



ADVANCED SENSORS AND INSTRUMENTATION

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Enhanced Micro-Pocket Fission Detector for High Temperature Reactors

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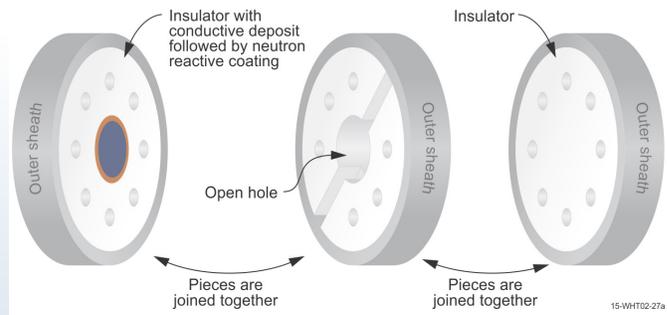


Figure 1. HT MPFD theory of operation.

Micro-Pocket Fission Detectors to High-Temperature Micro-Pocket Fission Detectors

Initial development of several prototypes MPFD designs began in the early 2000s at Kansas State University (KSU). These prototypes were tested in a neutron beam and in

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Micro-Pocket Fission Detectors

In-core fission chamber design has remained relatively unchanged for decades. Improvements in performance, overall size, and operational modes have been implemented; however, all have been based on the same design that utilizes coaxial cylinders with a high-pressure fill gas. These design considerations limit the robustness, lifetime, size, and operational performance of such sensors in high-performance Material Test Reactor (MTR) environments.

The Micro-Pocket Fission Detector (MPFD) technology utilizes the same operational concept of existing fission chamber designs, but deploys different geometry, construction, materials, and operational characteristics. The small design also allows two or more of these neutron detectors and a thermocouple to be co-located within a single sensor sheath (Figure 1) such that thermal flux, fast flux, and temperature can be simultaneously measured at very near the same location with a single penetration in the experimental pressure boundary.

In this issue...

1. Enhanced Micro-Pocket Fission Detector for High Temperature Reactors p. 1
2. Robust Online Monitoring for Calibration Assessment of Transmitters and Instrumentation .. p. 4
3. Development and Planned In-situ Testing of a High Temperature Fission Chamber for Molten Salt and High-temperature Gas Reactors p. 9
4. Automation in the work process..... p. 12
5. A Robust Wireless Communication System for the Harsh Environments in Nuclear Facilities p. 19
6. New Fiber Sensors for In-Core Measurements: Toward Intelligent and Safe Nuclear Reactors p. 22

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Continued from previous page

the reactor core at the KSU Training, Research, Isotopes, General Atomics (TRIGA) research reactor with successful results (Ohmes et al. 2007). However, it was recognized that the manufacturing process was not ideal to produce detectors for in-core applications.

The High-Temperature Micro-Pocket Fission Detector (HT MPFD) sensor redesign included several updates from the original MPFD design to improve detector robustness and performance for high-temperature applications. The sensor design was updated from a parallel plate (Unruh et al. 2014) to a parallel wire design (Figure 2). The parallel plate design uses a conductive adhesive that has a potential failure mechanism due to breakdown of the adhesive during a long-duration irradiation test. The parallel wire design does not use this adhesive, eliminating that failure mechanism, which is a significant improvement in HT MPFD survivability.

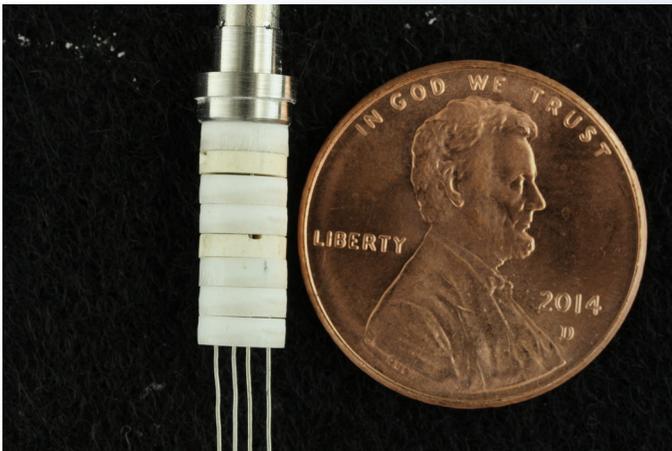


Figure 2. HT MPFD components prior to final assembly.

Fabrication methods and materials were also revisited to produce improved fissile material coatings (Reichenberger et al. 2015) as well as to use sheath materials compatible for installation into DOE-NE irradiation experiments. Modeling has shown that a wall thickness of 0.020 in. will allow the integrity of the sheath to survive in accident conditions up to 9000 psi as required for transient irradiation testing. In addition, the HT MPFD design moves the thermocouple to the extension cable (Figure 3) to improve thermocouple response (Unruh et al. 2016).

In addition to improvements in robustness, electrical performance was improved through the development of a specially designed four-channel amplifier electronic module. A commercial off-the-shelf system called MPFD-4 was developed by Mesytec Detector Readout Systems.

It includes a humidity-resistant pre-amplifier box that interfaces directly with a Nuclear Instrumentation Module (NIM) compatible processing module that can be controlled and transmitted via USB interface. Further research on pre-amplifier improvements has started with an International Nuclear Energy Research Initiative (I-NERI) collaboration between the United States of America and the Republic of Korea titled, "Radiation Hardened Readout Circuit Design for High Temperature Micro-Pocket Fission Detectors Operating in Harsh Environments."

HT MPFD Deployments

The Next Generation Nuclear Plant program is evaluating a suite of advanced real-time in-core sensors during their 3-year test campaign in the Advanced Test Reactor (ATR). The HT MPFD will be tested at unprecedented flux levels by leveraging the Advanced Gas-Cooled Reactor (AGR) 5/6/7 irradiation program. HT MPFD fabrication is complete and is undergoing installation into the irradiation test train.

The Accident Tolerant Fuels (ATF) program is deploying the HT MPFD technology in two material test reactors. The first irradiation, ATF-2, will evaluate a suite of advanced sensors, including the Nuclear Energy Enabling Technologies (NEET)-developed HT MPFD, in the ATR during a sensor qualification test. The irradiation is not expected to be as long as the AGR 5/6/7 irradiation, but will still provide valuable insight into the operation of a HT MPFD in a typical ATR irradiation. HT MPFD fabrication is complete and is undergoing installation into the irradiation test train.

The second ATF irradiation will evaluate a specialized version of the HT MPFD in Transient Reactor Test Facility (TREAT) transients. This effort is a departure from previous HT MPFD designs because the focus will be on developing a robust, fast-response MPFD that has four

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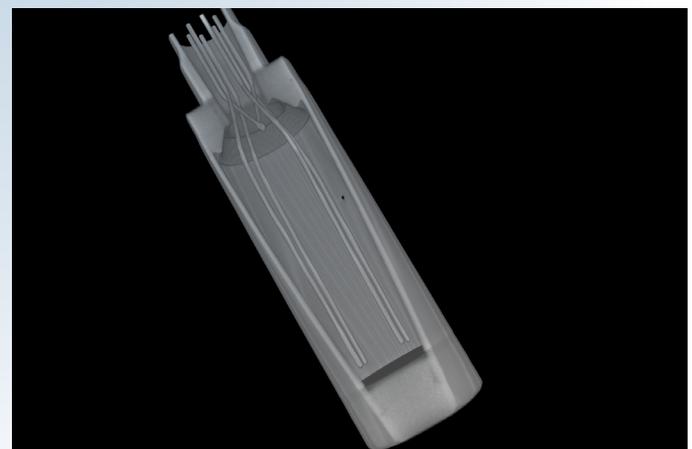


Figure 3. 3D computed tomography image of HT MPFD showing wire connections.

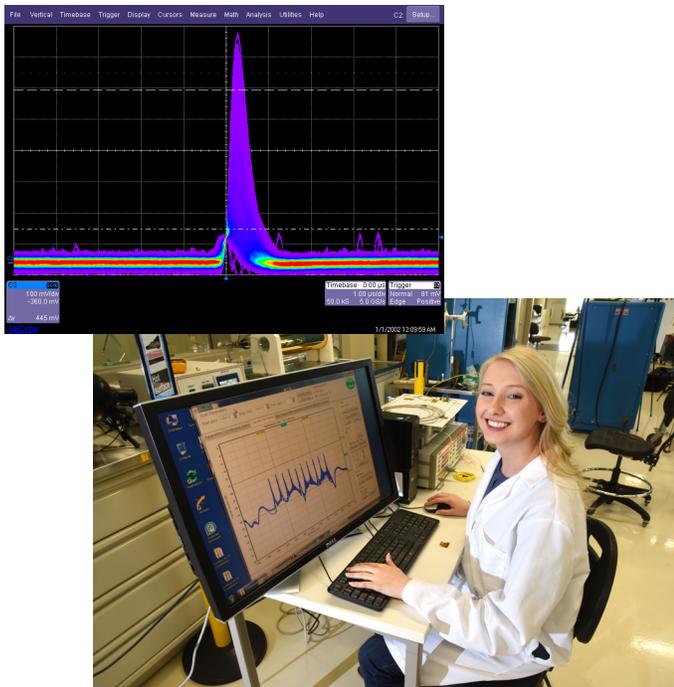


Figure 4. HT MPFD testing at MINERVE Reactor.

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neutron detectors and does not include a thermocouple. The information gained from initial transient irradiations will guide the future use of transient-specific HT MPFDs for TREAT irradiation testing in support of various DOE-NE programs requesting advanced instrumentation capabilities suitable for transient testing.

HT MPFD fissile material characterization efforts deployed several HT MPFDs in the Idaho State University (ISU) AGN-201 reactor. These evaluations allow the HT MPFD fissile material depositions to be measured prior to final assembly of the HT MPFD. This represents an important step in independent neutron characterization of the fissile material deposition process.

The MINERVE reactor at Commissariat à l'Énergie Atomique et aux Energies Alternatives (CEA) Cadarache, France, is a low-power reactor that is routinely used for fission chamber characterizations. Two MPFDs were evaluated at MINERVE in July 2017 for characterization against CEA-developed miniature fission chambers. In addition, an MPFD was deployed in the Massachusetts Institute of Technology (MIT) reactor in July 2017 with other advanced in-core instrumentation as part of an evaluation to test instrumentation for transient reactor tests. These low-power evaluations were used to determine the HT MPFD signal-to-noise ratio in a typical reactor environment. Both



Figure 5. HT MPFD testing at MIT Reactor.

July MPFD deployments successfully detected neutrons, as shown by the waveforms in Figure 4 and Figure 5.

Conclusion

HT MPFD research is continuing to develop robust sensors for DOE-NE irradiation testing programs and other reactors worldwide. Highlights from recent research accomplishments include an updated parallel wire HT MPFD design and improvement of electrical contact plating and fissile material deposition. These advancements have led to several projects that continue to develop and deploy the HT MPFD for a variety of irradiation testing programs.

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Robust Online Monitoring for Calibration Assessment of Transmitters and Instrumentation

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Safe, economical, and reliable operation of nuclear facilities, including nuclear power plants (NPPs), fuel-fabrication facilities, and used-fuel processing facilities, relies on accurate, reliable, and timely measurement of key process variables for monitoring and control. Maintaining accurate, precise, and responsive sensors is critical to providing the process data necessary to operate these nuclear facilities.

Maintenance testing plays an important role in characterizing and ensuring maximum utilization of instrument lifespan. Current industry practice for maintenance of sensors and instrumentation is a periodic assessment of calibration, typically every 18–24 months. This method involves testing of instrumentation in an isolated environment, followed by appropriate recalibration to ensure its functionality over the next cycle. This process requires the removal from service and extensive testing of every sensor and associated channels as specified in the Technical Specification and regulated by the U.S. Nuclear Regulatory Commission (NRC) and is highly intrusive, expensive, and inefficient (EPRI 2000, Coble et al. 2012).

Typically, the cost of calibrating a single sensor is between \$3000–\$6000, with about 50–150 sensors that need recalibration during any given cycle (Coble et al. 2012). The highly intrusive calibration process calls for extensive labor resources, which also contributes to as low as reasonably achievable (ALARA) goals (Shankar 2000). This recalibration process can also introduce errors in previously healthy sensors and transducers. Furthermore, this periodic approach may not be appropriate or sufficient in future reactors with longer operating cycles, harsher environments, and new sensor types.



The technical and economic inefficiencies of the current time-directed maintenance approach can be overcome using condition-based maintenance. Robust online monitoring (OLM) technologies are expected to enable the extension or elimination of periodic sensor calibration intervals in both operating and new reactors. OLM can facilitate continuous or near-continuous assessment of sensor calibration while the reactor or facility is operating, with recalibration performed at the next convenient opportunity only on sensors that exhibit calibration issues (Hashemian 2009). Hence, condition-based maintenance presents the possibility of extending and eventually eliminating the scheduled periodic recalibration activities over multiple reactor cycles.

Objectives

The goal of this research is to develop the next generation of OLM technologies for sensor calibration interval extension and signal validation in nuclear systems, through the development of advanced algorithms for monitoring sensor/system performance. Specific objectives are: (1) apply methods for data-driven uncertainty quantification (UQ) to develop methodologies for high-confidence fault detection and diagnostics; (2) develop a robust virtual sensor technology to derive plant process information that currently cannot be measured or estimated reliably (due to either sensor failure or a lack of sensors); and (3) develop a framework for OLM of both calibration and response time.

This project (part of the Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation program) supports the needs of several U.S. Department of Energy – Office of Nuclear Energy programs, including Light Water Reactor Sustainability; Advanced Reactor Technologies; Materials Protection, Accounting, and Control Technologies; and Fuel Cycle Research and Development.

This research is a collaborative effort between Pacific Northwest National Laboratory, the University of Tennessee-Knoxville, and AMS Corporation (AMS). The efforts are integrated and iteratively develop, verify, and validate algorithms to meet the research goals.

Approach, Recent Results, and Highlights

OLM uses a model of the plant process (Figure 1) to provide error-corrected estimates of the true process parameter values; these predictions are assumed to be more accurate than sensor measurements that may be affected by sensor degradation. The credibility of the model predictions

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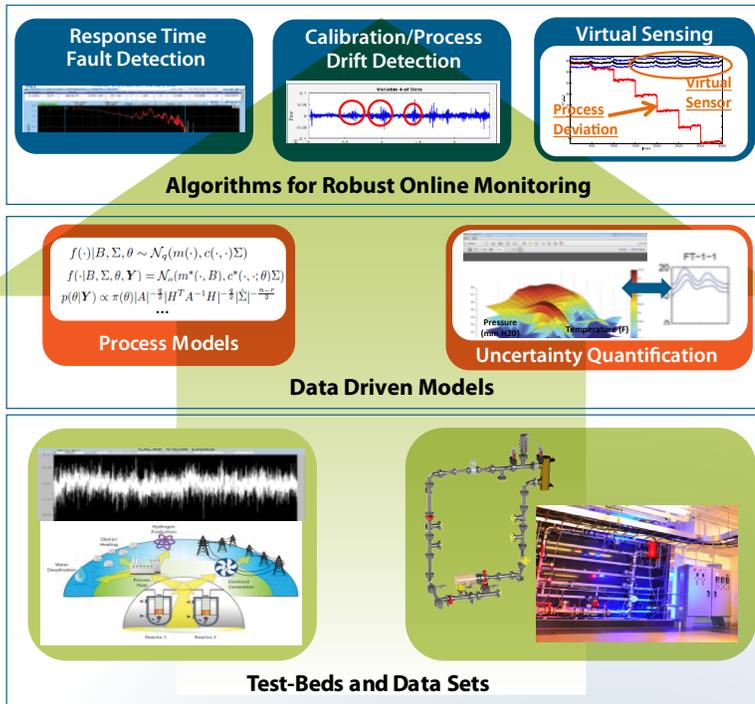


Figure 1. Data-driven robust OLM enables fault detection and virtual sensing through a combination of process models and uncertainty quantification methods. The examples use data from instrumented flow loops and pressure transducers in operating plants.

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requires that the uncertainty in the process estimates be quantitatively bounded and accounted for in the fault detection process. Furthermore, UQ forms the basis for various other requirements identified by safety evaluation reports on matters varying from fault differentiability to determination of OLM acceptance criteria (Hines and Seibert 2006).

The focus of the research described here is on OLM of process instrumentation (temperature, pressure, and flow) used for control of plant systems and monitoring safety. During operation, these sensors may degrade due to

age, environmental exposure, and maintenance interventions and result in anomalies such as signal drift and response time changes, challenging the ability to reliably identify plant or subsystem state. In the research described here, algorithm development is focused on OLM functions that address these types of anomalies by:

- Applying methods for data-driven UQ to develop methodologies for high-confidence signal validation and sensor-fault detection
- Using robust plant process models to develop virtual sensor technology and derive plant information that currently cannot be measured
- Automating existing analysis methods for response-time assessment to improve accuracy and timeliness of response time assessments.

Underlying most of these algorithms is a data-driven UQ methodology that is critical to realizing improvements over today’s OLM capabilities. This method allows the OLM algorithms to adapt to changing conditions (increased process or instrumentation noise, for instance) and provides a mechanism for dynamically adjusting the prediction uncertainty bounds for the OLM model.

As a result, the UQ method may be applied to adapt acceptance criteria as well as improve fault detection and diagnostic results. While several approaches to UQ are possible, Gaussian Process (GP) models were selected given their ease of adaptability to this problem (Bilionis et al. 2013).

UQ methods may be applied at multiple stages in the OLM approach shown in Figure 2. For sensor fault-detection, an auto-associative kernel regression model was used to model the time-domain sensor outputs, and the GP to model the contributors to the resulting residual. This arrangement estimates confidence bounds around the OLM residual, and can be an input to subsequent statistical

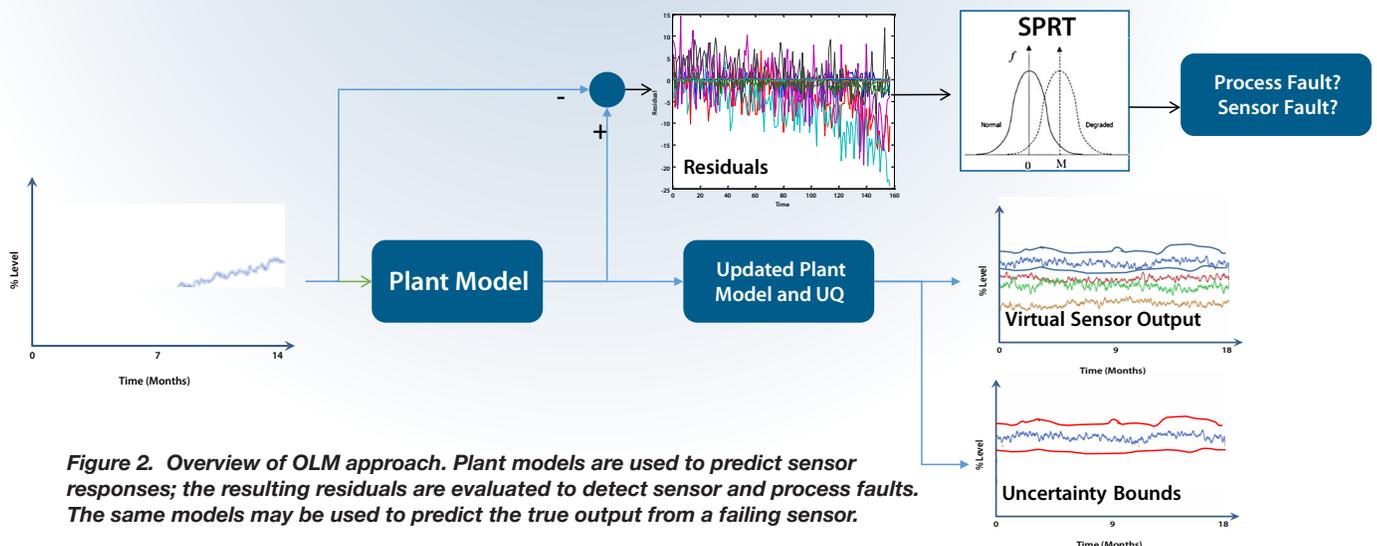


Figure 2. Overview of OLM approach. Plant models are used to predict sensor responses; the resulting residuals are evaluated to detect sensor and process faults. The same models may be used to predict the true output from a failing sensor.

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tests that determine if the residual indicates presence of a fault, such as a sensor drifting out of calibration (failing sensor). Response time degradation results in changes in the spectral response of the transmitter. As with the conventional OLM approaches, the spectral response may be modeled and the model used to extract response times for sensors (Figure 3). In the case of virtual sensors, the GP model was used as the plant model in a predictive mode to estimate the correct sensor reading for sensors that may be failing. In this case, the model output also includes the confidence bounds in the virtual sensor prediction.

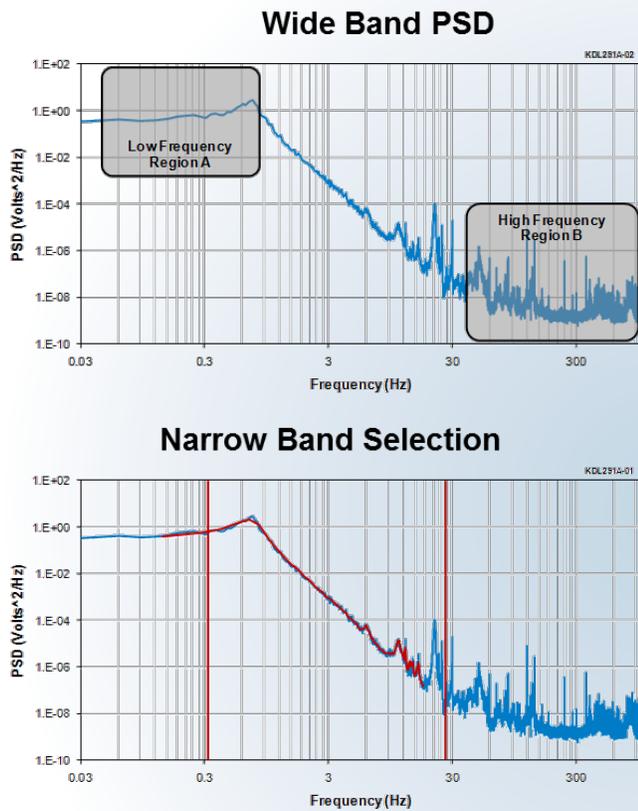


Figure 3. PSD “windowing” and model generation for automated noise analysis for response time OLM.

Variations on this basic theme are being developed in this research, with the objective of improving fault detection accuracy and obtaining tighter confidence bounds.

Simpler approaches for fault detection, including simple signal thresholding and sequential probability ratio test approaches, were implemented and tested. These approaches, while capable of reliable detection, are also subject to the limitations of the OLM models used (for instance, cross-talk from drifting sensors resulting in degraded model prediction performance). The results of evaluating these approaches on experimental data pointed to the need for model optimization, where the model

parameters are selected based on multiple criteria.

An alternative approach, evaluated for virtual sensing, was based on a hierarchical GP model. In this instance, the measurement data are transformed into a lower dimensional space, and the GPs use the lower dimensional latent variables as inputs. Using independent variables, such as control sensor measurements, as the inputs to virtual sensing algorithms appears to improve the virtual sensor prediction. Further, grouping the measurements based on location and type (redundancies) and transforming to lower dimensions appears to add additional robustness to the results. As a consequence of this, the hierarchical GP method appears to be capable of reliably predicting the true value of the sensor output (along with confidence bounds); therefore, this method is also a candidate for the OLM model (for use instead of auto-associative kernel regression or other empirical models).

Figure 4 shows an example of this robust OLM approach, where the physical sensor measurement is shown along

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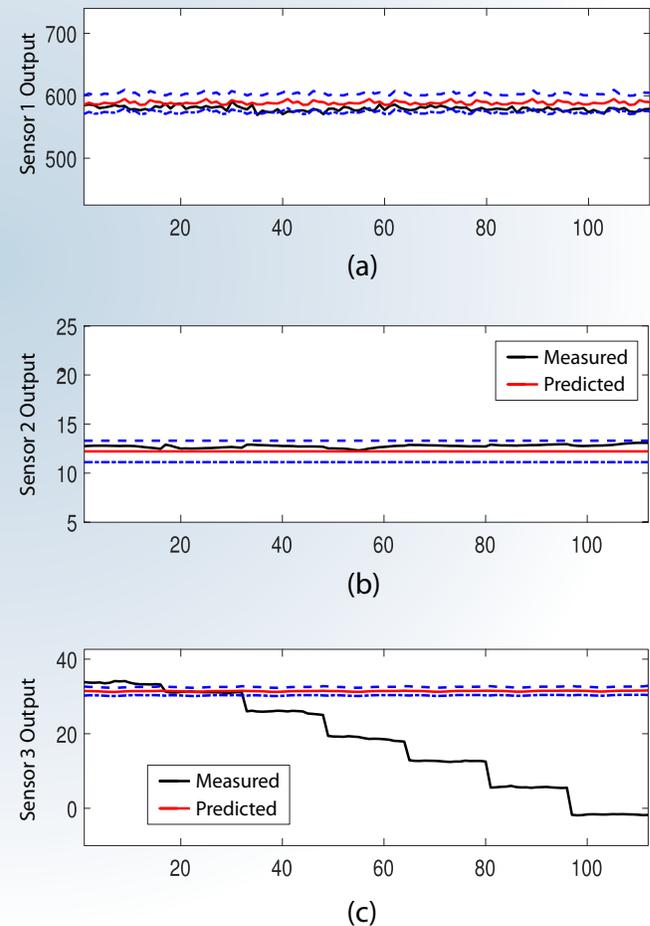


Figure 4. OLM model outputs showcasing their robust predictive capability for use as virtual sensors. (a) and (b): sensors within calibration (c) drifting sensor. The predicted value (virtual sensor) may be used as the correct sensor reading as the physical sensor drifts out of calibration. The predicted 95% confidence bounds (dashed lines) are also shown.

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with the predicted response from a hierarchical GP model. Examples of model predictions from unfaulted sensors show that this model is able to reliably predict the sensor response and the associated 95% confidence bounds depend on the noise levels in the measurements. Predictions are reasonably steady even when the physical sensor drifts out of calibration (Figure 4c). It is noteworthy that this model appears to minimize the effects of sensor cross-talk. These results indicate that the virtual sensor measurement calculated using the hierarchical GP model may potentially be applied to correct for measurement error due to sensor drift, enabling a simple form of online recalibration.

The algorithms being developed in this research were evaluated using data from multiple sources (Ramuhalli et al. 2016, Ramuhalli et al. 2017, Ramuhalli et al. 2014):

- Forced flow loop at University of Tennessee-Knoxville (UTK)
- Forced flow loops at Analysis and Measurement Services Corp. (AMS) (Figure 5)
- Pressure transmitter data from seven operating PWRs.

Data from the forced flow loops used in the evaluations included normal operation and various fault conditions. Examples of faulted conditions included drifting process transmitters (zero shift and span shift), sensing line blockages, sensing line leakages, sensing line voids, and electromagnetic interference (EMI) susceptibility. Process faults were also simulated to evaluate the OLM system's ability to differentiate process and sensor faults.

Results on these empirical data sets indicated that these models and algorithms may be able to improve the accuracy of fault detection when compared to existing techniques, while decreasing the cost of a calibration assessment. For instance, the estimated analysis time savings (using data from the operating PWRs) using the automated OLM response time method was about a 50% reduction in analysis time the first time an analysis is performed for a given reactor unit, and a 75% time savings in all subsequent analyses for a given unit. As conventional noise analysis can take up to 1 month to complete depending on the number of transmitters analyzed, this is a significant time savings.

Integration of sensor fault detection, diagnostics, and virtual sensing algorithms are expected to be critical to achieving a deployable robust OLM technique. Results

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Figure 5. AMS flow loop and test facility.

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to date indicate that successful integration of these methodologies and the use of a single predictive model for sensor outputs will require careful thought on the input data and data dimensionality.

Impact and Value to Nuclear Applications

Outcomes of this project lay the groundwork for wider deployment of advanced OLM in U.S. nuclear facilities by developing a methodology to: (1) support the regulatory basis for OLM-based calibration assessment, (2) provide the high confidence levels needed for signal validation, (3) provide virtual sensor estimates with meaningful confidence, (4) integrate response time testing of pressure transmitters with the OLM framework, and (5) evaluate the efficacy of these techniques for new sensor systems. These advances will provide a complete picture of health, reliability, accuracy, and speed of response of process instrumentation in legacy and future nuclear facilities, and are expected to improve safety, reliability, and economics of nuclear energy systems by enabling targeted instrumentation maintenance actions during planned outages.

Summary

This research is developing online monitoring technologies that will extend or eliminate periodic sensor calibration intervals and improve signal validation in operating and new reactors. Models and algorithms developed to date are enabling accurate prediction of sensor responses (including sensor response times). Further, robust models that incorporate UQ methods provide predictive confidence bounds and the model predictions are applicable as virtual sensor measurements even in cases where the physical sensor drifts out of calibration. Results on empirical measurement data sets indicate that these algorithms are capable of improving the accuracy of fault detection over existing techniques, and may provide a means for online recalibration of drifting sensors. Further, these algorithms appear to significantly reduce the time spent on calibration assessment, potentially improving the economics of

plant operation. These advances in OLM technologies are expected to improve the safety and reliability of current and planned nuclear power systems through improved accuracy and increased reliability of sensors used to monitor key parameters.

Ongoing work is focused on several aspects of OLM theory and implementation. Modifications to the models used for signal validation to address observed issues with cross-talk are also underway. Model optimization for signal validation is being applied to improve the robustness of the models. Additional evaluation of the algorithms is ongoing, with evaluation criteria focused on accuracy of the sensor value prediction, computational complexity, and ability to compute uncertainty bounds.

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Development and Planned In-situ Testing of a High Temperature Fission Chamber for Molten Salt and High-temperature Gas Reactors

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Implementing the next generation of nuclear reactors will require new instrumentation that can withstand the higher temperatures and harsher conditions present inside advanced reactors. One critical instrument in need of development is a neutron flux monitor capable of measuring reactor power levels from startup through full power. A fission chamber is one variation of neutron detector that operates as an ionization chamber, detecting pulses from ionized gas caused by high-energy fission products. These detectors typically have a set of electrically conducting plates, each with a thin coating of fissile material and can be used for reactor power control, in-core fuel management, and to satisfy safety requirements. Oak Ridge National Laboratory (ORNL) is developing a fission chamber with three conductive, concentric tubes coated with uranium and backfilled with a gas suitable for high temperatures. When a neutron is absorbed in the fissile coating, fission is induced, generating two energetic fission fragments emitted in opposite directions. Ideally, one of the fission fragments will travel into the gas region of the chamber and ionize gas particles along its trajectory. A high voltage is applied to the cylinders of the chamber causing the liberated electrons and ionized gas to drift to the anode and cathode, respectively. A mirror charge is induced on the electrodes of the fission chamber, integrated by the instrument electronics, and output in the form of pulses. At low power, the rate of pulse generation is proportional to the local neutron flux and is indicative of reactor power. At higher powers, pulse overlap occurs, and the direct current generated in the chamber can be correlated to reactor power. A prototype High-Temperature Fission Chamber



will be tested at The Ohio State University Research Reactor (OSURR) in the fall 2017. A follow-on commercial fission chamber will be developed and tested in an advanced reactor for at least 2 years if the prototype is successful.

High Temperature Fission Chamber Design

Although a fission chamber seems to be a relatively simple device, deploying such a device in a high-temperature, high flux, and potentially corrosive environment requires optimization of a number of parameters (Bell et al. 2012):

1. There must be sufficient fissile material deposited to make it adequately sensitive during reactor startup.
2. The atomic number of the fill gas and the operating pressure affect the range of fission fragments.
3. The electric field between the plates affects the drift velocity of ions and electrons, and determines the gain within the chamber.
4. Plate spacing, area, and fill gas control the capacitance of the chamber.
5. Plate spacing must be chosen so that the signal from photoelectrons and alpha particles can be distinguished from the fission fragment signal.
6. Structural materials must be sufficiently strong to support themselves at high temperatures.
7. Structural materials must not react with the external environment and be impervious to infiltrations of external materials.
8. The chamber must be hermetically sealed.
9. Wiring materials must be chosen that do not embrittle with age, thermal cycling, or irradiation.
10. The resistivity of most materials decreases several orders of magnitude between 300 K and 1073 K.
11. Thermal load from radiation absorption and gas ionization current must be accommodated.

These enumerated constraints, among others, were considered during development of this design.

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Figure 1 a three-dimensional (3D) model of the fission chamber. The fission chamber consists of three concentric molybdenum cylinders housed inside a third alumina cylinder and held in place using insulated alignment pins.

Mo wires are welded to the tops of the Mo cylinders for electrical connections, passing through the upper lid of the primary containment. The circuit representation of the fission chamber is displayed in Figure 2. Assembling

multiple Mo cylinder concentrically in this topology allows for an increased neutron detection sensitivity at low flux. By joining the outermost and innermost cylinders together to ground and applying the high voltage on the center cylinder, the fission chamber creates two capacitors in parallel. Since the chamber will operate across a wide range of neutron flux (from 1 n/cm²/s to greater than 10⁹ n/cm²/s), several techniques have been developed to accommodate the wide dynamic range. To understand the basic concepts, Campbell's theorem must be introduced, which states: A system whose input is a Poisson-distributed signal in time with a mean rate of λ and whose impulse response is $h(t)$ has an output mean and variance given by:

$$\bar{V}_s = \lambda \int_{-\infty}^{\infty} h(t) dt, \tag{1}$$

and

$$\sigma_s^2 = \lambda \int_{-\infty}^{\infty} h^2(t) dt, \tag{2}$$

where \bar{V}_s is the voltage from an individual event with a resultant "tail," as shown in Figure 3 (Papoulis 1986). Assuming the detector is connected to a simple R-C network, the pulse height of the individual event can be determined since the charge generated is proportional to the energy deposited in the detector medium by the incident particle. This assumes that $1/\lambda \gg \tau \gg t_c$ (with τ being the time constant of the R-C circuit, and t_c the detector charge-collection time). The rate can be determined by counting the number (n) of pulses with amplitude above a threshold, over a known period (T) and deriving λ from:

$$\lambda = \frac{n}{T}. \tag{3}$$

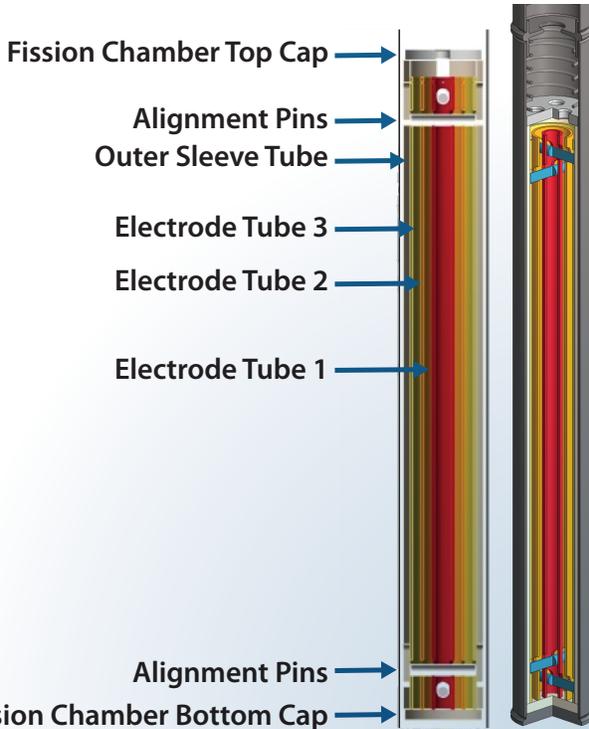


Figure 1. Illustration of high-temperature fission chamber topology.

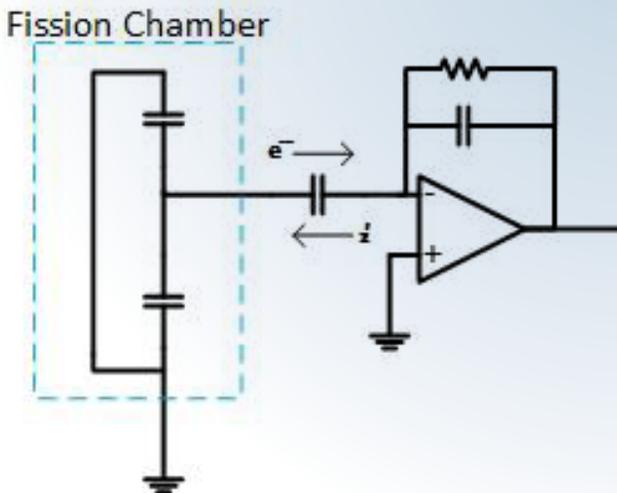


Figure 2. Circuit representation of fission chamber with front end electronics.

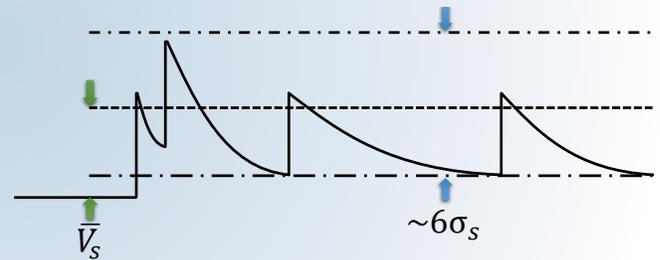


Figure 3. Campbell's theorem illustration

However, the pulse rate will increase as the reactor power and flux increases. Pulses will eventually build up and create a "pile-up" effect. The front-end electronics are designed to operate in both low rate (pulse mode) and high rate (current mode). Campbell's theorem for the mean and variance then becomes:

$$\bar{V}_s = \lambda \int_{-\infty}^{\infty} h(t) dt = \frac{Q}{c} \lambda \int e^{-\frac{t}{\tau}} dt = Q \lambda R = \bar{I} R, \tag{4}$$

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and

$$\sigma_s^2 = \lambda \int_{-\infty}^{\infty} h^2(t) dt = \frac{Q^2 \lambda \tau}{2C^2}, \quad (5)$$

where the value of $Q\lambda$ is simply the mean current from the detector so that the voltage across the resistor is proportional to the event rate in the detector. The variance can be minimized with proper low-pass filtering.

Housing the Fission Chamber

To minimize the risk of fission product escape during testing, the fission chamber is housed within two containment cylinders (Figure 4). The primary containment is a single-ended, welded titanium tube, sealed with a stainless-steel ConFlat (CF) flange. Multiple designated feedthroughs in the CF flange allow for backfilling of gas and electrical connections.

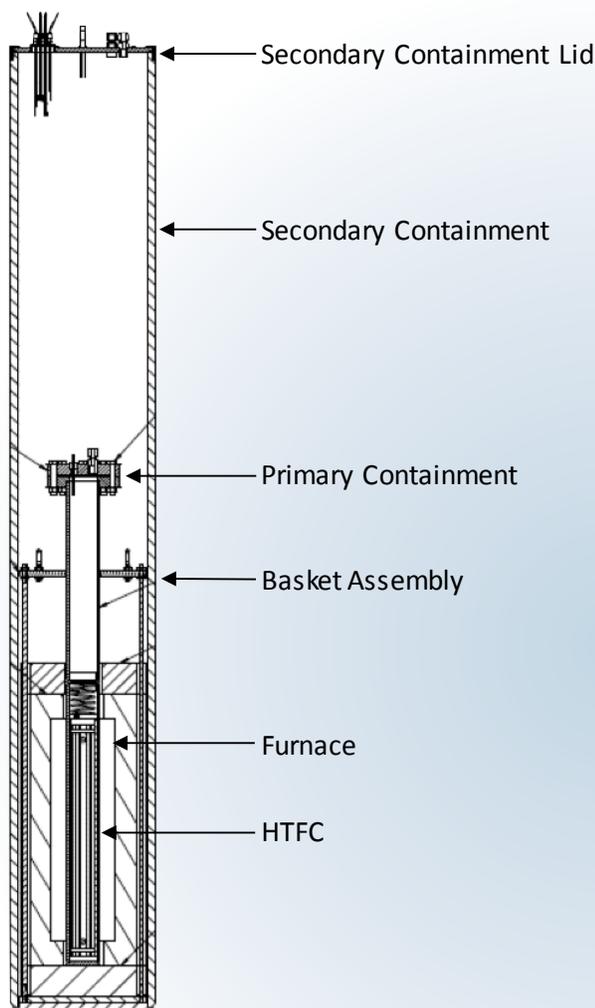


Figure 4. Fission chamber containment.

The primary containment is surrounded by a heating element (furnace) and is located within a secondary containment composed of a larger aluminum cylinder. The secondary containment serves as a redundant safety mechanism, should there be any fission gas leakage from the primary containment, and is actively monitored using a gas sampling system. Temperature is regulated in the assembly using a proportional, integral, derivative controlled DC power supply, with feedback from several thermocouples attached to the primary containment. Additional thermocouples are located throughout the secondary containment for additional safety precautions.

Experimenting with the Fission Chamber

An experiment at the Ohio State University Research Reactor (OSURR) is scheduled for late September 2017. Two test locations were selected (one within the reactor pool and a second external to the reactor pool) to enable operation in both pulse and current mode. A test plan was generated for each day of reactor operation and simulations provided the activity and dose rate of the experimental assembly at the end of each day. Figure 5 displays the planned power and temperature experiment for 5 days of operation. The test plan calls for ramping the fission chamber temperature to a steady-state of 800°C, then acquiring data over a broad range of reactor power levels. On the last day of testing, reactor power will stay at both a high-temperature and high-power level to simulate prototypic advanced reactor operation.

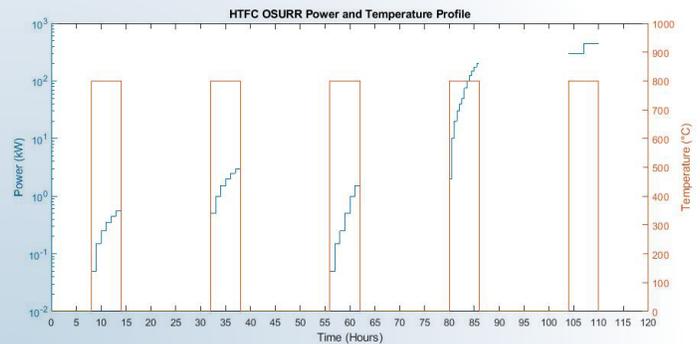


Figure 5. Power and temperature experimental plan at OSURR

Following irradiation testing, ORNL is limited to storing the fission chamber at the OSURR for 1 year. Based on this constraint, the test plan is designed to limit the final dose rate to occupational and transportation limits.

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Automation in the work process

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Idaho National Laboratory

The work process cost of nuclear power plants in the United States represents a large portion of the overall running cost, with maintenance (such as corrective maintenance, preventive maintenance, and design changes) being the most significant portion of this cost (Thomas et al., 2015). Maintenance work is controlled by work packages. As a result, improving the work package process reflects directly into improved plant economics. With the current technological advancements, it is possible



to automate several functions of the current work package process to reduce this cost while improving the process safety. The automated work package of the Light Water Reactor Sustainability Program is a pilot project aimed at achieving this objective.

The complexity of the current work package is driven by the amount and depth of information associated with every step in the work package (Figure 1). These associations are properties introduced to the work package by the planner or procedure writer to ensure systematic and controlled work progress and are time and cost demanding. The automated work package project researches the means to automate these associations from

the step level to the overall work package process level to significantly improve the process efficiency and safety.

A need study was performed to evaluate the automated work package scope alignment with the industry need. The survey included 12 participants with roles, including maintenance supervisors, planners, procedure coordinators, and information technology architects from various utilities and plants in the United States. The survey results demonstrated that most of the steps of the work process (EPRI 2015) need to be changed or automated (Figure 2), with the time-consuming and trivial tasks being the main target for automation. The survey also evaluated the perception of the industry on several automation functions (out of 50 automation functions described in Al Rashdan et al., 2016) to certain aspects of the work process (Figure 3 seen on page 13); the results of which demonstrated a strong desire for the industry to move towards state-of-the-art automation solutions. The automated work package project evaluated several of these functions through studying the use of radio frequency identification (RFID) for materials, tools, and equipment tracking in foreign materials zones, low-energy-enabled Bluetooth beacons for

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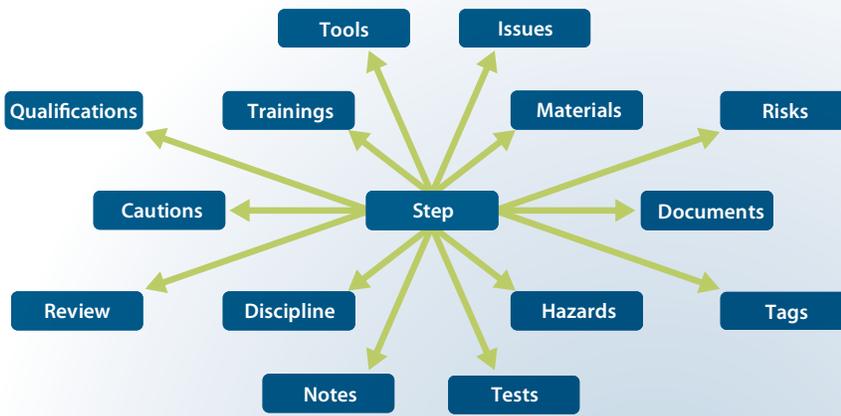


Figure 1. Example of properties of a step in the work package procedure.

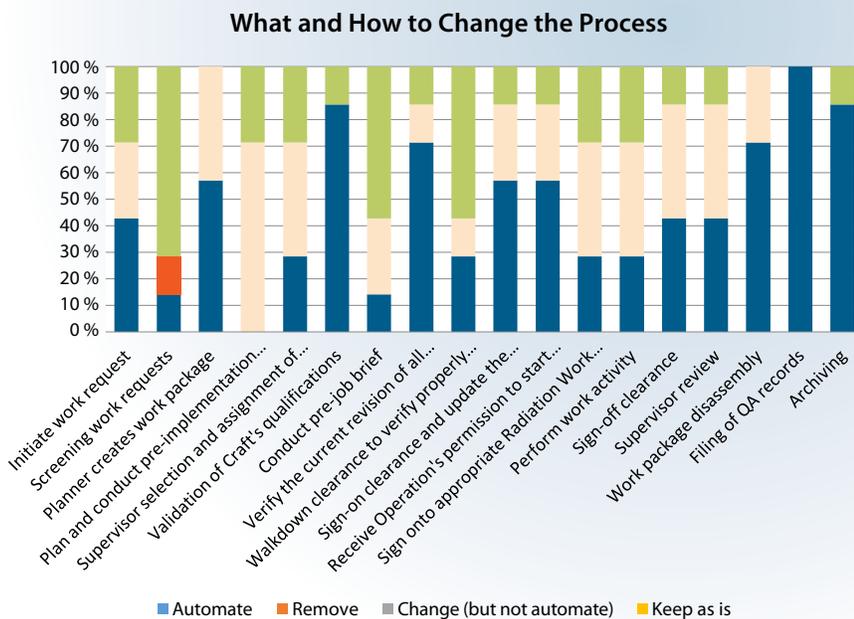


Figure 2. Results of the survey question: "What and how to change the process."

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Which of the listed capabilities would help increase the efficiency of the work package process?

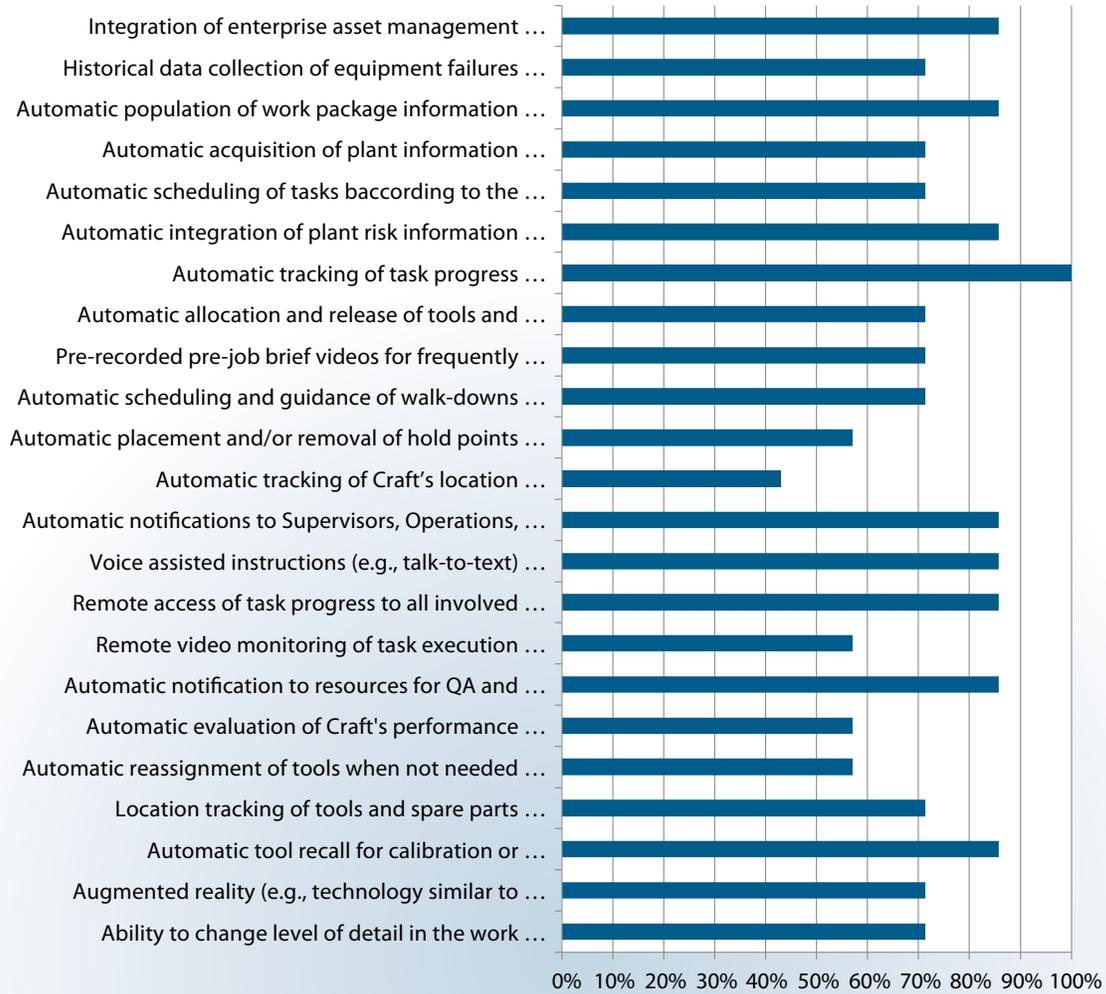


Figure 3. Results of the survey question: "Which of the listed capabilities would help increase the efficiency of the work package process?"

location tracking and automatic warnings and actions, video monitoring for quality assurance and peer review, remote video monitoring for remote approval and monitoring, and wireless instruments data acquisition for automatic population of plant information into the work package. Xcel Energy Inc. collaborated with Idaho National Laboratory (INL) on studying the feasibility and benefits of some of these functions for the nuclear power industry. The means to integrate the large and diverse functions into a single platform was also addressed through developing principles of the work package data architecture. This represents the backbone data architecture for the work package process on which to build and integrate the automation functions.

Work Packages Data Architecture

The development of the work package data architecture and the corresponding database structure requires a customized design that reflects the work package process in data correlations. The common optimization process, such as the compromise between flexibility and complexity or storage needs, were analyzed to develop principles that apply to the work package data architecture. The principles developed included evaluating:

1. Horizontal versus vertical data structure design: The data architecture needs to rely on both designs to various extents, with the vertical structure combining steps into tasks, tasks into work orders, then work orders to work packages in a hierarchal manner, and

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the horizontal structure representing properties associated with every element of the data tree. The horizontal structure was also found to spin into its own subtrees of properties and chains of properties co-association.

2. Properties inheritance and adoption: While every element in the work package has some properties (Figure 1), these properties can be horizontally and bi-directionally cascaded or vertically inherited. A mechanism to override and lock properties had to be defined.
3. Usage-driven segregation of data: In the context of the work package data architecture, two versions of the data elements are needed to segregate live data that can be accessed and updated by the craft from configuration data that are edited by the procedure writers or planners.
4. Replication: A method to handle replication needs to be developed for improved database performance and reduced storage need. This can be achieved by incorporating the concept of templates and instances into the data architecture, in a similar approach to object-oriented development.
5. Dynamic logical flow: Since the automated work package procedures rely on adaptive and intelligent decision making, the underlying data architecture needs to support these capabilities. The definition of flow elements into every dynamic decision making aspect of the data structure can be incorporated by introducing logical association tables and completion indicators.

Radio frequency Identification (RFID):

The need to automate the association of materials, tools, and equipment (MTEs) with the work package and its elements was identified as a needed function by the



Figure 4. Sample of radio frequency identification tags of various forms and designs studied.

nuclear power industry. In addition, Xcel Energy Inc. expressed interest in evaluating automating the logging process of MTEs into and out of a materials exclusion zone (MEZ). The most promising means to achieve this objective was determined to tag MTEs with passive (non-powered) RFID tags (Figure 4). These tags can be remotely powered and read by mobile and fixed readers (Figure 5). The use of RFID tags on a sample of MTEs (Figure 6) was

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Figure 5. Mobile radio frequency identification reader (top) and fixed antennas-based reader (middle and bottom).

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evaluated through a system prototype and software that was developed at INL (Figure 7). The aim of the evaluation was to determine the performance aspects of the technology, including the probability of false detection of MTE due to the variation of tags read range, missing an MTE due to blockage by an object or another tag, and the restrictions of applying the technology for the specified application such as losing an instrument or RFID tag. Scenarios were developed to handle all the possibilities and

the prototype was enhanced with measure to encounter found challenges. In addition, the association of RFID tags (of the MTEs) with craft procedures was developed on the backbone infrastructure to evaluate the potential economic and safety benefits of the technology on the current work process. The cost of implementing this technology was found to be negligible to the cost saving it introduces.

Continued on next page



Figure 6. Example radio frequency identification tags installation on materials, tools, and equipment.

Select All
 Unselect All

Select All
 Unselect All

Log In List

Ind.	Hits	Prox.(%)	ID	Description
0	34	100%	2016 1209 0851 8A01 1040 00C7	Screw driver Size 4
1	48	100%	0229 0500 0000 0000 0000 17EB	Adjustable Wrench RITCO
10	3	0%	0000 7DFC 0C09 0A1D E1F5 0863	
11	5	0%	0204 9300 0000 0000 0000 0327	
12	4	100%	0229 0500 0000 0000 0000 17DE	Tools bag
13	1	0%	3008 3382 DDD9 0140 0000 0000	Procedure: MV seal repl
2	87	95%	E200 9A70 1003 1AF0 0000 3601	Wrench 3/8
3	73	100%	E280 1160 6000 0205 0055 825D	Multimeter FLUKE 6062A
4	27	100%	2015 0429 8511 0300 0102 03D0	Wrench 7/8
5	1	100%	2016 0409 1083 5A01 1020 032F	Saw small
6	10	0%	2016 0525 0878 5A02 1050 04E7	
7	5	0%	E280 1160 6000 0205 0055 826D	

Update List

Ind.	Hits	Prox.(%)	ID	Description
1	48	100%	0229 0500 0000 0000 0000 17EB	Adjustable Wrench RITCO
13	1	0%	3008 3382 DDD9 0140 0000 0000	Procedure: MV seal replac
0	34	100%	2016 1209 0851 8A01 1040 00C7	Screw driver Size 4

Log Out List

Ind.	Hits	Prox.(%)	ID	Description

Missing Items List

Ind.	Hits	Prox.(%)	ID	Description
0000	0000	0000	0000 0040 2989	Hammer Low Force

Unassociated Items List

Ind.	Hits	Prox.(%)	ID	Description
0	34	100%	2016 1209 0851 8A01 1040 00C7	Screw driver Size 4
1	48	100%	0229 0500 0000 0000 0000 17EB	Adjustable Wrench RITCO
10	0	0%	0000 7DFC 0C09 0A1D E1F5 0863	
11	0	0%	0204 9300 0000 0000 0000 0327	
12	4	100%	0229 0500 0000 0000 0000 17DE	Tools bag
13	0	0%	3008 3382 DDD9 0140 0000 0000	Procedure: MV seal repl
3	73	100%	E280 1160 6000 0205 0055 825D	Multimeter FLUKE 6062A
4	27	100%	2015 0429 8511 0300 0102 03D0	Wrench 7/8
5	1	100%	2016 0409 1083 5A01 1020 032F	Saw small

Procedures List

Ind.	Hits	Prox.(%)	ID	Description
0	Ahmad Al Rashdan	3008 3382 DDD9 0140 0000 0000		MV seal replacem

Figure 7. Developed radio frequency identification prototype application.

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Figure 8. Bluetooth low energy beacons used for the pilot study.



Figure 9. Developed Bluetooth low energy location identification prototype.



Figure 10. Electric shock warning due to detection of Bluetooth low energy tag that is associated with this type of hazard.

Low Energy Bluetooth Beacon:

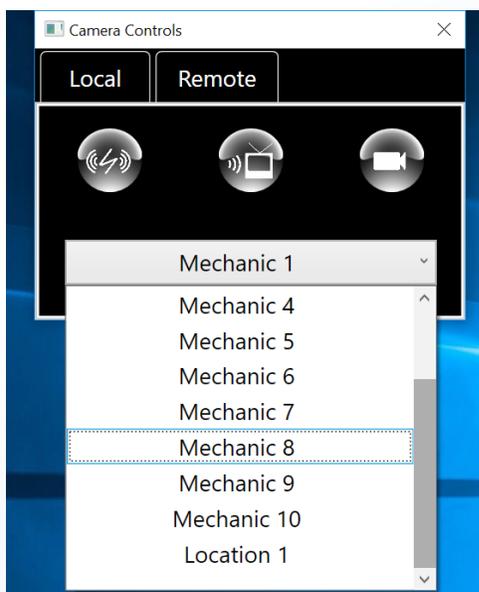
While the RFID tags require dedicated readers to power and remotely read RFID tags, the use of Bluetooth low energy (BLE) beacons (Figure 8) was identified as another potential technology that could have several applications in the nuclear power plant work package process. These beacons rely mainly on low data rates to preserve power; therefore, these beacons operate for more than a year without the need for battery replacement. Specifically through a prototype application (Figure 9), INL evaluated the use of this type of technology to automatically trigger tablet safety warnings (Figure 10) for areas that requires special attention of the crafts and to take actions such as switching off the wireless connections when entering radio/wireless exclusion zones. The application developed relied on assigning the BLE beacons with various types of actions through a text file. The feasibility of using different methods of radio signal strength indicators (RSSI) for location identification has been studied in literature for accurate location identification applications (see Goldoni et al., 2010 for more information). However, the use of RSSI for the above mentioned application necessitated a different approach using a calibrated threshold to trigger the desired action. The use of multiple identical-function beacons was found to overcome several limitations of implementing the technology for this application such as the slow detection time in comparison to the walking speed of a person with the mobile device and the misalignment between the scan cycle of the mobile device and broadcast cycle of the beacon. The evaluated application facilitates increasing reliance on mobile devices in the nuclear power plant work process and was of specific interest to Xcel Energy Inc. The cost of a beacon is in the order of tens of USDs, which is very cost attractive to implement in as many locations in the plant as possible. In addition, these beacons can also be used for tagging large assets in the plant to track their real-time presence for logistics applications. This is facilitated by the long-range radio signal detection capability of the technology.

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Video Monitoring and Recording:

Despite the recent advancements in video recording and monitoring applications, these applications in the work process of a nuclear power plant have not been significantly utilized. As a result, the automated work package project in collaboration with Xcel Energy Inc. evaluated the use video monitoring and recording for just-in-time training, quality assurance, peer review, and remote approvals. A prototype was developed that is customized to the need of the nuclear power industry (Figure 11). The prototype allows the craft, supervisor, or operator to access one or more current work package processes remotely,



and record the process if needed. The aim of this study was to determine the factors that restricted implementing this concept in a nuclear power plant work process from a technology and human factors point of view. Fixed and helmet-held cameras (Figure 12) were used for the prototype development and study.

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Figure 12. Fixed (left) and helmet held (right) cameras.

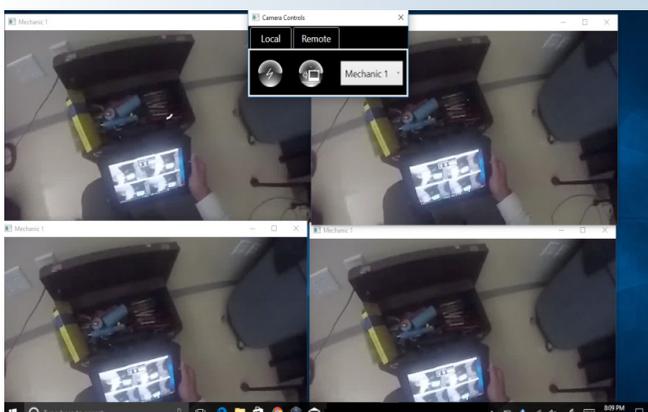


Figure 11. Developed video monitoring and recording prototype.

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Wireless Acquisition of Process Information

Due to the current limited wiring and cabling infrastructure in the nuclear power industry, the use of wireless instruments was deemed as the most attractive solution for additional process monitoring. The use of the wireless instruments readings in the work package was identified as one of the desired functions of the automated work package; therefore, this function was evaluated from a feasibility and communication architecture perspectives as part of a pilot study. The various architecture of communication architectures were evaluated, including the direct acquisition of instruments measurements in proximity or the use of a dedicated monitoring wireless infrastructure for remote process measurements (Figure 13). The aim of this function is to reduce the labor hours needed to acquire the measurements manually and

the safety aspect associated with reducing the human error due to acquiring the wrong reading or acquiring the measurement from the wrong instrument.

Conclusions

The current work package and work process is highly manual, resulting in significant cost to the overall operation of the plant. Most of the work package processes can be automated to reduce the operational cost of the plant while improving its safety. While the industry has been focusing on the means to advance the procedure to intelligent and adaptive procedures through information technology and human factors' methods, the automated work project has been researching the means to implement mature or soon-to-be-developed technologies to facilitate the transition of the industry to automated methods of executing the same tasks in a more efficient manner. The potential for the evaluated technologies was found to be enormous, and often require small investments to achieve significant returns.

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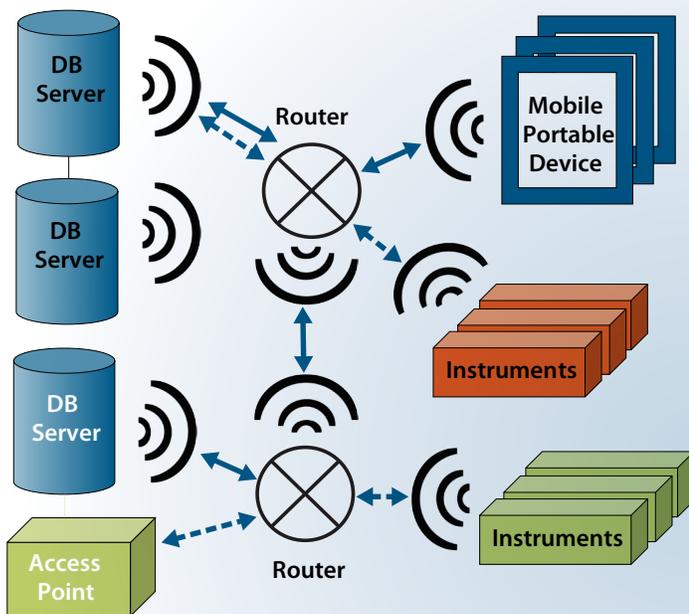


Figure 13. Server-based communication architecture for wireless instruments reading acquisition.

A Robust Wireless Communication System for the Harsh Environments in Nuclear Facilities

Dr. Faranak Nekoogar

Dirac Solutions Inc.

A typical nuclear power plant (NPP) instrumentation and control (I&C) system not only includes many hundreds of sensors, but also several kilometers of cables for reporting the sensor data. The issues with cable integrity and reliability, as well as the cost and time needed for structural modification for cable maintenance has been a daunting challenge for existing NPPs (IAEA 2012, Hashemian et al. 2011). Wireless sensor networking is potentially a key enabling technology for improving I&C process and monitoring next generation NPPs. However, the heavy metallic (reflective) environment, thick concrete walls, as well as electromagnetic interference (EMI) from other devices in NPPs results in channels that are hostile for radio frequency (RF) signal propagation. In addition, there is a concern that wireless RF systems may interfere with other electronic devices in NPPs. A highly robust and technologically advanced sensor communications system, specifically designed for use in such harsh environments, could provide invaluable enhancements to the current I&C monitoring practices such as reliable real-time monitoring for normal, abnormal, and emergency operations, while



reducing or eliminating the need for cables and the concerns associated with their integrity and longevity, reliability, as well as the potential need for structural modifications.

Objectives

In an effort to address the NPP's need for reliable wireless sensor communications, and in support of Department of Energy (DOE) Advanced Sensors and Instrumentation Program, Dirac Solutions Inc. (DSI) funded by DOE Small Business Innovation Research (SBIR) program has designed a unique ultra-wideband (UWB)-based communications system that is capable of reliable communications in challenging RF environments (Nekoogar 2005). (Figure 1)

Although DSI has currently developed and deployed a range of UWB communication products for voice and data communications, the outcome of the current project is a design specific to NPPs and is expected to deliver the same reliable performance as other previous applications. Furthermore, the new wireless technology provides data security and has unique features that take advantage of software-defined-radio (SDR) capability to self-adapt its communication parameters to the dynamic wireless channel of various NPPs.

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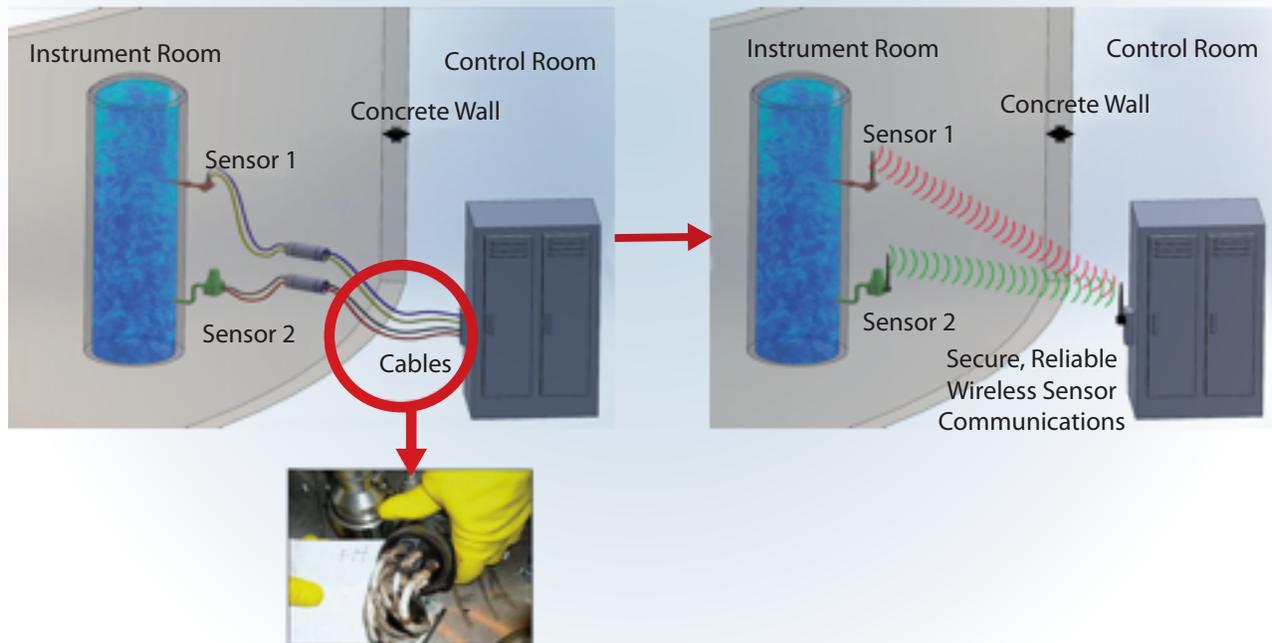


Figure 1. (Left) Current method, wired sensor communications and cable integrity issue [1,2], (b) DSI's vision for next generation reactors – secure, reliable wireless sensor communications.

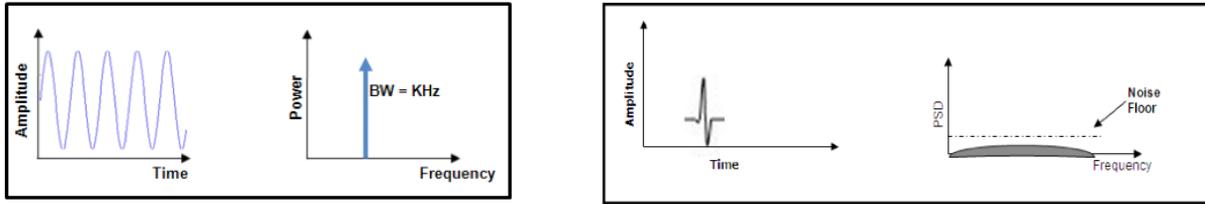


Figure 2. Comparison of a typical narrowband signal with a UWB pulse in both time and frequency domains (left) narrowband, continuous waveform (right) ultra-wideband, pulse based.

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Ultra-wideband Technology

Unlike conventional narrowband wireless technology that uses continuous waveforms for communications, UWB systems use short duration pulses (sub-nanosecond) as the communication building block. These narrow pulses naturally generate a very wide bandwidth, in the range of a few GHz, in frequency domain. This high bandwidth provides the ability to send large amounts of data for sensor networks at a very low power level with a low probability of interfering with other instrumentation devices. Figure 2 compares narrowband and ultra-wideband signals in both time and frequency domains.

Referring to Figure 2, the continuous waveforms in conventional narrowband signals generate high-spectral power levels over a very narrow band (spikes) in frequency domain. This narrowband high-spectral power not only can cause interference to other narrowband signals, it can also be easily detected and jammed. Furthermore, this narrow bandwidth limits the data rate for sensor networks. On the contrary, the frequency spectra of the UWB pulses are spread out over many GHz of bandwidth with a power spectral density residing below the noise floor of a typical narrowband receiver. Therefore, the UWB transmitted pulses are not only very difficult to detect when transmitted with a certain time-space coding, but are effectively invisible to unauthorized receivers. In addition,

the extremely wide bandwidth of UWB pulses (GHz) generates large channel capacity and a robust link with respect to relative immunity to multi-path and diffraction in harsh RF propagation channels such as cluttered and reflective environments.

Figure 3 shows the continuous wave narrowband LOS signals can experience significant degradation if destructively added to NLOS reflected signal (for example, dropped calls in an elevator). However, for the UWB pulse, the window of opportunity for destructive cancellation is less than a nano-second that normally does not give enough time for the reflected NLOS pulse to reach the LOS pulse causing cancellation. Another advantage of UWB signals for communications in a reactor environment is their ability to provide physical layer encryption by pulse coding techniques. Short-duration UWB pulses can be effectively coded with respect to their shape, polarity, and timing between pulses to look like random noise to an unauthorized receiver. This level of physical layer encryption can be enhanced by media access control (MAC) layer encryption for added security.

It is important to emphasize that to date, all the other forms of wireless systems using conventional standards such as Bluetooth, WiFi, Zigbee, etc., face the same challenges, as they all use the conventional continuous waveform RF signals for transmission.

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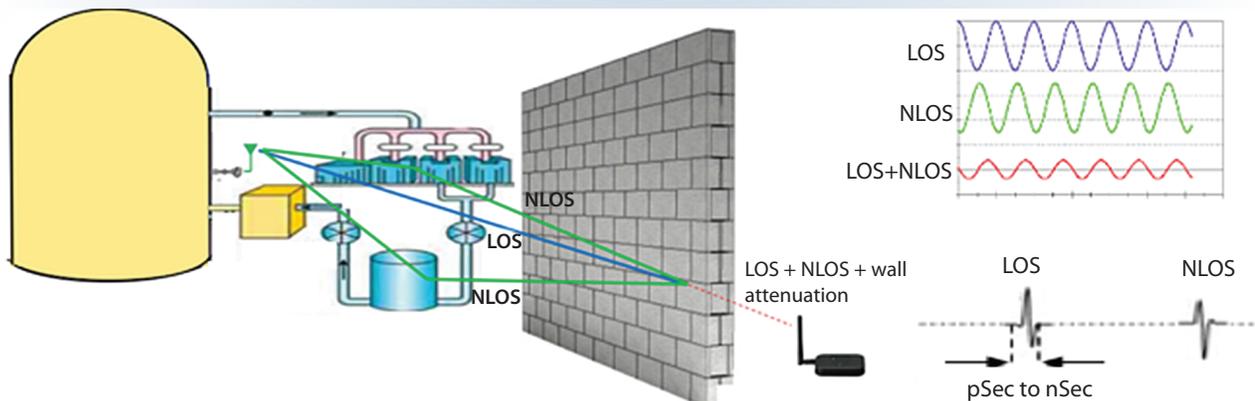


Figure 3. (Left) Example of hostile RF channel in a typical NPP where both the main signal, Line-of-Sight (LOS), and reflected signal, Non-Line-of-Sight (NLOS) are present due to heavy metallic environment. (Upper Right) Narrowband signal response, (lower Right) UWB signal response.

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Progress

DSI has recently completed its Phase I DOE SBIR effort with successful design of a unique UWB sensor communications system and is now ready to develop the SDR hardware and software platforms in Phase II. The NPP-specific communications design parameters were selected based on a series of extensive UWB propagation studies at Massachusetts Institute of Technology Research Reactor (MITR) as well a suite of MATLAB simulations for RF channel propagation conducted in Phase I. DSI experiments at MITR based on an existing DSI UWB transmitter demonstrated great success for data transmission in hostile RF environments (Figure 4). In this set of initial field experiments conducted in Phase I, SBIR effort showed reliable communications from various points in the instrument room to the control room through closed metallic doors and thick concrete walls.

Based on UWB propagation tests and experiments in Phase I, thereby systematically addressing the communications parameters, we now plan to develop the hardware, software, and firmware available from this research to fully productize a secure UWB communications system based on software-defined radio (SDR) in a 2-year Phase II research plan. Since every NPP environment might be different, an SDR is a better option compared to the

fixed architecture hardware systems as the communications parameters such as center frequency, bandwidth, pulse shape, link capacity, and duration between the pulses can self-adapt to various environments.

DSI's secure, wireless sensor communications system designed for hostile electromagnetically environment of NPPs, is expected to be ready for manufacturing in current Phase II work. A subsequent Phase III plan will serve the needs of various wireless sensor applications of next generation and modular nuclear reactors, as well as the broad range of applications requiring secure wireless communications such as high-end commercial markets (processing plant manufacturing, semiconductor capital equipment manufacturing, etc.).

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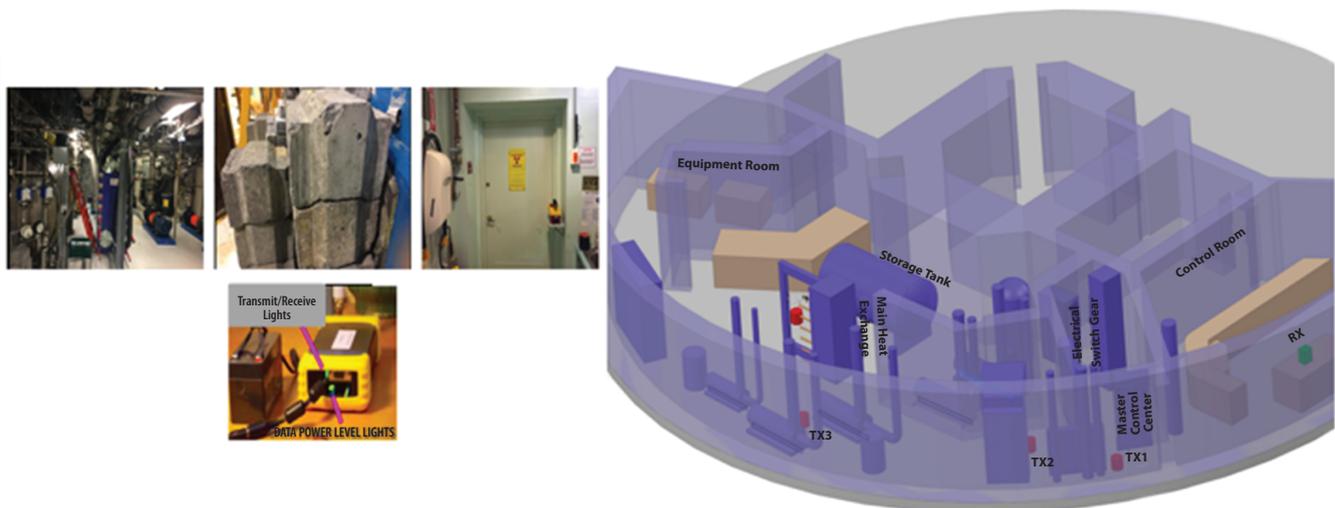


Figure 4. (Left) UWB sensor communications device and the challenging environment of MITR where the device was tested, (Right) Transmitter locations in the instrument room transmit UWB pulses and the receiver in control room reliably detects the pulses despite the closed metallic doors.

New Fiber Sensors for In-Core Measurements: Toward Intelligent and Safe Nuclear Reactors

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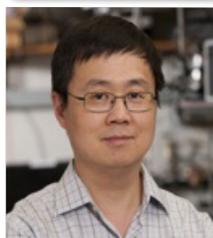
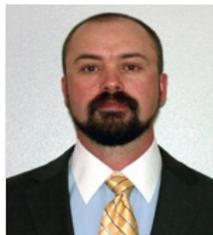
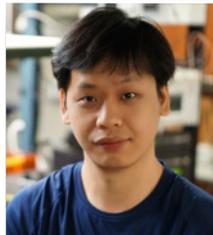
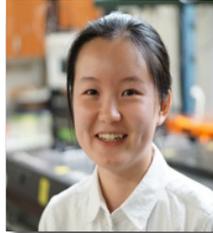
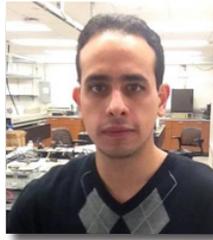
David Carpenter
MIT Nuclear Reactor Laboratory

Joshua Daw
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Kevin P. Chen
University of Pittsburgh

University of Pittsburgh researchers work with Industry Partners, MIT Reactors, and Idaho National Laboratory to Revolutionize Sensing Technology for Extreme Radioactive Environments

Nuclear reactor cores are arguably the most challenging artificial environments. High core temperatures up to 800°C and strong fast neutron flux at levels of 10¹⁴ /s/cm² essentially put most of sensor devices out of operation. Currently, thermocouple temperature sensors are probably the only reliable measurement devices for in-core applications. Yet, situational awareness in this harsh environment is essential to ensure safe and efficient operation of nuclear reactors. When Department of Energy scientists and industry engineers are designing next-generation nuclear reactors that are easier to construct at lower cost, operational safety remains the top priority for next generation reactor technology. To address reactor safety issues, a number of sensing technology are being explored.



Supported by a Nuclear Energy Enabling Technology (NEET) program and a Nuclear Science User Facilities (NSUF) program, a team of scientists developed two types of optical fiber sensors that can drastically improve situational awareness inside reactor cores. This team includes researchers from the University of Pittsburgh (Pitt), Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), National Energy Technology Lab (NETL), in collaboration with industry engineers from Corning Inc. and Westinghouse Electric Company LLC. An international partner, Dr. Stephen Mihailov, from National Research Council of Canada (NRCC) is also part of the team.

Compared with electronic sensors, fiber optical sensors are uniquely suitable for harsh environment applications. They are known to be able to withstand very environmentally high temperatures. A unique trait of the fiber optical sensors is their capability to perform distributed or multiplex measurements, while an entire section of optical fibers can be used to perform either physical or chemical measurements to achieve high spatial resolution data gathering. Thus, tens or even hundreds of sensors can be multiplexed on a single fiber interrogated through a single fiber feedthrough. This is an enormous advantage over electronic sensors, while every sensors must be serviced by individual leads. The implementation of the fiber sensors for in-core applications will greatly enhance situational awareness for nuclear reactors. However, the survivability of optical fiber and optical fiber sensors under intense neutron flux have always to be a great concern.

The NEET program led by Dr. Kevin Chen in Pittsburgh has spent the last 2 years focusing on both the survivability and functionalities of fiber sensors under high-temperature radiation environments. Working with Corning, we evaluated various existing radiation harden fibers such as F-doped glass fibers and pure silica fibers. A specialty random air-hole pure silica fiber emerges as a suitable candidate for radiation environments. Unlike photonic crystal fibers, the new fiber can be readily fabricated at a very low cost. At the same time, researchers at the University of Pittsburgh in collaboration with NETL and NRCC developed a unique laser fabrication technique to produce both multiplexible fiber Bragg grating (FBG) point sensors and temperature robust distributed fiber

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sensors in these air-hole fibers. Figure 1a shows a reflection spectrum of FBG sensors in random-hole fibers fabricated by a femtosecond ultrafast laser. Figure 1b shows a Rayleigh back-scattering profile in the same fiber. The Rayleigh backscattering is enhanced by up to 40-dB through

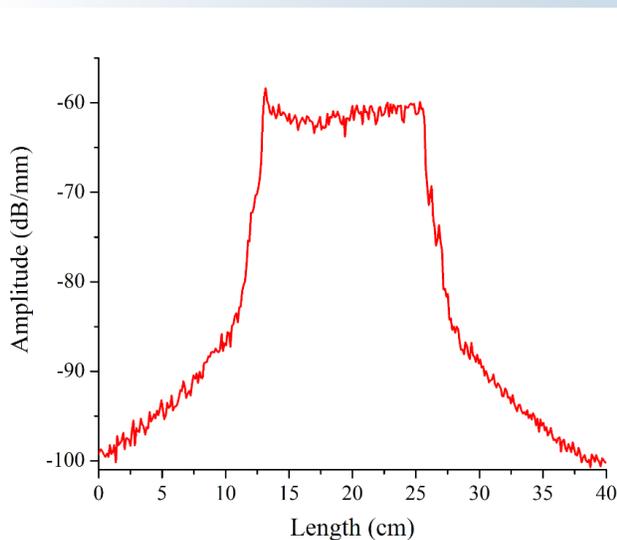
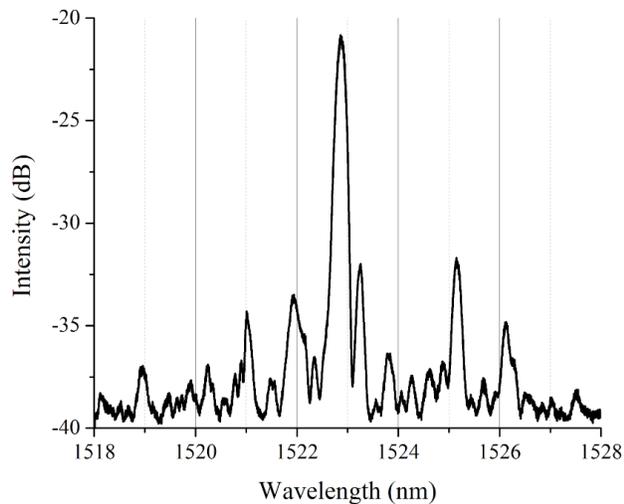


Figure 1. (a) Reflection spectrum of a FBG in a new specialty fiber. (b) Rayleigh scattering enhancement profile in a radiation-harden fibers for distributed temperature measurements.

ultrafast laser-induced nanogratings. These fiber sensors were evaluated outside reactors at temperatures as high as 1000°C. Without neutron flux, both showed stable performance. With stable Rayleigh scattering profiles and a drastically improved signal-to-noise ratio, the distributed fiber sensors can perform highly reproducible distributed temperature measurement at 800°C with 4-mm spatial resolution. A 15-cm section of the Rayleigh-enhanced fiber shown in Figure 1b is equivalent to at least 35 temperature sensors interrogated through one fiber, a capability unattainable by any electronic sensors.

Working with Dr. Joshua Daw of INL, we implemented an in-core testing experiments. Mr. David Carpenter and the entire technical crew at the MITR designed a sensor housing for a lead-out experiment. Fiber sensors were placed and sealed in 7 meter-long, 1/16-inch outer diameter metal tubes. The sensor sections of the tubes were placed in a graphite and titanium capsule as shown in Figure 2.

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Figure 2. Photograph of fiber sensors in metal tubes and capsule used at MITR for in-core lead-out testing.



Figure 3. (a) MIT scientists lower fiber sensor assembly into the reactor core. (b) University of Pittsburgh graduate student Mohamed Zaghoul in the reactor control room for remote monitoring.

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The in-core lead-out testing is scheduled for 1 year and started on May 5, 2017. The reactor temperature was controlled at 800°C, and various temperature cycling was implemented to simulate different scenarios of reactor operations. The reactor temperatures were controlled by the fuel power input and helium gas flow. Three thermocouple temperature sensors were also inserted into the capsule to monitor temperatures at the top, middle, and bottom sections of the capsule. These data will be used to compare with the fiber sensors measurements. Both distributed and point sensor devices were placed in reactors. In total, distributed and point sensors were fabricated on four different types of fibers for this round of in core testing. Figure 3a shows sensors being lowered to the reactor by MIT researchers. All sensors are remotely interrogated in the controller room. Mr. Mohamed Zaghoul (Figure 3b) from Pitt carried out the entire monitoring and data analysis for this in core testing.

The combined efforts of specialty fiber design and sensor fabrication specifically for in-core applications yields

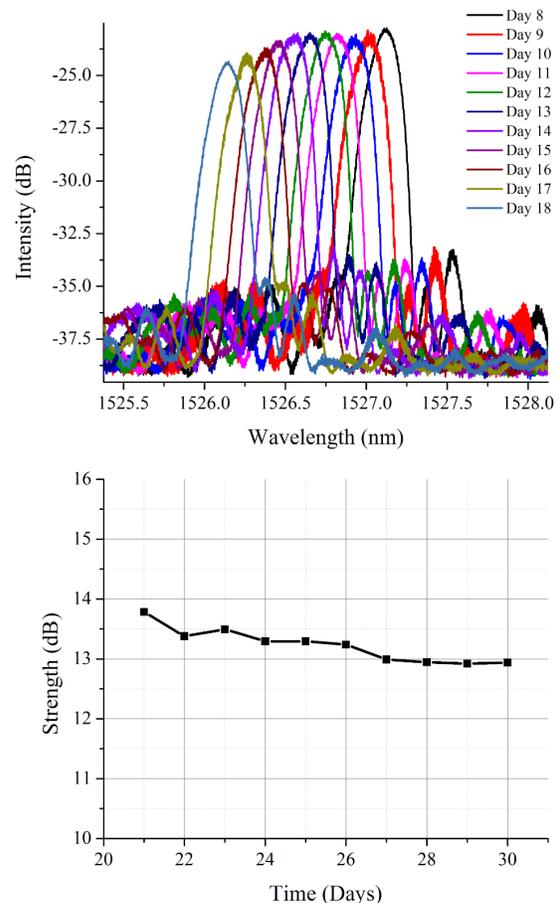


Figure 4. (a) FBG wavelength shift in reactor at 800°C and (b) FBG peak wavelength versus in-core testing time.

outstanding results for both distributed fiber sensors and point sensors. Figure 4a shows FBG spectra evolution in random-hole pure silica fiber under 800°C and 1014 n/s/cm² fast neutron flux. The FBG peaks shift toward shorter wavelength probably due to radiation-induced compaction. The FBG peak intensity also degrades slightly, as shown in Figure 4b, after 18-day radiations. Overall the FBG peak degraded less than 1-dB. The radiation-induced absorption is also minimal. Given that the depth neutron-intense region of a typical reactor is less than 3 meters, performance of both sensors and fibers, shown in Figures 3, are more than adequate for in-core applications. This is probably the best performance of a fiber point sensor in the in-core environment. Both FBG wavelength and peak intensity stabilized after 40 days. Not all FBG sensors survive the in-core conditions; FBG inscribed in conventional radiation-harden fibers (pure silica core, F-doped cladding) died after ~10 days. This highlights the importance of an integrated and teamed approach. The development viable in-core sensing technology should include a full spectra of expertise, including sensor materials, sensor fabrication, sensor packaging, testing, and industry implementation.

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To further evaluate sensor performances, MIT researchers created a number of temperature cycles by changing the reactor power and thermal exchange gas mixtures to simulate reactor anomalies. Figure 5 show the comparative measurement results of temperatures using both FBG and thermocouple under various neutron power. Since FBG sensors have not been calibrated, FBG wavelength shifts were used to reflect temperature changes in the reactor core.

Figure 6 shows temperature profile measurement stability using the distributed sensors. During this measurement, the reactor power remains constant. The figure reveals the importance of the laser manufacturing technique. Rayleigh profiles on sections of fiber without laser processing show a huge variation on temperature measurement as high as over 1000°C, this is due to the fact that fast neutrons

constantly change the backscattering characteristics of the fiber. However, in the section of the fiber stabilized by the ultrafast laser processing, the temperature profile remain constant. The distributed sensor can achieve 1-cm spatial resolution for in-core environments. It revealed a 9°C temperature difference in a 5-cm section of the testing capsule (Figure 2), which was confirmed by both simulation and thermocouple sensors.

Our test results presented in this article show that fiber sensors can be extremely useful tools to gather high-spatial resolution information in reactor cores. Although this paper only present temperature measurement results, similar fiber sensors (FBG and distributed) can also been used to perform high spatial resolution acoustic and pressure measurements with minor modification. The radiation-induced compaction could be compensated by on-fiber calibration optical structures. We believe fiber sensors will be an indispensable part of future nuclear energy systems.

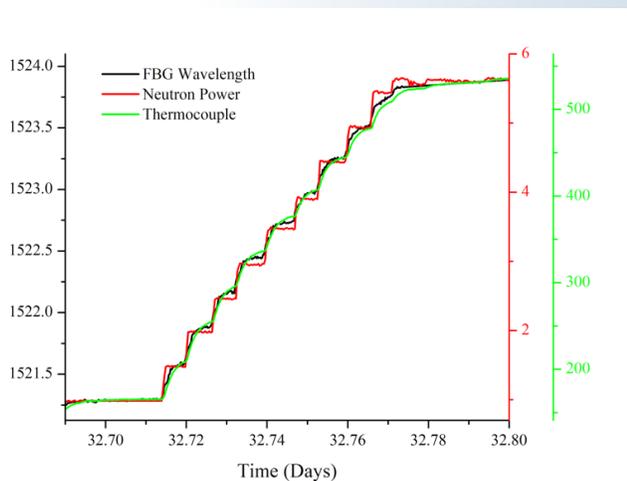


Figure 5. Comparative temperature measurements using both FBG sensor and a thermocouple sensor in various neutron power.



Figure 6. Photo of the triple bubbler system immersed in molten salt.