cost have limited widespread adoption in nuclear energy systems.

To fill the gap between low-cost electronic sensors and high-performance fiber-optic sensors, this program seeks to provide an acoustics-based sensing technique that takes advantage of the proven resiliency of fiber optic materials and commercially available acoustic transducers and electronics. The developed technology will provide operators with multiparameter measurements to better evaluate the aging and degradation of relevant structural components including concrete structures that serve as support and nuclear containment, cable insulation, and metal pressure boundaries in nuclear facilities.

Objectives

The goal of this research is to develop a first-of-a-kind, fully distributed, multi-parameter sensing platform that can operate reliably in a high-temperature nuclear environment. The inscription of acoustic fiber Bragg gratings (AFBGs) in radiation tolerant fused silica and sapphire fibers will enable a cost-effective solution for real-time sensing with performance that rivals that obtained with the use of optical fiber Bragg gratings (OFBGs). Specific objectives to meet these goals include: (1) develop radiation tolerant silica and single crystal sapphire acoustic waveguide fibers; (2) design and construct acoustic fiber Bragg grating sensing systems that integrate fused silica and single crystal sapphire fibers; and (3) performance test optimized acoustic fibers and sensors exposed to radiation, to benchmark with commercial optical fibers and sensors.

Current Status

The Center for Photonics Technology at Virginia Tech successfully developed fully integrated AFBG temperature sensing systems with fused silica and single crystal sapphire acoustic waveguides. In collaboration with Prysmian Group and Oak Ridge National Laboratory (ORNL), the prototype sensing systems were tested upon gamma radiation exposure and benchmarked against femto-second laser inscribed OFBG sensors. The successful system validation of the AFGB sensing technology in simulated laboratory environments sets the stage for continued technological advancement upon completion of the project in the Spring 2021.

Technology and Approach

The concept of creating Bragg gratings on acoustic fiber waveguides for sensing external perturbations harkens back to the development of the first OFBGs. Similar to an OFBG, the AFBG is formed by a large number of serial periodic property modulations (R) along the fiber (ΔL) that are interrogated with an acoustic pulse, as shown in Figure 1. The center frequency (k) of the acoustic signal reflected from an AFBG segment can

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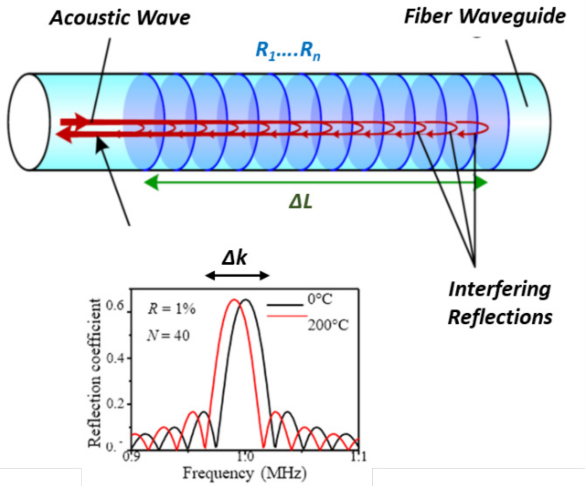

Figure 1. Schematic of AFBGs and temperature response.

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be related to perturbations of the AFBG at that location. The arrival time of the reflected acoustic signal can also be related to the location of its respective AFBG segment. Therefore, distributed measurements of a wide array of environmental parameters can be realized by real-time monitoring of the center frequencies of the acoustic pulses reflected from different locations on the fiber.

A significant advantage of acoustic sensor interrogation is that the single mode requirement for distributed measurements is more readily achieved in the acoustic wavelength regime. Therefore, the limitations in sensor performance imposed by the large modal volume in unclad optical fibers can be avoided with the use of acoustic fibers. Simplification of the waveguide design allows for expanded use of resilient and robust materials that are required with exposure to nuclear radiation and high temperatures. Furthermore, because of the low-bandwidth requirement on the interrogation electronics, the cost of the entire system can be significantly lower than most of the commercially available sensor types for the same spatial coverage.

AFBG Fabrication and Characterization

The acoustic waveguide and AFBG designs were optimized with the use of theoretical models that were created to ensure single mode operation and simulate sensor performance. AFBG reflectors were fabricated in fused silica and single crystal sapphire acoustic waveguides via CO_2 and femto-second laser inscription, respectively. Characterization was conducted on a custom acoustic sensor interrogation test stand to evaluate the spectral quality of the AFBG reflection, as shown by the time domain waveform in Figure 2. The AFBG can be configured to monitor a wide array of parameters by monitoring the central frequency of the AFBG reflection peak, as shown by the inset in Figure 2.

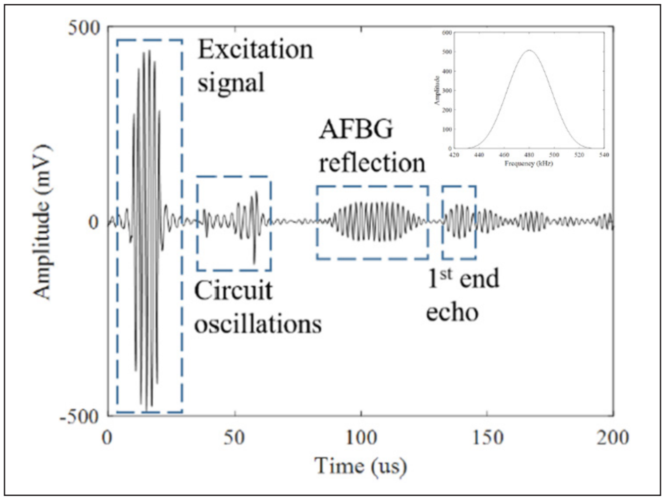

Figure 2. The time domain waveform of a fused silica waveguide with an AFBG. (inset) The spectrum of the AFBG signal obtained via fast Fourier transform (FFT).

Performance at Elevated Temperatures

The temperature response of the fused silica and single crystal sapphire AFBGs was evaluated and sensors were calibrated up to temperatures of 900°C and 1400°C, respectively, as shown for single crystal sapphire in Figure 3. Furthermore, sensor stability was demonstrated via long-term stability testing at an elevated temperature, shown by the inset in Figure 3.

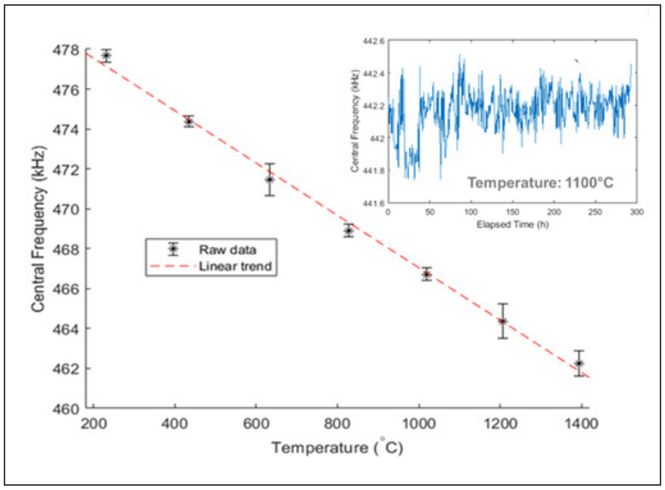

Figure 3. Temperature response of a single crystal sapphire AFBG up to 1400°C, (inset) long-term sensor stability of a single crystal sapphire AFBG at 1100°C.

Performance in Gamma Radiation

Prototype sensing systems with fused silica and single crystal sapphire AFBG sensors were fully integrated and installed in the gamma irradiator at ORNL. The fused silica sensor was exposed to approximately 70 Gy/h gamma radiation at room temperature and continually operated, unattended for 3550 hours, as shown in Figure 4. The AFBG performance was benchmarked against two OFBGs inscribed in a "Super RadHard" single-mode fiber provided by Prysmian Group. The AFBG co-located with the OFBG in the irradiator showed a similar trend of initial central wavelength drift and subsequent stabilization for the duration of the test.

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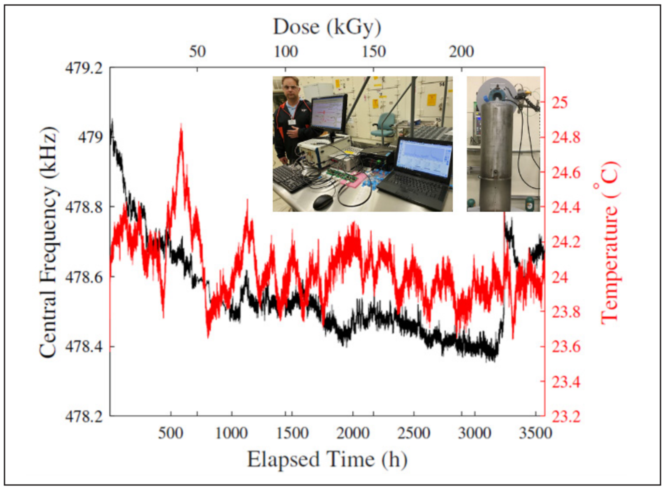

Figure 4. F The AFBG central frequency over time upon gamma radiation exposure. (Inset) AFBG and OFBG sensors and interrogation systems installed at ORNL.

A currently tested prototypic single crystal sapphire AFBG, has been continually exposed to similar conditions at ORNL for over 2300 hours, as shown in Figure 5. Excellent sensor stability, comparable to the single crystal sapphire OFBG, has been observed for the duration of the test. The results of the performance and gamma irradiation testing has demonstrated the potential for acoustics-based sensing to supplant optical fiber-based technologies in selected applications.

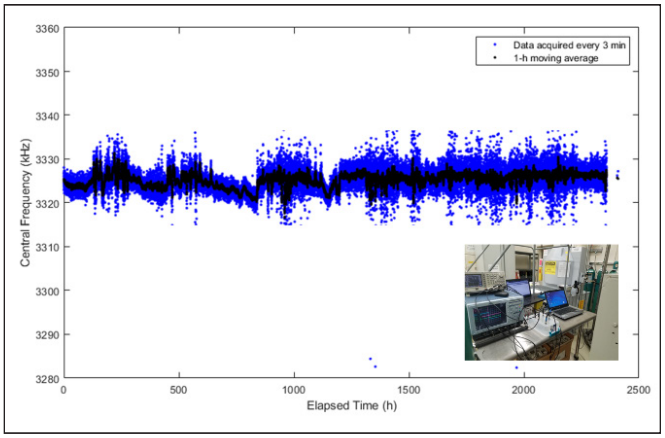

Figure 5. Stability of single crystal sapphire AFBG currently under gamma radiation exposure at ORNL. (Inset) AFBG and OFBG sensors interrogation systems installed at ORNL.

Technological Readiness and Next Steps

The early stage research conducted in this program is set to advance the AFBG technology from a Technology Readiness Level (TRL) = 2 to a TRL = 5. A high-fidelity, laboratory-scale system was constructed and evaluated in simulated environments. To advance the AFBG sensing technology towards commercialization, a specific application(s) must be identified so that the sensor and system components can be designed to meet the environmental and performance specifications. Upon full system integration and qualification, the AFBG sensing platform has the potential to provide end users with a cost-effective alternative to fiber-optic sensors without compromising performance.

Impact and Value to Nuclear Applications

The AFBG technology successfully developed (for the first time) in this program seeks to create a new arena for the development of the next generation of sensor technologies. The low-cost, fully distributed, multiparameter sensing platform has the potential to offer a powerful means for the deployment of distributed fiber sensor arrays for 3D network monitoring solutions in nuclear energy systems.

In addition, the research project provides an environment conducive to the development of graduate students, junior researchers, and faculty. Furthermore, the diverse and multidisciplinary research setting provides both faculty and students with the opportunity to cultivate a broad and diverse skillset that will provide benefit to the nuclear sciences, as well as the overall scientific community.

Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics

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Introduction

The U.S. nuclear power industry has encountered growing difficulties to remain economically competitive in an increasingly challenging energy marketplace, despite its enormous benefits as a baseload, low-carbon emitting source of electricity. For advanced non-light-water reactors to have commercial success and widespread deployment, the costs of construction and operation must be reduced. This project seeks to aid in the optimization of advanced reactor economics by addressing factors during both the design and operational phases of the plant life cycle.

The objective of this research is to improve the economic competitiveness of advanced reactors through the optimization of cost and plant performance, which can be achieved by coupling intelligent online monitoring with asset-management decision-making. As advanced reactors are early in the development life cycle, online monitoring systems and associated sensor networks can be incorporated directly into the design without constraints related to retrofitting and system upgrades. At the same time, due to their innovative designs and lack of operating experience, advanced reactors have large uncertainties regarding component reliability, potential failure modes, and long-term maintenance needs. Therefore, it is necessary to develop an online monitoring system that is capable of multifaceted plant performance cost-benefit analyses, which is both flexible and robust to tolerate operational uncertainties.

For this project, there are two development steps to optimize advanced reactor operation and asset management using online monitoring and diagnostics. First, during the reactor design phase, it is necessary to develop a sensor network that can properly monitor and diagnose important faults and component degradation throughout the lifetime of the plant, which can be difficult given the lack of operational experience and the associated costs regarding sensor deployment. Second, once reactor operation begins, the asset-management approach must seamlessly integrate online monitoring information and the plant's risk profile to optimize the schedule of maintenance interventions and plant operations. The challenges of this step include cost-benefit decision-making in multivariate space while ensuring the plant does not exceed risk or safety limits. To accomplish these goals within the 3-year timeframe of the project, existing tools and methods are leveraged, expanded, and integrated to rapidly construct a comprehensive approach.

Optimized Sensor Network Design

As part of the reactor design process, the desired monitoring capabilities are defined and then the minimum sensor set ensuring such capabilities is established as the result of an optimization process. The Integrated System Failure Analysis (ISFA) method created by The Ohio State University is utilized for this assessment. ISFA is an integrated fault analysis approach capable of analyzing the impacts of the components' faults in the system design stage without operating experience [1]. It can generate the paths on which faults will propagate based on a structured system representation, deducing the states of functions of each component in every path, and calculating the input and output signals for each component and related functions.

Figure 1 shows the structure and critical elements of the ISFA method, which models the system from two perspectives: the component perspective and the function perspective. From the component perspective, the configuration flow graph is used to represent the system structure, and the component diagram from the Unified Modeling Language (UML) represents the structure of

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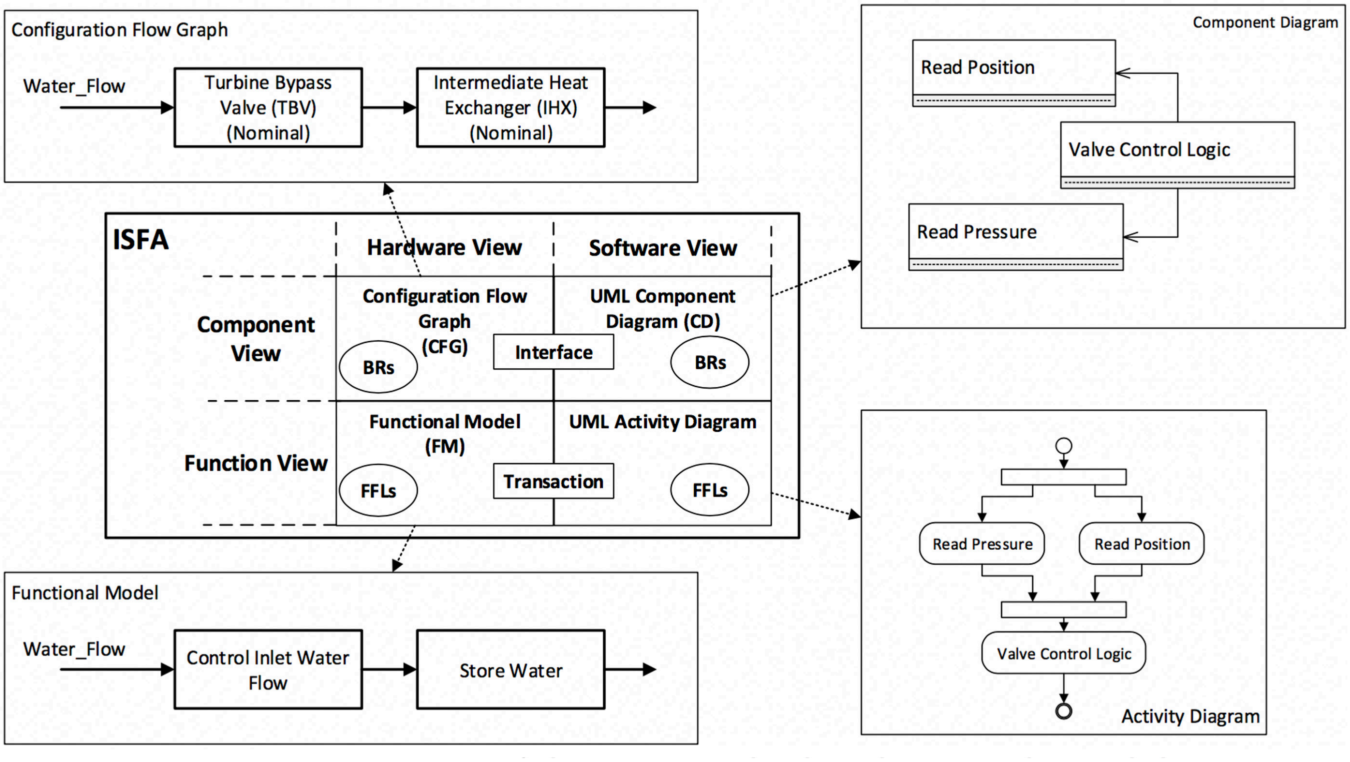

Figure 1. Structure of the ISFA method with example models.

software subsystems. ISFA defines interfaces used to represent the interaction between software and hardware components. From the function perspective, a functional model, consisting of function blocks and their links, is used as a standard to define functions and their relations to all hardware components. For software function modeling, ISFA uses activity diagrams from UML models of the software design to describe the working flow of software components. ISFA defines transactions to bridge the models for hardware and software. From the component perspective, qualitative behavioral models are defined for each component and are depicted as behavioral rules, including discrete nominal and faulty behaviors.

ISFA can be used to optimize sensor network design for fault diagnosis of complex systems based on different economic optimization criteria (such as number of sensors, etc.) [2]. The efficiency of the ISFA method is vital, as the system-level approach to sensor network design can yield many options. As part of the overarching process developed for the current project, the optimized sensor network obtained by ISFA is integrated into the advanced reactor design prior to construction.

Real-Time Asset-Management Decision-Making

Once reactor operation begins, the Argonne tool PRO-AID (Parameter-Free Reasoning Operator for Automated, Identification and Diagnosis) utilizes the developed sensor network for online monitoring and diagnosis of system conditions. PRO-AID is a powerful tool capable of automating the diagnosis of both slow component degradation and abrupt faults, as it uses data-driven models coupled with conservation laws. Major PRO-AID development efforts are underway as part of parallel Nuclear Energy Enabling Technology projects, while the current effort focuses on incorporating PRO-AID into the integral analysis approach.

The diagnostic information provided by PRO-AID is essential for creating a holistic view of enterprise risk of the facility during operation, which is necessary for real-time asset-management decision-making. For an operating plant, the risk profile includes safety considerations, which are evaluated through the probabilistic risk assessment (PRA), and productivity concerns, which are gauged through the use of a generation risk assessment (GRA).

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Through an integrated analysis between PRO-AID and the plant PRA/GRA, a real-time risk profile is developed that accurately depicts the evolving status of plant components and systems.

By utilizing the real-time plant risk profile, different asset-management strategies can be compared and the available actions can be optimized on plant economic performance, while also ensuring that all safety limits and regulatory criteria are successfully satisfied. This complex decision process utilizes the artificial intelligence method of Markov Decision Processes (MDPs) to efficiently select an action pathway that balances plant uptime, component maintenance, and supply chain issues.

Progress and Next Steps

The project is currently approaching the halfway point of the 3-year timeline. Completed tasks have focused on the integration of the various tools and methods, while also expanding capabilities as necessary. A method was established to validate that the sensor network developed by ISFA can be fully leveraged by the online monitoring and diagnostic tool PRO-AID. Also, through a combination of Bayesian updating and Markov component modeling, a technique was devised to directly integrate the diagnostic feedback from PRO-AID into the component models within the plant risk profile. The ISFA sensor network design approach is being expanded to increase analysis flexibility, as a necessary step for addressing uncertainties related to advanced reactor operation. Lastly, asset-management tools and techniques from the industry partner, Framatome, are currently being evaluated to determine how the real-time plant risk profile and utilization of MDPs can be integrated into decision analyses.

As the analysis methods and tools are finalized, the final year of the project will focus on a demonstration analysis using a high-temperature gas-cooled reactor design (HTGR). The goal of the demonstration analysis is to provide a practical, real-world example of the developed method, from design of the sensor network to online monitoring during operation and finally asset-management decisions. Based on the experience gained during the demonstration analysis, pathways for further technology-readiness level improvement or direct commercialization will be explored by the project team.

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Development of a Radiation Endurance Ultrasonic Transducer for Nuclear Reactors

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Introduction

New sensors and nondestructive evaluation (NDE) techniques are in considerable demand in locations where the ambient environment is harsh, such as in a nuclear reactor. The sensors used in such conditions and environments are generally subjected to high temperatures and extreme radiation levels. Some common applications where resilient sensors are desired due to substantial radiation fields include periodic inspections of nuclear reactor components, and continuous monitoring of potential leakage sites on irradiated fuel assemblies. The development of such sensing technologies and instrumentations is necessary to advance plant control, data analytics, and other nuclear applications. However, development of such sensors and instrumentations appropriate for deployment in radiation fields is challenging due to the radiation field itself. The presence of a radiation field raises the possibility of degradation or even complete failure of the sensor and instruments [1, 2]. Much has been written about the effects of gamma radiation (and combined neutron and gamma radiation) on individual materials used in sensors and their components, such as the piezoelectric element in ultrasonic transducers used in NDE and structural health monitoring (SHM) [3, 4, 5, 6]. However, there is little literature regarding the precise failure mechanisms and projected lifetimes of entire sensor assemblies [1]. Most of the literature on this topic tends to be in the form of isolated observations under unique operating conditions of various types of sensors and sensor materials. The limited extent of these studies makes it difficult to get an overall picture of the expected lifetime reduction of such systems as a function of radiation dosage. Additionally, some of the relevant data have never been published in the open literature, but have been acquired through operational experience and recorded as internal information at nuclear power plants or research facilities. There is constant demand for technologically advanced sensors, which can help run nuclear systems more reliably, by directly supporting improvements and advancement of sensors and instrumentations used in existing power reactors, material test reactors, and other similar systems. The desired technology should demonstrate greater accuracy, reliability, resilience, and ease of replacement and upgrades for applications in nuclear environments.

Objective

Ultrasonic sensing technologies are widely used for nondestructive testing (NDT) and SHM. Ultrasonic transducers are used to form physical sensors enabling measurement of a multitude of attributes, such as temperatures, pressures, and flow rates, to name a few. A major advantage of ultrasonic technology is that the sensors can be built using materials such as metals or ceramics, which are either already allowed for use in nuclear environments or present less susceptibility to damage in environments similar to that

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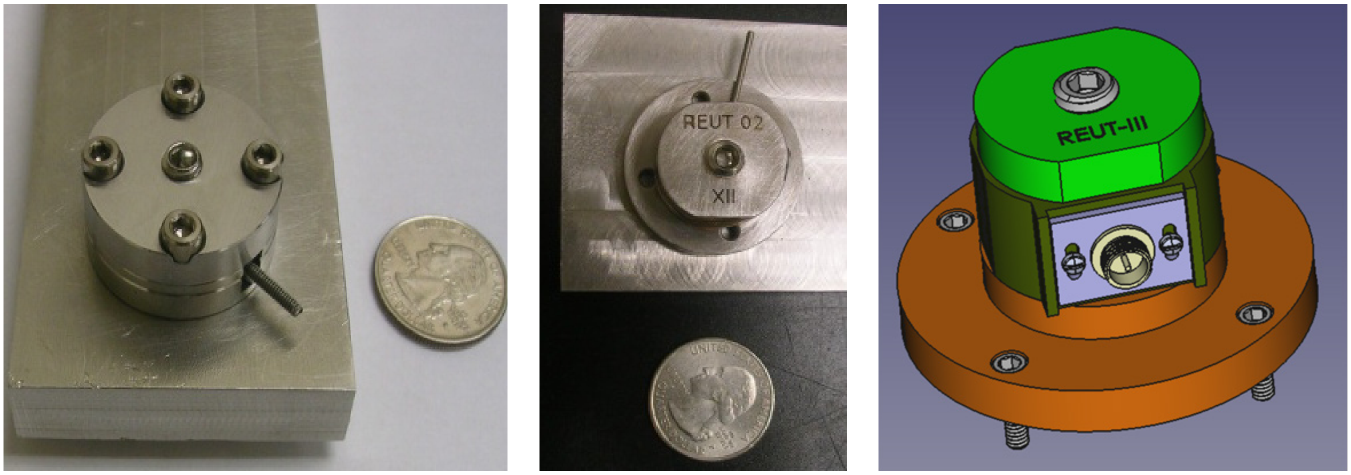

Figure 1. REUT - radiation endurance ultrasonic transducers prototype, (left) Version 1, (middle) Version 2, and (right) CAD model of Version 3.

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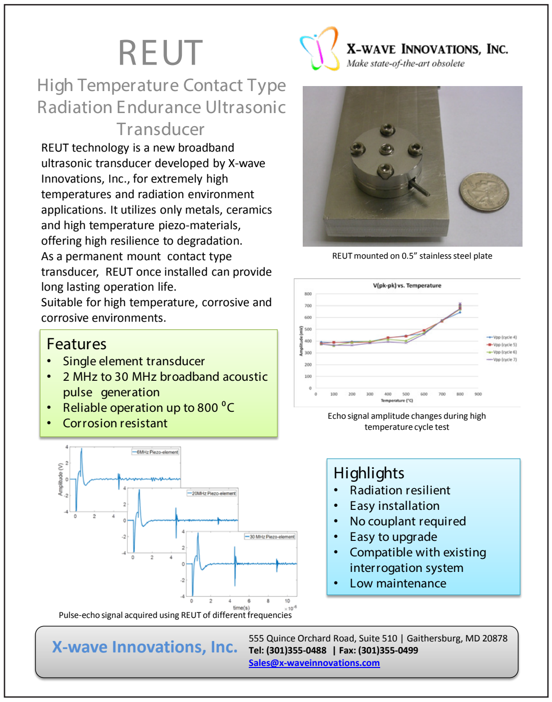
in the core of nuclear reactors. However, development of ultrasonic transducers suitable for survival and operation in harsh environments is a challenging task. X-wave Innovations, Inc. (XII) is developing ultrasonic transducers and sensor systems, which can operate in extreme conditions with long operational life.

The United States Department of Energy Small Business Innovation Research (DOE-SBIR) Phase I award DE SC0020019 aimed to develop radiation endurance ultrasonic transducers (REUT) with the capability to sustain and operate in extreme conditions. In Figure 1, the first two REUT prototypes developed in Phase I are shown, and performances of both these transducers have been tested up to 800°C. Now in the Phase II of this project, XII is modifying the REUT design and developing ultrasonic sensor systems utilizing the REUT design to support development of advanced sensors and instrumentations for nuclear environments. Figure 1 also shows the REUT CAD model of Version 3, with a standard microdot connector for establishing electrical connections.

Current Status

The REUT prototype developed in Phase I is made from materials such as stainless steel 316, ceramics (zirconia and alumina), and radiation-tolerant $LiNbO_3$ piezoelectric substrate. The fabrication and installation of REUT does not require any carbon-based materials and binders, which can potentially fail in a nuclear environment, thus offering long-term operation in extreme conditions. The REUT product brochure is shown in Figure 2 and lists the technical specifications of the REUT.



REUT

High Temperature Contact Type Radiation Endurance Ultrasonic Transducer

X-WAVE INNOVATIONS, INC.
Make state-of-the-art obsolete

REUT technology is a new broadband ultrasonic transducer developed by X-wave Innovations, Inc., for extremely high temperatures and radiation environment applications. It utilizes only metals, ceramics and high temperature piezo-materials, offering high resilience to degradation.
As a permanent mount contact type transducer, REUT once installed can provide long lasting operation life.
Suitable for high temperature, corrosive and corrosive environments.

REUT mounted on 0.5" stainless steel plate

Features
- Single element transducer
- 2 MHz to 30 MHz broadband acoustic pulse generation
- Reliable operation up to 800 °C
- Corrosion resistant

Echo signal amplitude changes during high temperature cycle test

Pulse-echo signal acquired using REUT of different frequencies

Highlights
- Radiation resilient
- Easy installation
- No couplant required
- Easy to upgrade
- Compatible with existing interrogation system
- Low maintenance

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Figure 2. REUT brochure.

The REUT presented here is a contact-type ultrasonic transducer, where desired acoustic properties are user configurable, which is easy to install and requires zero to no maintenance. The REUT housing design takes into account the thermal expansion of all constituent components and delivers transducer performance that improves at elevated temperatures, in contrast to commercially available off-the-shelf transducers where performance tends to degrade at elevated temperatures. The REUT operational life is limited only by the choice of materials used in its fabrication, such as the Curie temperature of the piezoelectric element and operational limit of stainless steel. With proper choice of materials in the fabrication of REUT and its piezoelectric element, the REUT offers the opportunity to advance all types of ultrasonic sensor systems designed for nuclear environments and other extreme conditions by extending their operational life.

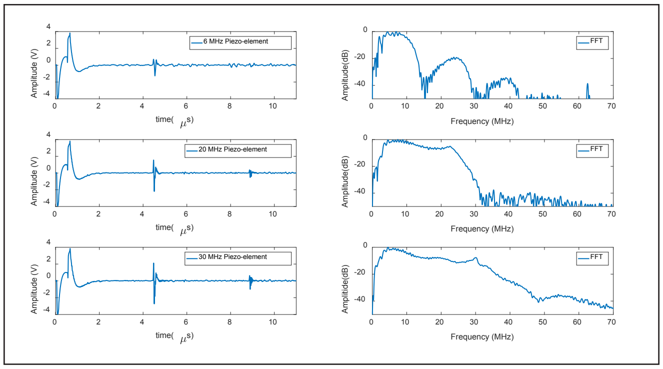

Figure 3. The pulse/echo signal captured with (left) different piezoelectric elements and (right) respect FFT of echo signals.

The acoustic property of REUT is easily configurable by changing the piezoelectric element before installation. In Figure 3, the pulse-echo signal captured using REUT having different piezoelectric elements and their respective Fast Fourier Transform (FFT) of the echo signals is shown. Z-cut LiNbO3 piezoelements coated with Cr/Au thin film on both sides and having thicknesses 0.5 mm, 0.2 mm, and 0.1 mm are employed to generate acoustic pulse signal of center frequency 6 MHz, 18 MHz, and 30 MHz, respectively. The REUT developed is a broadband transducer with bandwidth reaching up to 30 MHz.

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REUT performance has been tested at elevated temperatures reaching up to 1100°C. In Figure 4, REUT performance up to 800°C is shown. Performance of REUT with 0.5-mm z-cut LiNbO3 shows no degradation; rather, it improves at higher temperatures up to 800°C. Performances have been tested for seven thermal cycles, by repeatedly increasing the temperature from ambient conditions to 800°C and allowing it to cool at a natural cooling rate. No performance degradation has been observed so far. On further increasing the temperature beyond 900°C, the acoustic response starts to degrade due to the temperature reaching the Curie temperature of LiNbO3, and at 1100°C the acoustic response entirely vanishes, irreversibly. After observing this failure, the REUT was brought to room temperature and a new piezoelectric element was installed, after simple sand paper cleaning. After this exercise, the REUT continued to perform, thus supporting our claim that REUT operation is limited only by the choice of materials and its maintenance is easy if REUT suffers any failure. The REUT was also subjected to a 200-hour corrosion test in boric acid solution and showed changes in performance.

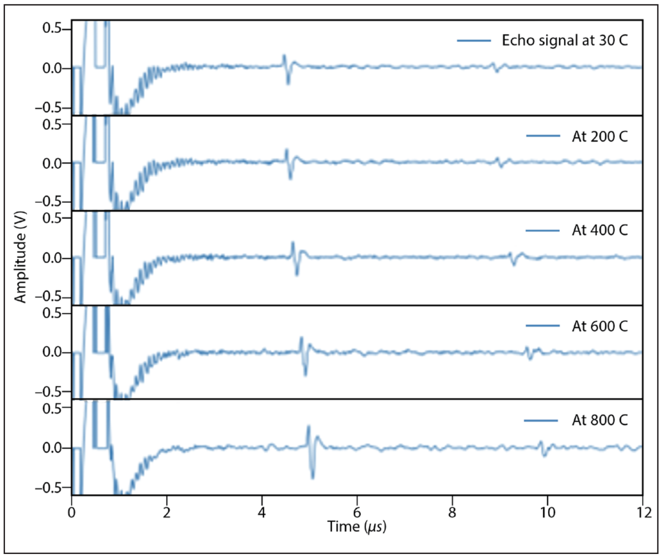

Figure 4. The pulse/echo signal captured at higher temperatures.

Path Forward

Presently, XII is in a process of further improving the REUT design. We are implementing modifications to enable wireless interrogation. We are also engaged in developing following sensor technology for nuclear reactors using our REUT:

- Temperature sensor
- Pressure sensor
- Flow rate sensor
- Acoustic emission sensor.

To further support our claim that REUT can operate in extreme radiation conditions, we are planning to use Nuclear Reactor Laboratory facility at the Massachusetts Institute of Technology to irradiate REUT at high temperatures in conditions similar to those in a nuclear reactor core. We are planning to perform in-situ measurements to demonstrate that REUT cannot only have high endurance to extreme radiation but can also continuously perform in such conditions.

Conclusion

Development of ultrasonic sensors based on REUT technology will provide an option of long-term SHM and sensing physical properties using ultrasonic techniques. REUT is simply a better ultrasonic transducer design which can provide long operational life to all types of ultrasonic sensors and ultrasonic technologies, to operate in harsh environments such as within nuclear reactors.

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