Advanced Sensors and Instrumentation

Issue 10 • March 2019

Program Update

Suibel Schuppner
U.S. Department of Energy

The Advanced Sensors and Instrumentation (ASI) program, on its seventh fiscal year, continues to address key technology gaps for future nuclear energy systems. ASI's goal is 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 its mission goals. Information on our projects can be found in our ASI annual awards summaries, annual review webinars, and newsletters posted at the Office of Nuclear Energy website (energy.gov/ne).

This year, we have initiated three newly awarded projects in the area of data analytics. We also initiated a project to develop and demonstrate a prototype passive wireless sensor network. This sensor will use advanced manufacturing and printing, and will be tested and demonstrated at a U.S. nuclear power plant facility. In addition, we are developing a sensor database to capture advanced sensor and instrumentation technology that is applicable to nuclear power plants.

Under the In-Pile Instrumentation program, we continue to develop unique in-pile sensors and instrumentation to provide real-time, accurate, and spatially resolved information regarding the performance of fuels and materials. Due to the closure of the Halden reactor, we are focusing our near-term research in providing equivalent capability for the instrumentation of irradiation experiments in the U.S. that are needed by the nuclear industry.

We had the opportunity to share our research with the nuclear I&C community during the American Nuclear Society's 11th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC & HMIT) held on February 10-14, 2019. We had sessions on the ASI current awards and the In-Pile projects, which were well attended and provided a great opportunity for questions, feedback, and discussion.

As the ASI program continues to award projects through competitive solicitations, we encourage the I&C community to visit our website for the current funding opportunity announcements—especially for the industry-focused solicitation entitled, "U.S. Industry Opportunities for Advanced Nuclear Technology Development."

In this issue...

For more program information, including recent publications, please visit www.energy.gov/ne

U.S. DEPARTMENT OF ENERGY

An Optical Waveguide Temperature Sensor for Nuclear Facilities

Maria Mitkova
Boise State University

Harish Subbaraman
Boise State University

All components inside nuclear reactors are exposed to extreme conditions, which include high temperatures, high-radiation doses, and corrosive agents. Precise monitoring of a reactor environment is critical for its stability and proper functionality over its operational lifetime. Real-time monitoring is required to observe material performance (i.e., microstructure, chemistry, mechanical, and other property changes with changing conditions) during exposure to the reactor environment. Several supporting experiments are measuring cladding conditions and temperatures inside nuclear reactors. Widely used melt-wire techniques provide a reasonable estimate of temperatures; however, it does not deliver this information in real-time. Thermocouples are another standard thermometry tool used to measure outer and inner cladding and internal fuel temperature. However, their performance degrades in a radiation environment due to the harsh conditions inherent therein. As such, the nuclear power industry presently faces significant challenges for achieving the real-time determination of in-pile temperatures.

Project Objectives

The project is focused on the development of a new real-time, reusable, and reversible sensor concept for cohesive temperature monitoring. The device design integrates the photonic properties of ultra-compact silicon waveguides and the phase change properties of chalcogenide glasses in a single platform to enable monitoring of the cladding temperature of Light Water Reactors and metallic or ceramic Sodium-cooled Fast Reactors within a temperature range of 400°C to 650°C. This project helps advance NEET crosscutting program goals for innovative research that directly supports and enables the development of new, next-generation reactors and fuel cycle technologies.

The Goals

To meet the project objectives, we devised the following interrelated goals:

1. Synthesize a suite of chalcogenide glasses, characterize them with their thermal and optical properties, and determine the correlation between structure and performance for optimizing the materials for the temperature sensor.
2. Simulate the plasmonic effects for establishing device architecture.
3. Apply additive technology for printing chalcogenides on silicon waveguides, developing chalcogenide glass ink, and optimizing the printing method and films quality.
4. Demonstrate proof-of-concept devices based on the waveguides and radiation hardened optical fibers.

The Method

Device performance is based on the fact that when chalcogenide glasses are in their amorphous phase, they behave like dielectrics with very low absorption loss in near-infrared light. In this configuration, the fundamental quasi-transverse electric mode is confined within the silicon waveguide. When the temperature increases and reaches the crystallization temperature of the chalcogenide materials, the chalcogenides undergo a phase transformation to material with high conductivity. The presence of a conductor on top of silicon waveguide leads to large plasmonic mode propagation losses [1]. In this configuration, the fundamental quasi-transverse mode disappears and tightly confined plasmonic modes appear at the interface between the silicon and the conductive material.

The Material

Chalcogenide glasses are materials that include elements from group 16 of the Periodic Table (S, Se, and Te) and their combinations with elements from groups 14 and 15. We synthesized glasses from the Ge-Se and Ge-S systems, as well as ternary glasses Ge-Sn-Se, some of which have several crystallization temperatures, allowing for the monitoring of multiple temperatures. We chose these materials as an active medium of the temperature sensors because they possess crystallization temperatures in the region of interest for the project and are radiation hardened. The lack of order in the chalcogenide glasses and the presence of lone pair *p*-shell electrons are the reasons behind the radiation hardness and the unique electrical and optical properties of these materials. They have band tail states and localized states that pin the

Continued on next page

Continued from previous page

Fermi level independently of surrounding radiation in the middle of the bandgap [2]. As the temperature increases, the glasses' viscosity also increases until it crystallizes. This phase transition is characterized with a drastic change among the others of their extinction coefficient, as presented in Figure 1, as well as their refractive index and absorption coefficient. By the application of a short electrical pulse that melts the material, it can be reversed back to its initial amorphous condition, allowing for the re-use of devices.

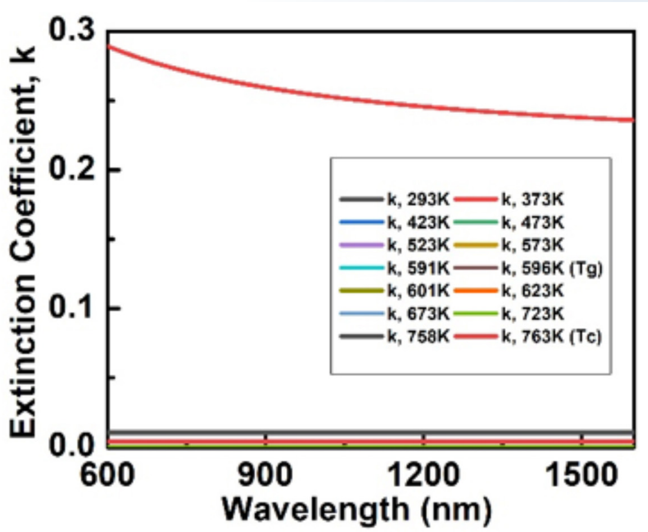


Figure 1. Temperature dependence of the extinction coefficient of a thin $Ge_{40}Se_{60}$ film.

Assessment Methodology

Owing to their fabrication compatibility with CMOS technology, silicon waveguides simplify fabrication of our temperature sensors. This low-cost technology, coupled with the temperature sensitivity of chalcogenide glasses, leads to an effective device structure allowing for temperature measurement and reversibility combined with radiation hardness. Thus, these unique properties of chalcogenide glasses, together with the excellent light-guiding properties of silicon waveguides, are exploited in the design and development of a multiple time-use, high-accurate and high-sensitive temperature sensor.

A schematic of our proposed novel high-temperature sensor is shown in Figure 2. Optimized design parameters for operation at the 1550 nm wavelength are shown in Table I.

We represent a Si/Ge-S system in our design. In this structure, chalcogenide glass acts as a top cladding to the single mode Si waveguide. It is covered by a SiO_2 passivation layer that protects the film from environmental effects. We studied the behavior of fundamental transverse magnetic mode propagating along a single mode silicon waveguide.

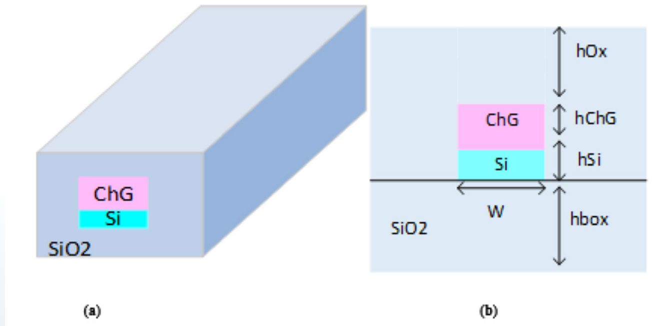


Figure 2. a) 3D view, b) Cross section of proposed temperature sensor.

Material	Refractive index (n)	Extinction coefficient (k)
Chalogenide (ChG)-(amorphous)	2.45	0.10
Chacogenide (ChG)-(crystalline)	3.39	0.17
Si	3.47	0
SiO_2	1.45	0

Table I. Refractive index and optimum design parameters.

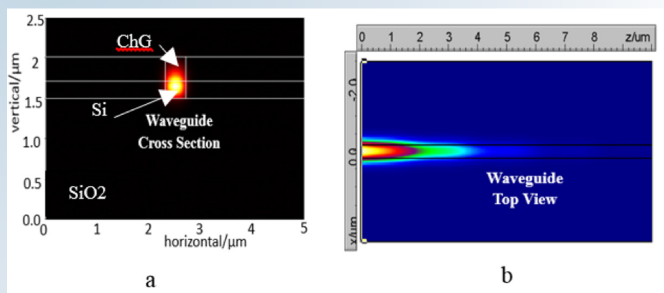


Figure 3. Amorphous phase, a) Cross section view, intensity profile of TM mode, b) Top view, intensity distribution along the waveguide.

In the amorphous state (i.e., when the temperature is below the phase transition temperature and n_{ChG} is set to n_{amor}), the fundamental transverse magnetic mode is confined near the interface of Si and chalcogenide glass, but primarily is present within the silicon waveguide. This mode propagates along the waveguide with minimum loss, as shown in Figure 3.

As the temperature increases beyond the phase transition/crystallization temperature, chalcogenide glass exhibits conductive characteristics, n_{ChG} is set to n_{cryst}. In this case, a surface plasmonic wave at the Si-chalcogenide glass

Continued on next page

Continued from previous page

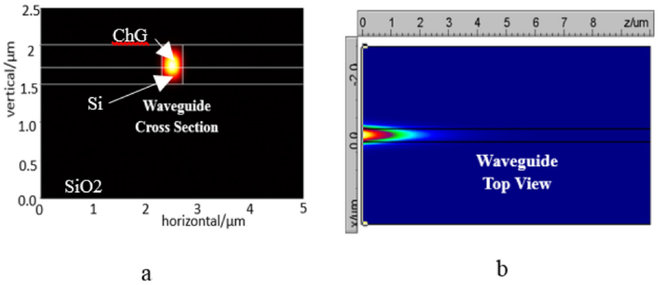


Figure 4. Crystalline phase, a) Cross section, intensity profile of TM mode, b) Top view, intensity distribution along the waveguide.

interface is excited. Then the fundamental transverse magnetic mode disappears and a surface plasmon mode confined at the interface between silicon and conductive chalcogenide glass, as shown in Figure 4, is generated [3]. Such surface plasmons are characterized by very high transmission losses.

The calculated extinction ratio, which describes the output power in amorphous phase to output power in crystalline phase of chalcogenide material, is 70 dB within a short length of the waveguide (<22 µm). Therefore, this makes the sensor extremely compact and easier to embed or deploy.

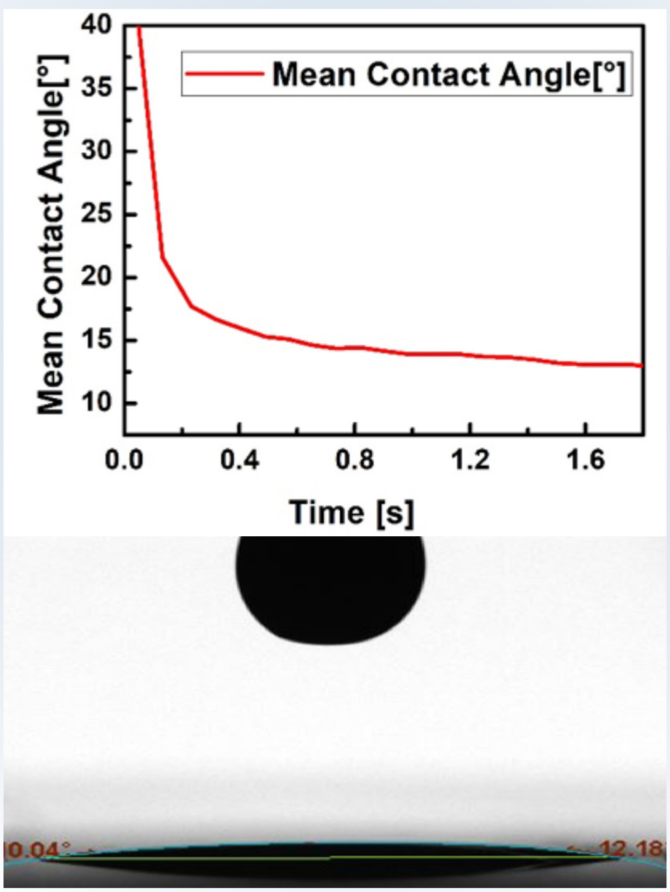


Figure 5. Contact angle measurement of $Ge_{20}Se_{80}$ 100 nm particle ink suspended in alcohol on Si substrate and demonstration of the contact angle.

Finally, integrating an array of the designed waveguide with chalcogenide glass compositions, with different specific crystallization temperatures, allows for accurate real-time determination of the temperature profile inside nuclear reactors.

Chalcogenide Glass Inks Formation

Additive technology for devices printing applying ink on monitored surfaces offers many advantages and we plan to apply it to get the best results possible. Two ink formulation techniques were developed specifically for this project: (1) ink formulation through glass dissolution in basic solutions; and (2) milling of the glassy material to ≤ 100 nm-sized particles that were mixed with surfactants to keep the ink viscosity and surface properties within a range compatible with the print heads. An example of the contact angle of this ink is shown in Figure 5.

Impact and Value to Nuclear Applications

In the first year of our research, we paved the way to the successful development of a low-cost, Si-chalcogenide glass-based hybrid plasmonic waveguide for use as a real-time temperature monitoring device inside nuclear facilities. Through exploiting the significant optical property changes of chalcogenide glasses around the phase transition temperature, an ultra-compact temperature sensor with a very high extinction ratio is achievable. The real-time temperature monitoring inside the nuclear facilities is determined by following the output power from a waveguide array coated with different chalcogenide glass compositions. The ability to revert back to the original phase through the application of an electric field in chalcogenide glass facilitates multiple time use of the sensors. In this way, we will advance resolving some of the existing issues of temperature monitoring in nuclear facilities.

Plan Forward

Our future work will be primarily related to the optimization of the ink technology for application in additive technology and device parameters. We will experiment with the technology on Si waveguides, as well as on optical fibers with respect of direct requirements from the nuclear facility for which this technology was developed and progress it further to make it more universal for complex applications in the nuclear industry.

References

[1] H. Subbaraman, X. Xu, A. Hosseini, X. Zhang, Y. Zhang, D. Kwong, and R. T. Chen, "Recent advances in silicon-based passive and active optical interconnects," Opt. Express, vol. 23, no. 3, pp. 2487–2511, 2015.

[2] K. Tanaka and K. Shimakawa, Amorphous Chalcogenide Semiconductors and Related Materials. Springer Science & Business Media, 2011.

[3] J. A. Schuller, E. S. Barnard, W. Cai, Y. C. Jun, J. S. White, and M. L. Brongersma, "Plasmonics for extreme light concentration and manipulation," Nat. Mater., vol. 9, no. 3, pp. 193–204, 2010.

How can we see damage that's unseen in nuclear power plant pipes?

Douglas E. Adams
Vanderbilt University

The Light Water Reactor Sustainability program is performing research to extend the life of commercial light water reactors beyond their current 60-year licensing periods. One area of intense work deals with developing and deploying online monitoring systems that can assist operators to reduce their high maintenance costs and avoid potential plant outages. For example, pressure vessels and piping used in cooling systems are tremendously challenging and costly to maintain in today's nuclear power plants. Upkeep of these cooling systems will also pose similar challenges for new small modular reactor designs in next generation nuclear power plants.

Degradation in the piping networks that comprise cooling systems in nuclear power plants is often associated with some sort of corrosion process, such as flow-accelerated corrosion. Tens-of-miles of piping must be inspected in each power plant, and the vast majority of these inspections are conducted visually. Unfortunately, early stage corrosion cannot be visually detected from the outside of a pipe. There are a few techniques available such as ultrasonic and radiography testing for detecting degradation inside of piping structures, but these techniques are time-intensive due to their highly localized nature, cannot detect early stage corrosion, and are not implemented during operation.

To address this need for monitoring of piping structures in current and future nuclear power plants, our team of researchers is developing a network of sensors for detecting the chemical and mechanical changes that occur inside pipes as they corrode. To detect the earliest stages of corrosion and help plant operators make timely decisions, we have developed a sensing approach that monitors the inside of a pipe for chemical reactions that drive corrosion. We then monitor the outside surface of the pipe to track changes in the material using an optical sensor that will pinpoint where corrosion is occurring to assist operators with their inspections. Our team—comprising Vanderbilt University, the University of Notre Dame, and Idaho National Laboratory—is using a representative cooling circuit testbed to experiment with these sensing networks in operation in order to demonstrate the online monitoring approach. The overall research approach is illustrated in Figure 1 and the circuit testbed is pictured in Figure 2.

The four interrelated research goals of the project are to:

1. Develop a smart film on the inside of the pipe that can detect early-stage corrosion and monitor the rate of the corrosive process.

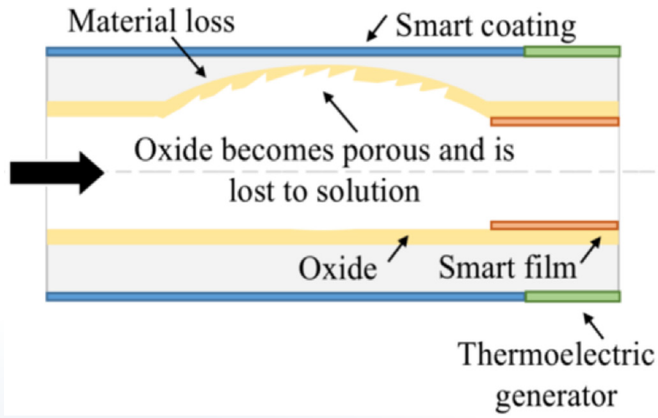
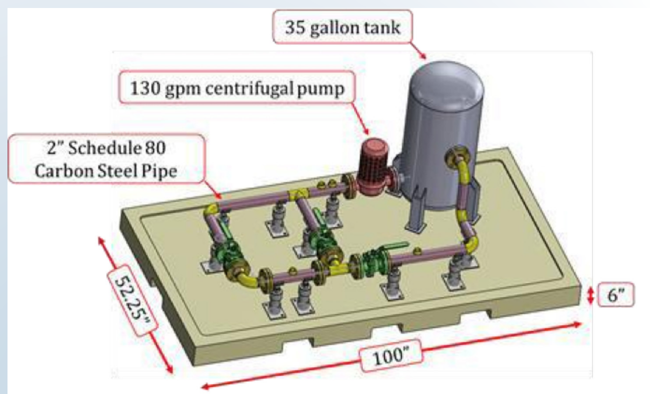


Figure 1. Overall research strategy comprising a smart film for detecting and monitoring corrosion processes on the inside of the pipe, a smart coating for monitoring changes in the pipe due to corrosion, and a thermoelectric generator for powering the sensing network.



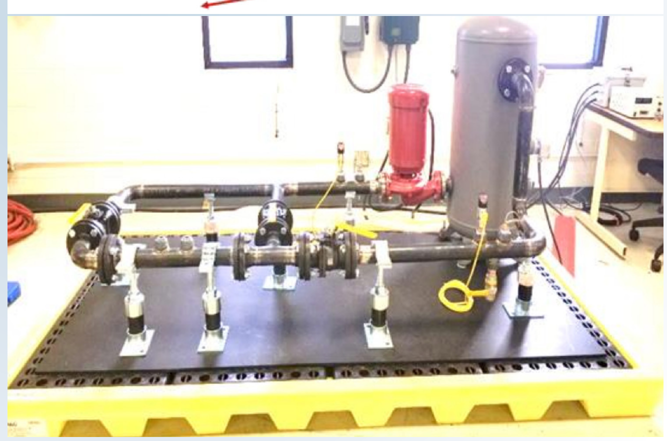


Figure 2. Cooling circuit testbed rendering (left) and fabricated (right) for experimenting with the proposed sensing approaches. This testbed design was developed along with Idaho National Laboratory to be representative of nuclear power plant secondary cooling circuits while allowing for experimentation with corroded pipe fittings.

Continued on next page

Continued from previous page

2. Monitor changes in the pipe material due to corrosion using a sensing network on the outside surface of the pipe.
3. Provide power for the sensor network by applying thermoelectric materials on the surface of the pipe to convert thermal energy into electric energy.
4. Optimize the design and placement of the sensor network using Bayesian statistical analysis techniques to support maintenance decision-making.

In the first year, we made progress on the first three of these goals. Some of the insights we have achieved in this work are summarized below. These results are documented in three journal articles that have been submitted for review to *Material Horizons*, *Langmuir*, and *Nature Communications*. Two of our PhD students, Mr. Cole Brubaker in Civil Engineering and Mr. Xuanli Deng in Chemical Engineering, recently defended their PhD dissertations successfully. Two of our undergraduate students who are earning their Masters of Science degrees in engineering while working on the project, Ms. Kailey Newcome from Civil Engineering and Mr. Thomas Stilson from Mechanical Engineering, also presented their findings in research symposia that were held at Vanderbilt University.

This year, our team developed a novel polymer thin film chemistry to deposit a "smart film" sensor that detects the onset of the metal corrosion process. The smart film works by capturing particles that are produced as the metal corrodes and oxidizes. We use ring opening metathesis polymerization to create a film that is then exposed to hydroxylamine. This process produces a film that selectively captures metal cations that are released in the initial stages of the corrosion process. We developed insights about how this film senses these metal cations using various ways to characterize the film once it captures the ions.

As an initial test of the smart film's sensing capability, we placed the film a half millimeter above a carbon steel working electrode that was biased with a 300 mV potential for three minutes to drive corrosion.

The onset of corrosion is seen both visually as the surface becomes slightly discolored and via metal capture by the smart film. As Figure 3 shows, the ex situ infrared spectroscopy measurement indicates that the film has captured corrosion products that would otherwise be lost in the solution in the earliest stages of corrosion. As we increased the voltage applied to the steel electrode, we captured more metal cations indicating worsening degradation due to corrosion. These results demonstrate that the smart film can be used to capture various divalent metal ions from the beginning of the corrosion process.

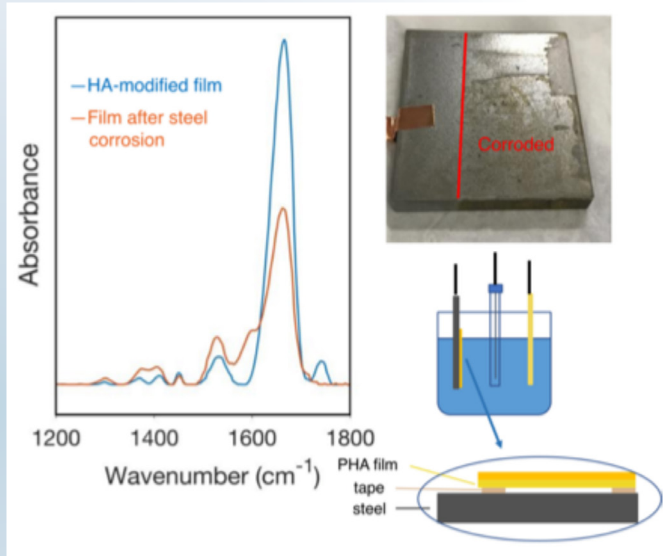


Figure 3. Infrared spectrum (left) that shows metal ion capture in a smart film that was affixed to a carbon steel specimen (right, top) and exposed to a 300 mV overpotential for 3 minutes. The layout of the electrochemical experiment is shown in the bottom right.

We also progressed in developing a thermoelectric power harvester by printing multiple layers of ink that was nano-engineered to maximize the conversion of thermal to electrical energy. The performance of the thermal power harvesters were tested by measuring the power factor and power density of a printed device. The process used to fabricate these power harvesting devices is illustrated in Figure 4.

The next step in our research is to fully develop and integrate the optical sensing approach onto the surface of the pipe so that the changes registered in the smart film due to corrosion on the inside of the pipe can be visually detected from the outside of the pipe. The sensor network will also be analyzed using Bayesian statistical techniques to optimize the layout of the sensors and power harvesters. We want to gratefully acknowledge the U.S. Department of Energy through the NEET program for supporting this research and we invite you to contact us if you would like to discuss the work in further detail.

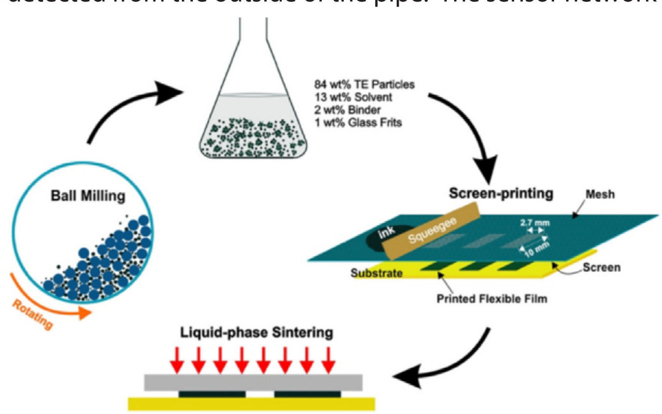
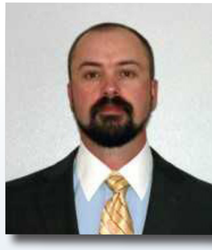


Figure 4. Process of converting nanoparticle ink into a flexible thermoelectric generator using a scalable and low-cost printing and liquid-phase sintering technique.

Development of Ultrasonic Thermometer at INL

Joshua Daw
Idaho National Laboratory

Lance Hone
Idaho National Laboratory



Ultrasonic technologies offer the potential for high accuracy and resolution for in-pile measurement on a range of parameters, including geometry changes, temperature, crack initiation and growth, gas pressure and composition, and microstructural changes. These technologies, which have been successfully performed in out-of-pile tests, have not been well qualified in a test reactor environment. The uncertainty of successful operation of instruments at this level of development has typically been a significant barrier to in-core deployment. Many Department of Energy-Office of Nuclear Energy (DOE-NE) programs are exploring the use of these technologies to provide enhanced sensors for irradiation testing. The first in-core sensor based on ultrasonic technologies targeted for deployment is the ultrasonic thermometer (UT), which can provide a temperature profile in candidate metallic and oxide fuels and would provide much needed data for validating new fuel performance models.

The UT has recently been included in two separate irradiation tests. The first, sponsored by the Nuclear Science User Facilities (NSUF), includes three UTs of different configurations in the Massachusetts Institute of Technology Research Reactor (MITR). The second includes a single UT in an advanced fuel irradiation in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL).

Introduction

DOE-NE programs are investigating new fuels and materials for advanced and existing reactors. A primary objective of such programs is to characterize the irradiation performance of these fuels and materials. Examples of the key temperatures needed to evaluate fuel performance, as well as the desired accuracies and resolutions, are shown in Table I [1]. Similar measurement requirements exist for other parameters (i.e., fission gas pressure). Ultrasonic technologies can be used to measure most of the key parameters of interest, but temperature was selected for initial development, as this is the most common measurement requested of irradiation programs.

	Estimated Peak Value	Desired Accuracy and Spatial Resolution
Fuel Temperature	Ceramic Light Water Reactor (LWR): 1400°C	2% 1-2 cm (axially) 0.5 cm (radially)
	Ceramic Sodium Fast Reactor (SFR): 2600°C	
	Metallic SFR: 1100°C	
	Tristructural-isotropic (TRISO) High Temperature Gas Reactor (HTGR): 1250°C	
Cladding Temperature	Ceramic LWR: <400°C	1-2 cm (axially)
	Ceramic SFR: 650°C	
	Metallic SFR: 650°C	

Table I. Summary of desired fuel measurement parameters for irradiation testing.

Ultrasonic Thermometry

Ultrasonic thermometry has the potential to improve upon temperature sensors currently used for in-pile fuel temperature measurements. Current methods for in-pile temperature detection primarily rely on either thermocouples or post-irradiation examination methods (such as melt-wires). Commercially available thermocouples (e.g., Type K, Type N, Type C, etc.) are widely used and cover a wide temperature range. However, their use is limited. Type K and Type N thermocouples decalibrate at temperatures in excess of 1100°C. Material transmutation causes decalibration in tungsten/rhenium (e.g., Type C) or platinum/rhodium (e.g., Type R or S) thermocouples in neutron radiation environments. Although larger diameter, multi-point thermocouples are available, most thermocouples only measure temperature at a single location. Melt-wires and other post-irradiation methods only allow estimation of maximum test temperatures at the point of installation. The labor and time to remove, examine, and return (if necessary) irradiated samples for each measurement also makes this out-of-pile approach very expensive. Prior ultrasonic thermometry applications have demonstrated the viability of this technology, but in-pile applications were primarily limited to high-temperature fuel damage tests, which ceased several decades ago [2].

Theory of Operation

Waveguide-based UTs work on the principle that the speed at which sound travels through a material (acoustic velocity) is dependent on the temperature of the material. The average acoustic velocity of a material can be

Continued on next page

Continued from previous page

measured by sending an ultrasonic pulse through a thin rod of known length and measuring the time between the initial pulse and the reflection of the pulse from the opposite end of the rod. By introducing acoustic discontinuities, such as notches or sudden diameter changes into the rod, the probe may be segmented into a multiple zone (the average acoustic velocity of each segment derived from timing of the successive reflections). If the ultrasonic waves are non-dispersive (the rod having a diameter of less than one tenth of the signal wavelength [3]), the temperature-dependent acoustic velocity of the sensor material, c(T), is related to density, ρ(T), and elastic modulus, E(T), (both properties are also temperature-dependent) of the sensor material through the following equation:

$$c(T) = \sqrt{\frac{E(T)}{\rho(T)}} \qquad (1)$$

A typical multi-sensor UT system, with key components identified, is shown in Figure 1. As indicated in this figure, a narrow ultrasonic pulse is generated in a magnetostrictive rod by a short duration magnetic field pulse produced by an excitation coil. The ultrasonic pulse propagates to the sensor wire, where a fraction of the pulse energy is reflected at each discontinuity (notches or diameter change). Each reflected pulse is received by the excitation coil, transformed into an electrical signal, amplified and evaluated in a start/stop counter system. The time interval between two adjacent echoes is evaluated and compared to a calibration curve to give the average temperature in the corresponding sensor segment. When a number of notches are available on the wire sensor, the various delay time measurements give access to a temperature profile along the probe.

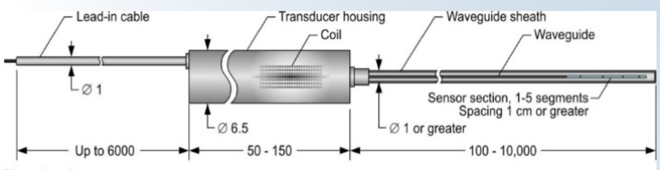


Figure 1. Schematic diagram of magnetostriction-based ultrasonic thermometer.

Irradiation Testing

Until recently, UTs developed at INL were tested at high temperatures in furnace environments (i.e., inert gas or vacuum atmosphere), but not in an irradiation environment. In-core qualification of a new sensor is a necessary step prior to deployment in irradiation test campaigns.

ULTRA

To generate and receive ultrasonic pulses and signals, two of the most commonly used technologies are piezoelectric and magnetostrictive transducers (only the magnetostrictive transducers will be discussed here). The current capabilities of magnetostrictive transducers are typically limited to operation at frequencies up to the order of 100 kHz. However, mechanical coupling and guided wave mode generation makes magnetostrictive transduction ideal for low frequency measurements, such as ultrasonic thermometry [4]. The irradiation behavior of magnetostrictive materials have not previously been studied in-depth, leaving their appropriateness for use in irradiation tests unknown.

An NSUF-funded irradiation, dubbed the ULtrasonic TRAnsducer (ULTRA) irradiation, which was test-lead by Pennsylvania State University and executed at the MITR allowed for long-term irradiation testing of both piezoelectric and magnetostrictive transducers and evaluation of their survival within a high-radiation environment. The magnetostrictive transducer designed for this test was based on research by Lynnworth [5] and Daw [6]. The magnetostrictive transducers consist of a small driving/sensing coil, a biasing magnet, and a magnetostrictive waveguide. The ultrasonic signal is generated when a high-frequency alternating current pulse is driven through the coil. The induced magnetic field causes magnetic domains within the material to oscillate. The domains are pre-biased by the magnet to maximize the response. Received echoes are detected through the reciprocal effect.

The design of the transducers was identical to the UT shown in Figure 1, except the entire waveguide consisted of the magnetostrictive alloy being evaluated.

The magnetostrictive transducer materials were selected based on previous use in radiation environments, amounts of neutron sensitive materials, Curie temperature, and saturation magnetostriction.

1) Remendur

Remendur has the most history of use in nuclear applications of all the magnetostrictive alloys, having been used previously for short duration thermometry applications. Remendur has a high Curie temperature (950°C) and relatively high-saturation magnetostriction (~70 µstrains). Remendur is an alloy composed of approximately 49% iron, 49% cobalt, and 2% vanadium. Because of its cobalt content, Remendur was not considered to be an ideal choice (due to concerns about the production of Cobalt-60 during irradiation). However, its prior successful use was deemed sufficient reason to warrant inclusion.

Continued on next page

Continued from previous page

2) Galfenol

Galfenol is a relatively new alloy of iron and gallium (approximately 13% gallium). Galfenol is a member of the "giant" magnetostrictive alloys and has a very large saturation magnetostriction (100-400 µstrains). It also has an appropriately high Curie temperature (700°C). Neither of its constituent elements react strongly with neutron radiation. These factors made Galfenol a very appealing magnetostrictive material candidate.

Performance of the magnetostrictive transducers was characterized using the normalized magnitude of the Fast Fourier Transform (FFT) of the first reflected acoustic signal (normalized to the time when the reactor first reached full power). The frequency transformed signal is used because it is less sensitive to the interference effects of noise and signal transients.

The Galfenol transducer was stable over the course of the irradiation, though the total peak-to-peak signal amplitude was typically on the order of one third of that observed for Remendur. Figure 2 shows the normalized peak-to-peak amplitude for the Galfenol transducer as a function of accumulated fluence. The green trace shows the reactor power history. The Galfenol transducer shows steady operation during periods when the reactor power level was stable. There is little decrease in the signal strength over these periods. The decreases in signal strength observed when reactor power is increased appear to be due to increases in operating temperature, as the signal strength stabilizes shortly after each power increase.

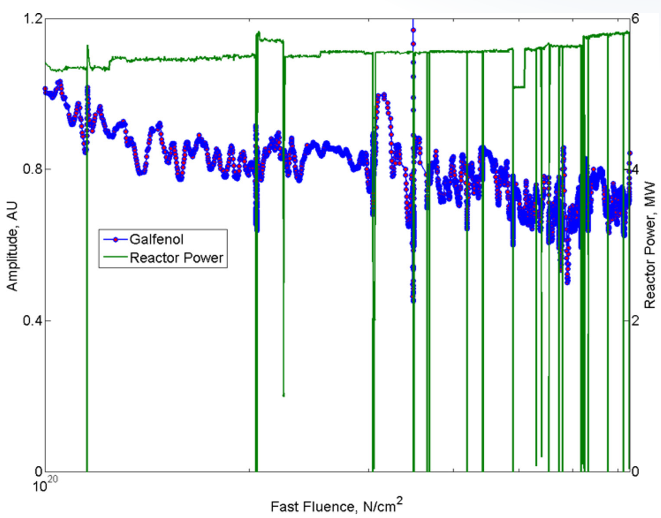


Figure 2. Galfenol element transducer signal amplitude as a function of accumulated fast fluence.

Figure 3 shows the normalized amplitude for the Remendur transducer as a function of accumulated fluence. There is a general decreasing trend, but signal recovery after temperature transients indicate that some of the signal attenuation is due to temperature effects, in this case binding of the wire against the coil bobbin (see Figure 1 for transducer component diagram). As with the Galfenol transducer, increased noise after the first reactor restart after refueling may indicate an intermittent short in the drive/sense coil.

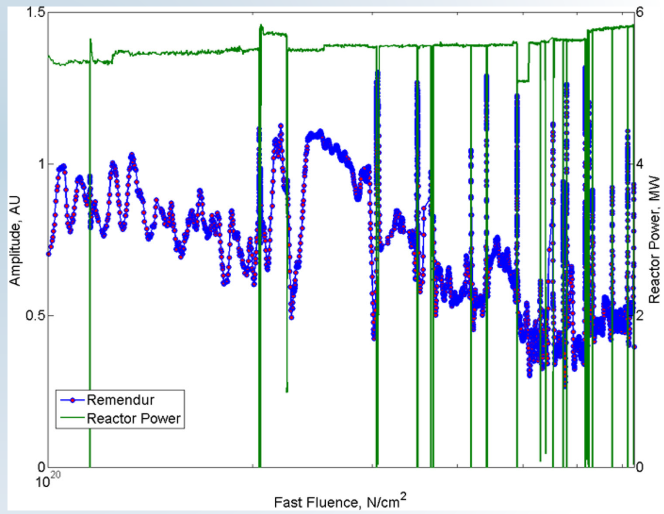


Figure 3. Remendur element transducer signal amplitude as a function of accumulated fast fluence.

The transducers were irradiated to a fast fluence of 8.8×1020 n/cm^2 (E>1 MeV). Post-irradiation examination of each irradiated material indicated negligible effects on the magnetostrictive behavior of either tested material. Observed online signal changes were deemed to have been caused by thermal and mechanical effects within the transducers.

ULTRA2

Based on the results of the ULTRA irradiation test, a follow-on irradiation test (ULTRA2) was selected for funding by NSUF. This test included the UTs developed at INL and fiber optic sensors provided by the French Atomic and Alternative Energy Commission and by the University of Pittsburgh (only the UTs will be discussed here). Three UTs were included in the ULTRA2 irradiation test. Two of the experimental UTs use Inconel 606 wire as the sensing element—one had a single measurement zone and the other had three zones. The third UT had a single zone and used commercially pure titanium wire as the sensing element. Spatial constraints of the MIT test capsule restricted the length of these UTs. As such, the UTs could not be directly calibrated without damaging the

Continued from previous page

Continued from previous page

transducers. Performance was determined by examining the trends in measured delay times against temperatures measured by included thermocouples.

Each of the three UTs included in this test experienced failures of the driver coil before the completion of the test. This is likely due to a material change that was made between the original ULTRA experiment and ULTRA2. All UTs survived between ~5000 and 7000 hours and produced reasonable signals over that time.

Figure 4 shows the normalized delay time and thermocouple temperature of the single segment Inconel sensor. The data during initial reactor start-up was unusable, possibly due to a mechanical pinch in the sensors wire, which cleared up after temperature cycling. The signal follows the reactor temperature well for most of the test. Some intermittent signal loss was observed over the last few reactor cycles. This is evidence that the coil was the component that failed, as any other component failing would not allow for a recovery.

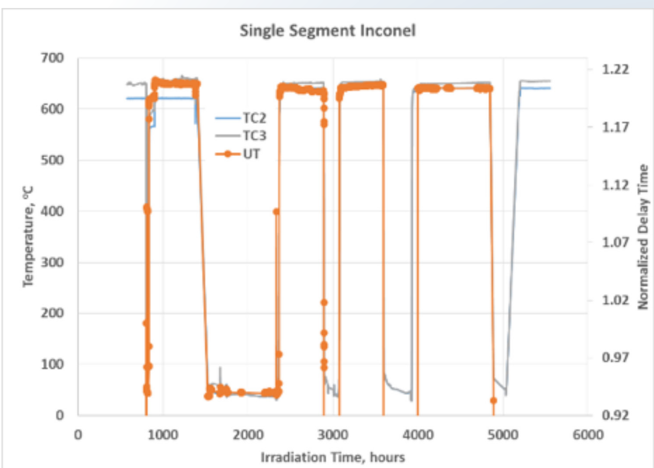


Figure 4. Single segment Inconel sensor results.

Figure 5 shows the normalized delay time and thermocouple temperature of the three segment Inconel sensor. As with the single segment sensor, for most of the irradiation, the signal closely matches the reactor temperature. Some anomalous behavior can be observed during the early part of the irradiation, seen as an opposing response between the first and second segments (as one signal increases, the other decreases proportionately). It is unclear at this point if this is a physical phenomenon or an artifact of the signal acquisition process. This sensor also failed intermittently before finally failing after ~7000 hours.

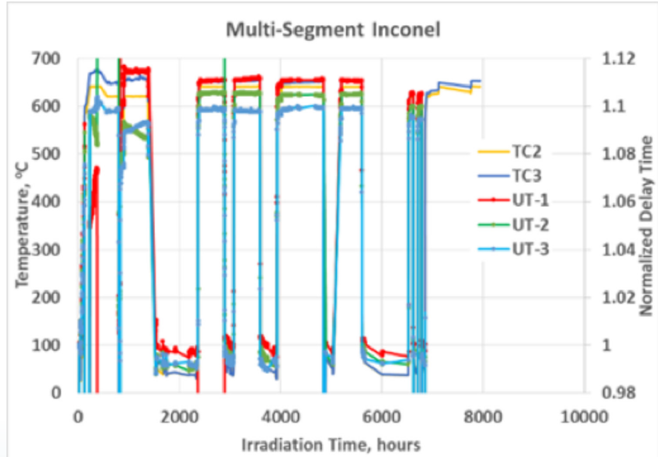


Figure 5. Multi-segment Inconel sensor results.

Figure 6 shows the normalized delay time and thermocouple temperature of the single segment Inconel sensor. This sensor performed well through almost 3000 hours before failure. Unlike the Inconel sensors, a slow decrease was observed in the measured delay time. The likely explanation of this drift is fast neutron damage causing a slow increase in the Young's modulus of the titanium. The effect appears to have saturated by the last operational reactor cycle, but this behavior may make titanium a poor material for UTs.

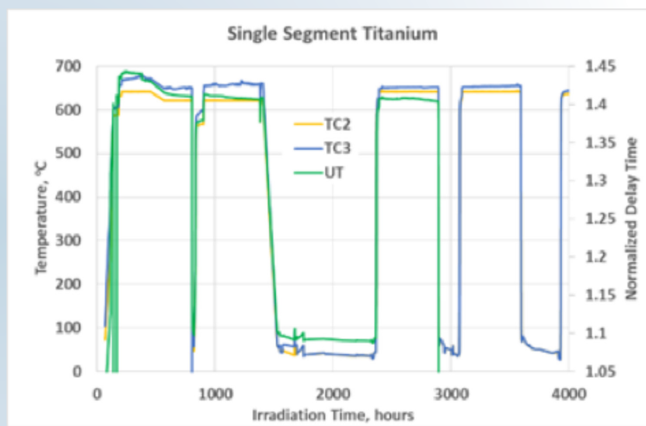


Figure 6. Single segment titanium results.

AGR 5/6/7

Also based on the results of the ULTRA irradiation, one UT, using molybdenum as the sensing waveguide, was included in the Advanced Graphite Reactor (AGR) 5/6/7 irradiation test at INL's ATR. This UT has performed very well through early irradiation tests. This thermocouple was calibrated prior to installation in the experiment. Figure 7 shows the temperatures measured by the UT and by several thermocouples located near the UT. The

Continued on next page

Continued from previous page

thermocouples labeled TCSPND4 is closest to the UT, and offers the best comparison. The standard deviation of the UT temperature is ~2°C at the maximum test temperatures.

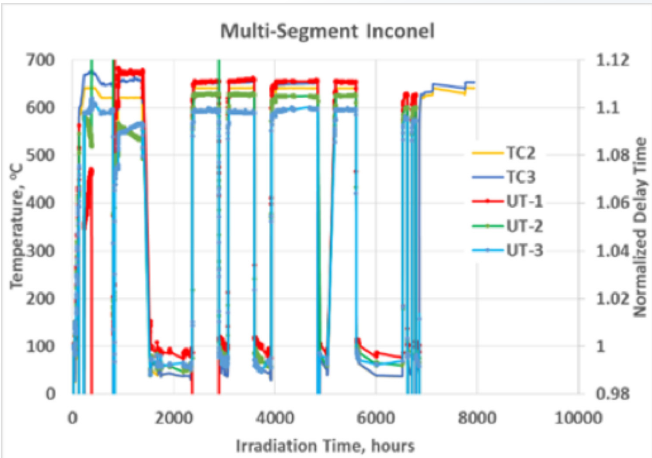


Figure 7. AGR 5/6/7 UT results.

Future Deployment

The results of testing to date have been very promising, but some work remains in order to consider the UT completely qualified for in-core deployment. First, the issue observed in the ULTRA2 test is likely due to changes made to a ceramic cement used to fill the transducer housing, but this has not been verified. This issue may be solved by identifying a better potting compound or by making the coil wire more robust, either by changing materials or wire diameter, which will affect the performance of the UT. Either change must be tested.

DISECT

A planned NSUF-sponsored irradiation test, DISECT, will be performed in the Belgian BR2 reactor in collaboration with SCK-CEN. DISECT is meant to study metallic fuel foils arranged along a ~1 meter test vehicle. Multi-point temperature measurements along the length of the DISECT capsule are needed in order to fully characterize the experiment. Multi-point thermocouples are planned as the primary instrumentation, but an INL UT will also be included in the test, along with a promising fiber optic sensor. The expected temperatures are relatively low for a UT, less than 300°C for the first phase of testing, but the need for a temperature profile measurement make the test ideal for demonstration of the performance of the UT, as the temperatures measured by the single UT can be directly compared to those of the multi-point thermocouples. The UT designed for this application will have ten measurement zones along the length of the test, making this the most complicated irradiation yet for the sensor.

CONCLUSIONS

This article documents the development of a multi-point ultrasonic thermometer and the progress to date toward regular deployment in irradiation experiments. The largest hurdle a new in-core sensor must overcome to be considered qualified is demonstration in prototypic irradiation conditions. The reactor access provided by NSUF has been critical in progressing the UT through several stages of design improvement, and has shown that the UT is a viable option for making multi-point temperature measurements in extreme irradiation environments such as those experienced in the ATR.

ACKNOWLEDGMENTS

Thanks to the NSUF for providing access to the MITR facility. Thanks also to the MIT Nuclear Reactor Laboratory for conducting the irradiation test.

References

1. B. G. Kim, J. L. Rempe, J-F Villard, S. Solstad, "Review of Instrumentation for Irradiation Testing of Fuels and Materials," Nuclear Technology, 176, 155-187, 2011.
2. M. Laurie, et al., "Ultrasonic High Temperature Sensors: Past Experiments and Prospective for Future Use," Proc. International Symposium on Temperature and Thermal Measurements in Industry and Science (TEMPMEKO), Portorož, Slovenia, June 2010.
3. E.P. Papdakis, L.C. Lynnworth, D.R. Patch, E.H. Carnevale, "Ultrasonic Thermometry in LMFBR Systems," Final Report NYO-3906-13, Panametrics Inc. 1972.
4. H.A. Tasman, M. Campana, D. Pel, J. Richter, "Ultrasonic Thin-Wire Thermometry for Nuclear Applications," Temperature: Its Measurement and Control in Science and Industry, Vol. 5, Part 2, 1191-1196, 1982.
5. L.C. Lynnworth, E.H. Carnevale, M.S. McDonough, S.S. Fam, "Ultrasonic Thermometry for Nuclear Reactors," IEEE Transactions on Nuclear Science, Vol. NS-16, 184-187, 1968.
6. J. Daw, J. Rempe, S. Taylor, J. Crepeau, and S.C. Wilkins, "Ultrasonic Thermometry for In-Pile Temperature Detection," Proceedings of NPIC&HMIT 2010, 2010.

Optimizing incremental control room modernization toward a more efficient end state

Katya Le Blanc
Idaho National Laboratory

The Light Water Reactor Sustainability's control room modernization project leverages the use of technology to improve the way nuclear power plants are operated to reduce operations and maintenance costs by automating manual, labor-intensive tasks. Most plants in the United States are approaching the end of their initial operating lifetimes and are undergoing or have completed extensions of their operating licenses. In order to continue to operate for 20 or 40 years beyond their initial license, many plants will need to maintain outdated equipment for longer than originally planned. Unfortunately, many plants are encountering a challenge in maintaining those systems because replacement parts are no longer available. While many plants are replacing worn-out systems on an as-needed basis, some have their sights set on more ambitious full-scale modernization. While a full-scale modernization is desirable because it could result in a cohesive fully modernized control room all at once, most plants cannot justify the lost revenue of an extended outage to achieve that vision. Further, simply updating existing instrumentation and controls and human machine interfaces does not guarantee performance benefits or cost-savings. Therefore, the reality is that many plants are updating systems in piecemeal fashion.

Some plants have recognized that a strategic upgrade plan could potentially achieve the next best thing to a full-scale all-in-one modernization. Some of those plants have partnered with LWRS human factors and instrumentation and controls researchers to develop and execute the methodology to realize a control room modernization end state that is cohesive and provides opportunities to use advanced technology and data analytics to reduce operating costs to ensure the long-term, economical operation of the existing plants.

The first step in a strategic upgrade plan is to identify where on the existing control boards old components will be replaced and optimize the placement of new digital human-system interfaces to come up with the end-state control room layout. The new layout can then be effectively visualized using three-dimensional modeling as shown in Figure 1, or can be displayed in augmented reality as depicted in Figure 2. Once the end-state layout has been identified, the next step is to develop an end-state design philosophy that describes the design principles for information architecture, alarm design, and the human-system interface (HSI) design element including use of graphics, color, and navigation. These principles should be carefully documented so that engineers and designers working on the project throughout the life-cycle can consistently apply the philosophy.

Figure 1. Optimized control board layout with new digital human system interfaces.

Figure 2. Palo Verde operators seeing what their future control room could look like in the CAVE.

One risk in embarking on a phased upgrade rather than a full-scale, all-in-one modernization is that the phased approach may result in a piecemeal look and feel in the control room even in the presence of an overarching design philosophy. It is important to consider how to maximize the effectiveness of information abstraction and aggregation even when some systems may not yet be upgraded. The next step is to identify information that is relevant to high-level plant overview and for integrated system overview. Also, to ensure that process parameters

Continued on next page

Continued from previous page

and component status for all relevant equipment be brought into the digital control system regardless of whether it will be upgraded into the current or future phases of the control system upgrade. This ensures that information needed to provide effective plant and system status is available through the Human System Interactions.

Initially, this may be accomplished by providing information pulled from a plant computer or other system that is used to store and process plant information. As each phase is complete, relevant information will be pulled directly from the digital control system as it is made available. This approach enables the use of effective overview and integrated displays—even when information needed is not yet part of an upgraded system—and ensures that there will be no need for the redesign of individual system displays or plant overviews when the plant upgrades reach the final end state.

Another key aspect of the approach that LWRS researchers take is to provide the technical basis for design decisions based on industry standards, open literature, and original experimental studies. The researchers use a variety of methods and tools to compare competing design concepts identifying which designs support operators and increase efficiency. Figure 3 shows an example of how eye-tracking technology can help researchers identify the distribution of attention and provide more intuitive interfaces.

The work done in this project provides general guidance on how human factors can be used to design advanced control rooms as part of a phased upgrade program.

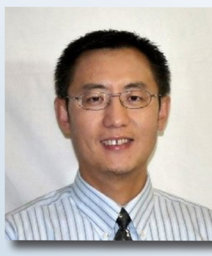
Figure 3. Heat Map showing where operator attention is on the boards with and without overview displays.

Intelligent III-V GaN based neutron flux detector array

Vasil Hlinka
AwareAbility Technologies

Larry Larson
AwareAbility Technologies

Dr. L. Raymond Cao
The Ohio State University



Nuclear power plant operators require accurate and timely information to maintain safe and efficient operation of the fleet. Instrumentation and sensors provide many levels of reactor information from start-up, normal/abnormal operation, shut-down, and accident and post-accident monitoring, as well as process monitoring. Hundreds of sensors are deployed in a typical nuclear plant to provide pressure, temperature, steam flow, water level, control rod position, and plant radiation monitoring instrumentation. Of particular importance is the timely and accurate understanding of the fission reactions inside the reactor core, calculated indirectly by measuring the neutron flux density. But measuring neutron flux in the narrow space inside and outside the reactor core presents a challenge to the operation of the reactor for the critical information about the heat generation rate.

The current state-of-the-art in nuclear reactor neutron flux density monitoring centers on metal or gas-filled fission chambers for in-core measurements (usually at a single remote location) and additional neutron detectors, such as fission or ion chambers in various ex-core locations. These imperfect configurations result in gaps and inaccuracies in the neutron flux density measurements.

From a safety and neutron economy standpoint, the neutron flux should be as uniform as possible. Correlation of control rod positioning to the core reactivity is vital for the safe and efficient operation of the reactor. Just as important, mispositioning of the control rods must be detected and corrected quickly. A new detection technology with fast, accurate response and wide dynamic range is needed.

Goals and Objectives

This project addresses the measurement issues with an intelligent neutron flux detector array based on a Gallium Nitride (GaN) semiconductor. The goal is to design and build a small, representative portion of a complete sensor array as a testing platform to provide data to train a new algorithm based on machine-learning. The Proof of Concept (POC) will be tested in The Ohio State University's Nuclear Reactor Laboratory with performance data collected from both individual and groups of the new semiconductor detectors using commercially available digital data acquisition instruments. Raw waveform data will be analyzed by new digital signal processing (DSP) techniques with the results being compared to conventional instrumentation, thus illustrating the benefits of the new approach.

Data from both the conventional and new DSP data sets will be used as the basis for an initial set of features to be applied to a fully connected multi-layer Neural Network (NN). Varied methods are being evaluated to recast the detector signal components into useful "features" to train and test a pair of NN models that can automatically detect at least one reactor safety scenario, such as inadvertent control rod withdrawal (IRW).

Project goals are to:

- Illustrate that the thin-film GaN detector is intrinsically sensitive to neutron radiation.
- Demonstrate the ability of the enhanced DSP analysis to discriminate detector signals induced by gamma-rays captured from neutron-induced signals.
- Demonstrate the performance of the sytem in a simulated IRW event.
- Demonstrate a new data analytics approach that is implementable to other in-core detector arrays.

Technology and Approach

The project will advance the state-of-the-art in neutron flux density measurement through the development of an intelligent neutron flux detector array. The three key elements of the approach are an intrinsic neutron sensor, advanced DSP algorithms for superior sensor performance,

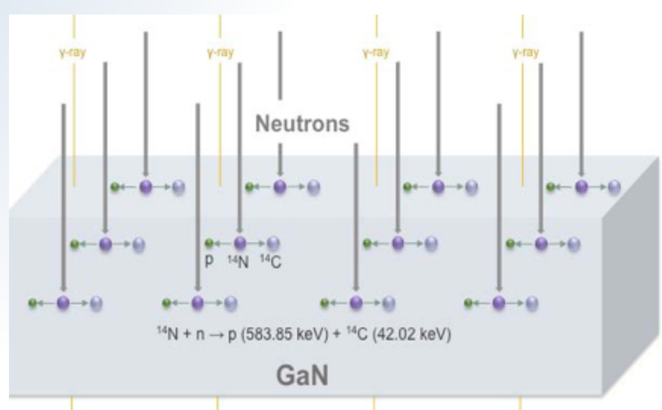


Figure 1. Direct-Conversion neutron detector.

Continued on next page

Continued from previous page

and the application of big data techniques and machine-learning to the large sensor array data sets to improve the diagnostic performance of the new instrumentation.

The semiconductor sensor array augments the current in-core detectors and is composed of three main elements:

- Novel, low-cost and self-powered neutron detectors based on advanced GaN III-V semiconductor material.
- Advanced digital signal processing techniques to significantly improve the signal-to-noise ratio of the neutron detectors.
- Intelligence instilled via machine-learning (Neural Networks) techniques to provide the reactor operator with useful insights into the reactor operation and alerts when appropriate.

The rapid advancement of new sensor and sensor materials technologies in non-nuclear fields over a few decades have provided many new choices for in-pile instrumentation selection. Wide band-gap solid-state sensors, such as those based on GaN, hold much promise in the area of neutron detection. The combination of the excellent radiation hardness and intrinsic sensitivity to neutrons in the material make the GaN detectors well-suited to offer low-cost neutron detection option for in-pile instrumentation, such as providing ample data to data-driven new analytical techniques applied in this project. In order to maximize accuracy and responsiveness of the flux monitoring, the resulting small-size, low-cost, and low-power requirements of the detector allow for their placement in a multi-point array configuration.

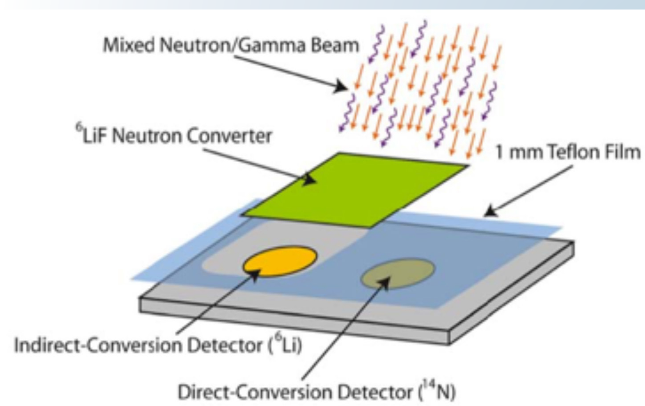


Figure 2. Illustration of two types of GaN neutron detection [2].

Digital Signal Processing offers improvements in detector noise and complex signal discrimination capabilities, which should greatly improve detector performance.

Finally, the application of artificial intelligence and machine-learning techniques and improved methods to handle very large volumes of data using Big Data techniques, provide the opportunity to more effectively process the raw data from both individual and groups of detectors. The ability to effectively correlate the detector data with other instrumentation data opens new possibilities in terms of proactive and autonomous safety monitoring.

Initial Test Results

Initial work has focused on collecting baseline data using detectors based on silicon carbide (SiC), while the GaN detectors are fabricated and characterized. Baseline detector signals were collected from bench tests using varied radiation sources.

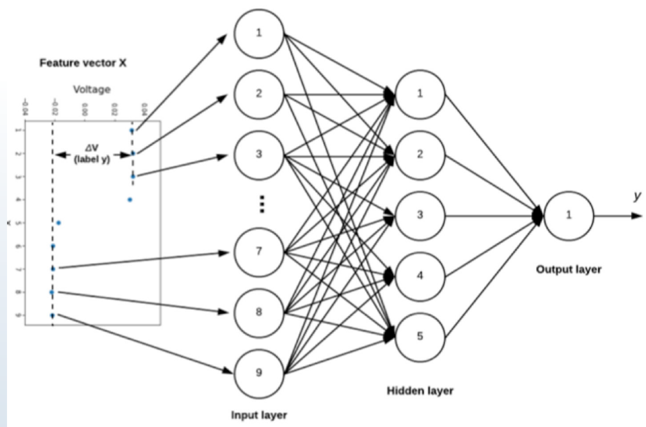


Figure 3. Sample Neural Network applied to signal data.

These signals were then processed using traditional Costruzioni Apparecchiature Elettroniche Nucleari S.p.A. test equipment and via new techniques using the raw signals and a Neural Network approach.

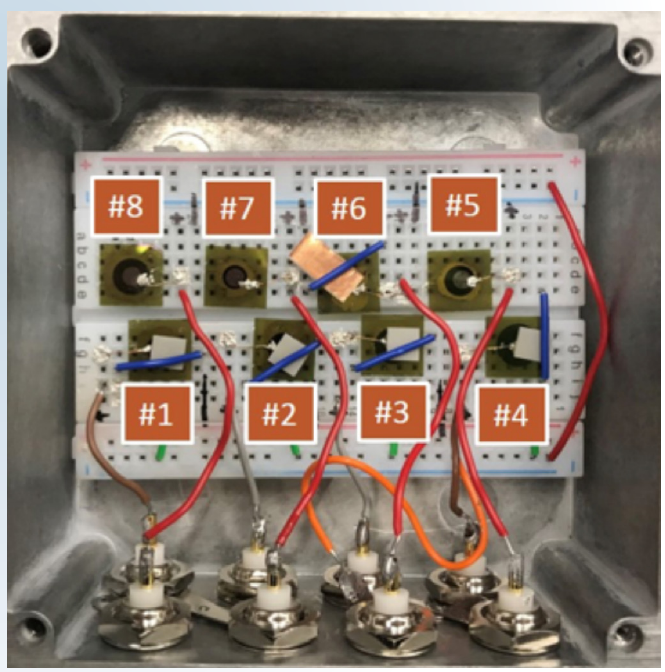


Figure 4. SiC detectors covered by neutron converter films positioned in an aluminum box during the neutron response measurements.

Continued on next page

Continued from previous page

Early stage experiments were then conducted in the thermal column facility of The Ohio State University Research Reactor to measure the neutron response of SiC detectors for flux mapping. Figure 1 showed eight SiC detectors arranged in an array within an aluminum enclosure and covered by neutron converter materials, AlN (devices 1-4), and B4C (device 6). The detectors were tested at various reactor power levels, up to a maximum 300 kWth with peak flux of 1×10^{10} n/cm^2/s and total accumulated fluence of 3.2×10^{13} n/cm^2 at a near-core location. During the experiments, raw-waveform data, as well as pulse height histograms, were acquired from multiple detectors simultaneously using GHz multi-channel oscilloscope and digitizer, respectively (see Figure 5). The collected waveform data will be used to train a neural network based algorithm (see Figure 6) and subsequently derive histogram data from it, which will then be validated against the experimentally acquired histograms.

Figure 5. Researchers acquiring detector data during the experiment using multichannel data acquisition systems.

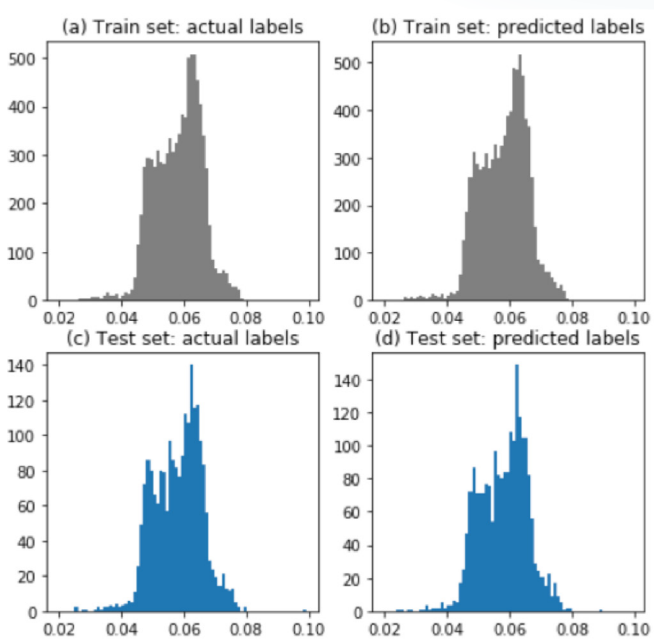


Figure 6. Sample Neural Network Training Results.

Plan Forward

Further tests are planned using both SiC and GaN detectors. These tests will include a simulated control rod drop, as well as dispersed detector configuration. These experiments will allow for the refinement of the configuration of the POC and support the final upscaling concept to a full operational array. Other test objectives include fine tuning of the DSP algorithm to maximize signal-to-noise ratio and reject gamma interference, and feature identification to train the machine learning neural network.

Value to Nuclear Applications

This project will demonstrate a new state-of-the-art method of in-pile experimentation, with material improvements in multiple areas over the current employed technologies. Immediate technical benefits of the new approach include:

- Very fast response time, down to the nanosecond level, to reactor reactivity disturbances/variations.
- Large dynamic range, which would allow for monitoring chain reactions at orders of magnitude below full power, supporting accurate measurement of reactivity changes in a sub-critical reactor environment.
- Small form factor increasing flexibility in detector placement including in-core and near-core implementations.
- Vital real-time control parameters and monitoring during startup and other non-steady state operation.

Operational benefits will result from the use of many individual detectors, organized and processed in a novel fashion, and analyzed to identify normal and anomalous parameters in real-time to the operator. The ability to gather varied data points from many locations throughout the neutron flux field will serve to further improve the overall system performance far beyond what is possible with current, individual detector approaches.

Summary

Nuclear power safety is a paramount societal concern. The need for affordable and dependable power has resulted in the adoption of nuclear power for civilian use. The new research represented in this work would shed light on the viability and usefulness of a lower cost detector technology. Employment of machine-learning techniques open the possibility for additional plant risk reduction via improved and autonomous anomaly and error mode detection.

References

1] Review of using gallium nitride for ionizing radiation detection Jinghui Wang, Padhraic Mulligan, Leonard Brillson, and Lei R. Cao

[2] L. Cao, Battelle Energy Alliance, LLC Project No. 11–3004, 2015, pp. 1–44.