Advanced Sensors and Instrumentation

Issue 9 • September 2018

Program Update

Craig Primer
Idaho National Laboratory

The Department of Energy hosted a workshop, Digital Environment for Advanced Reators Workshop, on June 5 and 6, 2018, to gather input from stakeholders on current challenges associated with design and implementation of digital environments for advanced reactors. The workshop specifically focused on advanced sensors, monitoring, control, and human automation interaction and the specific technologies needed in these areas to support the deployment of advanced reactors. This workshop provided the new and existing reactor communities a forum for exchanging information on available technologies, ongoing research and development (R&D) activities, as well as identifying gaps in needed technology. In addition to the review of technologies needed to support completion of instrumentation and control (I&C) systems, operating experience and lessons learned were provided by the current reactor community. These challenges were considered by the advanced reactor community as they reviewed their relevant design features and the supporting technologies.

The key deliverable from the workshop was to identify gaps between needed and existing technologies, which were grouped into four key areas: (1) sensors and communication, (2) control, protection, and monitoring, (3) online monitoring and diagnostics, and (4) concept of operations/control rooms.

Gateway to Accelerated Innovation in Nuclear (GAIN) website located at:

https://gain.inl.gov/SitePages/Workshops.aspx

The information presented during the workshop has been captured in a summary report, available at the website. The key research areas identified were:

1. Developing state-of-the-art advanced control rooms, controls systems, and plant protection technology systems. Research should:
   a. Reduce instrumentation and control testing and verification and validation (V&V) efforts associated with fulfilling current licensing requirements for cybersecurity, common cause failure, and design basis accidents through methods that would credit passive safety features instead.
   b. Provide radiation hardening of digital-based electronic components, such as programmable logic controllers and field-programmable gate arrays.
   c. Create a technical basis for reduced staffing and/or autonomous operation in minimal control rooms (e.g., remote operations or single workstation).

In this issue...

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

U.S. DEPARTMENT OF ENERGY

Continued from previous page

2. Developing advanced online monitoring systems for nuclear plant operation and maintenance. Research should:
   a. Demonstrate an optimal balance between cost and plant performance for achieving reliability, availability, maintainability, and security.
   b. Integrate predictive analytics and risk-informed condition monitoring with business process applications, which would enable a transformational approach to supply chain and asset management.
3. Developing new sensors and instrumentation to support improved plant control and data analytics applications. Research should:
   a. Demonstrate advanced instrumentation and communication of data that can be located in high-temperature, high-radiation reactor cores.
   b. Upgrade smart multimodal measurement devices that can measure multiple parameters simultaneously.

The information obtained during the workshop is being used by the NEET ASI program to identify gaps between existing and needed capabilities by the advanced reactors community and to establish research priorities for planned solicitations, cost-shared R&D, and pilot projects through private-public partnerships. Any questions regarding the Digital Environment Advanced Reactor workshop or NEET ASI program objectives can be sent to the Craig A. Primer, who is the NEET ASI National Technical Director at craig.primer@inl.gov.

Versatile Acoustic and Optical Sensing Platforms for Passive Structural Systems Monitoring

Gary Pickrell
Virginia Tech

Anbo Wang
Virginia Tech

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 optimized 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 three-dimensional (3D) network monitoring solutions. Nonetheless, prevalent concerns related to reliability and cost have limited widespread adoption in nuclear energy systems.

In an effort to fill the gap between low-cost electronic sensors and high-performance fiber optic sensors, a diverse research team led by the Center of Photonics Technology (CPT) at Virginia Tech seeks to provide an acoustic-based distributed sensing system. This system is capable of monitoring phenomena such as strain, temperature, pressure, and corrosion to better evaluate the aging and degradation of relevant structural components, including concrete that serves as support and nuclear containment; cable insulation; and metal pressure boundaries, in nuclear facilities. Supported by a Nuclear Energy Enabling Technology (NEET) program, Dr. Gary Pickrell from Virginia Tech is leading a multidisciplinary team that will develop an acoustics-based sensing technique that takes advantage of the proven resiliency of fiber optic materials via sensor interrogation with low-cost electronics.

Goals and 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 real-time sensing with unprecedented resolution, versatility, reliability, and economic viability. 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.

The Center for Photonics Technology (CPT) at Virginia Tech, will collaborate with Prysmian Group, an industry leader in optical fiber and cable manufacturing, and Oak Ridge National Laboratory (ORNL), to develop the distributed acoustic fiber Bragg grating sensing (AFBGs) technology.

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 optical fiber Bragg gratings (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 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.

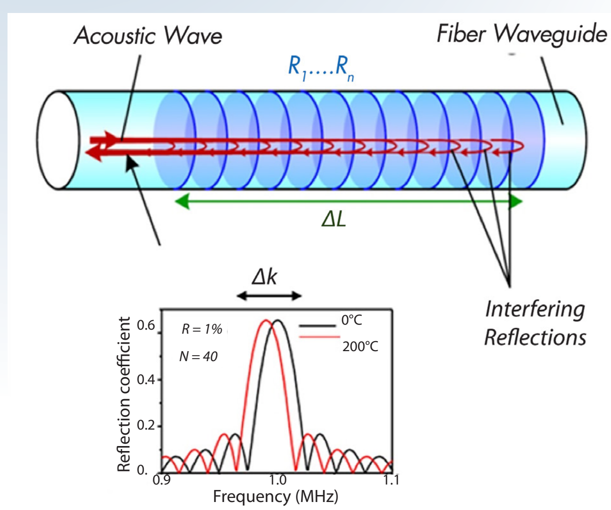


Figure 1. Schematic of AFBGs and temperature response.

Continued on next page

Continued from previous page

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.

Current Status

In this first year of the project, significant efforts have been dedicated to the optimization of acoustic fiber waveguides, development of the fiber Bragg grating fabrication processes, and the design of the sensor interrogation system. Theoretical models were developed to simulate the performance of a host of acoustic waveguide materials and designs. As shown in Figure 2 (a), a "suspended core" waveguide design was developed to achieve strong

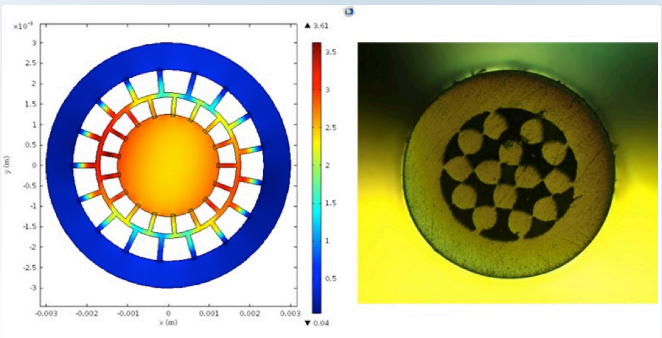


Figure 2. (a) Theoretical waveguide modeling of fused silica acoustic fiber. (b) Optical micrograph of acoustic fiber fabricated on commercial optical fiber draw tower.

power confinement of a single acoustic mode. Based on the simulation results, fused silica fibers were fabricated on our custom glass-working lathe and commercial fiber optic draw tower, as shown in Figure 2 (b). An acoustic waveguide characterization system was also designed

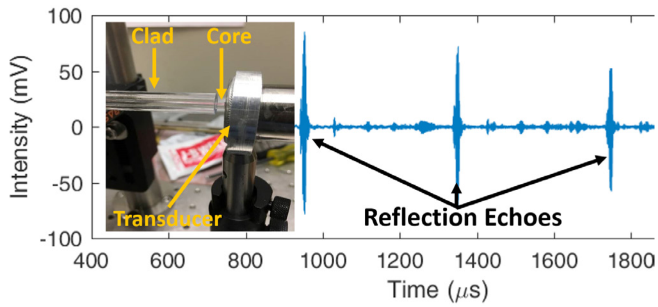


Figure 3. Acoustic excitation and detection of "suspended core" acoustic fiber and reflection spectrum.

and constructed to evaluate the performance of the as-fabricated prototype fibers, as shown in Figure 3.

Reflectors were fabricated in the "suspended core" acoustic waveguide via a CO_2 laser inscription technique. As shown in Figure 4, the core rod was traversed at fixed steps via a motorized stage to create the periodically located reflectors necessary to form the AFBG. A pair of copper mirrors was used to ensure that the entire circumference of the core rod was exposed to the laser beam. After the inscription of the reflectors was complete, the core rod was sleeved with a silica tube and positioned via glass rings that were fused to both the core and cladding. The successful demonstration of reflectors inscribed in an

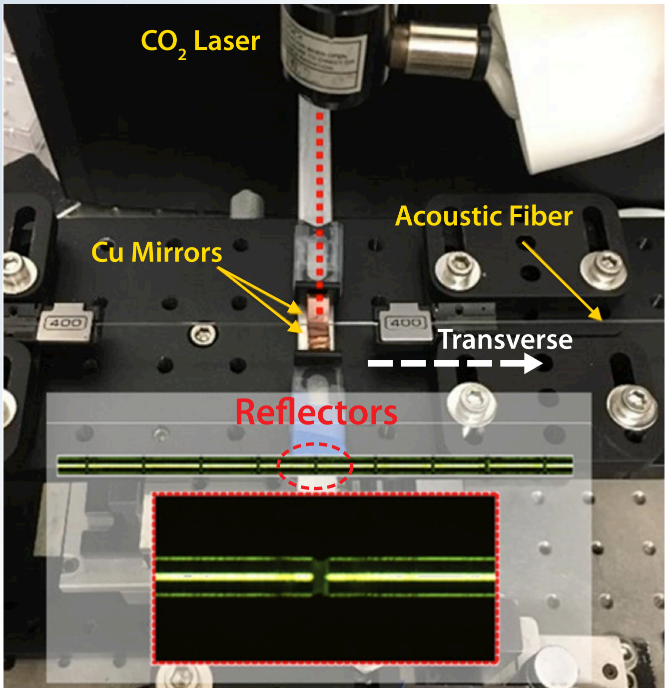


Figure 3. Acoustic excitation and detection of "suspended core" acoustic fiber and reflection spectrum.

Continued on next page

Continued from previous page

acoustic fiber waveguide with strong power confinement represents the first step in the development of the AFBG sensing system.

Efficient coupling between the transducer and acoustic fiber will improve the overall performance of the sensing system. Thus, work is ongoing to design an ultrasonic transducer and actuator assembly that is optimized for the interrogation of AFBGs. Specifically, the use of acoustic horns has been shown to dramatically improve the signal quality in conventional acoustic-based monitoring techniques. All fused silica horns were fabricated on a glass-working lathe by flaring the end of a glass capillary tube. As shown in Figure 5, a dramatic increase in the amplitude of the reflected acoustic signal was achieved

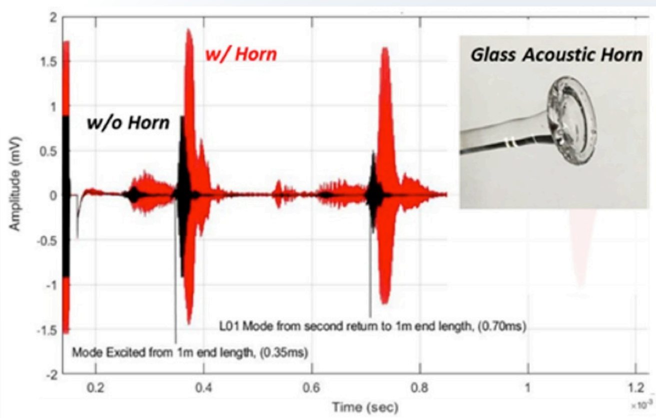


Figure 3. Acoustic excitation and detection of "suspended core" acoustic fiber and reflection spectrum.

with the use of the hollow glass horn as coupling between the transducer and fiber. Finite element modeling efforts via Abaqus are ongoing to optimize the acoustic horn and its interface with the transducer and fiber waveguide.

In parrallel with the acoustic waveguide and sensor development efforts, an initial design review of the AFBG sensor interrogation system was performed. The LabVIEW Platform-based "Multifunctional Acoustic and Optical Sensing System" (MAOSS) was identified for real-time high-speed data acquistion and control. The modular system allows for traveling-wave-setup and generation while the LabVIEW-based platform maintains the small footprint necessary for testing and deployment in nuclear testing facillities and power plants.

Plan Forward

The optimization of the acoustic waveguide and sensors will continue, in conjuction with the associated fabrication processes, over the duration of the project. The development of the ultrasonic transducer and coupling assembly with the AFBG interrogation system will assure the successful integration of all the system components. Prototype acoustic fibers and sensors will be selected for radiation and thermal testing at Oak Ridge National Laboratory in the second and third years of the project. Upon completion of the program, recommendations will be made for a potential field trial of the sensing technology in an operating nuclear power plant.

Impact and Value to Nuclear Applications

The proposed research performed in this project will fill the gap between low-cost electronic sensors and high-performance fiber optic sensors, and create a new arena for the development of the next generation of sensor technologies. Successful demonstration of the technology will provide a first-of-a-kind, low-cost, fully distributed, multi-parameter sensing platform that will offer a powerful means for the deployment of distributed fiber sensor arrays for 3D network monitoring solutions in nuclear energy systems.

The research project also provides an environment conducive to the development of graduate students, junior researchers, and faculty. Furthermore, the diverse and multi-disciplinary 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.

Wireless Reactor Power Distribution Measurement System Utilizing an In-Core Radiation and Temperature Tolerant Wireless Transmitter and Radiation-Harvesting Power Supply

Jorge Carvajal
Westinghouse Electric Company

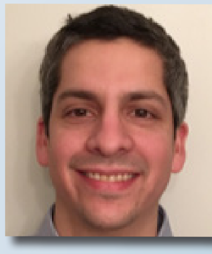
Shawn Stafford
Westinghouse Electric Company

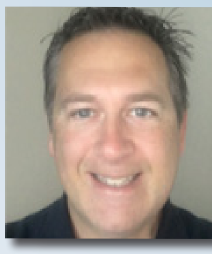
Michael Heibel
Westinghouse Electric Company

Paul Sirianni
Westinghouse Electric Company

James Turso
Pennsylvania State University

Kenan Unlu
Pennsylvania State University





Given the stringent safety requirements imposed on nuclear power plants (NPPs) and the economic pressures faced by utilities, sensors and instrumentation that can precisely monitor process variables inside an operating nuclear reactor vessel, while withstanding its harsh environment, are of great potential benefit to NPPs. Current sensors such as thermocouples, resistance temperature devices (RTDs), and neutron flux detectors, employed in measuring critical in-core parameters, do not contain solid state electronics because of the harsh environmental conditions. This article describes the vacuum micro-electronic (VME)-based amplitude modulated (AM) wireless transmitter capable of withstanding fast neutrons and gamma radiation at significantly higher dose levels than commercially available radiation-hardened electronic devices on the market today [1].

Project Description

The objective of this project is to develop the technology necessary for a wireless reactor power distribution measurement system based on a novel in-core neutron monitor [2]. This innovative power distribution measurement system utilizes highly radiation- and temperature-resistant VME technology and supporting components configured to continuously broadcast Self-Powered Detector (SPD) signals and reactor coolant temperature sensor signal measurements to a single receiving antenna located within the reactor vessel. The temperature and radiation sensitivity performance of the VME device, which is the key component of the system, will be evaluated as well as the supporting passive components of the circuit. The project will also include the design, construction, and testing of a radiation harvesting power supply.

Nuclear Application Impact

Power distribution measurements currently utilize Self-Powered Neutron Detectors (SPND) axially located within approximately one-third of the fuel assemblies. The proposed project would enable 100% of fuel assemblies to be instrumented by placing a VME wireless transmitter in the top nozzle of each fuel assembly. Each transmitter is designed to transmit at a unique frequency, slightly different from that of other devices contained in other fuel assemblies. In this way, the receiving hardware can be minimized to a single antenna and receiver capable of frequency multiplexing the various transmitted signals. It is expected that this technology would enable the plant to increase the reactor operating margin due to improved fuel usage knowledge. Another benefit of the radiation-powered VME wireless transmitters is that the transmitters provide a means to generate the required state variable measurements without the need for more cabling or additional penetrations in the reactor coolant system boundary.

System Configuration

Figure 1 shows the hardware installed and their locations within the Penn State Breazeale Reactor (PSBR) core. The PSBR facility offered the flexibility to install the main

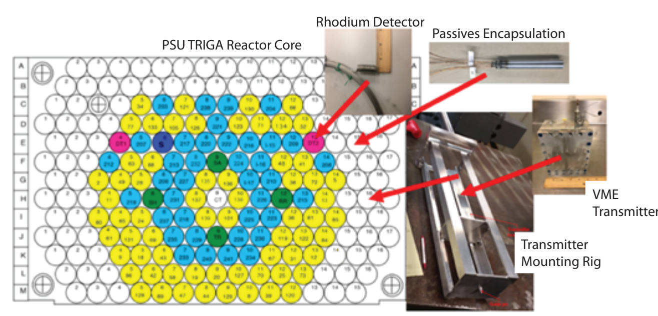


Figure 1. PSBR core hardware location.

Continued on next page

Continued from previous page

transmitter hardware on the reactor bottom grid plate and two other assemblies in permanent dry tubes near the core.

Figure 2 depicts the configuration of the equipment under test (EUT) and the supporting equipment. The EUT includes two types of VME-based AM wireless transmitters, which transmit a low frequency signal proportional to the Rhodium (Rh) SPD signal input. The carrier frequency used was 20 MHz, while the modulation frequency was proportional to the neutron flux. A third SPD was monitored independently using a Keithley picoammeter. Several passive components critical to the operation of the AM wireless transmitter were inserted in a permanent dry tube and monitored separately to assess their performance independently of the main circuit.

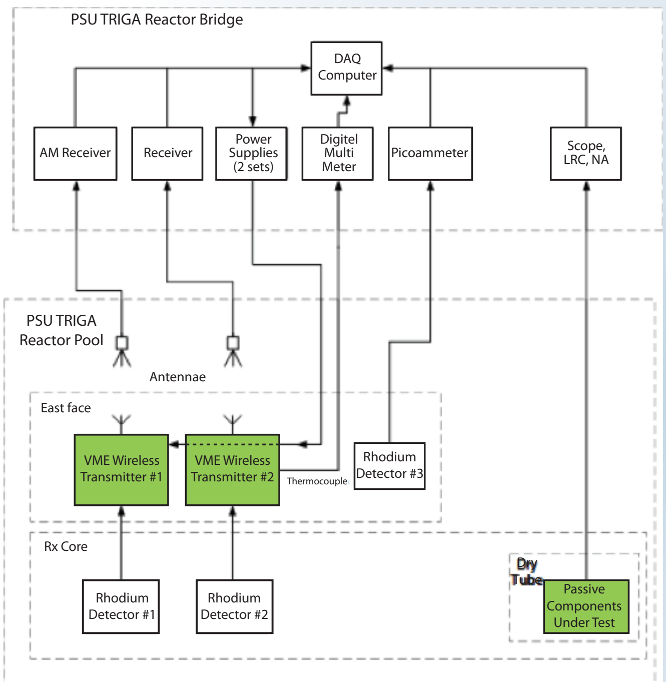


Figure 2. PSBR test configuration.

Transmission Test Results

The tests conducted by the team have demonstrated that the AM transmitter installed at the PSBR facility is capable of processing the small DC Rh SPD signal while exposed to a neutron flux of 1 x 10_{12} n/cm_2/sec. Figure 3 shows the equipment installed next to the core, the receiver location, and the AM transmitter signal response. The blue trace in Figure 3 represents the Rh SPD signal as recorded by the picoammeter, while the red trace represents the transmitted signal in response to the same Rh SPD signal. The AM transmitter signal is converted to a frequency signal by the signal processing hardware. At 25% reactor power steps, the transmitted signal closely matches the Rh SPD signal. The transmitter has been irradiated to a total neutron fluence of 3 x 10_{18} n/cm_2.

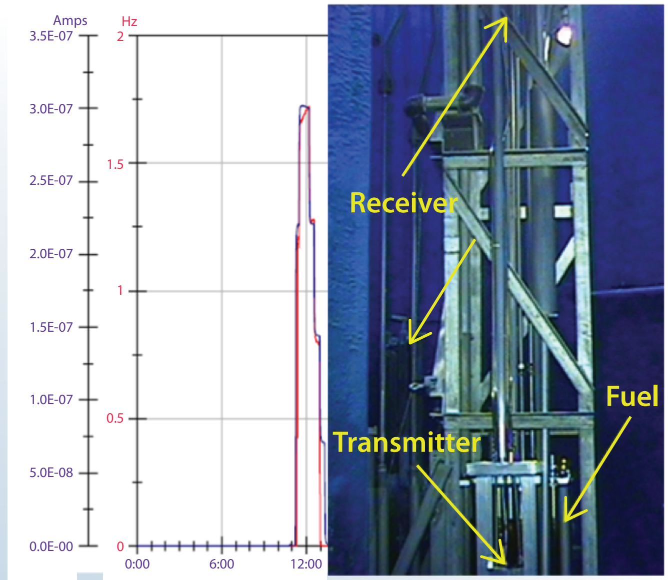


Figure 3. SPD output versus AM transmitter, and PSBR core.

Real time reactor power sensing test results

Another area investigated during this program has been real-time applications, such as reactor operations and closed-loop reactor control. Use of the raw self-powered detector signal is ineffective due to the significant delay times associated with their dependence on radioactive decay after irradiation to produce a current signal. Preliminary results have been obtained, which demonstrate that delay compensation can be applied, using an inverse detector model or digital/analog filtering to accelerate the output signal from the detector. This acceleration method provides near real-time performance of the detector system, which provides feedback to an operator (or automatic controls system) for monitoring and control of reactor power. Figure 4 shows the experimental control rod drive (ECRD), motor drive, and National Instruments equipment used to implement closed-loop control with the SPD. The licensed control rod drives are the cylinders pictured below the ECRD.im

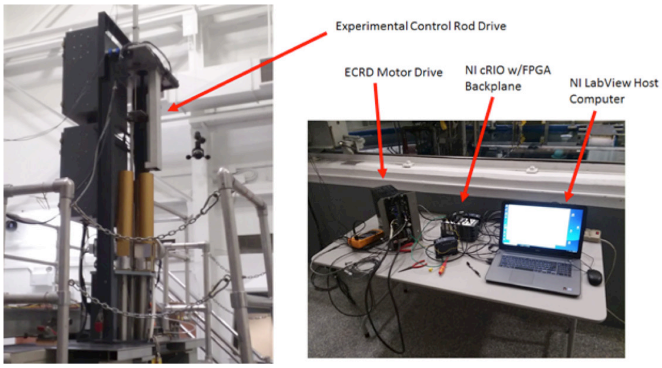


Figure 4. ECRD motor drive, and National Instruments equipment used for implementing SPD-based closed-loop control.

Figure 5 represents application of the accelerated Rh SPD as the feedback signal to the LabVIEW-based PI controller, which demonstrates that these sensors, with significant inherent delays, can be effectively used in real-time applications. The blue trace represents the raw SPD signal with its significant delay time, the red trace is the controller setpoint, and the black trace is the digitally compensated version of the signal. It is important to note that the acceleration method using a simple op-amp-based analog circuit can provide similar results as the digital approach. While the closed-loop response is not as precise as that provided by the licensed control console (the licensed console implements a somewhat more-complex closed-loop control algorithm), these results do demonstrate that stable closed-loop control with these detectors is achievable.

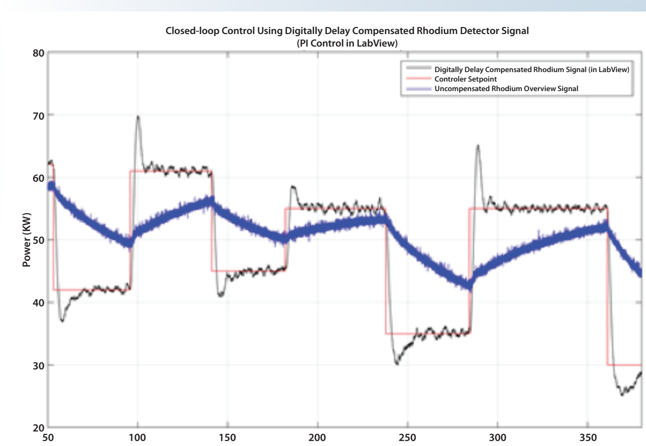


Figure 5. Closed-loop reactor control using the accelerated Rhodium SPND signal (licensed control system in manual)

Conclusions

The work performed to date has demonstrated that processing the small signal output (300 nA to 600 nA) generated by the Rh SPD can be wirelessly transmitted with somewhat robust modulating transmission methods in the presence of neutron and gamma radiation.

FUTURE PLANS

During the final year of this project, the key activities will include increasing the power density of the radiation harvesting power supply by adjusting the geometry and materials used. Irradiation testing will continue to accumulate higher dose on the existing hardware and to also irradiate other radiation-tolerant devices such as JFET-based components. Finally, the devices will be electrically heated while in the reactor dry tube in order to simulate more prototypical LWR conditions.

REFERENCES

[1] Q. Huang, J. Jiang, "A Literature Review on Radiation Effects on Wireless Post-Accident Monitoring Systems and Rad-Hardened Design Techniques," Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC & HMIT), February 2015.

[2] J. G. Seidel, et al, "Wireless In-Core Neutron Monitor," U.S. Patent 8,767,903 B2. July 1, 2014.

Mondernization Pivot

Ken Thomas
Idaho National Laboratory

Introduction

The Light Water Reactor Sustainability (LWRS) Program implemented a significant change in direction in fiscal year (FY) 2018 known as the "pivot." This addresses a pressing need for cost reduction in the LWR operating fleet to remain competitive in current electric markets. For the Plant Modernization Pathway, the pivot sharpens the focus on developing technologies that bring near-term operating efficiencies to the fleet while continuing to address long-term reliability and obsolescence issues of the aging legacy instrumentation and control (I&C) infrastructure. The strategy is three-fold: (1) modernize the I&C infrastructure with digital technology, (2) maximize plant automation, and (3) enhance plant worker and process efficiency. These collective developments will put the nuclear plants on a technically and financially sound basis for decades to come.

Digital Modernization

The light water reactor (LWR) operating fleet has an aging I&C infrastructure based on 1960's vintage technology. While it continues to provide safe operations, it has become more and more difficult to maintain due to component obsolescence and scarcity of replacement parts. Being largely analog-based, it does not support the type of operational efficiencies that have been instrumental in reducing the cost of operations in other safety-critical industries.

To address this, the Plant Modernization Pathway is conducting research on new applications of advanced human factors science and technologies to reduce operational work requirements while enhancing plant safety and reliability. The Pathway collaborates with several leading nuclear operators to ensure that the research results reflect realistic operating requirements and constraints, including Duke Energy, Arizona Public Service, Exelon Nuclear, and Dominion Energy.

As part of the pivot, the Pathway is developing concepts for full digital modernization of the I&C infrastructure,

Continued on next page

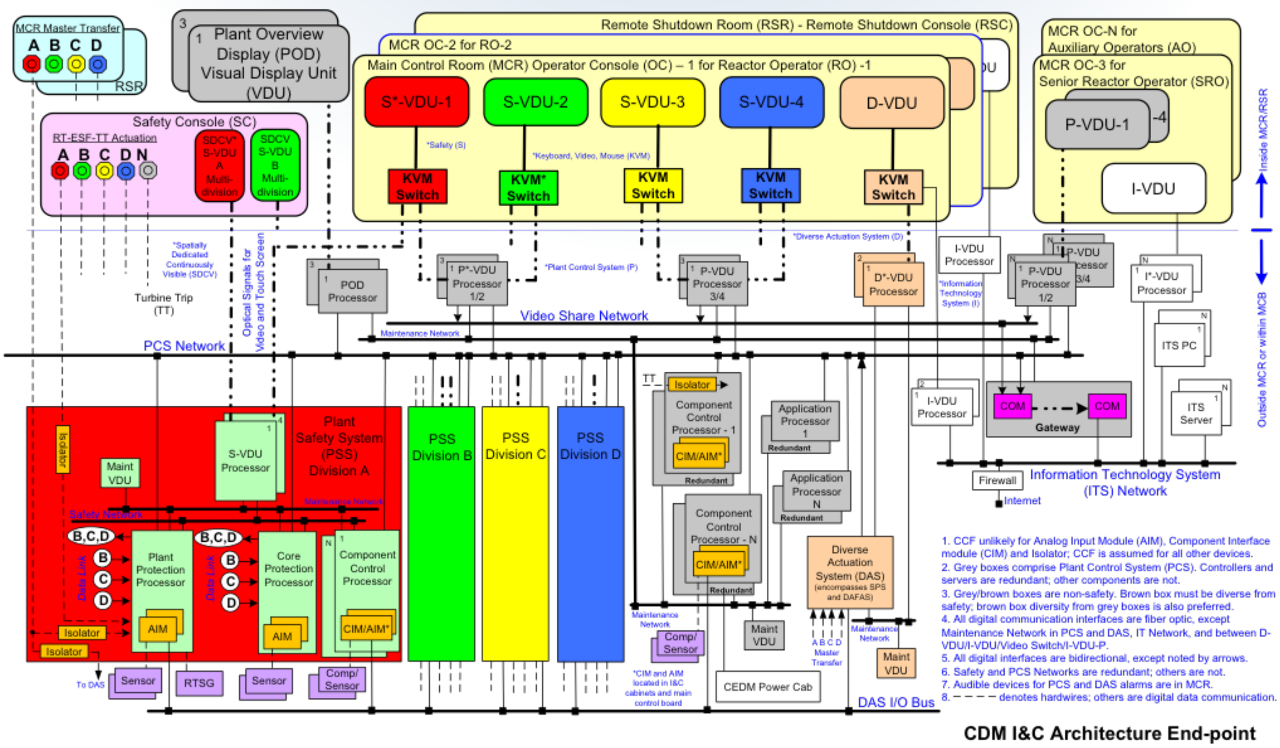


Figure 1. CDM I&C architecture.

Continued from previous page

including a fully digital I&C architecture and control room. This will provide the greatest cost reduction benefits both directly in plant operations and more broadly across all plant support work activities. This means addressing safety-related I&C systems, something the nuclear industry has been reluctant to take on due to perceived regulatory and cost barriers.

The Pathway has worked with Nuclear Automation Engineering, LLC, to develop a reference fully digital I&C architecture that maximizes work reduction benefits. Termed the Compact Digital Modernization (CDM), it is a complete plant-wide reference design that encompasses all safety and non safety I&C systems of a nuclear plant, including human system interface (HSI), and the interface to plant sensors and controlled plant components (e.g., pumps, valves, electrical breakers). The CDM is characterized by:

- A fully digital control room consisting of a large plant overview display, compact operator-consoles for reactor operators, and additional consoles for other control room staff, including a senior reactor operator, a shift supervisor, and a shift technical advisor.
- A very high level of I&C system integration, while maintaining sufficient segmentation to comply with safety criteria, including common cause failure (CCF) that can result from shared hardware resources and common designs.
- A robust design that enables substantial plant work activity reductions, while addressing all engineering standards and regulatory requirements, including cyber security.

The highly integrated CDM I&C architecture end point is shown in Figure 1.

Specific research is also being conducted in new means of qualifying digital technologies for safety-related applications, especially in addressing digital CCF. Digital CCF is the largest technical and regulatory barrier to modernization of safety-related systems. One particular project is exploring the feasibility and methods of exhaustive software testing using high-performance computing as a means of eliminating the possibility of digital CCF.

Plant Automation

The Plant Modernization Pathway is developing a range of modern digital to automate labor-intensive activities to reduce operations and maintenance costs. A major focus area is plant-wide online monitoring (OLM), which enables nuclear plants to move from time-based periodic maintenance and testing to condition-based maintenance, taking actions only when indicated by data reflecting the actual condition of plant structures, systems, and components. This also reduces maintenance-induced failures and excessive component wear due to testing.

OLM uses normal plant instrumentation as well as an augmented set of sensors designed to detect certain degradation mechanisms. The sensor signals are sent to centralized monitoring centers with failure diagnostic experts and analytical capabilities for characterizing degradation in time to take actions before incipient failures. These centers interfaced to work process, risk

Continued on next page

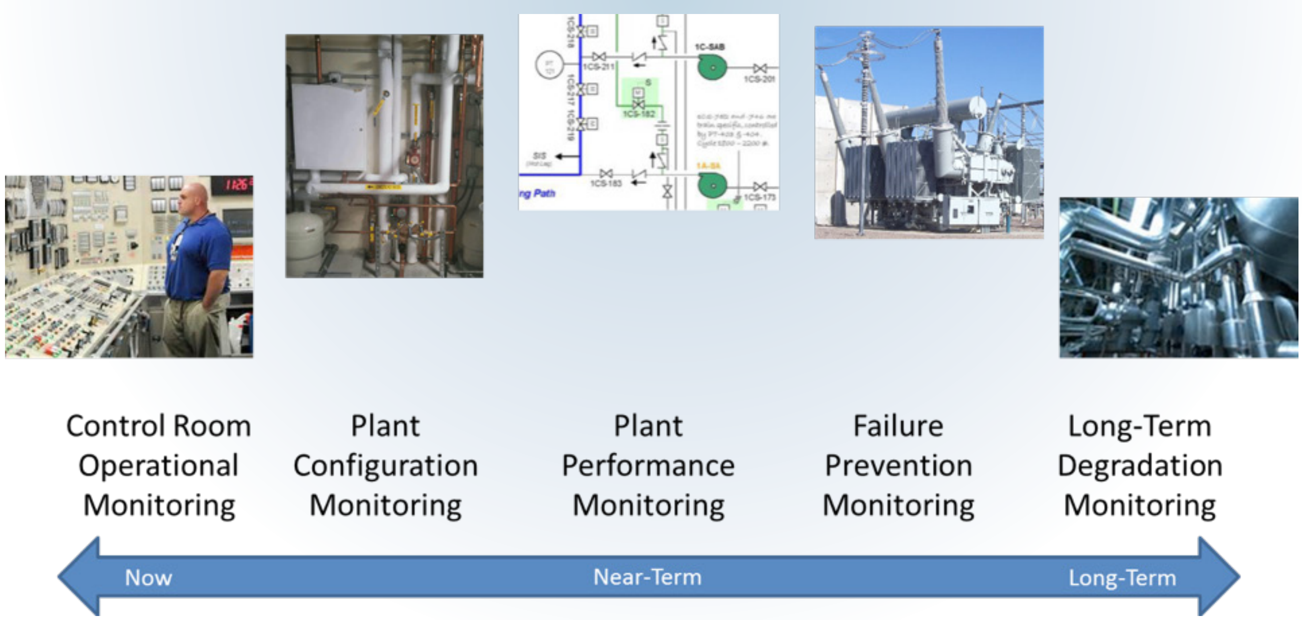


Figure 2. Intermediate and long-term concerns with plant health.

Continued from previous page

management, and mobile work technologies to initiate corrective actions with maximum efficiency.

In the broader sense, online monitoring consists of overlapping areas of monitoring from the immediate concern on operations and configuration management through the intermediate and longer-term concerns with plant health, as indicated in Figure 2.

The Pathway is developing other means of reducing plant support costs through automation of plant work activities by employing technologies such as RFIDs, computer vision, and wireless sensors. Along with other developed technologies, these have the potential to eliminate many plant work activities such as foreign material monitoring, and fire and security watches.

Process Modernization

The nuclear power industry has been engaged in deploying new digital technologies for plant workers for several years now, focusing on capabilities to improve the efficiency of work and reduce human error. These technologies include computer-based procedures and work packages, which provide an array of features that reduce time to complete field work, reduce the number of plant workers per task, improve work coordination, and prevent errors that would otherwise result in costly corrective actions. In addition to these, there are new standalone technologies that can offset human worker requirements of today, such as use of in-line chemistry instruments, RFID technologies, use of computer vision, etc. These technologies can transform how current labor intensive work activities are accomplished and reduce operating costs accordingly.

A specification will be developed as to the most effective means of mapping these technologies onto the typical nuclear plant operating model and related organization structure, resulting in the broadest possible application of these technologies. The specification will be developed in a top-down manner to identify both technology coverage and technology gaps with respect to automating plant work activities and processes. The specification will identify technology sources and best practices for implementation. It will address the technology gaps as research priorities for DOE, EPRI, other research organizations, and commercial product developers for future operating cost reductions.

The end state architecture will also enable new virtual-based business models in which remote third parties can provide real-time services just as effectively as if they were onsite. This is expected to have significant cost savings potential compared to maintaining on site competency and continuous availability for so many technical services. New service models for these technical areas are expected to emerge as the nuclear plants make provisions for them in their business models and digital architectures.

Summary

Plant modernization is critical to driving the work efficiencies that will allow the LWR fleet to be competitive in the forecasted energy markets over the coming decades. Coordinated research efforts in digital modernization, plant automation, and plant worker efficiencies will enable a technology base for significant cost reductions while maintaining the highest nuclear safety and reliability standards. This technology base will serve as a comprehensive digital platform for cost-saving applications across the range of plant support functions.

Evaluations of BR2 Silicon Carbide Temperature Monitors

Kurt Davis
Idaho National Laboratory

Brenden Heidrich
Idaho National Laboratory

Troy Unruh
Idaho National Laboratory

Pattrick Calderoni
Idaho National Laboratory

Steven Van Dyck
SCK•CEN Belgian Nuclear Research Centre

Andrei Gusarov
SCK•CEN Belgian Nuclear Research Centre

I. Uytdenhouwen
SCK•CEN Belgian Nuclear Research Centre

Kelley Verner
Univeristy of Idaho, PhD Student

Ahmad Al Rashdan
Idaho National Laboratory

Ashley Lambson
Idaho National Laboratory

Since the early 1960s, SiC has been used as a post-irradiation temperature monitor. As noted in References 1–7, several researchers have observed that neutron irradiation-induced lattice expansion of SiC annealed out when the post-irradiation annealing temperature exceeds the peak irradiation temperature.

Twelve silicon carbide (SiC) temperature monitors were irradiated in the Belgian Reactor 2 (BR2) as part of a Nuclear Science User Facilities (NSUF) Project and were delivered to the High Temperature Test Lab (HTTL) for evaluation to determine their peak temperature achieved during irradiation. Each monitor had a sister monitor exposed to identical irradiation test conditions. Monitors with the "A" designation (six in total) were evaluated using the resistance measurement method described in Reference 8. Sister monitors with the "B" designation are to be evaluated using a new method described in Reference 9.

The quality of material used to manufacture the SiC temperature monitor has a major impact on the radiation-induced swelling, and thus the ensuing peak irradiation temperature evaluation. Temperature monitors were fabricated from material meeting the Rohm Haas specification SC003. This material was produced via chemical vapor deposition (CVD) process with a high purity (99.9995%) and a density close the maxim theoretical. Using this characteristic, the SiC monitors were manufactured to exceed a resistivity >1000 ohm/m. SiC monitors used in the experiment were manufactured as cylinders with a 1 mm diameter and a 12.5 mm (±5 µm) length (reference Figure 1).

Figure 1. SiC temperature monitors available for use in irradiation testing include small rods and disks. Monitors photographed with U.S. penny for size perspective.

Methodology

HTTL uses resistivity measurements to infer peak irradiation temperature. SiC monitors may be evaluated for peak irradiation temperatures ranging from 150–800°C with a recommended dose ranging from 1–8 dpa (References 10–12).

Figure 2 depicts the equipment at the HTTL used to evaluate the SiC monitors. The SiC monitors are heated in the annealing furnace using isochronal temperature steps. After each isochronal annealing, the specimens are placed in a resistivity measurement fixture located in the constant temperature chamber (maintained at 40°C) for a minimum of 30 minutes. After the 30-minute wait time, each specimen's resistance is measured. The peak irradiation temperature evaluation was conducted in accordance with Reference 8.

Continued on next page

Continued from previous page

Figure 2. SiC evaluation system components.

Irradiation of the SiC Temperature Monitors

The reactor exposure was performed using the Basket for Material Irradiation (BAMI) rig of the BR2, Mol, using standard non-instrumented capsules. The cross section of the capsule is schematically shown in Figure 3. Each 15-mm-long stainless-steel section had four symmetrically located 1.1-mm-diameter channels, in which the SiC monitors were inserted.

The capsule has no active heating element; the temperature of the samples during irradiation is defined by the thermal balance between the radiation heat generation in the internal components and heat transfer through the He gas gap, and the aluminum body to reactor cooling water. Temperatures were calculated with an analytical model and verified using ANSYS numerical simulations. Calculated peak irradiation temperatures are presented in Table 2. DPA calculations were completed using flux outputs from MCNP and displacement cross sections from SPECTER. SPECTER is a computational tool developed at Argonne National Laboratory to assist in material damage calculations [13].

Two identical capsules were prepared. The capsule M1 was exposed during two cycles and the capsule M2 during only the first cycle. The irradiation was performed by placing the capsules inside BR2 driver fuel elements with a high burn-up located in the same channel for both cycles. The estimated irradiation conditions are given in Table 1. The gamma-heating levels in the irradiation channel during the two cycles were nearly identical, which means that the temperatures of the samples were also nearly the same. The difference in the neutron fluxes of ~10% is related with a lower fuel burn-up in the second cycle.

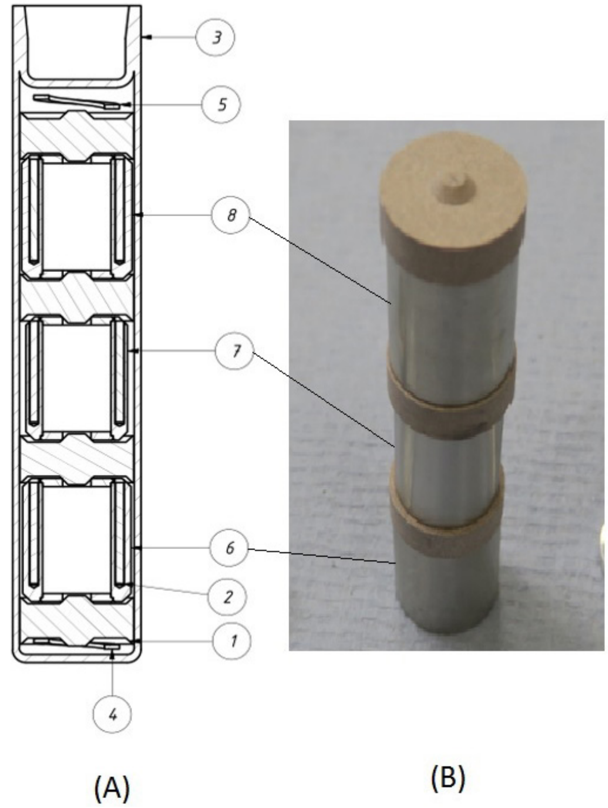


Figure 3. (A) Cross section of the aluminum irradiation capsule (3), stainless steel holders (6, 7, and 8) for SiC monitors (2). The holders are separated with ceramic discs (1) which are held in place with springs (4 and 5). (B) Photograph of the three holders and the three ceramic spacers before irradiation.

BR2 Cycle Information		Cycle 1 (1/31/17)	Cycle 2 (3/14/17)
Reactor Power [MW]		55	55
Cycle Length [days]		21	28
Fuel Burnup		42%	28%
φth	n/cm2/s E<0.5eV	3.27E+14	3.03E+14
φfast	n/cm2/s E>0.1MeV	3.93E+14	4.41E+14
Q	W/g (in Al)	10.1	10.3
Φtotal	n/cm2	7.13E+20	1.07E+21

Table 1. BR2 irradiation environment.

Continued on next page

Continued from previous page

SiC Temperature Monitor Evaluations

An ohmic response curve was generated for each monitor prior to heating. Monitor M1-High-A exhibited a typical ohmic response and is displayed in Figure 4. These data were used to check for linearity and to select a target voltage (with corresponding current) that would result in minimal heating of the SiC monitor during resistance testing and remain within the range of the test instrumentation.

Figure 5 represents typical resistivity data taken at each isochronal annealing temperature for each SiC temperature monitor. The peak irradiation temperature using an electrical resistivity technique can be taken as the point where the resistivity begins, and consistently remains, above the error band. The error band bounds the data and is represented by the dotted lines. For this evaluation the error band was established as the ±2σ value based on a sample size of the first five data points taken below 150°C.

Table 2 shows the results for the evaluation. The calculated verses measured peak irradiation temperatures had good agreement comparable to published data (see References 1–3). This result is significant considering that the received doses were less than 1 dpa.

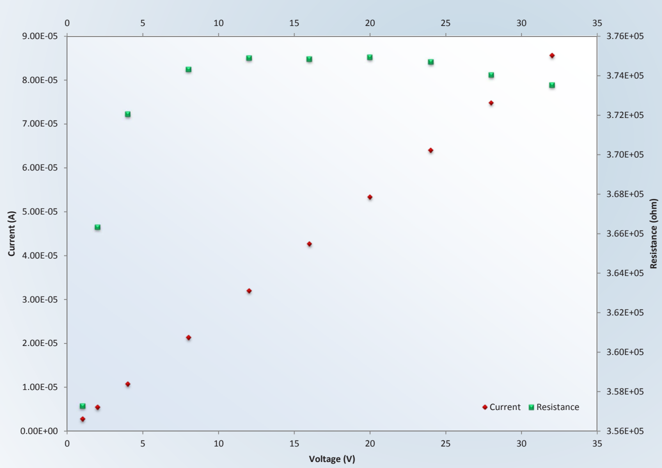


Figure 4. Typical ohmic response as demonstrated by SiC temperature monitor M1-High-A.

All of the monitors responded well with the exception of the BR2 M2-Low-A (see Table 2). This temperature monitor received the lowest dose (0.5–0.6 dpa) and was exposed to the lowest temperature (255°C). There are several factors that may be considered as to why M2-Low-A did not respond to the isochronal heating. Further analysis such as microscopy, three-dimensional computed tomography, and material analysis could be used to determine why M2-Low-A did not respond.

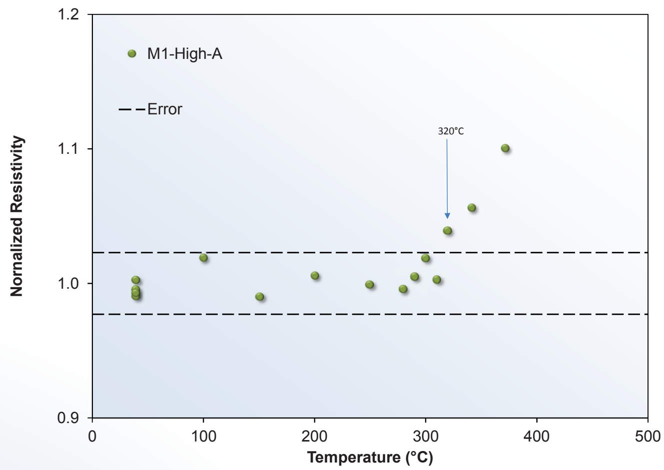


Figure 5. Resistivity data for BR2 M1-High-A.

Conclusion

SiC temperature monitors were irradiated in BR2 as part of an NSUF Project and evaluated at the HTTL to determine their peak temperature achieved during irradiation. Each monitor was evaluated using the resistance measurement method. SiC monitors may be evaluated for peak irradiation temperatures ranging from 150 to 800°C with a recommended dose ranging from 1 to 8 dpa (References 1–2). For this evaluation, the temperature criteria was met, but it is significant to note that some doses were well below the minimum value of 1 dpa. Deviations between calculated temperature and evaluated temperature were within or near published limits, even for doses less than 1 dpa.

Continued on next page

	Dose	Temperature[°C]		%
ID	[dpa]	Calc.	Meas.	Dev
M1-Low-A	1.4	255	240	-6%
M2-Low-A	0.5	255	Indet.	n/a
M1-High-A	1.4	310	320	3%
M2-High-A	0.5	310	330	6%
M1-Med-A	1.4	410	390	-5%
M2-Med-A	0.5	410	380	-8%

Table 2. Evaluation results for the BR2 monitors.

Continued from previous page

References

1. J. L. Rempe, K. G. Condie, D. L. Knudson, and L.L. Snead, Silicon Carbide Temperature Monitor Measurements at the High Temperature Test Laboratory, INL/EXT-10-17608, January 2010.

2. L L. Snead, A. M. Williams, and A. L. Qualls, "Revisiting the use of SiC as a Post Irradiation Temperature Monitor," Effects of Radiation on Materials, ASTM STP 1447, M L. Grossbeck, Ed, ASTM International, West Conshohocken, PA, 2003.

3. A. A. Campbell, W. D. Porter, Y. Katoh, L. L. Snead, "Method for Analyzing Passive Silicon Carbide Thermometry with a Continuous Dilatometer to Determine Irradiation Temperature," Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 370, March 2016, pp. 49–58

4. N. F. Pravdyuk, V. A. Nikolaenko, V. I. Kapuchin, V. N. Kusnetsov, in: Ed. D. J. Littler, Proceedings of the Properties of Reactor Materials and the Effects of Radiation Damage, Butterworths, 1962, p. 57.

5. J. I. Bramman and A.S. Frazer, W.H. Martin, J. Nuclear Energy, Vol. 25, 1971 p. 223.

6. H. Suzuki, T. Iseki, and M. Ito, "Annealing Behavior of Neutron-Irradiated Beta-SiC," Journal of Nuclear Materials, Vol. 48, No. 3, 1973, p. 247.

7. J. E. Palentine, "Development of Silicon-Carbide as a Routine Irradiation Temperature Monitor and its Calibration in a Thermal Reactor," Journal of Nuclear Materials, Vol. 61, No. 3, 1976, pp. 243–253.

8. K. L. Davis and T. C. Unruh, "Silicon Carbide Temperature Monitor Evaluation." PLN-3473, Rev. 2, Idaho National Laboratory, February 2018.

9. A. Al Rashdan, K. Davis, T. Unruh, and J. Daw, "Silicon Carbide Temperature Monitor Online Evaluation," PLN-5465, September 2017.

10. K. L. Davis, B. M. Chase, T. C. Unruh, D. L. Knudson, J. L. Rempe, Drexel University Temperature Sensors, INL/EXT-14-33067, September 2014.

11. B. M. Chase, J. L. Rempe, K. L. Davis, Evaluation of Temperature Sensors form the EPRI Zirconium Growth Irradiation Tests, INL/LTD-14-32210, June 2014.

12. K. L. Davis, D. L. Knudson, J. L. Rempe, and B. M. Chase, University of Illinois Temperature Sensors, INL/EXT-14-33136, September 2014.

13. L. R. Greenwood and R. K. Smither. SPECTER: Neutron damage calculations for materials irradiations, Technical report, Argonne National Laboratory, ANL-FPP/TM-197, 1985.

Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure

S. Derek Rountree
Luna Innovations Incorporated

New nuclear power generation is an important non-fossil fuel option to meet future global electricity demands. To ensure public safety and maintain energy security, the new reactors must be significantly safer and more efficient than previous designs. The Gen-IV design initiative is driving the development of the next generation nuclear plants (NGNP) with designs such as the molten salt reactor (MSR), sodium-cooled fast reactor (SFR), lead-cooled fast reactor (LFR), very high temperature reactor (VHTR) and supercriticalwater-cooled reactor (SCWR).[1] These reactors will operate at temperatures between 500°C and 1200°C, allowing them to operate with higher efficiencies than their predecessors, and provide the required heat to produce hydrogen in large quantities without producing additional CO_2.[2] The safe and efficient operations of these systems will require pressure and temperature sensors that can survive in the harsh enviroments of the proposed Gen-IV reactor designs.

Thus, Luna is developing and validating a reliable, high-temperature, radiation-tolerant sensor that provides many inline temperature measurements and high-accuracy pressure data using only a single optical fiber (Figure 1). To Luna's knowledge, no such temperature or pressure measurement technology exists that is suitable for the planned Gen-IV reactor designs, though harsh environment single point thermocouples have been developed [3]. Current temperature sensors in-core are generally Type-K thermocouples; however, these sensors are single point, experience green-rot in hydrogen-oxygen atmospheres, experience drift at high temperatures, and are electrically conductive, which is non-ideal for liquid metal-cooled reactors. Accurate temperature measurements are needed to identify hot spots, control thermal cycles, and perform temperature compensation of other sensors. Reliable pressure measurements are needed to assure material stresses are kept within design limits and to validate fluid flow designs in the plants' flow loops. Therefore, it is critical to have accurate temperature and pressure sensors to safeguard operation of these reactors.

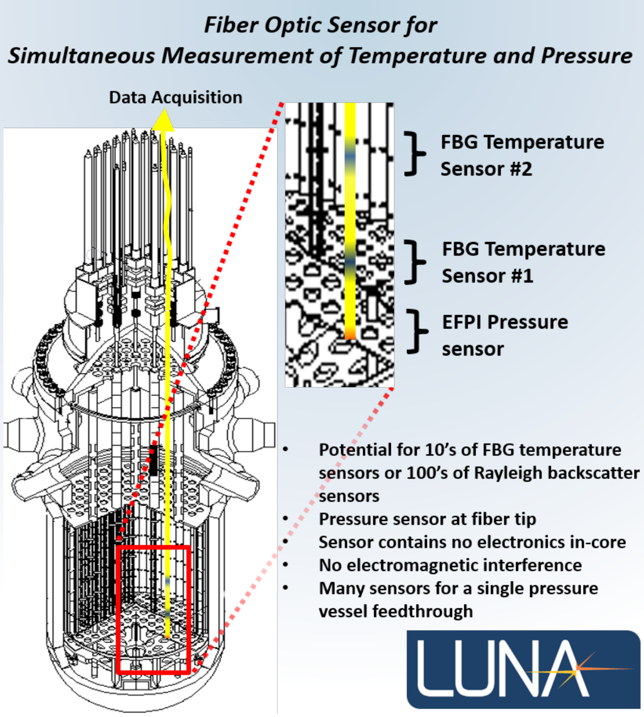


Figure 1. Concept diagram describing planned inline multipoint temperature and endpoint pressure fiber optic sensor.

Objectives

Luna's objectives for this program are toward the development of inline temperature and pressure sensors for the advancement of Gen-IV nuclear power, Luna Innovations, funded by the United States Department of Energy (DOE) Small Business Innovation Research (SBIR) Phase I Program contract number DE-SC0017826. Luna's Phase I objectives included successful demonstration of inline temperature and pressure measurements independently in the laboratory environment, in a reactor environment to a neutron fluence of 10E18 n/cm_2 and to a combined temperature and pressure of 275°C and 2500 psi—additionally temperature sensors were successfully tested to 1000°C. The recently selected DOE SBIR Phase II proposal will provide for the development of high-temperature fiber optic pressure feedthroughs, refinements to sensor analysis, advancements in sensor packaging for Gen IV molten salt and molten metal environments, and demonstration of sensor performance at:

- 300°C at 3500 psi
- 525°C at 100 psi
- 1019n/cm_2 fluence.

Luna's innovative inline radiation resistant temperature and pressure sensor technology

The recent development of radiation-hardened femtosecond-laser-written Fiber Brag Gratings (fsFBG/FBG) [4] and the development of Luna's harsh environment Extrinsic Fabry-Perot Interferometer (EFPI) sensor [5] lead to the sensor concept of combining the two for nuclear application. Figure 2 top shows the wavelength dependent reflection coefficients for a dual-FBG, and EFPI at 0°C and 100°C and with an EFPI gap of 120 µm and 160 µm. Figure

Continued on next page

Continued from previous page

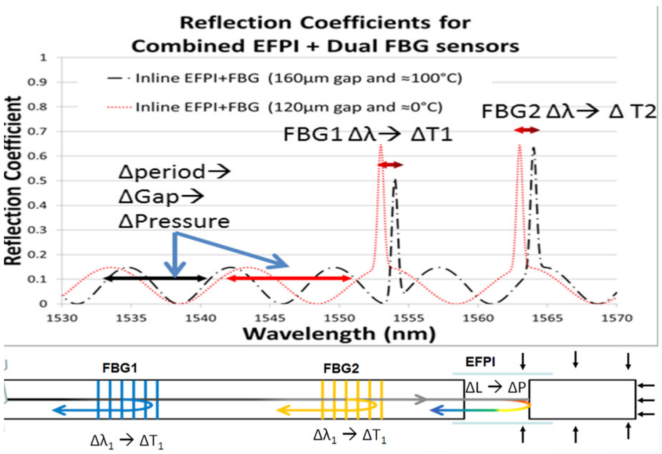


Figure 2. (Left) EFPI, FBG and combined EFPI+FBG sensor response for an EFPI gap of 120 µm and 0°C. (Right) The same sensor at the same conditions and the sensor undergoing a change in pressure that causes the EFPI cavity to transition from 120 µm to 160 µm with a change in temperature of 100°C.

2 illustrates the sensor design, showing two FBGs written in the fiber and an EFPI gap constructed at the fibers tip. The FBGs strongly reflect light at a single wavelength that increases to first order linearly with temperature. The EFPI reflection coefficients are a fringe pattern. As the EFPI gap shrinks due to increased pressure, the wavelength range between the fringe maxima increases.

Current Status

Luna completed the "Fiber Optic Sensor for Simultaneous Measurement of Temperature and Pressure" DOE SBIR Phase I project successfully in the spring of 2018, and will tentatively begin the Phase II program in late August 2018. The Phase I project independently demonstrated the fsFBG sensor performance to 1000°C and to 9.18E17 n/cm2 fluence and combined fsFBG-EFPI sensor performance to 9.18E17 n/cm_2 fluence, and to combined temperature and pressure of 275°C and 2500 psi. The variance, from an empirically determined model, in temperature for tests from 20°C to 1000°C was ±4.4°C. Figure 3 shows the sensor spectral response for a combined fsFBG-EFPI sensor interrogated with Luna's OBR 4600. The blue trace shows

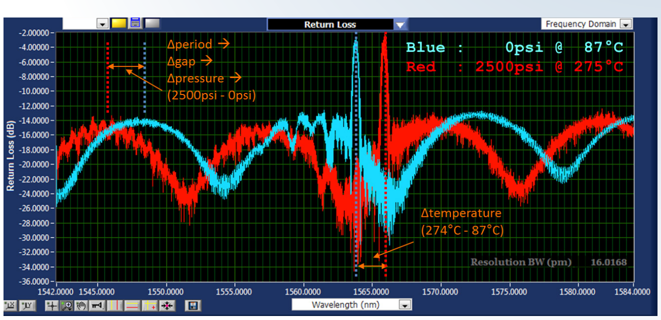


Figure 3. Two Luna OBR 4600 scans of an inline fsFBG and EFPI during pressure tests at Luna's facility in Blacksburg, Va.

a scan at 0psi and 87°C and the red trace shows a scan at 2500psi and 275°C. The fsFBG peak wavelength clearly shifts to higher wavelength going from 87°C to 275°C, and the EFPI fringe shifts between the blue and read traces. The temperature compensated pressure measurement is still being worked out and will be reported via publication early in the Phase II program. Comprehensive results on the high temperature measurements and combined temperature and pressure measurements will be published in the future. The following section provides results from tests at The Ohio State University Research Reactor, where sensors were irradiated to 9.18E17 n/cm_2 fluence, Figure 4.

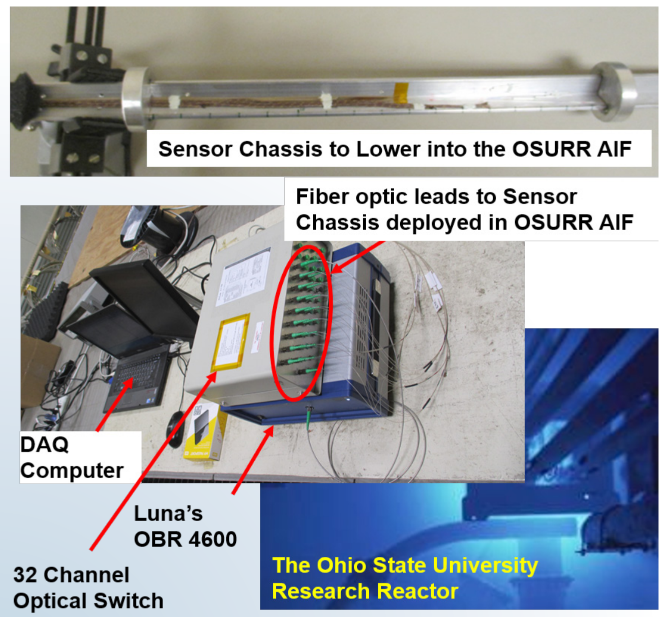


Figure 4. Test setup for irradiation tests at The Ohio State University Research Reactor (OSURR) (Top) Chassis holding 17 fiber sensors. (Middle) DAQ system with 32 channel switch. (Bottom) OSURR in operation.

FBG analysis

After converting delay domain data from Luna's OBR 4600 to frequency domain data for each FBG, the spectrum was ran through a peak finding algorithm to determine the fsFBG wavelength. A sample of the FBG temperature response, while being irradiated to a total neutron fluence of 9.18E17 n/cm_2, is shown in Figure 5 (top) with thermocouple measurements. In addition to analysis of the FBG-wavelength, the team also looked at the FBG reflection amplitude as a function of neutron fluence. The response of the F101 fiber type shown in Figure 5 top showed a reduction in amplitude of 6E-21 (1/mm * 1/(neutron/cm2)) with initial reflection amplitude of 0.25/mm. This reduction in detected light is believed to be caused by a decrease in transmission through the fiber and not a change in the fsFBG reflectivity.

Continued on next page

Continued from previous page

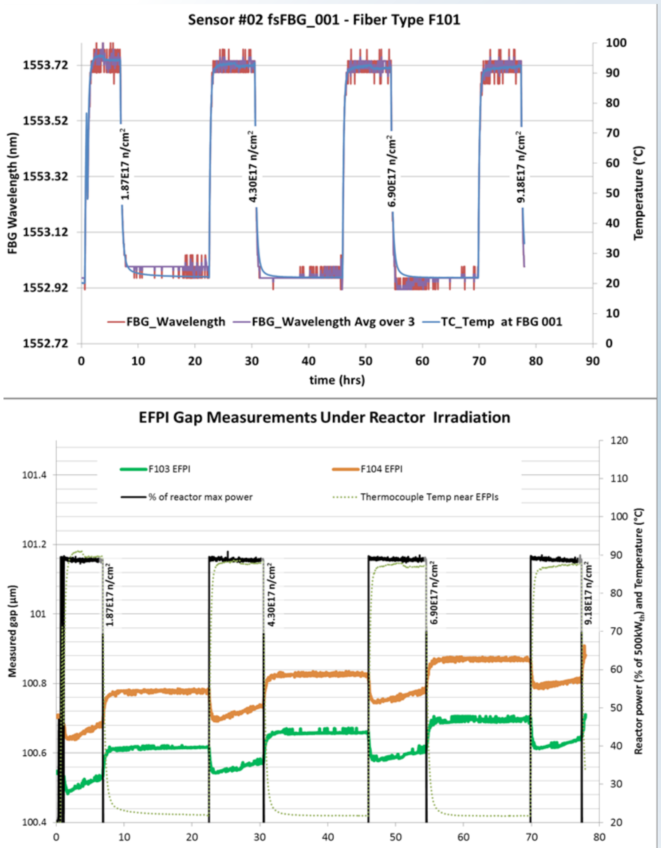


Figure 5. Sensor measurements while being irradiated at OSURR. Irradiation occurred over four days with approximately eight hours of reactor operation each day. (Top) Comparison of FBG Wavelength and thermocouple response for F101 fiber type (Bottom) EFPI response during reactor operation.

EFPI analysis

During the data acquisition (DAQ), the DAQ software performed a Fourier transform of the sensor fringe data, and extracted the peak of this Fourier transform, from which the EFPI gap is estimated. Gap measurements, temperature, and percent of max reactor power are plotted against time in Figure 5 bottom. As the sensors are not being actively pressurized in this test, the response should be relatively flat for the EFPI gap. The deviations from flat are due to the temperature dependence of the EFPI components—thermal expansion of glass and air within the EFPI cavity. The measurements of EFPIs on sensors for F103 and 105 are stable with a gap change of ~0.1 µm (~50 psi) during reactor on-off cycles.

Conclusions

This Phase I research effort successfully showed the feasibility of combining radiation tolerant fsFBG temperature sensors and EFPI pressure sensors. The initial results of this study show great promise for future high-temperature radiation-resilient multipoint temperature and pressure sensors. During Phase II, Luna will develop a more thorough analysis of Phase I data, including analysis for irradiated Rayleigh scatter-based temperature sensors, develop precise pressure-temperature compensation matrices, identify additional radiation resilient fibers, and test sensors at high temperatures for extended periods of time and to a neutron fluence of 1E19 n/cm$_2$.

References

[1] Gen-IV, Generation IV Systems," Gen-IV International Forum, 2017, https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

[2] INEEL, Next Generation Nuclear Plant Research and Development Program Plan, Idaho National Laboratory, Oak Ridge National Laboratory, Argonne National Laboratory, January 2005, INEEL/EXT-05-02581.

[3] Rempe, Joy L., Darrell L. Knudson, Keith G. Condie, and S. C. Wilkins "High Temperature Thermocouple Design and Fabrication," U.S. patent filed by Battelle Energy Alliance (IDR #BA-142) on behalf of DOE (Serial Number 11/678,901), published by US PTO as No. 2008/0205483 and issued January 18, 2011, Patent 7871198.

[4] Loptek & FemtoFiberTec, "Fiber Optic Solutions for Sensing in Extreme Environments," 2016.