ADVANCED SENSORS AND INSTRUMENTATION

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Embedded Instrumentation & Control for Extreme Environments

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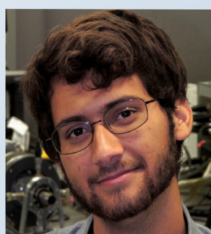

Modern nuclear reactor designs are creating new challenges in component design, operation, and maintenance. Many advanced reactor types, such as fluoride salt reactors, increase intrinsic safety margins and efficiency but require new components that can operate reliably in extreme environments. These extreme environments can include high temperatures and corrosive liquids that limit or exclude the use of legacy commercial components. These extreme environments challenge materials and components, including the instrumentation and control systems. Most legacy mechanical systems and electronic components such as sensors, actuators, and control systems will not survive in a high-radiation, high-temperature corrosive environment. The goal of the Embedded Instrumentation and Control for Extreme Environments project at Oak Ridge National Laboratory (ORNL) is to demonstrate the benefits of tightly integrating and embedding the instrumentation and controls into a system designed to operate in the extreme environment of a salt reactor system.

These benefits translate to component designs with significant advantages: higher reliabilities, lower maintenance costs, and in some cases additional system functionality that would not otherwise be feasible using traditional design methods. ORNL has extensive experience in embedded systems, control theory and application, novel sensor design, nuclear engineering, materials science, and molten salt reactors that are being applied to this challenging project. This current research builds on previous work at ORNL that developed a conceptual design of a high-temperature molten salt pump.[1–3]

In nuclear power plants, significant challenges to reliability goals are the legacy coolant pump systems. Pump bearings and seals, which can be complex systems, require periodic maintenance that can be quite expensive. Bearing and seal failures can also cause serious safety incidents, such as loss of coolant accidents.[3] In many reactor system designs, primary and secondary coolant seals require independent cooling and lubrication. These requirements introduce additional system complexity and increase the number of failure points. The failure rate of seals and bearings in the corrosive high-temperature environment of molten salt reactors would likely be higher.

ORNL is building a series of two testbeds to demonstrate the effectiveness and new functionality created by applying integrated and embedded instrumentation and controls. These test beds are the start of a development

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path towards a practical liquid salt pump that can operate immersed in the 700°C (1292°F) coolant. The proposed design eliminates the need for rotating seals and mechanical bearings that would quickly degrade in the extreme environment of molten salt. The current legacy approach for pumping liquid salt is an overhung vertical sump pump style that uses a long shaft to separate the motor from the high-temperature impeller environment. The shaft sealing system utilizes a dry gas metallic gasket seal that relies on inert gas flow. Figure 1 shows the 7.5 kW overhung sump pump used as the coolant pump in the ORNL molten salt test-loop.

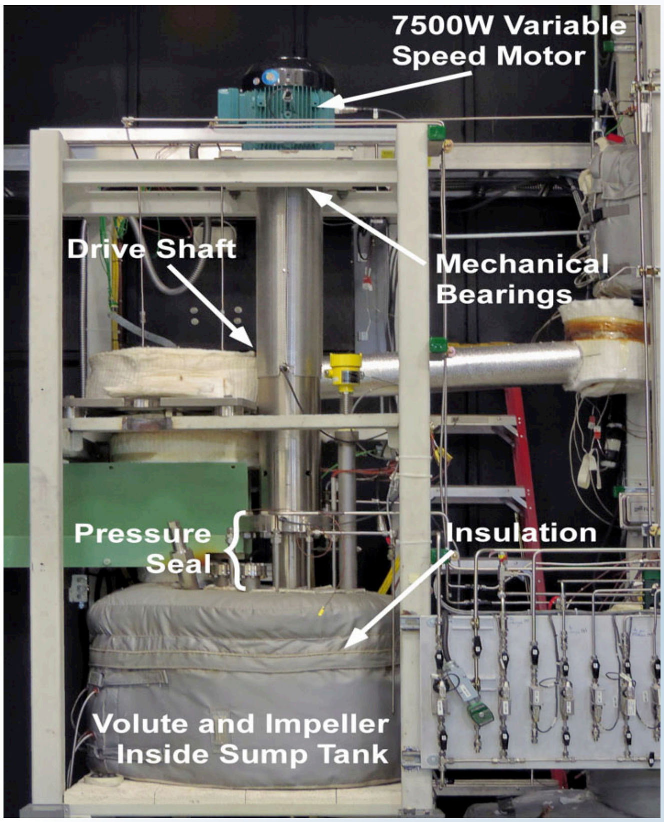

Figure 1. Overhung pump used in the ORNL molten salt loop experiment.

The overhung pump design is sufficient for research purposes with small-scale systems, but does not scale well to larger commercial power generation designs (e.g., 5 to 10 MW electric motors). Some of the challenges are shaft machining and balancing. The usefulness of the overhung design on large nuclear power plants is limited by the bearing life, seal degradation, and low pump efficiencies. An alternative design approach is a canned-rotor pump, which is commonly used in food service and other industries. A canned rotor pump is a seal-less design where the rotor and stator have a thin metal sheath between them that separates the fluid being pumped from the pump electrical components. The canned rotor design allows the pump and motor rotor to operate submerged in the liquid salt by using a material to shield the electrical motor (stator) components from the corrosiveness of liquid salt.

Separating the rotor and stator environment by a can barrier is only one of several required technical implementations for successful operation. Immersion in liquid salts creates challenges for materials, such as bearing design, motor design, sensors, and controls. At 700°C, which is well above the Curie temperature of most magnetic materials, components that rely on magnetic field interactions will no longer function. Specifically, permanent magnets and silicon steels will not maintain a magnetic field at those temperatures. There are nickel-cobalt alloys with a Curie temperature that is sufficiently above the operating temperature to support a magnetic field. The nickel-cobalt alloy material can enable the design of a switched reluctance motor that can function at liquid salt temperatures.

The high temperature and corrosiveness of the liquid salt will also rapidly degrade mechanical bearings. A magnetic bearing suspension system for the rotor shaft in place of the mechanical bearings decreases pump maintenance while increasing reliability and efficiency. The internal access limitations imposed by a canned rotor design and the extreme environment limit the options for applying legacy-sensing approaches; therefore, a sensorless design is required. The physics of the magnetic bearing actuators will be exploited to measure and determine shaft position. In effect, the stator actuators that are providing the shaft holding forces will also be utilized as position sensors in place of discrete position and speed sensors. An illustration of the motor-pump concept is shown in Figure 2 with front and rear magnetic suspension bearings, switched reluctance motor, and can barriers indicated.

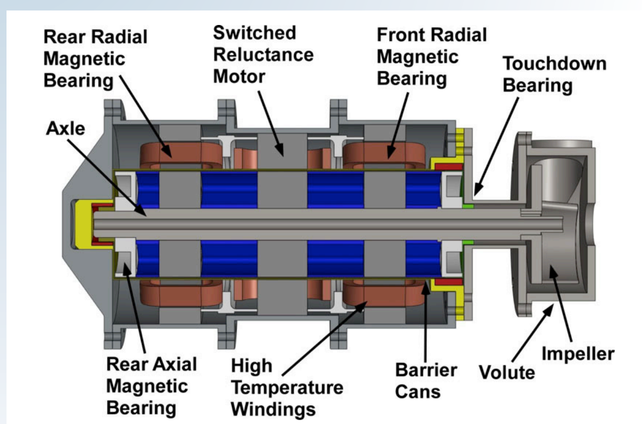

Figure 2. Concept drawing of a canned-rotor, magnetically suspended, reluctance drive motor-pump.

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Objective

To achieve these research goals, a 3-year research program was initiated to begin developing the theoretical and applied knowledge needed to achieve a high-temperature liquid salt pump. The project will demonstrate the functional and operational improvements that can be achieved by applying embedded instrumentation and controls techniques. The first three project years were devoted to developing a conceptual high-temperature design; creating and testing a bench-scale magnetic bearing testbed for developing the embedded instrumentation and controls; and designing, fabricating, and testing a low-temperature pump (i.e., room temperature water loop). The low-temperature pump allows refining the embedded instrumentation and controls in a fluid system with real impeller forces, disturbances, and nonlinearities consistent with what would be found in a high-temperature pump. The engineering and development costs associated with the design and testing of a high-temperature pump are beyond the scope of this current project, so the gradual approach to technical development was deemed the most feasible. We are currently in the second year of the project. The project objectives are as follows:

Year 1: Design and build a bench-scale magnetic bearing testbed. The first year produced a hardware-in-the-loop test and development platform for embedded instrumentation and controls. The first year's work included mechanical and power electronics design and analysis and integration of a real-time control and data acquisition system. After completion of the bench-scale testbed, system identification tests were performed to verify the (nonlinear) first-principle models of the electromagnetics, power amplifiers, and rotordynamics. Finally, a stabilizing controller for the magnetic bearings was designed and tested.

Year 2: Develop a complete pump with active magnetic bearing shaft suspension. A hardware-in-the-loop embedded instrumentation and controls test and development platform is scheduled to be completed. The platform will introduce additional complexities and dynamics that are similar to conditions to be encountered in a high-temperature fluid salt pump. Example dynamics that require attention include fluid-shaft interactions that cause axial coupling effects and nonlinear bifurcations of the fluid flow,[4] varying shaft forces at different pump flow rates and speeds, and clearance interference from shaft deflection during operation. This testbed will be used to evaluate the efficiency and reliability of the embedded instrumentation and control system.

Year 3: Integrate magnetic bearing pump testbed with an instrumented water loop and complete performance testing. Water is a good analogue to liquid salt in fluid flow, making the largest differences between operation on the water loop and high-temperature operations material property changes with temperature and eddy current effects in the protective can. The can barrier acts as a low-pass filter to magnetic circuits, and the effects must be characterized. Testing will consist of studying efficiency, identifying reliability vulnerabilities, analyzing resiliency to sudden changes in operating regimes (e.g., valve closing), and emulating high-temperature operation.

Current Status

An important engineering effort was accomplished in the first project year to design and build a bench-scale magnetic bearing testbed. The components were designed to provide the proper system integration and capability, including the magnetics, power electronics, and embedded instrumentation and control system. More detailed information on this design can be found in Melin et al.'s 2013 and 2015 reports.[5,6]

The bench-scale testbed is a modular mechanical design that can be easily reconfigured to change components and system dynamics. This configurability allows the embedded instrumentation and controls to be tested using varied dynamics and to be validated with parametric uncertainty. The testbed was also designed with large airgaps between the rotor and stator. The large airgap was chosen because a canned-rotor design needs extra annular space to accommodate the protective can barriers around the rotor and stator. The additional gap is a destabilizing influence of the nonlinear magnetic dynamics and control. During the mechanical design process, software was developed to analyze the nonlinear magnetic performance of the rotor-stator system and optimize the geometry to maximizing the bearing force while minimizing the bearing size and mass. Figure 3 shows the final mechanical and electromagnetic design of the bench-scale testbed.

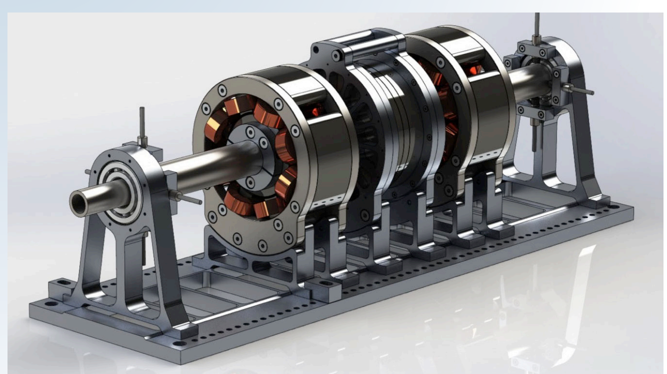

Figure 3. Bench-scale testbed conceptual rendering.

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The power electronics for the testbed were designed concurrently with the mechanical and electromagnetic design which is consistent with the embedded design process. The electronics consists of two 1440-watt Class-D amplifiers and one 720-watt Class-D amplifier that power 10 H Bridge modules. The power electronics drive circuits are used to supply the magnetic coil currents and are also equipped with integrated current sensing that is part of protection and feedback. The power electronics system also supplies auxiliary power to the sensors. A custom enclosure was designed and built to house the power electronics (see Figure 4).

Figure 4. Custom electronics enclosure for the power electronics and data acquisition.

A real-time computing and test system was integrated with the testbed, allowing design and implementation of the instrumentation and control algorithms. System identification experiments were performed to identify dynamic models of the bearing coils. The models, in-turn, were used to design a model-based feedback controller. Model-based feedback control enabled current-control mode operation, which improved the rise-time of the H-Bridge driver and increased accuracy. Following the system identification activities, a three-axis stabilizing feedback control was developed to levitate the shaft and maintain its position to within 30 µm of set point. Figure 5 shows the fully assembled, operational bench-scale testbed.

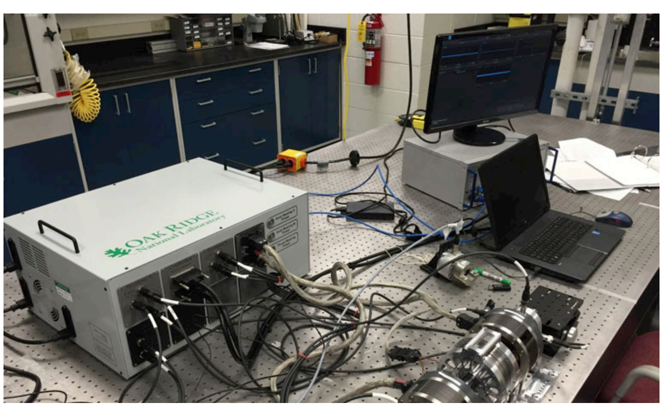

Figure 5. Complete bench-scale testbed.

System identification experiments were performed to gather data for rotor-dynamics using the stabilizing controller. Figure 6 illustrates the first mode shape frequency of the shaft in its current configuration of 414 Hz. The limited aerodynamic forces on the shaft (in air) indicate a small coupling of the radial axes. These forces will become more pronounced when the shaft is suspended in a liquid.

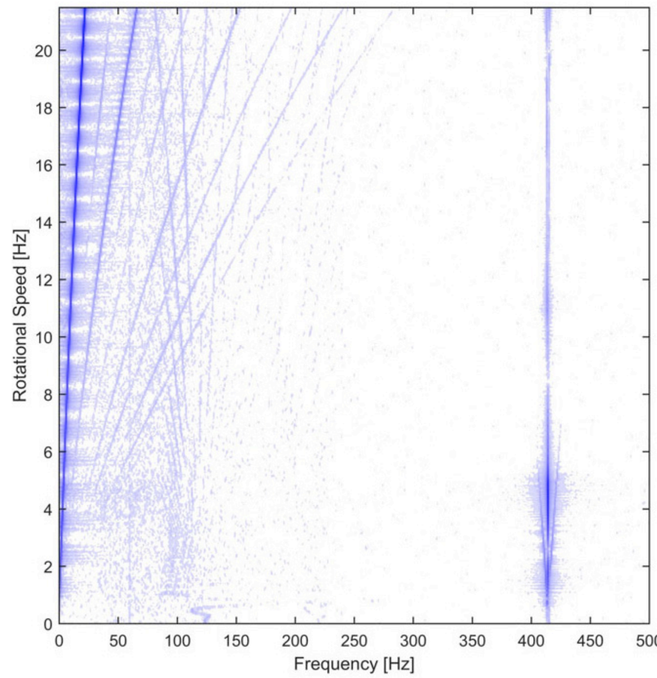

Figure 6. Waterfall plot of rotordynamics

Substantial engineering work was dedicated to the design of the magnetic bearing loop-scale pump during the second year of the project. The project strategy is for the ORNL molten salt test-loop system to test the embedded instrumentation and controls under challenging conditions that are similar to a high-temperature liquid salt pump. The development of a loop-scale canned-rotor pump will encounter significantly more design and analysis challenges than in the bench-scale testbed design. A commercial canned-rotor pump was purchased to use as a starting point for the loop-scale testbed to reduce engineering time and fabrication cost. The purchase of the commercial canned-rotor pump eliminated many design and fabrication costs, such as casting the impeller. A Teikoku™ pump was chosen, which has a 3600-RPM operating speed and a flow rate of 510 L/min. This pump was then measured and a three-dimensional model of all its components was created. A preliminary design was completed for two magnetic bearings that will replace the mechanical/fluid bearings of the original pump. Using this

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initial design and calculations for the impeller's tangential, radial, and axial forces, the electromagnetic design was analyzed and refined to meet the expected shaft forces. The mechanical design was analyzed to ensure that stator deflection was small enough to meet the functional requirements of the magnetic bearings. The design was further refined, in consultation with the manufacturer, to meet functional requirements and tolerances while minimizing the manufacturing time and cost. Figure 7 shows the final design of the loop-scale pump testbed. The loop-scale pump testbed components are currently being manufactured.

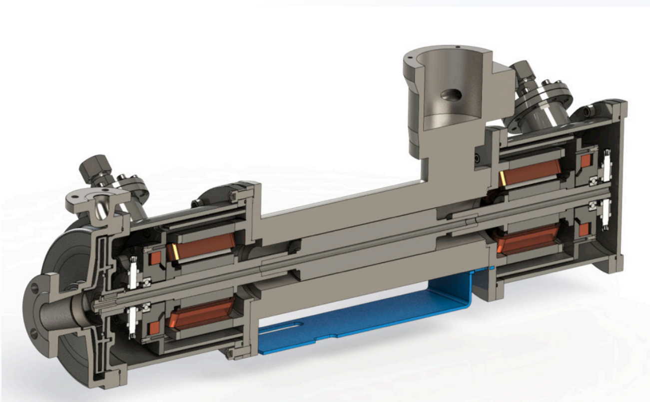

Figure 7. Loop-scale pump testbed final design.

Conclusions

ORNL has spent substantial engineering effort to design and create two magnetic bearing testbeds of increasing complexity over the last several years. The efforts are aimed at demonstrating performance benefits and increased functionality provided by embedded instrumentation and controls. After completion of this 3-year project, this foundation of multi-disciplinary, cross-cutting research knowledge can be extended to the challenge of developing high-temperature electromagnetic components with embedded instrumentation and controls. Solving the next phase of difficult and complex design challenges will enable the creation of critical new component designs that are necessary to the development and commercialization of modern advanced reactor designs. These high-temperature components will also find usefulness in a variety of other applications such as solar energy and future spacecraft. We expect the advantages of embedded instrumentation and controls to open up new design possibilities because of the ability to operate in previously unexplored extreme environments.

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Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Nodes

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The power harvesting technology has crosscutting significance to address critical technology gaps in monitoring nuclear reactors and fuel cycle. The self-powered wireless sensor node (WSN) can significantly advance sensors and instrumentation technology by reducing cost, improving monitoring reliability, which will enhance safety. The self-powered WSN could support the long-term safe and economical operation of the reactor designs and fuel cycle concepts, as well as spent fuel storage and many other nuclear science and engineering applications.

As shown in Figure 1, the objective of this research is to develop high-efficiency and reliable nanostructured thermoelectric generators (TEGs) for self-powered WSNs by harvesting thermal energy from nuclear reactors or fuel cycle.

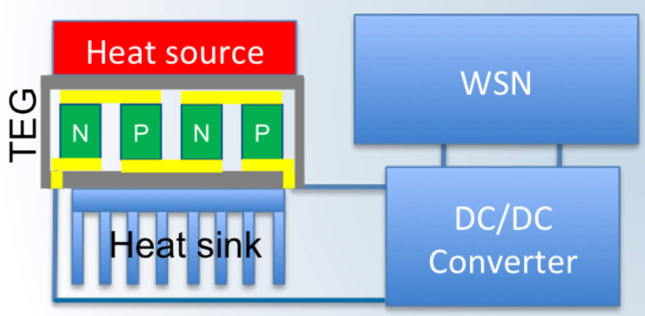

Figure 1. Schematic of self-powered wireless sensor node (WSN) using thermoelectric generator (TEG).

Background

Thermoelectric generators

The thermoelectric generator is a solid-state energy conversion technology that directly converts heat into electricity with no moving parts. Thermoelectric material efficiency is described by the non-dimensional *thermoelectric figure of merit (ZT)* defined as $ZT = \alpha^2 \sigma T / \kappa$ where α, σ, κ and T are the Seebeck coefficient, electrical conductivity, thermal conductivity, and absolute temperature, respectively.[1] Since the 1990s, a fruitful and exciting approach has led to significant ZT improvement by controlling electron and phonon transport via nanostructuring.[2] The TEG systems have attracted considerable attention due to their broad applications in power generation, waste heat recovery, and energy harvesting. A recent study suggests that among all potential power harvesting technologies for use in a nuclear facility, the TEG is one of the most promising options as waste heat is often available, and TEGs have relatively high power density and reliability and have low space requirements.[3] However, the application of TEG power harvesting in the nuclear industry still largely remains underexplored.

Wireless sensor nodes

Design and technical advancements in sensing, processing, and wireless communication capabilities of small, portable devices, known as wireless sensor nodes, have drawn extensive research attention and are vastly applied in science and engineering applications.[4] WSNs are typically powered by a battery source that has a load-dependent finite lifetime. Most applications, including nuclear industry applications, require WSNs to operate for an extended period of time beginning with their deployment. To ensure longevity, it is important to develop self-powered WSNs. The benefit of self-powered WSNs goes far beyond the cost savings of removing the need for cable installation and maintenance. Self-powered WSNs will potentially offer significant expansion in remote monitoring of nuclear facilities, and provide important data on plant equipment and component status during normal operation, as well as during abnormal operation or station blackouts and for post-accident evaluation. Schedule-driven operation, also known as duty-cycle operation, of a WSN is considered in this research because deployed WSNs are required to periodically send collected data to the base station under normal operation in most nuclear industry applications. With abnormal operation, the periodicity of data transmission can be increased as needed. A WSN will imply a schedule-driven WSN hereinafter unless otherwise noted. A WSN comprises sleep and active time periods corresponding to SLEEP and ACTIVE states. During the SLEEP state, the WSN is dormant and consumes very little power. During the ACTIVE state, the WSN senses the environment for the occurrence of an event, processes any sensed event, and transmits (utilizing defined communication protocol) the processed information to the base station or other WSNs. It also routes information packets received from other WSNs.

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Results to dates

WSN power consumption

Prior to design and development of a self-powered WSN, it is important to estimate the energy consumption of a WSN under different operating conditions. This research developed a rigorous mathematical model by utilizing the structure of a semi-Markov process to estimate the expected energy consumed by a WSN based on IEEE 802.11 and IEEE 802.15.[4] communication protocols for different duty-cycle (shown in Figure 2). Here duty-cycle is defined as a ratio of the ACTIVE time period and total cycle period. The structure of a semi-Markov process described the stochastic operational behavior of a WSN. The expected energy consumption model captures the generic operation of a WSN by considering the node level activities (i.e., sensing and processing) and network level activities. The modeling results are verified via MATLAB® simulation.

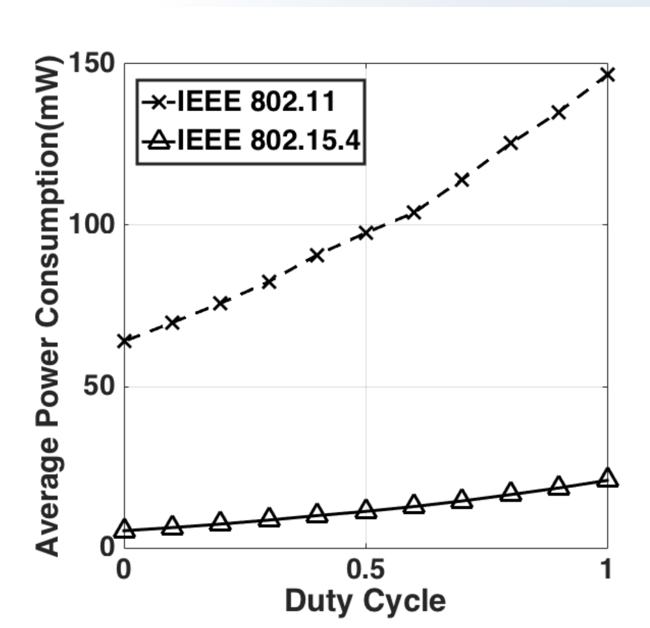

Figure 2. Expected power consumed by a WSN based on IEEE 802.11 and IEEE 802.15.4 communication protocols for different duty cycles.

TEG development

To deliver a self-powered WSN for nuclear application, a TEG power harvester of high-power density and radiation resistance is required. To achieve this goal, we employ high-efficiency and high-temperature nanostructured thermoelectric materials. An initial thermoelectric unicouple device has been fabricated using the nanostructured bulk (nanobulk) half-Heuslers thermoelectric materials that enable direct heat-to-electricity conversion over a wide temperature range from near room-temperature to 700°C. Figure 3a shows the power density of the unicouple device tested under various temperature differences (ΔT) between the hot side and cold side while the cold side is maintained at 100°C. The device reaches an ultrahigh power density above 7 W/cm² with 500°C ΔT—significantly higher than previous reports. We also investigated the effect of Gamma radiation on the electrical resistance of our nanobulk devices and a commercial thermoelectric device based on bismuth telluride (BiTe) materials. Figure 3b shows that our nanobulk devices demonstrate no changes before, during, and after radiation, whereas the commercial device shows noticeable increases in electrical resistance. This indicates that the nanostructured thermoelectric generators can potentially have enhanced radiation resistances compared with conventional TEGs made by bulk materials.

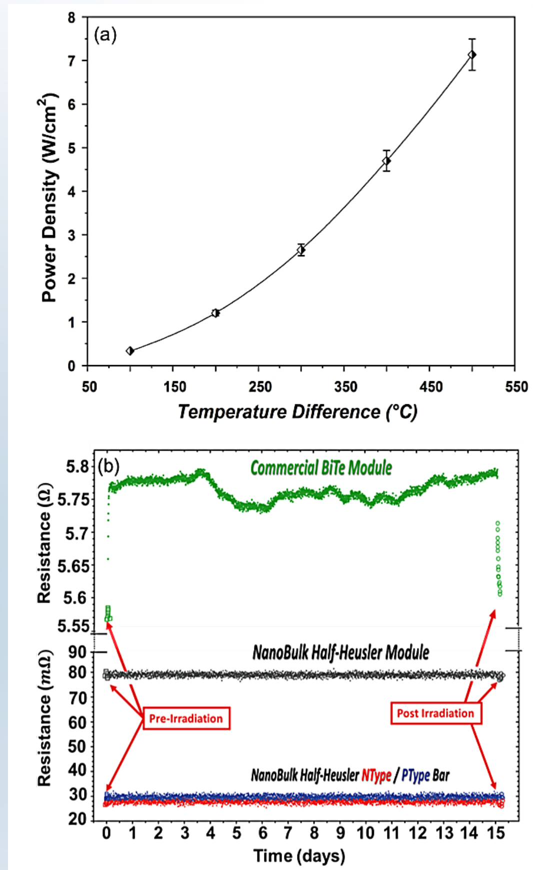

Figure 3. (a) Electric power density versus temperature difference of a nanobulk half-Heusler unicouple device at a constant cold-side temperature of 100°C. (b) Gamma radiation effect on the electric resistances of the nanobulk half-Heusler devices and a commercial BiTe device.

TEG and WSN integration

Power management is necessary to ensure efficient and reliable integration between the TEG power production and the WSN power consumption. As shown in Figure 1, a

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DC-DC converter is inserted between the TEG and the WSN to convert a DC source of a certain voltage level to another level. Therefore, it is important to consider both efficiency and regulation issues associated with DC-DC converters, both of which can be addressed by impedance matching between the TEG internal resistance and the input resistance of DC-DC converter. However, the temperature sensitivity is another issue that must be taken into consideration. The TEG systems usually operate in conditions under which temperature and power output varies with time. Therefore, dynamic impedance matching is performed in this research by using the maximum power point tracking (MPPT) algorithm. Among possible approaches, MPPT methods based on perturb, observe, and extreme seeking algorithms are adopted in this research.[5]

Conclusions

The combination of power harvesting and wireless communication will lead to truly wireless sensor nodes of significant cost and safety advantages over state-of-the-art sensor technologies used in nuclear industry. Low-cost and reliable power harvesting technology has crosscutting importance to advanced sensors and instrumentation program. Thermal energy harvesting is a natural fit for powering sensors in nuclear power plant due to abundant and persisting heat sources. Our project funded by NEET ASI program has produced a thermoelectric power harvester of ultrahigh power density of 7 W/cm^2. Our research also shows that typical power consumption for a WSN is on the order of 100 mW, indicating a very small area of less than 5 mm^2 is required to implement the TEG to power a WSN. In addition, the TEG device we developed showed enhanced radiation resistances over commercially available TEG devices due to the nanostructured thermoelectric materials employed in this research. Future research will focus on further improvement of TEG devices, irradiation effect testing and integration of TEG and WSN to deliver a TEG-powered WSN system.

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Technologies for Enabling In-service Inspection and Proactive Maintenance in Advanced Reactors

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Prognostic health management (PHM) is a proactive philosophy where operational decisions, maintenance, and repairs to systems, structures, and components (SSC) are performed prior to failure based on diagnostic input on component condition and prognostic models that predict when failure is likely to occur given the present condition of the component.

With support from the U.S. Department of Energy Office of Nuclear Energy's (DOE-NE's) Advanced Reactor Technologies program, Pacific Northwest National Laboratory (PNNL) has been working toward addressing technical gaps to developing and deploying sensors for in-situ health monitoring of passive components, and developing the associated PHM methodology, including a general framework for integrating equipment condition assessment data with risk monitors. This research helps address the program goals of improving safety and economics of advanced reactors.

PHM technologies can play a vital role in the deployment and safe, cost-effective operation of advanced reactors (AdvRx), defined here as non-light-water cooled reactor concepts. These include sodium-cooled fast reactors, high-temperature gas-cooled reactors, and molten salt cooled reactors, among other concepts. In these reactor concepts, these technologies can provide information on component failure probability when combined with condition information of SSC. Such information is important to maintaining adequate safety margins and avoiding unplanned outages, and thereby enabling lifetime management of significant passive components and reactor internals.

Key enabling technologies in this context are sensor technologies that enable in-situ dependable high-fidelity assessments of component conditions and incipient failure detection in AdvRx SSC (particularly passive SSC), and models of degradation accumulation that enable predictive assessment of probabilities of failure. By integrating these technologies for condition assessment with risk monitors, improved safety and economics of AdvRx are enabled by:

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- Providing early warning of potential degradation in inaccessible passive components leading to failure in AdvRx environments.
- Reducing risks by providing enhanced situational awareness of plant equipment and component conditions and margins to failure, particularly in conditions where knowledge of physics of failure in the AdvRx environment is limited
- Relieving the cost and labor burden of currently required periodic in-service inspections during refueling outages, especially for components in hard-to-access areas such as those in-vessel/in-containment
- Enabling real-time decisions on stress-relief for risk-significant equipment susceptible to degradation and damage, thereby enabling lifetime management.

Periodic in-service inspection technologies are used in operating nuclear power plants to provide an assessment of passive component condition, including whether significant cracking exists that could compromise structural integrity. However, the applicability of existing technologies may be limited in AdvRx, because of compact design, limited access to key in-vessel and in-containment components, and extended periods between inspection and maintenance opportunities. PHM systems, with their emphasis on increased in-situ structural health monitoring and approaches to assess the current degradation state and remaining service life (also referred to as remaining useful life) provide a mechanism to address the limitations of current in-service inspection approaches for use with AdvRx. These technologies provide improved awareness of system conditions and, in coordination with supervisory control algorithms, can enable these reactors to stay within the operational envelope while maintaining adequate safety margins.

In-situ Structural Health Monitoring and Diagnostics

To assess condition and estimate probabilities of failure, PHM systems require some type of input (data) about the state of the component(s) of interest. These inputs could be in the form of information on stressors to which the system or component is exposed, or information on the condition of a specific system or component.

For passive components, nondestructive evaluation (NDE) methods are widely used for detecting cracking or other forms of degradation. NDE methods applied in existing plants use ultrasonic waves, eddy currents, or magnetic fields for determining the presence of a crack. Visual (and remotely operated camera systems) are also widely used. These techniques are sensitive to macroscopic cracking, but are likely to be challenged by degradation mechanisms, such as high-temperature creep or embrittlement that may occur in materials exposed to the higher temperatures and fluxes in advanced reactor designs.

To increase sensitivity to degradation mechanisms of interest in advanced reactors, non-traditional NDE methods (such as nonlinear ultrasound) are necessary, with the measurements carried out through sensors permanently installed on the components. These techniques rely on the measurement of small effects that microstructural changes have on applied energy. An example is the generation of harmonics by elastic nonlinearities in structural materials, when excited by an elastic wave (ultrasound). The nonlinear ultrasound measurement has been shown to be sensitive to early stages of crack formation as well as other types of degradation (such as irradiation embrittlement). These measurements are typically performed using piezoelectric sensors, which may be adapted to in-situ monitoring but will require associated instrumentation for applying the excitation signal and recording the response. Another example is the pinning of magnetic domain walls in ferromagnetic materials by microstructural defects. In the presence of an applied time-varying magnetic field, such pinning behavior manifests itself as magnetic Barkhausen emissions whenever the applied field is large enough to overcome the pinning. These magnetic Barkhausen noise measurements may be performed using coil or Hall probe sensors. These sensors are also readily adaptable to in-situ monitoring.

In these (and other) measurement methods, several challenges need to be overcome for use in AdvRx. First and foremost is the determination of the sensitivity and reliability of these methods. In most cases, these are influenced by external factors, such as temperature, location of the flaws relative to the sensor, material

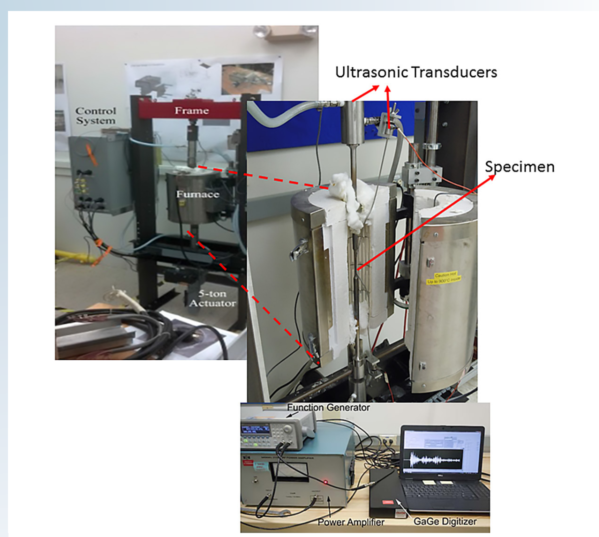

Figure 1. Accelerated aging test-bed with in-situ online condition monitoring sensors.

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microstructure, probe stand-off from the component, etc. The reliability of the measurement, in particular, is related to the probability of detecting flaws of varying sizes, and has a human reliability element when the measurement process requires a person in the loop for data collection and/or interpretation. Ongoing research at PNNL is using a combination of measurements and simulation models of the measurement physics to determine the sensitivity and reliability of these methods to cracking, as well as the effect of some of these factors on the reliability.

A second challenge is the availability of sensors that can survive in the environments in AdvRx. This can be a significant issue for in-situ, online monitoring of component condition for primary system passive components. Most piezoelectric and magnetic materials cannot operate at the high temperatures (>550°C) that they are likely to face in-vessel or around primary system components. Research conducted under other DOE-NE programs (such as Nuclear Energy Enabling Technologies [NEET] and Nuclear Energy University Program [NEUP]) has identified piezoelectric materials with reasonable sensitivity that can survive at these temperatures, and PNNL is taking advantage of these findings in our sensor design. These sensors are being evaluated for their survivability at temperature and their sensitivity to crack initiation and growth using accelerated aging and in-situ monitoring testbeds.

Integrated Approach to Diagnostics, Prognostics, and Risk-informed Decision Making

Measurement data acquired from sensors (either in-situ online monitoring or periodic in-service inspection) are generally used for decision-making about the likely impact of the flaw on the structural integrity of the component. Diagnostics and prognostics is focused on assessing the condition and the probability of failure of a component based on the flaws present and the anticipated environmental stressors it is likely to experience. PNNL has developed a Bayesian approach for diagnostics and prognostics using NDE measurements and measurements of environmental variables (such as temperature or load) that act as stressors on the material. Testing using synthetic data helped verify the ability to provide predictive estimates of different damage mechanisms (fatigue crack growth, secondary-stage creep strain accumulation), and the ability to update these predictions as additional measurements become available. Results on synthetic and experimental data (specifically linear and nonlinear ultrasonic measurements from in-situ monitoring of specimens within the accelerated aging and in-situ monitoring test-bed) have also shown the ability to account for a reasonable amount of variability in NDE measurements due to, for instance, measurement noise.

PNNL has also developed a framework for enhanced risk monitors that integrate equipment condition assessment and prognostics information to calculate time-dependent failure probabilities. Predictive risk estimates in terms of core damage frequency for a generic multi-module AdvRx case study were obtained using this methodology. Results to date include predictive risk estimates due to different failure probabilities for components, and account for periodic maintenance actions that are assumed to return components to "as-new" conditions. When combined with economic models (again a simplified case study for the purposes of evaluating the framework), these predictive risk estimates enable trade-off analyses that can help target maintenance actions as needed instead of on a preventive time-based schedule.

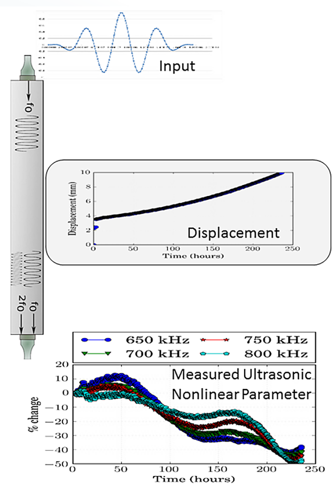

Figure 2. Example of nonlinear ultrasonic parameter measured as a function of time as specimen was subjected to high-temperature creep. The graphic also shows the arrangement of the transducers for applying the excitation and recording the response.

Summary

Technologies such as PHM, when combined with advanced sensors for condition assessment and monitoring of passive components, enable enhanced situational awareness and improved operations and maintenance decision making for AdvRx. Several technical gaps exist in applying these technologies to AdvRx components, and are being addressed by the DOE-NE Advanced Reactor Technologies program. Ongoing research includes:

- Sensor design for in-situ online monitoring of AdvRx passive component condition
- Sensor evaluation for survivability in advanced reactor environments
- Quantification of measurement reliability of in-situ online NDE measurements in AdvRx.

Sensing to Support Interim Dry Storage of Used Nuclear Fuel: Liquid Water Detection

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As the United States transitions to storing used fuel from commercial nuclear reactors in interim dry storage facilities for extended periods, utilities must be prepared to technically justify the viability of extended storage to the regulating authority. This requires an analysis of credible aging degradation mechanisms that could contribute to a release of radiological material into the environment. In many cases, the technical data needed to resolve the significance of potential aging degradation mechanisms may not yet exist.[1] Thus, one of the key objectives of the Used Fuel Disposition Campaign (UFDC) within the Fuel Cycle Research and Development (FCR&D) program is to acquire the technical data necessary to support eventual licensing for extended periods.

This work focuses specifically on methods for detecting and measuring liquid water inside of dry cask storage systems (DCSSs). Ideally, the environment inside of a DCSS confinement is inert and free of water to prevent potential corrosion of used fuel cladding or other internal hardware. However, there is some uncertainty about the amount of residual water potentially left behind in a DCSS as a result of drying processes. Considering the complex spatial and time-dependent temperature profiles in dry storage casks, water may be in liquid or gas phase depending on where it is located in the cask and how long the cask has been in storage. A review of drying specifications by several vendors concludes that if the specifications are followed correctly, the residual moisture left behind in dry casks should present an insignificant risk to cladding degradation.[2] A more recent analysis has concluded that much larger quantities of residual water could remain in dry storage casks, but the amount would still not be expected to lead to significant corrosion of fuel cladding or other internal components.[3] However, assumptions about the possible quantities of residual water or their potential significance have not yet been corroborated with field experience for periods of extended storage. The measurement techniques described here can facilitate the direct observation of residual water in the field, which help establish operational data that can inform operating and licensing decisions for extended periods of storage.

Overview of Dry Storage Systems

Although there are many different DCSS designs and models on the market, this work considered only canister-based systems. Two types of canister systems can be characterized as having two major components: (1) a thin stainless steel canister that encloses the fuel and is welded shut to provide a confinement boundary, and (2) thick concrete shielding that is often referred to as an "overpack" to shield radiation and to provide physical protection of the canister. The significant distinguishing feature of these two types of systems is the orientation of the canister in a vertical or horizontal position as illustrated in Figure 1a and 1b, respectively. To facilitate application to already loaded systems, the techniques for water detection are based on

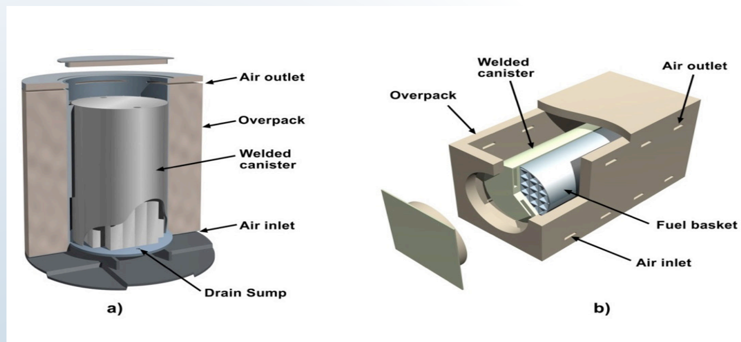

Figure 1. Illustrations of generalized dry storage systems consisting of a welded stainless steel canister and concrete overpack. Two types of systems are distinguished by orientation of the canister a) vertically and b) horizontally.

the placement of ultrasonic sensors on the outside surface of the canister so that the integrity of the confinement is never compromised. Accessibility to the canister surface is a challenge because of the proximity of the concrete overpack. However, favorable synergy with efforts by industry[4] and the Department of Energy to develop sensor delivery technologies for examining the surface of canisters for the effects of chloride-induced corrosion will greatly reduce the burden of performing the proposed measurements.

Liquid Water Measurement in a Vertical System

The technique assessed for measuring liquid water in a vertically oriented canister relies on the presence of a drain sump, which is a feature in many, but not all vertical system designs. The drain sump is a cylindrical recess in the baseplate, or floor (see Figure 1a), of a vertical system that is intended to collect liquid water during the draining process at loading. Thus, the technique for measuring

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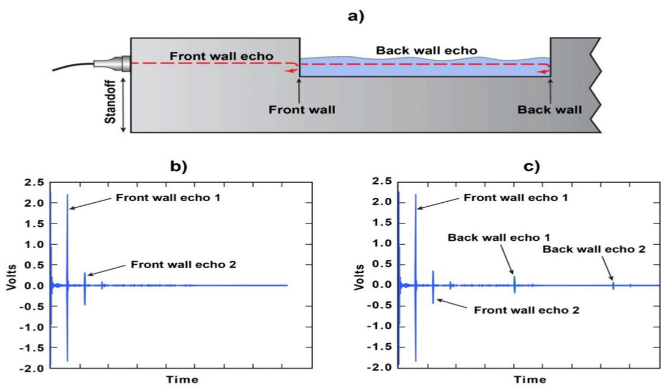

Figure 2. a) Illustration of ultrasonic energy propagating through a stainless steel baseplate and reflecting off of drain sump surfaces (i.e., front wall and back wall). Depiction of signals containing b) features of multiple front wall echo signals for the condition of an empty drain sump and c) features of multiple front wall and back wall echo signals for a drain sump containing water.

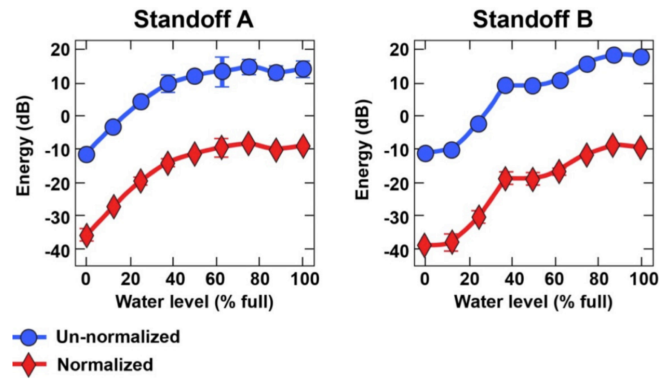

Figure 3. The back wall echo signal energy as a function of the water level in the sump at two different standoffs near the top of the drain sump. Results for back wall echo signal normalized to front wall echo signal are provided (red) along with the signal with no normalization (blue).

liquid water is based on mounting an ultrasonic sensor on the exterior surface of the canister and targeting the sound field at the drain sump location. An illustration of the measurement configuration is provided in Figure 2.

Ultrasound is sensitive to the presence of water in the drain sump because of the contrast in the transmission coefficient between a steel-water interface and a steel-gas interface. A larger amount of incident ultrasonic energy is able to transmit across the steel-water interface in comparison to a steel-gas interface. This allows the transmitted energy to propagate through the water in the drain sump and reflect off of the next water-steel interface. The reflected signal off the water-steel interface (the back wall) can be detected and can provide an indication of the presence of water. In the case of a steel-gas interface (empty drain sump), virtually all of the energy is reflected at the first steel-gas interface (the front wall) and no signals associated with the gas-steel interface (the back wall) are observed. This is confirmed by reviewing A-scan data collected for an empty drain sump and a drain sump containing water in Figure 2b and 2c, respectively, which show the absence of back wall echo signals for the empty drain sump and the presence of back-wall signals for the drain sump with water. Measurements were performed for several frequencies, transducer standoff positions, and for water levels ranging from empty to 100% of the drain sump height. Measurements were also performed for an un-normalized and normalized condition. The normalized condition was explored by taking the ratio of the back wall echo signal energy to the front wall echo signal energy. This was considered in an effort to minimize the sensitivity of the measurement to coupling conditions associated with mounting the transducer on the canister.

An example of the results obtained for one of the frequencies tested is provided in Figure 3. The results in Figure 3 show that for stand-off Positions A and B, which are near the middle of the drain sump, a monotonic trend is observed between signal energy level and water level over the full-drain sump volume from 0% to 100%. An approximate dynamic range of 30 dB can be achieved between the empty (0%) and full (100%) conditions. These trends are the same for the normalized and un-normalized scenarios.

Liquid Water Measurement in a Horizontal System

The technique assessed for measuring liquid water in a horizontally oriented canister is based on the propagation of a surface wave along the inner surface of the canister shell. An illustration of the measurement concept is provided in Figure 4. Two piezoelectric ultrasonic transducers are mounted at an angle to the canister surface using wedges. The angle of

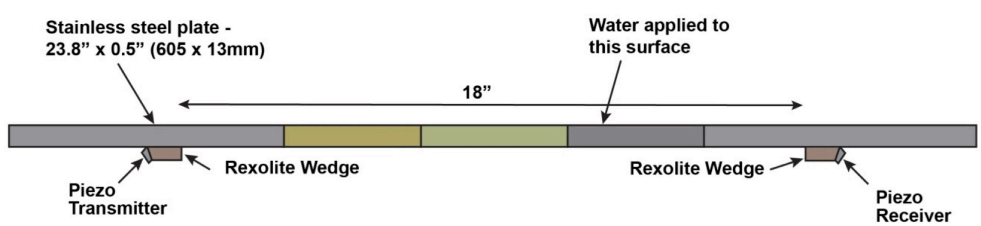

Figure 4. Illustration of experimental set-up used to demonstrate capability to detect small quantities of water on the surface of stainless steel plate opposite to the surface that transducers are mounted.

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incidence results in partial mode conversions of the bulk wave to weak surface waves at the outer and inner surfaces. The principle challenge of this effort is to be able to generate and detect an inner surface wave and observe attenuation as a result of damping caused by the presence of liquid water. Finite element modeling was performed for the geometry of a flat stainless steel plate with thickness of 12.7 mm (1/2 in.). A frequency analysis determined that the frequency band from 400 kHz to 600 kHz would be most sensitive to damping on the inner and outer surfaces.

Measurements were conducted in the laboratory on a flat stainless steel plate with thickness of 12.7 mm (1/2 in.). With transducers mounted to the plate in the configuration indicated by Figure 4, a chirp signal at 400 kHz was used for excitation. Received waveforms for several inside and outside surface damping conditions and for inside damping conditions representing different quantities of liquid water on the inside surface are shown in Figure 5. The oscilloscope traces show that sensitivity to inside surface damping is achieved and that the amplitude of the signal varies with the amount of water applied to the insides surface, displaying a decreasing trend in amplitude with increasing amount of water.

Summary and Conclusions

The feasibility of detecting modest quantities of liquid water inside the vertically and horizontally oriented dry storage canisters was demonstrated empirically with laboratory measurements. For the vertical system, the ability to measure the fill level of the drain sump was demonstrated from the empty to full condition. For the horizontal canisters, the ability to transmit and detect a surface wave on the inner surface of the canister using transducers mounted on the outside surface was demonstrated. Further, sensitivity to small quantities of liquid water was demonstrated. The measurement techniques described here provide a means to observe liquid water in dry storage casks directly, which can enable the accumulation of experiential data to support licensing of dry storage casks for extended storage periods.

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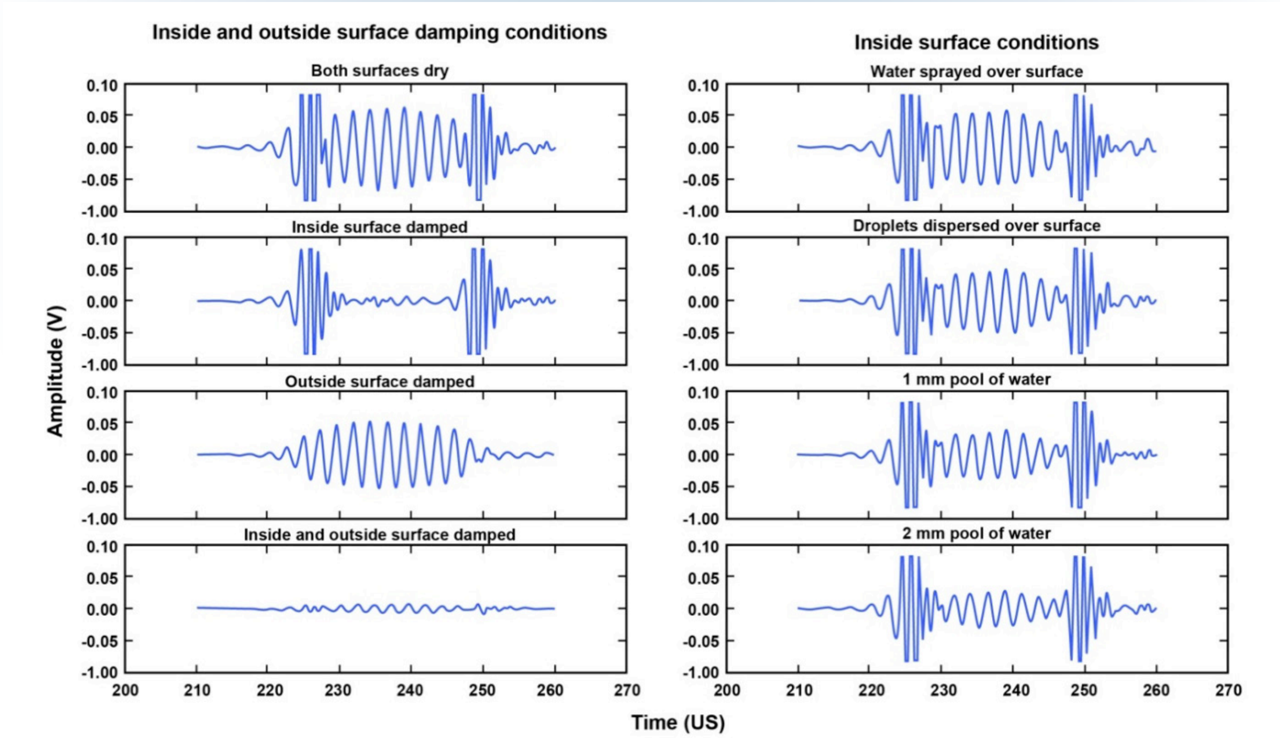

Figure 5. Receiver responses – left series: progressive waveforms for both sides dry, inside (top) surface damped, outside (bottom) surface damped, and both surfaces damped; right series: both sides dry, inside (top) surface droplets, 1 mm, and 2 mm of water on plate top surface.

A High Temperature High Reliability Control Rod Position Sensor for Improved Nuclear Power System Instrumentation

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Advancements in sensors and instrumentation are needed to enhance economic competitiveness, to improve/optimize the performance, and enhance the safe operation of future nuclear power plants and nuclear power systems. Of particular need, is to develop and improve the reliability of advanced sensors (and associated instrumentation) that can withstand harsh environments to increase the accuracy/certainty of measurements for key reactor and plant parameters, improve monitoring of performance/aging, and improve diagnostic in-service examinations.

Several nuclear power system original equipment manufacturers (OEMs) have identified a high-priority need for a control rod position sensor for fault-free confirmation of proper control rod drive mechanism (CRDM) function, maximizing safety control rods activation mechanism (SCRAM) reliability and minimizing SCRAM disengaging time. In addition to needing a reliable method for knowing CRDM position across full range of travel (with millimeter accuracy), a primary need/challenge is determining the control rods positions in the event of a SCRAM, where existing insertion verification techniques cannot be used or fully trusted. For the internal CRDM design in particular, it is not possible to verify full insertion externally, which is critical to the safe operation of the reactor.

These OEMs need a sensor that can reliably verify the control rod position and, ultimately, full control rod insertion. The technical challenges of developing such a sensor are insensitivity to particulates, small size, high reliability, and harsh environment operation, including very high temperatures (600°C), high pressures (2200 psig), borated Grade A water environment, and high irradiation. Ideally, such a sensor system would consist entirely of solid-state-sensing (no moving parts) hardware and minimal electrical connections/vessel penetrations.

Objectives

Sporian is currently working with nuclear power system OEMs under a Department of Energy (DOE)-funded grant to develop a small, high-reliability, high-temperature operable, control rod position sensor. This work is building upon prior Sporian-OEM collaboration efforts toward a single-point control rod position (rod bottom location confirmation) sensor. As part of prior efforts, Sporian collaborated with makers of CRDM for nuclear system OEMs to evaluate/demonstrate the feasibility of a compact, high-temperature, solid-state-magnetic field-based position sensor to confirm that the control rod was at the bottom position (during operation, after SCRAM event, etc.). This technology was conceived as a smaller, more-durable alternative to the physically cumbersome position monitoring approaches based on linear variable differential transformers and other induction-based methods, and contamination-prone optical-based methods. A rod bottom sensor can be realized as a byproduct of the rod positon system development, as it is essentially a smaller, simplified version of the position sensor. Thus, the development of a rod bottom variant of the hardware is an additional goal of the DOE-funded effort. The requirements for the rod bottom sensor are identical to those of the rod position sensor, with the exception of the position range (<3 inches) and resolution (<2mm).

The target application under the DOE-funded effort for the high-temperature, solid-state magnetic-field-based position sensor technology is for use in a control rod position sensor/system for fault-free confirmation of proper control rod drive mechanism (CRDM) function. The rod positon system is more than just the high-temperature sensor element. In addition to the high-temperature hardware, the system will ultimately need to include signal conditioning and communications, which have unique reliability/testability requirements for nuclear power system use, as well as the CRDM environment-compatible, magnetic field-guiding, high-magnetic permeability alloy hardware components and associated fixturing.

While CRDM position systems are the near-term target application for the technology, the proposed-compact, solid-state, magnetic-field-based position sensor could have application in many future nuclear power plants, nuclear power systems, as well as other commercial applications.

Technology

CRDMs utilize both permanent- and electro-magnets for SCRAM response. The core technology premise of the proposed sensor technology is to advanced high-temperature electronics and magnetic materials and packaging technologies to infer position from the measurement of a magnetic field with no moving parts or minimal system penetrations, without the use of

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encompassing inductive coils such as used in linear variable differential transformers and similar inductive technologies.

The essence to the performance of the device is the choice of high-temperature operable materials (largely ceramics) used to realize structural, electrical, and magnetic components within the position sensing system that can survive high-temperature, high-radiation use for very long durations. Typical silicon-based electronic components and materials used in equivalent semiconductor devices are not suitable for use at the proposed temperatures. Important to this technology development, Sporian has identified novel materials, manufacturing, and signal conditioning methods for resulting in greater magnetic field sensitivity in high-temperature environments, while minimizing system size and weight.

The complex, multi-component, mixed-material sensing core structure is reinforced for mechanical robustness and packaged into a flange structure that is designed to protect the sensing core from the harsh environment as well as interface to the higher level CRDM hardware. This flange structure includes an electrical feed-through seal to transition the electrical conductors to a mineral-insulated (MI) cable for the connection to signal conditioning and higher level control and safety systems.

In addition to sensor signal conditioning and temperature compensation, the sensor electronics (located away from the elevated temperature region) include internal fault detection/indication and "smart" sensor functionality as required. A key to this developing technical approach is a fundamentally simple device, designed for environmental durability with the end goal of realizing a highly reliable device. Based on experience, the survival temperature of the developing structure should be greater than 1000°C (~1800°F), and potentially as high as 1600°C, but the operable temperature range will likely be limited ultimately by the properties packaging material required for interfacing with existing CRDM systems.

Progress

Sporian is currently in the second year of the 2-year DOE-funded effort. Thus far, efforts have included the successful development of 850°C capable sensor hardware and "smart" electronics prototype hardware (Figure 1) that has demonstrated in laboratory-scale test systems to be capable of the target position sensing resolution up to 96 inches of travel. Preliminary test data is shown in Figure 2. Efforts have also included successful initial functional testing under high-neutron flux.

Benefits

The value proposition for Sporian's developing sensor is to provide control rod position information utilizing a lightweight, solid-state technology with no moving parts. The benefits will be a lighter, more-reliable part that reduces maintenance costs while increasing safety and uptime/operator revenue. The sensor technology also contributes to the safe operation of nuclear power systems by providing sensing diversity. It also enables an important capability for the monitoring and control of existing and future nuclear power systems. Provision of a reactor coolant flow sensor has the potential to enhance public safety and enable advanced reactor concepts, such as small modular reactors.

Figure 1. Sporian HT Rod Position Sensor with dedicated signal conditioning electronics.

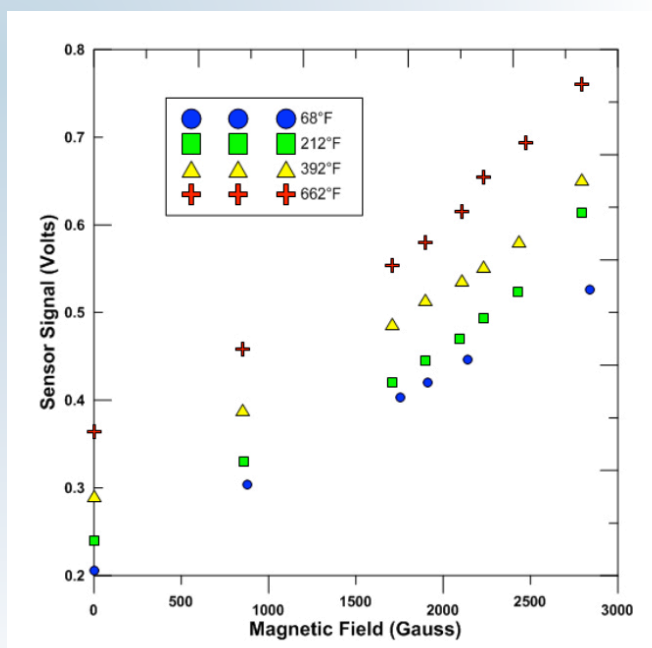

Figure 2. Response of Rod Position Sensor at varying temperatures.