Advanced Sensors and Instrumentation

Issue 18 • April 2023

ASI Program Update

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This marks the 18th newsletter sent out by the U.S. Department of Energy Office of Nuclear Energy (DOE-NE) Advanced Sensors and Instrumentation (ASI) program, and is the first of two newsletters planned for fiscal year (FY) 2023. The ASI program's goal is to further the development and deployment of advanced sensor and instrumentation technologies for ensuring safe, efficient operation of current and future nuclear power plants, and for supporting irradiation experiments conducted in research reactors and material test reactors.

Over the last 11 years, the ASI program has fostered the development and commercialization of a wide range of technologies, spanning the inception of novel sensing methods as well as enhancements made to various types of instrumentation featuring a long history of commercial utilization. The program has provided over $58M in RD&D funding to help support the missions of both DOE and DOE-NE. Sensors developed under the ASI program have been used in support of other DOE-NE programs and have even been commercialized for nuclear industry adoption.

The ASI program's 2022 Annual Review meeting was held virtually from October 24 to October 27, 2022, showcasing the various technical accomplishments that have been made, and discussing the status of active R&D activities being conducted by participating universities, national laboratories, and industry collaborators.

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For more program information, including recent publications, please visit www.asi.inl.gov

U.S. DEPARTMENT OF ENERGY

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The content was organized into the following four sessions:

- Sensors for Irradiation Experiments, focusing on technologies necessary for conducting instrumented experiments in research reactors and material test reactors, but that have limited application to power plants.
- Sensors for Advanced Reactors, focusing on the maturation of innovative technical solutions for advanced reactor instrumentation.
- Sensor Integration, focusing on integrating sensors in advanced reactor instrumentation and control (I&C) systems.
- Small Business Innovation Research (SBIR) / Industry Funding Opportunity Announcement (FOA), showcasing the results generated by industries engaged in ASI R&D activities.

The meeting agenda, the presentations, and recorded videos of each session are available on the ASI program website via the following link: https://asi.inl.gov/researchlibrary.

The ASI program website has been significantly improved in terms of user experience. The content is regularly updated and has been expanded to include a list of recent publications on work funded by the ASI program. This list includes a selection of technical reports as well as links to journal publications. Fact sheets detailing laboratory capabilities relevant to ASI program activities are also provided, when available. The website links to the Nuclear Energy Sensor (NES) database (see Sensors for Nuclear Applications at Your Fingertips! | Nuclear Energy Sensors (NES) Database). A discussion on the status of this database is included in the "Nuclear Energy Sensors Database" contribution to this newsletter.

In the first quarter of FY-23, directed research projects funded by the ASI program completed, on time, three high-level milestones and the associated deliverables, along with a total of 16 lower level ones. The Level 2 deliverables included reports on high-temperature testing of miniature fission chambers in the Ohio State University Research Reactor (OSURR), fiber-optic pressure sensor testing in INL's Transient Reactor Test (TREAT) Facility, and the effort to establish a commercial U.S. supply chain for linear variable differential transformers (LVDTs). Among the noteworthy deliverables completed in 2022 were two reports—"Assessment of Acoustic Sensor Application to Structural Health Monitoring of Reactor Components" (Dec. 2022, co-authored by INL, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and EPRI) and "Integration of Control Methods and Digital Twins for Advanced Reactors" (Nov. 2022, authored by INL, with support from Argonne National Laboratory)—that provided the technical basis for planning future ASI program research activities.

Five competitively awarded projects were also completed in the first quarter of FY-23. A harvesting assessment for transitioning to directed research for maturation and/or commercialization was successfully performed. The project titles and performing institutions are as follows (more information on the project scopes is given in the Summary of Accomplishments for 2022, and can be found for earlier years by viewing the ASI program website's research library):

- High Temperature Embedded/Integrated Sensors (HiTEIS) for Remote Monitoring of Reactor and Fuel Cycle Systems (North Carolina State University)
- Radiation Effects on Optical Fiber Sensor Fused Smart Alloy Parts with Graded Alloy Composition Manufactured by Additive Manufacturing Processes (University of Pittsburgh)
- Acousto-optic Smart Multimodal Sensors for Advanced Reactor Monitoring and Control (Pacific Northwest National Laboratory)
- Design of Risk-informed Autonomous Operation for Advanced Reactors (Massachusetts Institute of Technology)
- Context-Aware Safety Information Display for Nuclear Field Workers (Arizona State University).

In addition to the annual review meeting, the ASI program performs monthly status reviews of directed research and competitively awarded projects, mid-year reviews of industry contributions, and technical workshops dedicated to specific research areas of interest to the program. Documents from the technical workshops are also listed in the Program Review section of the ASI program website's research library. However, the intention moving forward is to summarize the workshop outcomes in future issues of this newsletter, beginning with the 19th edition in the fall of 2023. That particular issue will collect contributions stemming from a planned workshop at Argonne National Laboratory (tentatively scheduled for July 12 and 13, 2023) on advanced control methods for advanced reactors.

While this issue of the newsletter still features contributions from different technical areas in which the ASI program is engaged, it focuses on the application of advanced instrumentation to experiments being conducted at INL's TREAT Facility. TREAT is a research reactor for conducting experiments on nuclear fuels and materials under extreme conditions. It is capable

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of simulating various transient conditions that occur in nuclear reactors (e.g., power transients and loss-of-coolant accidents). To conduct experiments in the TREAT Facility, advanced instrumentation and sensors are needed for measuring parameters such as temperature, pressure, neutron flux, and radiation levels. Such measurements are critical for understanding the behavior of nuclear fuels and materials under extreme conditions, as well as for developing enhanced models for use in reactor safety analyses. At the same time, sensors and instrumentation being developed under the ASI program are tested as part of the TREAT experiments and discussed in the contribution titled "Instrumentation under Extreme Conditions in TREAT", as well as in other available locations affording flexible access discussed in the contribution titled "Deployment of Fiber Optic Sensors in TREAT experiments".

Instrumentation under Extreme Conditions in TREAT

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Last fall marked the fifth-year anniversary of the restart of Idaho National Laboratory's Transient Reactor Test Facility (TREAT), following a 23-year period of dormancy. A remarkable effort was made to revitalize the facility and build an R&D program that tapped into long-neglected research needs, both domestic and international. This transient testing program has rapidly grown to include five primary experimental testbeds operated for Department of Energy programs and for various industry and international collaborators. These testbeds encompass light-water reactor fuels (accident-tolerant fuels and burnup extension efforts), sodium fast reactor fuels, nuclear thermal propulsion, other types of advanced reactor fuel designs, national security projects, in addition to a platform for in-pile instrumentation testing and development.

A crucial aspect of conducting transient testing on nuclear fuels and materials is in-situ diagnostics, necessary to unravel the complex evolution of these experiments. The program now executes dozens of highly instrumented experiments each year in order to accomplish a diverse range of technical goals, the most important being to advance the understanding of nuclear fuel safety and performance. This approach has impacted other Department of Energy test reactors by helping them overcome barriers to in-pile testing and various advanced sensor applications.

TREAT is a transient power-shaping reactor whose primary mission is to enhance safety performance by testing nuclear fuels and materials under thermodynamic and neutronic conditions ranging from off-normal to extreme. Transient testing of nuclear fuels is analogous to car crash testing, in that the dramatic changes commonly seen when comparing the test specimens' initial and final state points necessitate in-situ measuring in order to interpret and understand the evolution of the experiment. TREAT's experiment design strategy utilizes a highly reconfigurable and accessible reactor core that affords flexibility when installing experiment devices, thanks to the lack of a primary coolant boundary and the inclusion of multiple access points in the reactor bioshield. Within the experiment devices, the test specimens (which are integrated with their test environments), desired instrumentation diagnostics, and safety considerations are all contained in a single engineered package. The experiments encompass various types of environments (e.g., water, sodium, and gas at temperature and pressure), as well as a range of control options (e.g., static or flowing coolants). The experimental conditions are uniquely representative of advanced reactors, providing challenges to sensor performance but also affording a unique opportunity for development and qualification of sensors suited to these environments.

In early 2018, TREAT re-opened its doors for experimental testing. A key strategy for meeting the goals of the experiments was to incorporate a variety of crucial sensors and data acquisition technologies into the facility, starting at this earliest opportunity. The reactor and its safety basis enabled a streamlined approach to sensor deployment, with instrument-friendly access to the core (as there was no pressure boundary to pass), relatively short lead wire runs, and a conveniently located data acquisition system right next to the reactor yet outside the radiation buffer area. Nearly every transient irradiation performed since the restart has entailed a multitude of instruments, including self-powered neutron detectors (SPNDs), linear variable differential transformers (LVDT), ultrasonic sensors, and optical fibers. Prompt-response SPNDs were an initial target for TREAT testing, as their simple, robust design and ability to measure thermal neutrons via a fast temporal response on the scale of sub-milliseconds are well-suited for TREAT applications. The sensors demonstrated excellent performance, providing unique insights into the local TREAT flux, which can reach up to 10^{17} n·cm^{-2}·s^{-1} during high-power transient pulses.

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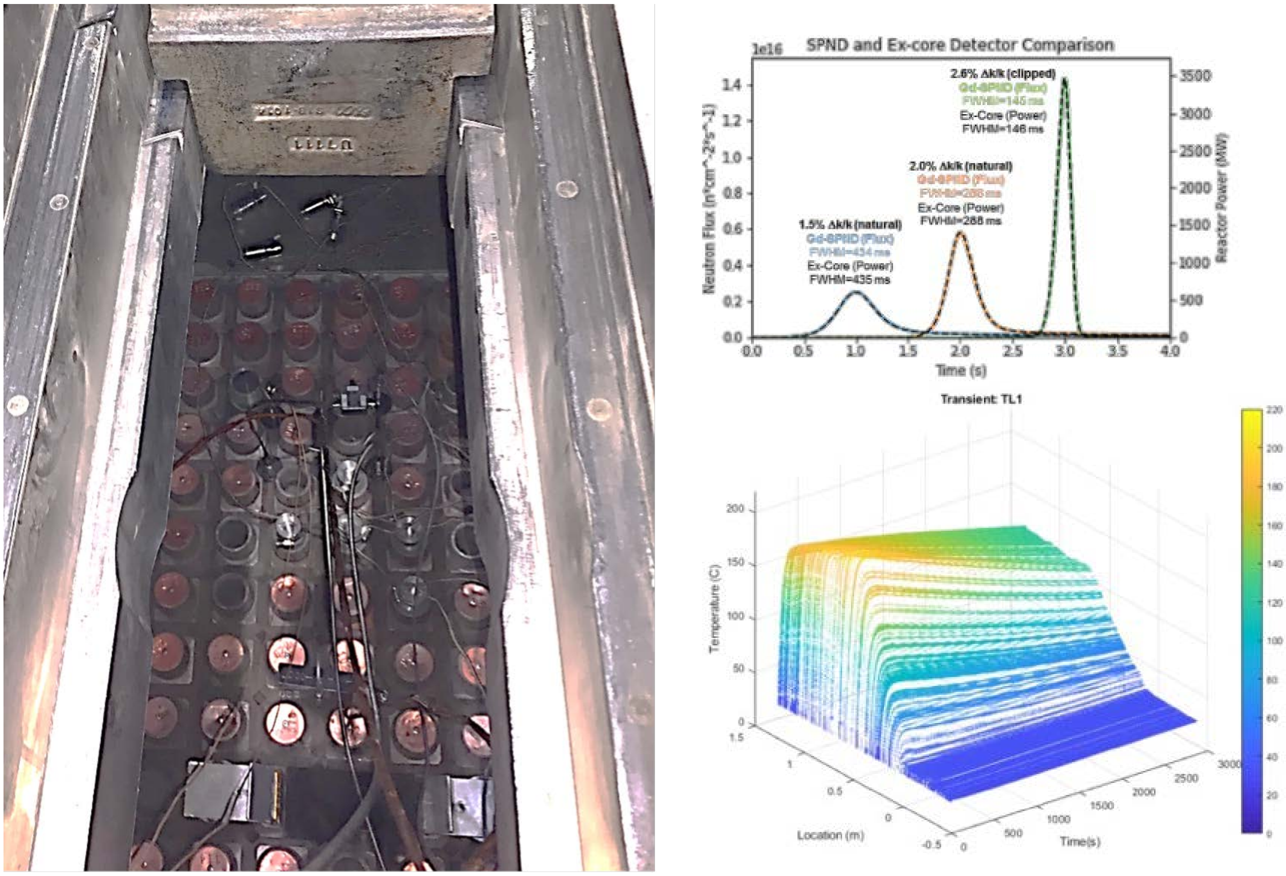

Figure 1. Testing of in-core sensors at TREAT. (Left) Top view of the TREAT core assembly, loaded with instruments and showing lead wiring. (Right) Example data results from instrumentation testing in TREAT. The top plot compares data collected from a Gd-SPND to the measured reactor power. The bottom plot shows the axial core temperature measurements taken by a distributed temperature optical fiber sensor.

These sensors have measured the local neutron flux in nearly every transient performed in TREAT to date, and were selected as a development target for enabling a small business to begin fabrication and testing of Gd-SPNDs. Figure 1 presents a top view of the TREAT core—with a common arrangement of instrument leads protruding out—and gives examples of in-pile measurements performed to evaluate sensor performance.

Several experiment devices have been developed and deployed in TREAT. In the years since its restart, experiment sophistication and complexity have continually increased, creating new challenges regarding the accompanying instrumentation packages. Figure 2 shows a recent experiment involving a static sodium capsule. Around 60 individual leadwires/fibers exit the capsule through leak-tight seals. As is seen, the standard instrumentation includes distributed temperature optical fiber sensors, optical-fiber-coupled infrared pyrometer, thermocouples, linear variable differential transformers, and acoustic sensors. Due to its unique requirements, the experiment was custom-built and assembled at Idaho National Laboratory. Off-the-shelf sensors are used whenever possible, though several custom devices such as custom-built optical fiber cables and connectors are built in-house. A primary challenge in these experiments is the overall assembly logistics and the ability to ensure the leak tightness of the many feedthroughs accompanying these devices.

Over the past 5 years, dozens of experiments have been performed in TREAT, utilizing a wide array of instrumentation. Although, by and large, the sensors used in these experiments performed successfully, the

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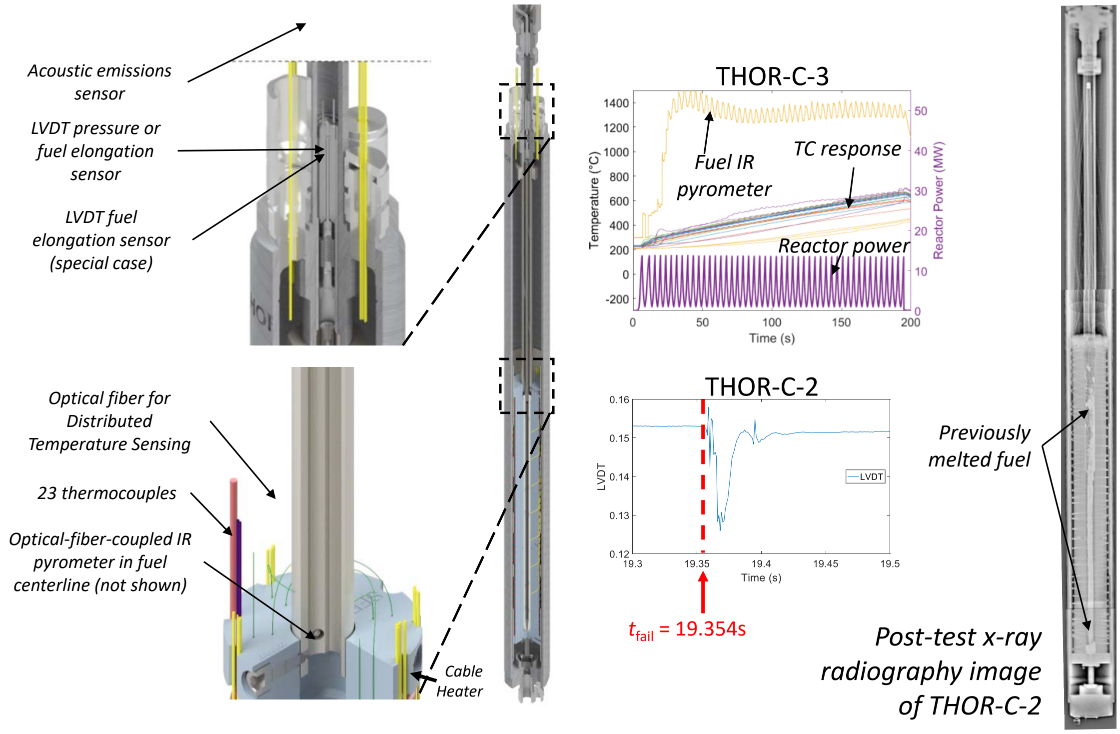

Figure 2. Example highlighting the instrumentation of a newly deployed sodium capsule used in TREAT. (Left) Capsule instrumentation design. (Right) Example data collected using this device.

designs have also included less mature, first-of-a-kind instrumentation to drive rapid maturation and readiness for application. As expected, experience with—and an increased understanding of—these devices has led to improved reliability and performance. Experiments performed last year on the TREAT sodium capsule serve to provide representative examples of sensor results (see Figure 2 for example data collected during some of the first experiments involving this capsule). Two of the first experiments conducted using this test device were performed on an advanced metallic alloy fuel. They were conducted to characterize fuel failure under extreme conditions, in addition to the thermal transport in the fuel. The data results from the first experiment, THOR-C-2, clearly reflect fuel failure and corroborate the data from the TREAT fuel motion monitoring system (not shown). Post-test radiography showed the final state of the fuel in the aftermath of the very extreme event with fuel melting and cladding rupture. The second experiment, THOR-C-3, was performed to characterize the thermal transport in the fuel. This experiment device was a complete measurement system that used thermal measurements, in combination with heat input from the reactor to extract the thermal properties of the fuel. The in-situ diagnostic equipment performed as desired, revealing the temporal sinusoidal temperature response of both the fuel and the surrounding metal. Detailed evaluation of the experiment results is underway, along with a series of non-destructive/destructive examinations to derive final conclusions and data for model benchmarking.

After 5 years of testing and development, in-pile instrumentation continues to play a central role in transient experiments. Much of this instrumentation has matured rapidly thanks to the steady development that has occurred thanks to the unique nuclear environments generated in TREAT experiments, and strategies applied to in-core testing in TREAT are now being extended to other test reactors (e.g., the Advanced Test Reactor) to accelerate the development of nuclear materials. The unique experimental capabilities developed at TREAT currently support a wide range of advanced reactor technologies still under development, and will aid in establishing licensing data to foster their eventual deployment. Future experiments in TREAT will rely on novel capabilities, building upon the progress achieved to date, to measure the challenging multiphysics characteristics of the environments it produces, and strategic development of such in-pile measurement devices is crucial for achieving success in this regard.

Linear Variable Differential Transformer (LVDT) Sensors in Transient Reactor Test Facility (TREAT) Experiments

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Introduction

Real-time pressure and dimensional changes in fuel and/or fuel cladding undergoing irradiation can provide insights into phenomena such as fuel/cladding elongation, the buildup of "crud," pressurization from fission gas release, and pellet-clad mechanical interaction. These phenomena can adversely affect fuel performance and/or heat transfer pathways away from the fuel. Therefore, in-situ measurements are critical for advancing the knowledge base on the effect of irradiation on advanced fuels/cladding and associated structural materials. Linear variable differential transformer (LVDT) sensors, known for their superior in-pile performance under irradiation, can provide micron-scale-resolution data for enabling fuel performance evaluations. Such high-resolution measurements require a careful understanding of not only the sensor itself but also the complete implementation strategy, including thermal conditions, hardware selection and design, and data processing. To evaluate sensor performance and achieve reduced sensor sizes and optimized sensor configurations, both numerical simulations and detailed experimental studies should be performed. Furthermore, transient irradiation testing requires fast response performance (~1 ms) from LVDT measurement devices, thus necessitating innovative data acquisition approaches that are distinct from the traditional systems employed at steady-state test reactors. Figure 1 shows a LVDT pressure transducer implemented in the Temperature Heat-Sink Overpower Response (THOR) irradiation capsule used at the Transient Reactor Test Facility (TREAT). This transducer can measure pressure spikes caused by fission gas release following fuel rod cladding failure.

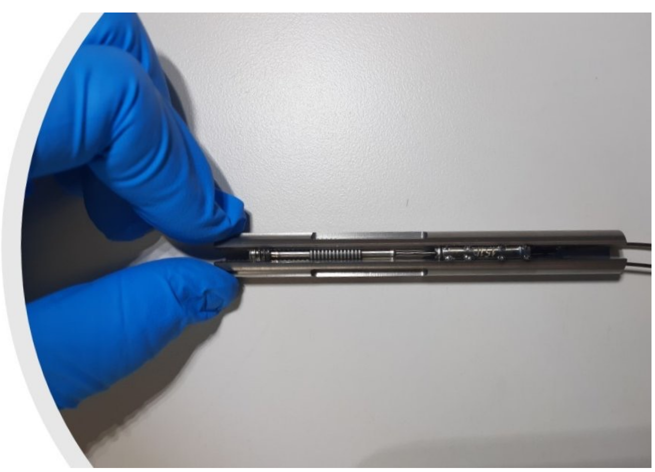

Figure 1. LVDT pressure transducer used in the THOR irradiation capsule at TREAT.

Methodology

The Institute for Energy Technology (IFE) is helping pioneer LVDT development for in-pile testing. In the time since IFE began conducting in-core measurements, over 2,200 different LVDTs have been installed in test rigs inserted into the Halden Boiling Water Reactor. Failure rates that remain under 10% after 5 years of operation are expected for IFE LVDTs operating in boiling-water reactor, pressurized-water reactor, or Canada Deuterium Uranium (CANDU) reactor conditions [1,2]. In June 2018, the Halden Boiling Water Reactor was permanently shut down, and budgets for fuels research and sensor development were eliminated. This forced IFE to limit the availability of their LVDTs, despite the fact that Idaho National Laboratory (INL) and the rest of the international in-pile testing community relied heavily on IFE to supply them with LVDTs and corresponding sensors. To mitigate this problem, INL researchers conducted a study [3] to identify other potential LVDT suppliers capable of meeting in-pile testing needs. Through this study, two potential suppliers—RDP Electrosense and Newtek Sensor Solutions—were identified. INL has begun to procure and evaluate these commercial LVDTs [4], and has developed a calibration and test rig specifically for evaluating LVDT-based sensors. The rig allows for both displacement and pressure calibrations at elevated temperatures (ranges: +/-12 mm, 20–1000°C, and 0–2800 psi). It is also capable of long-term motion testing and transient pressure evaluations.

Many LVDT evaluations have been performed using INL's LVDT test and calibration rig. Figure 2 shows the transient testing results for the above-discussed THOR LVDT pressure sensor. The red-colored data represent the LVDT pressure sensor; the blue-colored data represent a fast response Honeywell pressure sensor. The THOR LVDT pressure sensor performed well, though its initial response showed a slight lag (5 milliseconds) compared to the Honeywell sensor.

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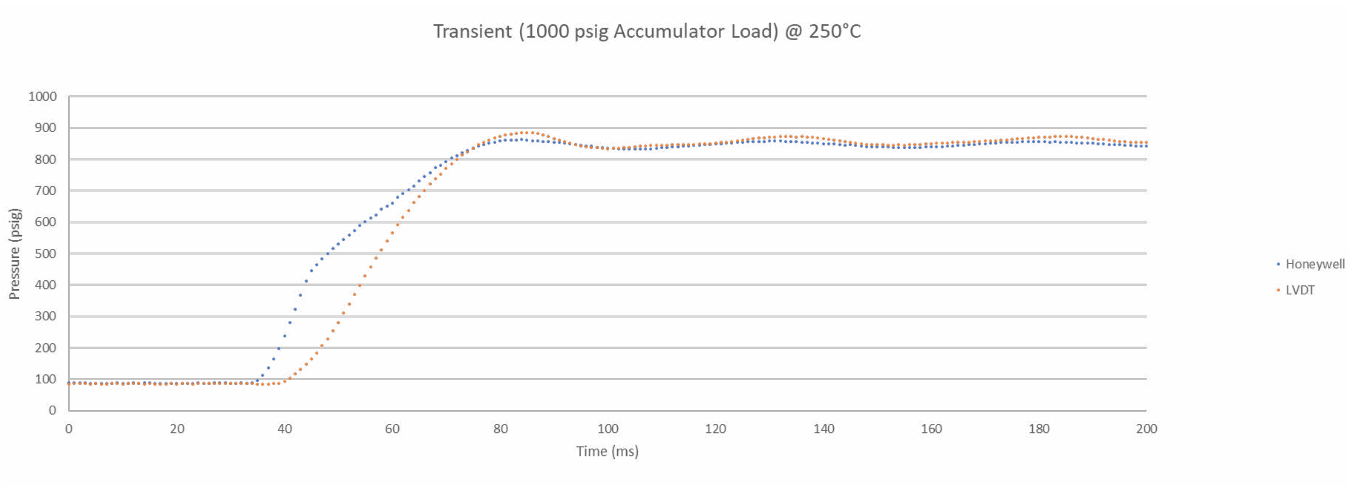

Figure 2. Transient testing of the THOR LVDT and Honeywell pressure sensors.

This is due to the larger inertial mass of the THOR LVDT sensor, which quickly recovered and was then able to keep up with the Honeywell pressure sensor.

Testing in TREAT has demonstrated the superior performance of LVDT pressure sensors. Pressure transducers similar to the Honeywell sensor have also been used in TREAT irradiation testing, but have yet to survive the initial power pulse generated by the reactor itself.

As mentioned, extensive data from the Halden Reactor Project reveal that failure rates of less than 10% after 5 years of operation can be expected for IFE LVDTs operating in boiling-water reactor, pressurized-water reactor, or CANDU reactor conditions. Such performance is phenomenal for any sensor under these conditions. The data suggest that if LVDTs are to be used, enhanced fabrication techniques and additional testing will be needed to meet the high demand of future in-pile tests. The high-temperature testing expected for the advanced test reactors will be limited by what is currently available for LVDTs. As things currently stand, reactor-grade LVDTs undergoing irradiation experimentation are rated to run from room temperature to as high as 700°C.

Conclusion

Development of new types of reactor-grade LVDT-based sensors are critical for supporting future tests conducted in material test reactors. Specifically, this pertains to TREAT testing conducted in support of near-term light-water reactor and liquid-metal experiments. The modeling and development of a wireless LVDT sensor will be integral of a successful deployment. High data acquisition speeds for LVDTs will also be required.

References

[1] S. Solstad and R. V. Nieuwenhove, "Instrument Capabilities and Developments at the Halden Reactor Project," Proceedings of the ANS NPIC HMIT 2009 Topical Meeting on Nuclear Plant Instrumentation, Controls, and Human Machine Interface Technology, Knoxville, TN, April 2009.

[2] K. L. Davis, D. L. Knudson, J. L. Rempe, J. C. Crepeau, and S. Solstad, "Design and Laboratory Evaluation of Future Elongation and Diameter Measurements at the Advanced Test Reactor," Nuclear Technology, Volume 191, pp 92-105, July 2015.

[3] K. L. Davis, "Assessment of Supply Chain for Nuclear LVDTs and Related Components Manufacturing," Idaho National Laboratory, INL-LTD-21-62217, 2021.

[4] K. L. Davis, A. Fleming, M. Wilding, Z. Deng, A. Draper, and J. Poorbaugh, "Status of Research Activities on LVDTs: Modeling and Simulation Development and Performance Characterization of Commercial LVDTs," Idaho National Laboratory, INL/RPT-22-69979, 2022.

Deployment of Fiber Optic Sensors in TREAT Experiments

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Sensors used for irradiation experiments are often required to be capable of withstanding harsh environments whose characteristics may include extreme temperatures, high levels of pressure, high-radiation fields, corrosive elements, etc. To meet the metrological needs of these experiments, a wide range of sensor technologies have been deployed. In recent years, a growing number of fiber-optic-based sensors have been utilized in these types of environments. In general, fiber optic sensors are attractive for use in irradiation experiments, thanks to their small size and high-speed contactless measurement capabilities. However, they are not without their own unique set of challenges, as they suffer from radiation-induced attenuation, emission, and compaction. These phenomena can adversely impact sensor performance, though careful sensor design can minimize this impact under specific conditions.

Experiments conducted at the Transient Reactor Test Facility (TREAT) generally involve—due to the reactor's transient nature—irradiations with a high flux but low neutron fluence. Therefore, radiation-induced attenuation and compaction are of little concern, though radiation-induced emission remains of high importance for many sensor technologies. Since the restart of TREAT, a wide range of fiber optic based sensors have been deployed in experiments including fiber-optic-based pyrometry, fiber Bragg gratings (FBGs), optical frequency domain reflectometry (OFDR) for distributed temperature measurements, Fabry-Perot pressure sensors, and imaging through a coherent fiber optic bundle. Currently, these sensor types all reflect varying levels of maturity and technology readiness.

One of the most mature and often deployed types of fiber optic sensor is the fiber optic pyrometer. This sensor measures surface temperatures by collecting the blackbody radiation emitted by the target, then analyzing it via a spectrometer or series of photodiodes. These signals are then interpreted in accordance with Planck's law. The non-contact nature of this measurement lends itself well to transient measurements, which often entail significant time delays due to sensor thermal response. Furthermore, this measurement neither thermally nor mechanically disturbs the target—something of high importance in many nuclear applications. Notable deployments of this sensor include its utilization in the Separate Effects Test Holder (SETH), Critical Heat Flux (CHF), and NASA-SIRIUS experiments. Figure 1 shows a photograph of the experiment and a summary of the data taken from the SETH experiment series, which provided a good demonstration of the high-temperature measurement capabilities of this sensor technology. These data demonstrate the capability of fiber optic pyrometry to measure extremely high-temperature conditions, including those that occur during cladding melting scenarios.

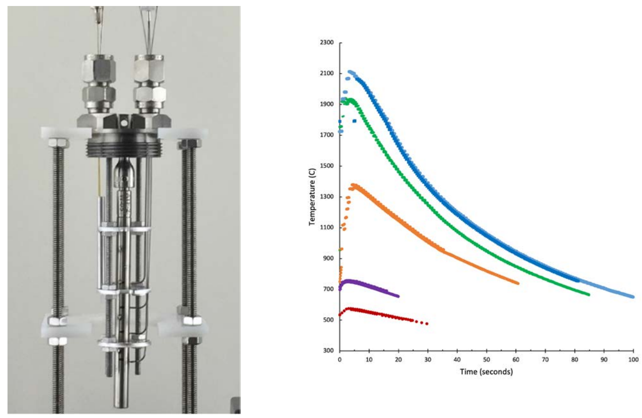

Figure 1. (Left) photograph of the SETH experiment in TREAT; (Right) summary of the data collected from the fiber-optic-based pyrometry used in that experiment series

In several irradiation experiments, distributed temperature measurements were taken via OFDR, which relies on natural imperfections in optical fibers to provide back reflections of light. These back reflections are dependent on the local temperature of the fiber. Though similar to the time domain reflectometry widely used in communications applications, OFDR instead utilizes a swept laser to encode the backscatter information in a frequency domain. This type of configuration allows for a temperature measurement spatial resolution on the order of 1 mm over the length of the optical fiber. This technology has predominately been applied to experiments that have a data objective requiring a lot of sensing locations featuring limited space and/or a limited number of feedthroughs. Good examples of such experiments are the Dry In-pile Fracture Test (DRIFT) and Temperature Heat-Sink Overpower Response (THOR) experiment series, both of which required significant spatial thermometry measurements throughout. To accomplish this, electrical discharge machining (EDM) was used to drill small holes throughout the heat sink at different radial and azimuthal

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angles. A single optical fiber was then routed through each hole by looping it back at each end of the heat sink and then threading it through the next hole in the sequence.

Figure 2 shows a photograph, along with some results obtained from this experiment. A fiber routing diagram identifying the hole number is shown in the upper-middle image in the figure. The test was preheated to about 130°C prior to the reactor transient. The plot on the upper right shows this uniform temperature distribution throughout the heat sink. At 10 seconds after the start of the transient, the heat generated in the fuel begins to transfer to the heat sink. The fiber segments in the innermost holes (i.e., holes 3, 5, and 8) begin to experience a temperature rise, while all the other holes remain at the preheat temperature. The temperature distribution at 35 seconds is shown in the plot on the bottom right of Figure 2. At that time, the heat begins to reach the outer radial locations, with the inner locations having already reached a significantly higher temperature. In all these plots, good axisymmetry and uniformity can be seen in the heating along the axis. Unfueled regions at the top and bottom of the test lead to the reduced temperatures at both ends of the heat sink. Overall, this is a powerful demonstration of the distributed temperature sensing capability of optical fibers. These data were all collected from a single optical fiber that requires only one feedthrough and leaves a very small overall footprint.

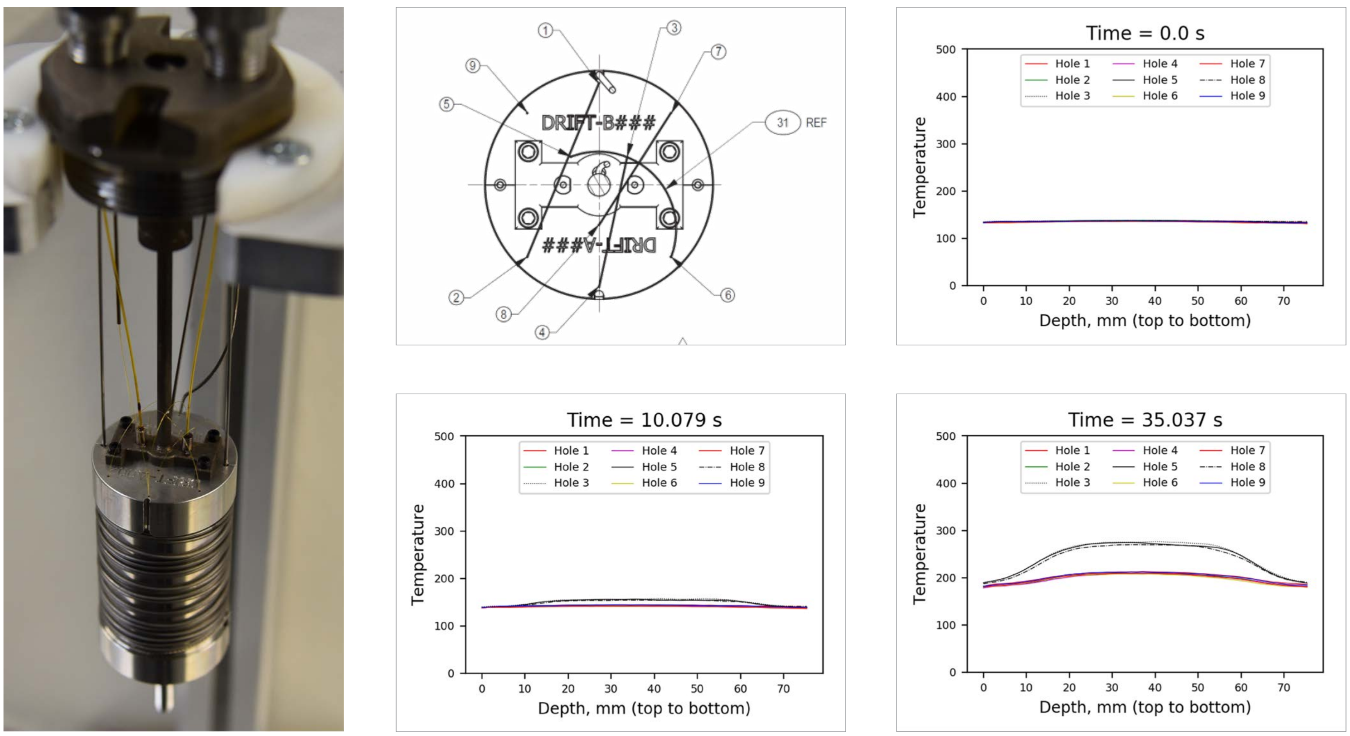

Figure 2. Photograph of the DRIFT experiment, fiber routing diagram, and three temperature "snapshots" at time = 0 seconds, = 10 seconds after the start of the transient, and = 35 seconds after the start of the transient.

Acoustic Emission Sensors in TREAT

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Introduction

Acoustic and ultrasonic sensors offer potential enhancements current measurement technologies that could potentially accelerate the development of fuels and materials for advanced reactor concepts. A key factor in the qualification of these fuels—and one that significantly impacts both fuel performance and safety—is the amount of energy a fuel pin (i.e., fuel and cladding) can absorb before experiencing failure. Fuel pins undergoing transient testing in the Transient Reactor Test Facility (TREAT) are tested to failure. The rapid nature of these tests makes determining the precise time of failure both crucial and highly difficult.

Acoustic Sensors in Irradiation Experiments

Acoustic and ultrasonic transducers can serve as a base technology in numerous types of sensors designed for measuring a multitude of parameters (e.g., temperature, gas pressure, and vibration). One drawback to using acoustic sensors in irradiation testing is that most piezoelectric materials have low tolerance to radiation and high temperatures. But although the Advanced Sensors and Instrumentation (ASI) program is working to develop sensors and transducers that can be used in such experiments, products currently on the commercial market may be feasible for use in transient testing at TREAT, where total doses are low and the required duration of survival is short.

Objective

In TREAT, a commercial acoustic emission (AE) sensor (namely, a Physical Acoustics D9215 sensor) was first employed during an irradiation of the Temperature Heatsink Overpower Response module (THOR) (see Figure 1). THOR allows engineers to test fuels in a liquid-metal-coolant environment relevant to advanced reactors. The long-term goal of AE sensor deployment is real-time detection of cladding failure caused by over-pressurization, pellet-cladding mechanical interaction, or pellet-cladding chemical interaction. Ideally, two sensors will eventually be employed in identifying not only the time of failure of the fuel pin (allowing for correlation between failure and power deposition), but also the location of failure. In future testing, a modified AE trigger system will be developed so that accurate time signatures of each event (e.g., cracking) can be obtained. Additionally, due to the high sensitivity of the AE sensors and noisy ambient environment, an additional AE sensor may be installed for background noise subtraction.

Current Status

As of this writing, only one AE sensor has so far been deployed. The experiment to which that sensor was applied was not a full-power transient, nor was it designed to cause fuel pin failure. Instead, the AE sensor was included to test survivability and enable characterization of potential sources of background noise. Ultimately, the sensor did indeed survive, yielding data corresponding to the period spanning the start of the transient all the way to the end of the test roughly 22 minutes later. A degree of electrical interference was also recorded. Analysis of these data will allow for enhanced test design in terms of electrical and acoustic isolation for future experiments.

Impact

While the long-term development of acoustic technologies under the ASI program targets increased tolerance for high-radiation and high-temperature applications, a commercially available sensor has been identified that can survive TREAT transients. Further refinement of the sensor installation will enable fuel pin failure times and locations to be determined. With the ability to install more sensors in future tests, detection of fuel pellet cracking may also be possible.

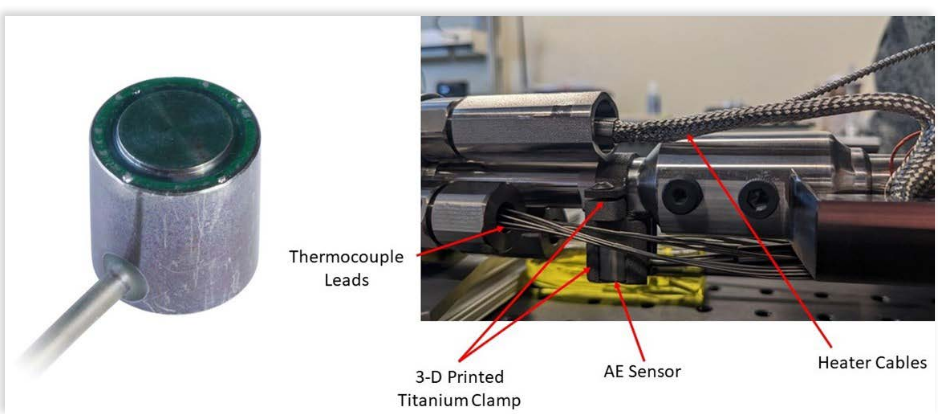

Figure 1. Acoustic emission sensor (left) and installation on THOR experiment (right).

Extreme Neutron Irradiation Testing of Advanced Sensor Technologies in ORNL's High Flux Isotope Reactor

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Introduction

The process of conceptualizing, designing, testing, and ultimately qualifying new sensor technologies for deployment in nuclear reactor applications requires significant investment and access to unique facilities. Perhaps the most critical aspect of the sensor qualification process is demonstrating acceptable performance during experimental testing in research and test reactors. Typically, sensor performance is first evaluated during testing in relatively low-power university research reactors, particularly when evaluating sensors with a relatively low technology readiness level. If this testing is successful, additional testing can be performed in facilities such as the Massachusetts Institute of Technology Reactor (MITR) to achieve neutron flux energy spectra similar to those of a commercial light-water reactor (LWR). However, some sensors can only be properly evaluated if they are tested in a higher neutron flux environment, either to reduce the time required to achieve end-of-life neutron fluence levels or to evaluate rate effects under a neutron flux energy spectrum that is more representative of some advanced reactor concepts.

In the United States, steady-state sensor testing under a fast neutron flux >2×10^{14} n/cm^2/s is possible only in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) and the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL), as shown in Figure 1. Thanks to its extremely high fast neutron flux (>10^{15} n/cm^2/s in some positions), the HFIR flux trap has long been considered the ideal location for performing accelerated irradiation testing of structural materials. More recently, separate-effects fuel irradiation tests have been performed to take advantage of HFIR's high neutron flux to accelerate burnup accumulation in small fuel samples [1].

ATR includes multiple flux traps with flow loops for testing LWR fuels and materials, as well as larger irradiation facilities for performing integral fuel irradiation testing for both LWR and advanced reactor applications. Both reactors have a history of incorporating sensors into experiments, but until recently, most experiments used only thermocouples for monitoring and controlling experiment temperatures.

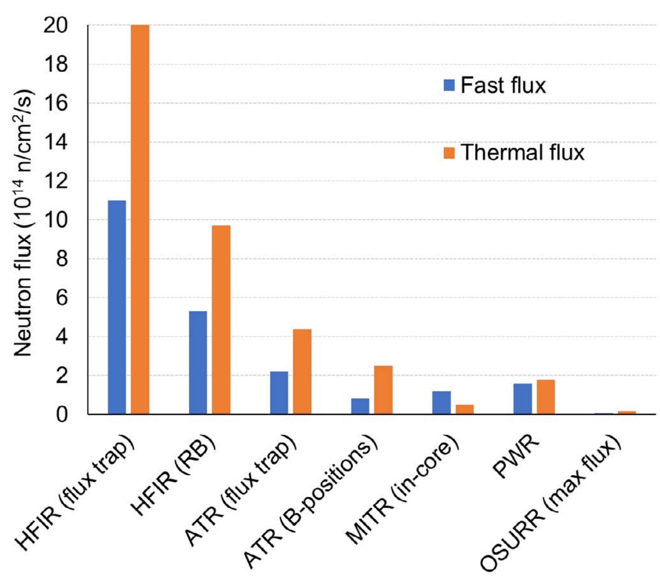

Figure 1. Neutron flux comparison for common reactors used for testing sensors spanning lower flux university reactors such as the Ohio State University Research Reactor (OSURR) to HFIR.

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Across the US Department of Energy Office of Nuclear Energy (DOE-NE), there is a consensus that advanced sensors could provide a wealth of data regarding the in situ performance of fuels and materials during irradiation testing as well as improved monitoring and control of commercial reactors. The Nuclear Science User Facilities (NSUF) program provides access to the facilities required to perform accelerated sensor irradiation testing. This article summarizes a recent NSUF award that has resulted in the deployment of new sensor technologies in instrumented experiments performed in the removable beryllium (RB) of HFIR to evaluate sensor performance under the highest steady-state neutron flux in the United States. DOE-NE's Advanced Sensors and Instrumentation (ASI) program is leveraging the investment by NSUF to support improved understanding of some of the sensors being tested in HFIR under these unique environmental conditions.

Background

Westinghouse Electric Company (WEC) is developing wireless sensor technologies for monitoring fuel centerline temperatures and rod internal pressures without requiring sensor penetrations through the fuel rod. This sensor development campaign began with testing in the Penn State Breazeale Reactor [2] and MITR before access to HFIR was sought to approach end-of-life fluence levels for LWR fuel applications. NSUF funding was provided to design, fabricate, and irradiate an experiment to test WEC's wireless temperature and pressure sensors to fast neutron fluences as high as 5×10^{21} n/cm^2. As the first dedicated sensor irradiation ever performed in HFIR, the experiment provided an opportunity to incorporate additional advanced sensor technologies to compare with WEC's wireless sensors.

WIRE-21 Experiment

The Wireless Instrumented RB Experiment 2021 (WIRE-21) is the most highly instrumented experiment ever performed in HFIR's >60 year operating history. Figure 2 shows a schematic of the experiment layout and the instrumentation [3]. The experiment includes 4 self-powered neutron detectors (SPNDs), 8 silica fiber (SF) optic sensors, 12 thermocouples (TCs), 38 passive SiC temperature monitors (TMs), and 4 neutron activation flux wire assemblies, in addition to WEC's wireless temperature and pressure sensors. The Materials Irradiation Facility (MIF) at HFIR allows for in situ control of temperature and pressure based on feedback from in-core sensors. The MIF has been used for a wide range of fuels and materials experiments and has now been upgraded to accommodate a wider range of sensors. In WIRE-21, the wireless pressure sensor was pneumatically actuated during irradiation so that its response could be compared with an ex-core conventional pressure transducer. Temperature was controlled using a gas delivery system that adjusted the flow rate of helium and argon into different regions of the experiment to vary the heat transfer from the internal components to HFIR's coolant. The control gas lines (G) and purge line (P) are also shown in Figure 2.

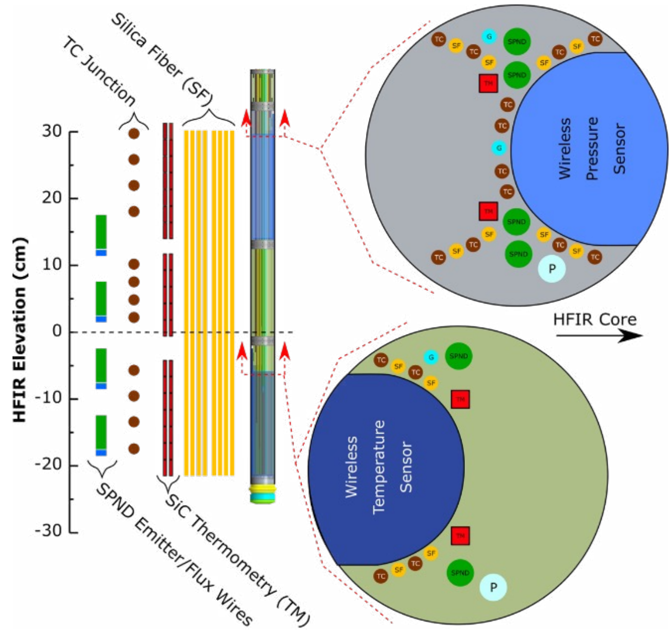

Figure 2. Schematic showing the instrumentation included in the WIRE-21 experiment.

The experiment was assembled, delivered to HFIR, and inserted during HFIR cycle 498 in April 2022. Figure 3 shows pictures of the assembly and insertion. Three HFIR irradiation cycles are now complete (~75 days total), resulting in a fast neutron fluence as high as 3×10^{21} n/cm^2. Signals were recorded from 7 of 8 SFs (one was damaged during experiment handling after the first cycle), all 4 SPNDs, and 10 of the 12 TCs (2 failed during the first cycle). Figure 4 shows the temperature history recorded from the TCs. The remaining terabytes of data (both measured and modeled) are currently being evaluated but will take more time to analyze, including synchronizing each data set in both time and space. This will allow for the evaluation of trends with respect to neutron flux, fluence, temperature, pressure, gas flow rates, etc.

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Figure 3. Pictures of the assembly, hoisting, and lowering of WIRE-21 for insertion into HFIR.

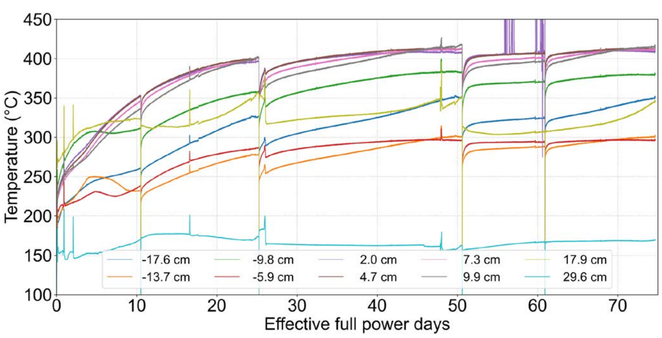

Figure 4. Temperature recorded from TCs during ~75 days of HFIR irradiation at various locations relative to the core midplane.

Benefits to the Nuclear Industry

WIRE-21 provides a unique opportunity to evaluate sensor performance under extremely harsh conditions. It also sets an important precedent showing that dedicated irradiations of sensors can be performed even in the most extreme radiation environment available in the United States. Some important phenomena that will be evaluated under both NSUF and ASI funding include:

- fundamental degradation modes for wireless temperature and pressure sensors based on inductive coupling,
- the survivability of modern stainless steel–sheathed, mineral-insulated Type N thermocouples under extreme neutron flux,
- the survivability and potential signal drift of SPNDs with a V emitter due to changes in temperature and neutron fluence,
- signal attenuation and drift in distributed fiber optic temperature sensors, with and without inscribed Bragg gratings, as a function of fiber dopants (F, Ge), grating type (Type I or II), and light-guiding mechanism (total internal reflection vs. photonic crystals) [4],
- and the comparison of passive sensors (flux wires and SiC TMs) with in situ measurements from other sensors as well as neutronic/thermal hydraulic models.

References

[1] C.M. Petrie, J.R. Burns, A.M. Raftery, A.T. Nelson, K.A. Terrani, Separate effects irradiation testing of miniature fuel specimens, J. Nucl. Mater. 526 (2019) 151783.

[2] J.V. Carvajal, M.D. Heibel, N.G. Arlia, A. Bascom, K. Ünlü, Nuclear Radiation–Tolerant Wireless Transmitter Irradiation Test Results, Nucl. Technol. 197(2) (2017) 201–208.

[3] C. Petrie, A.S. Chapel, P.L. Mulligan, D. Bryant, D.C. Sweeney, A. James, N.D.B. Ezell, K. Smith, K. Godsey, M. Searles, S. Stafford, J. Arndt, J. Carvajal, WIRE-21 Sensor Irradiation Experiment Ready for HFIR Insertion, ORNL/TM-2022/2354, Oak Ridge National Laboratory, Oak Ridge, TN (2022).

[4] C.M. Petrie, D.C. Sweeney, Enhanced backscatter and unsaturated blue wavelength shifts in F-doped fused silica optical fibers exposed to extreme neutron radiation damage, Optica (under review).

International Nuclear Energy Research Initiative – Radiation-Hardened Readout System for the Micro-Pocket Fission Detector

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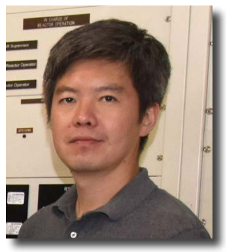
KAERI



Introduction to the International Nuclear Energy Research Initiative

In fiscal year 2001, the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) established the International Nuclear Energy Research Initiative (I-NERI) to conduct advanced nuclear energy systems research in collaboration with international partners. I-NERI was designed to foster international partnerships in order to address key issues affecting the future use of nuclear energy around the globe. The I-NERI collaborations enable DOE to effectively leverage its economic resources, more readily expand the knowledge base for nuclear science and engineering, and establish valuable scientific networks with researchers from other countries [1].

This I-NERI collaborative framework was utilized to achieve a ruggedized neutron flux system by combining expertise gained from both Idaho National Laboratory (INL)'s development of robust nuclear sensors and the Korean Atomic Energy Research Institute (KAERI)'s development of radiation-hardened electronics [2-3].

I-NERI Project

The Micro-Pocket Fission Detector (MPFD) can measure the local neutron flux in irradiation experiments conducted at research reactors as well as advanced reactors. The MPFD, a fission chamber designed to withstand the extreme environments encountered in INL's Advanced Test Reactor (ATR) and Transient Reactor Test Facility (TREAT) [4], could be deployed in small modular reactors and microreactors. The MPFD's small size, variable sensitivity, and increased accuracy represent a paradigm shift in neutron flux measurement (see Figure 1). Previous research conducted under the Nuclear Energy Enabling Technologies (NEET) Advanced Sensors and Instrumentation (ASI) program [5] showed that the MPFD technology could be made robust and be successfully deployed in research reactor experiments throughout the world.

These MFPD deployments led researchers to consider the next component (i.e., the electronics readout system) needing ruggedized for eventual use in the types of advanced reactors currently being developed. To achieve optimal performance of the MPFD, the electronics must be located near the reactor—and thus near high-radiation fields. Unlike what is typically the case for larger reactors, compact reactor systems cannot rely on distance and shielding to protect their electronics from radiation sources. However, by initiating the development of a radiation-hardened readout system, this research adds a new layer of operational resilience and reliability for next-generation reactors. Radiation-hardened reactor systems will be useful for standard reactor operations as well as for the extra layer of robustness they can provide during severe accident conditions.

For many decades, various radiation-hardened-by-design (RHBD) techniques have been developed to meet various design requirements pertaining to different types of radiation environments (e.g., space), but none have ever been developed for use in nuclear power plants. On the circuit side, improvements in performance, chip size, and radiation-hardening are being adopted for radiation sensors; however, next-generation reactors—as well as

Figure 1. Schematic diagram of the INL-developed MPFD (left), the process of fabricating the new MPFD geometry (middle), and a computer tomography image of the MPFD (right)

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existing reactors preparing for severe events—require advanced circuit structures that can afford relatively long lifetimes under harsh conditions.

KAERI reaserachers designed a radiation-hardened readout system architecture that delivers, via an inexpensive rad-hard design, high total ionizing dose tolerance and sensitivity for perfroming precise particle identification in high-flux environments. After designing the basic architecture based on the results of a transistor-level analysis, the KAERI researchers, by combining different RHBD techniques, confirmed that any radiation-induced noise and errors could be successfully removed from the detector signals.

Testing the MPFD readout sytem at TREAT

The MPFD readout system was set up at TREAT to demonstrate that it could process the MPFD signal during a reactor pulse (see Figure 2). A total of four tests were conducted. Figure 3 displays the results for three of these tests. The readout system can count the number of pulses generated whenever the output is saturated. Thus, the y-axis can be written as the number of counts detected, though this value is not equivalent to the neutron flux. However, after post-processing to convert the counts detected into the neutron flux, one can calibrate the system to measure the local neutron flux.

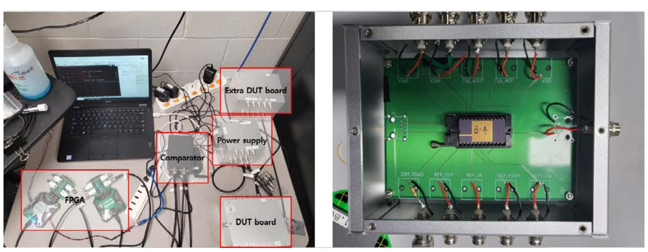

Figure 2. (Left) MPFD readout system setup in TREAT; (Right) test board with packaged fabricated chip

The test results show that the proposed readout system operates fast enough to be used with a MPFD in transient reactor experiments.

Conclusion

The four main objectives of this I-NERI project were successfully completed: (1) determine the MPFD readout system architecture that optimizes speed (a rise time of a few nanoseconds), radiation tolerance (>10 kGy for preamplifiers and >100 Gy for downstream signal processing units located away from the reactor), and costs by minimizing the silicon footprint; (2) develop RHBD techniques that can be integrated during the circuit design phase; (3) conduct radiation testing at INL and KAERI to demonstrate improved irradiation testing results following chip fabrication; and (4) develop methods of optimizing the RHBD sensor readout system.

In conclusion, this project met all its objectives for coupling the radiation-hardened readout circuits to a MPFD produced a fully integrated fission detector module containing both sensor and readout circuitry that can be implemented in practical applications such as irradiation experiments, microreactors, small modular reactors, and radiation-tolerant devices used in space.

References

[1] "International Nuclear Energy Research Initiative Annual Report," U.S. Department of Energy, Office of Nuclear Energy, 2010 I-NERI Annual Report, 2010.

[2] I. Kwon and T. Unruh, "Radiation Hardened Readout System for Micro-Pocket Fission Detectors," Awarded full proposal 2019-003-K for U.S./Korea International Nuclear Energy Research Initiative (I-NERI), 2019.

[3] I. Kwon and T. Unruh, "Radiation Hardened Readout System for Micro-Pocket Fission Detectors (2019-003-K), Final Technical Report" for U.S./Korea International Nuclear Energy Research Initiative (I-NERI), 2022.

[4] C. Jensen et al., "FY17 Report for Instrumentation Development for the Transient Testing Program," INL/EXT-17-43444, September 2017.

[5] T. Unruh et al., "Enhanced Micro-Pocket Fission Detector for High Temperature Reactors - FY17 Final Project Report," INL/EXT-17-43397, September 2017.

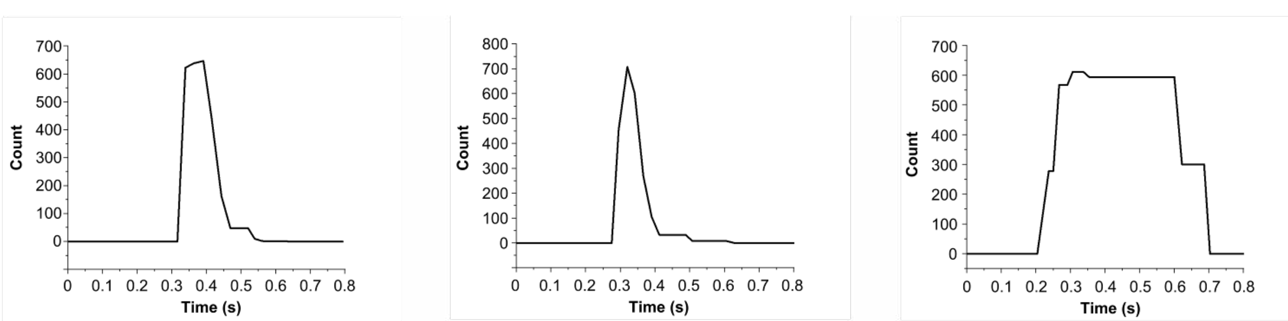

Figure 3. MPFD signal readout verification test results

2023 Workshop on Optical Sensors for Crosscutting Energy Applications

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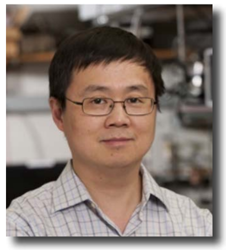

Motivation and Objectives

The energy industry is experiencing a rapid and profound transformation from centralized, carbon-intense energy production to distributed, carbon-neutral energy infrastructure. Within two decades, intermittent renewable energy might play significant roles in electricity production, while the next generation of the nuclear energy system will replace coal-fired power plants to serve as the baseload for the power grid. These changes will fundamentally alter the entire value chain of the energy industry. They will also impact the missions of National Laboratories and the R&D portfolio of the U.S. Department of Energy (DOE) research programs.

The transition to new energy infrastructure demands extensive deployments of sensors. The ability to collect a multitude of information with high temporal and spatial resolution across the entire value chain of the energy industry is the key to developing greener, smarter, safer, and more cost-effective new energy infrastructure. As an important sensor technology, optical sensors have been explored at all National Laboratories and funded by many DOE research programs to perform stand-off, distributed physical or chemical measurements in harsh environments. In addition, many researchers and industry leaders have noted that Sensor technologies previously developed for fossil energy applications are now finding new applications in new nuclear and renewable energy systems. For example, distributed fiber sensors developed under the University Coal Research programs are being explored to monitor the gasification of municipal plastic waste for hydrogen production.

Under this premise, the University of Pittsburgh (Pitt), in collaboration with Idaho National Laboratory (INL), hosted a Virtual Workshop on Optical Sensors for Crosscutting Energy Applications. Dr. Kevin Chen organized this workshop at Pitt (also a jointly appointed scientist of INL). It was co-hosted by Dr. Michael Buric, a National Energy Technology Laboratory research scientist, and Dr. Christian Petrie, a Senior R&D Staff member at Oak Ridge National Laboratory (ORNL). The organization team highlights crosscutting nature of the enterprise.

This workshop provides a venue to exchange information among optical sensor researchers, data scientists, and advanced energy system developers; fosters crosscutting synergy; and promotes collaboration among universities, national laboratories, and industry.

The Workshop

The two-day workshop was hosted by Pitt on March 2 and 3, 2023. Researchers from nine National research organizations, four universities, and two companies presented 18 invited talks, which covered a wide range of topics related to optical sensors.

Dr. Pattrick Calderoni, National Technical Director of the Advanced Sensor and Instrumentation (ASI) Program within Office of Nuclear Energy, opened Day 1's workshop. He discussed fiber optic sensor development as part of the DoE ASI program. Following the opening, Dr. Christian Petrie from ORNL, Mr. Paul Gerber from Naval Nuclear Laboratory (NNL), and Dr. Michael Buric from NETL presented fiber optical research from their respective organizations. They cover fiber sensor technology from complementary perspectives in nuclear, fossil, and renewable energy applications. Dr. Petrie presented important experimental results, which explore the applicability of various optical fibers and fiber sensors in extreme radiation environments. His works on radiation vulnerability between silica and sapphire fibers are particularly enlightening. Dr. Michael Buric presented NETL's R&D efforts on single crystal fiber fabrication for energy applications. His research presentation addressed a key challenge of single crystal fiber as a claddless multimode optical waveguide. Dr. Buric presents NETL's latest achievement in fabricating low-loss, few-mode single-crystal fibers with a cladding layer using a Laser-Heated Pedestal Growth approach. Although still in the R&D phase, this work could fundamentally change how single-crystal fibers are used for sensing and direct energy applications.

The US navy maintains and operates about 160 nuclear reactors, more than the number of civilian nuclear reactors currently operated in the United States. NNL has extensive experience in sensors for nuclear energy applications, which are valuable for civilian industry. Mr. Paul Gerber shared NNL's perspective on fiber optical sensors.

The morning session also included a presentation from Corning Inc. Dr. Ming-Jun Li, an inductee of the National Inventors Hall of Fame, discussed novel optical fibers developed at Corning for distributed sensor applications. Dr. Li's works highlight technical capabilities in both telecom and sensing fibers and Corning's openness to working with the energy industry to develop intelligent energy infrastructures.

The afternoon session included four talks. First, Dr. Kevin Chen from Pitt discussed the proliferation of fiber sensor technology through cost reduction, packaging, and

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data analytics. This talk discussed possibilities to reduce the deployment cost of fiber sensors by ×10+ times to expand the usability of fiber sensors for a wide range of applications. In this talk, Dr. Chen also presented a sensor fusion technique to address sensor drifts induced by radiations, which enabled the first-ever temperature profile mapping of a nuclear reactor core with 3-cm spatial resolution. The next talk, presented by Dr. Alexander Heifetz from Argonne National Laboratory, took the sensor fusion approach to the next level. His talk focus on machine learning of data harnessed by a host of wave sensors (optical, microwave, and ultrasonic) for thermal-hydraulics and nondestructive evaluation. Dr. Heifetz's talk highlighted the need for interdisciplinary approaches to address complex and challenging problems, as other sensor technologies can effectively address shortcomings of optical sensors.

The remaining two presentations focused on sensor applications. First, Mr. Thomas Tweedle, Fellow Engineer from Westinghouse Electric Company LLC (WEC), presents WEC's efforts to implement fiber optical sensors for the eVinci micro-reactor. Mr. Tweedle's talk provided unique insights into how advanced optical sensors can improve new reactors' safety and operation efficiency for civilian, military, and space applications. Next, Dr. Albert To from Pitt presented the last talk on Day 1. His presentation discussed optical sensor applications in additive manufacturing, while sensor measurements, coupled with digital twin modeling, were used to improve the fabrication accuracy of 3D printing and to reduce residual stress through laser deposition path optimization. Dr. To's talk also covered fiber-sensor fused additive manufacturing while highlighting fiber-sensor embedding opportunities through the bottom-up 3D printing process for smart component manufacturing.

Day 2 of the workshop was opened by Ms. Eva Rodezno, Program Manager for the Office of Fossil Energy and Carbon Management (FECM) for Sensors, Control, and Novel Concept. Ms. Rodezno discussed FECM's R&D efforts on optical sensors, which covered both extramurally funded research work and research projects at the National Energy Technology Laboratory. Dr. Rodezno's presentation attracted strong interest from audiences as many sensors technology developed by FECM are finding new applications in sustainability, nuclear energy, and renewable applications.

The interdisciplinary nature of optical sensors is further discussed by Dr. Jyotsna Sharma from Louisiana State University in her talk on Case Study on Gas Monitoring in a 5000-ft-deep wellbore using DAS, DTS, and DSS. Dr. Sharma first discussed distributed fiber sensor applications in the oil and gas industries. Leveraged from capabilities and experience gained from fossil energy industries, Dr. Sharma then discussed potential applications of distributed fiber sensor technology for hydrogen infrastructure monitoring and carbon storage applications.

While most talks on Day 1 focused on fiber optical sensors, Day 2's agenda included two presentations on stand-off laser sensors. The first talk was presented by Dr. Amanda Lines from Pacific Northwest National Laboratory on the CoDCon Online monitoring system that utilizes Raman, UV-vis-NIR absorption spectroscopy for harsh environments applications. Dr. Lines presented a wide range of applications of stand-off sensors, including process control, UNF fuel recycling, and Molten Salt Reactors. Dr. Yongfeng Lu from the University of Nebraska – Lincoln also presented relevant topics on Nanofabrication, Optical Spectroscopy, and Imaging for Fusion and Energy Applications. Dr. Lu is a leading scientist in laser processing and optical sensing who served as the President of the Laser Institute

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of America in 2014. His presentation discussed the cross-cutting application of laser-induced breakdown spectroscopy, Coherent Anti-Stokes Raman spectroscopy, and Laser-induced fluorescent spectroscopy in isotope separation, biofuel production, diamond coating, and characterization of fuel targets for laser inertial fusion.

Most of the sensor technology discussed in the workshop focused on optical sensors. However, Prof. Gary Pickrell from Virginia Tech used a unique approach to address sensors for harsh environment applications. Prof. Pickrell's presentation discussed two guided-wave approaches for distributed sensing in harsh environments. While his research group is well-known for developing sapphire-based optical sensors, Prof. Pickrell raised an exciting possibility that frequency domain reflectometry can be used for distributed temperature sensing through guided acoustic waves on a metal wire. This collaborative work with Dr. Joshua Daw of INL could provide an alternative of sensors based on silica and sapphire fibers.

During Day 2's workshop, crosscutting applications of optical sensors are highlighted in four talks with distinct topics in electricity distribution, space flight, natural gas infrastructure monitoring, and Spallation Neutron Source target monitoring.

Dr. Indra Chakraborty from Lawrence Livermore National Laboratory discussed an open-sourced software toolkit (GridDS) for energy forecasting. This tool kit is developed to address the power grid congestion due to the explosive growth of intermittent energy sources such as solar and wind powers tied to the power grid. Although this talk is not explicitly related to optical sensors, the challenges, and opportunities presented highlight the need for distributed sensors for grid applications such as Dynamic Line Rating to improve grid resilience amid the explosive growth of renewable energy.

Dr. Patrick Chan from NASA Dryden Flight Research Center presents a distributed fiber sensor system (FOSS) developed by NASA. Dr. Chan discussed the technical details of FOSS, which are weak fiber Bragg grating array sensing fibers interrogated by an Optical Frequency Domain Reflectometer, and its applications for dynamic strain measurements for aircraft and space systems. This talk attracted intense interest from the energy industry audiences, highlighting the need for interdisciplinary engagements.

Dr. Ruishu Wright from NETL presented a comprehensive overview of optical sensors' R&D efforts for natural gas infrastructure monitoring. Dr. Wright is a Technical Portfolio Lead for Natural Gas Infrastructure FWP and Principal Investigator for multiple projects at NETL. Her presentation discussed interdisciplinary R&D efforts on developing real-time sensors and functional sensitive materials to monitor and mitigate corrosion and gas leaks of natural gas pipelines, support safe hydrogen transportation and H2@ scale projects, enable subsurface geochemical monitoring in support of subsurface hydrogen-natural gas storage, wellbore integrity monitoring of carbon storage wells and plugged abandoned wells.

Dr. Elvis Dominguez-Ontiveros from ONL presented the last talk of the workshop. He discussed applications of fiber optical sensors to monitor the Spallation Neutron Source (SNS). SNS is an accelerator-enabled neutron source facility that provides the world's most intense pulsed neutron beam. Through high-speed optical sensor measurements in extreme radiation environments, ORNL scientists could determine rapid strain rise at -μs time scale due to proton pulse impacts. Dr. Dominguez-Ontiveros presented an excellent case study of optical sensor applications, which enable ORNL scientists to develop mitigation strategies to improve SNS's longevity and operation.

Summary

The workshop received 143 online registrations. Each technical presentation attracted a 60-90 online audience. All presentation materials, including PowerPoint Presentations and videos, are now publicly available online [1]. This virtual workshop provided an important brainstorming venue for scientists and engineers to exchange ideas and find new ways to develop and use optical sensors to accelerate green energy transitions.

References

[1] https://engineering.pitt.edu/optical-sensors-workshop

Nuclear Energy Sensors Database

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Introduction

Previously developed sensor technology assessments for advanced nuclear reactor systems have helped identify technology gaps and prioritize R&D efforts. However, there was a need for improved access and visualization of information to aid in these decisions.

To address this need, a Nuclear Energy Sensors website database (https://nes.energy.gov) was created for nuclear facilities, universities, and industry staff members to find sensor information used in the nuclear energy field.

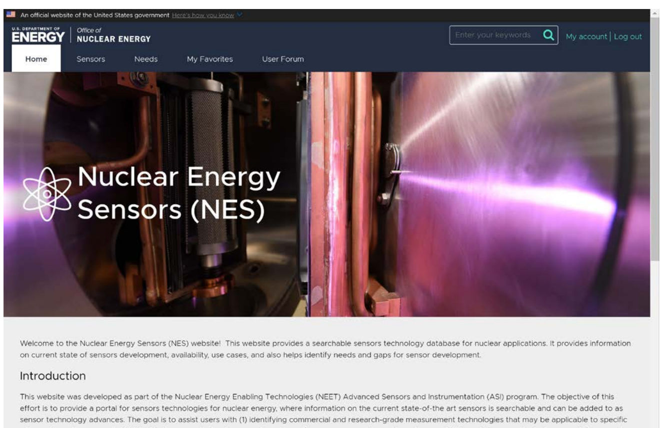

Figure 1. Front page of the NES database website.

Impact and Value to Nuclear Applications

This website is intended to be used as a "one stop shop" to search for information related to nuclear energy sensors and prioritized needs and gaps. In addition to providing this content, the website also allows subject matter experts to suggest additional sensors, needs, or site enhancements.

Recent Results and Highlights

The initial site went live in early FY21 with 71 sensors identified from the "Assessment of Sensor Technologies for Advanced Reactors" document. This document is publicly available at https://www.osti.gov/biblio/1345781/.

Since the initial site launch, PNNL has worked with INL, industry, and other entities to gather additional sensor information. The level of detail varies among the sensor data provided, however, there is currently at least some information on over 150 sensors.

Below is a look at the current sensor listing page. On the left-hand side of the page there are faceted checkmarks to filter the results of a specified search. The listing on the right-hand side will show the results based on those filter selections. From this page, you can also click into the detailed listing of any given sensor. The site also includes a site-wide text search at the top of this form, and the results from that search, can also be filtered further via further checkmark selections.

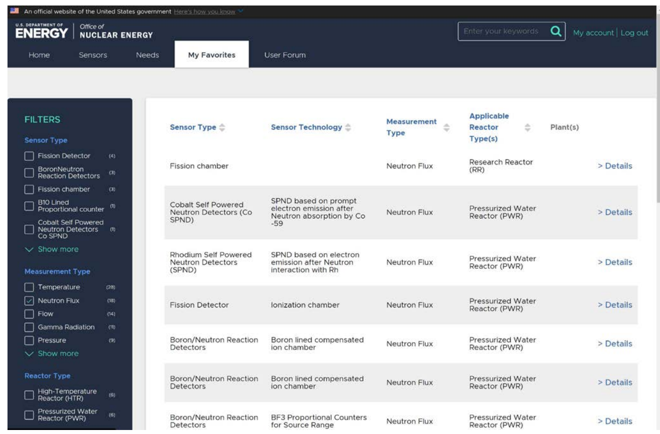

Figure 2. List of sensors with options for the user to filter entries.

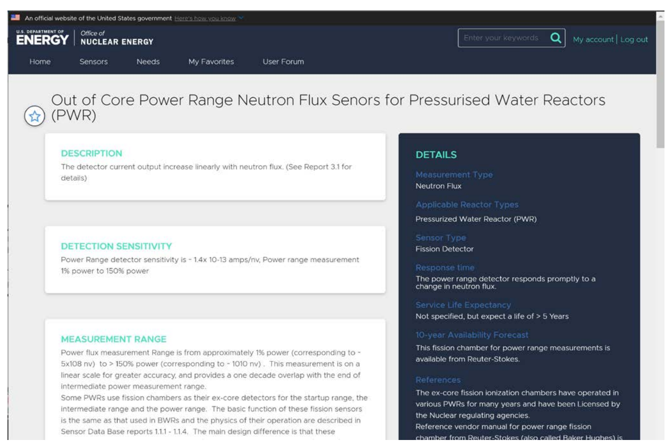

Figure 3. Example of a sensor entry showing technical details.

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Next Steps:

With guidance from DOE, this year PNNL and INL are collaborating on improving data quality, expanding available attributes, and creating a better user experience on the website. Specific focus is being centered on the following items:

1. For the sensor data to be useful, there is a minimum set of parameters that should be required for each sensor to be included in the database. We are setting a minimum number of required fields for all new sensors and will be reviewing existing sensors to include this information as well.
2. An updated design is being created for the user interface to help guide users more easily through the system. For example, rather than having all sensor types listed as searchable together, bin them into categories so that the search results only show values for the specific sensor category you are interested in. In other words, if you are looking for sensors to measure temperature, then your results should only include results in that category, and so on.
3. As part of a push to only list sensors with at least a minimal set of required attributes, the detailed view of sensor information is being reformatted for improved readability and consistency.
4. For improved data quality, we are analyzing the existing sensor data in the database to see if there are duplicate values that came from different sources. If there are duplicates, the duplicate entries are being merged into a single, more complete entry.
5. We are continuing to pursue new sensor entries for the database and responding to approved software requests with the goal of continually improved content and site functionality.