Advanced Sensors and Instrumentation

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Welcome to the Advanced Sensors and Instrumentation Newsletter

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U.S. Department of Energy

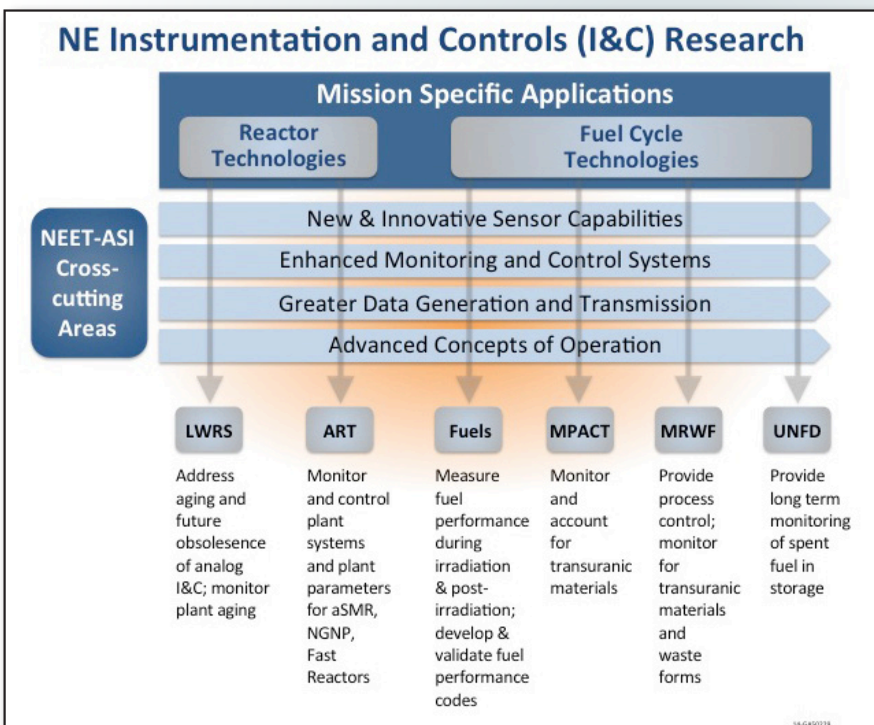
Welcome to the first edition of the Nuclear Energy Enabling Technologies Crosscutting Technology Development (NEET CTD) Advanced Sensors and Instrumentation (ASI) newsletter. This newsletter provides information on Instrumentation and Controls (I&C), sensors, and related technology research being funded by the Department of Energy's (DOE) Office of Nuclear Energy (NE). This quarterly newsletter will provide readers with updates on NE's I&C research, development and demonstration (RD&D) activities.

The development of advanced I&C systems will benefit current and advanced reactors, fuel development, and future fuel cycle facilities. Therefore, NE supports specific I&C RD&D under its various programs to address high priority research needs. NE's Reactor and Fuel Cycle Technologies programs develop I&C-related technologies as a direct result of their mission (to facilitate the transition to digital technologies for LWR sustainability, etc.) or as needed to satisfy their mission (to measure a physical property of nuclear fuels, etc.).

The NEET CTD ASI program was created in FY 2012 to coordinate I&C RD&D across NE - identifying gaps and leading prioritized efforts to address common needs. The figure below shows how NE's I&C research is organized in the different programs. ASI also works with stakeholders across DOE, other government agencies, national laboratories, academia, and industry to coordinate needed research.

In addition to the directed research funded by the Reactor and Fuel Cycle Technologies programs, multi-year I&C research is competitively awarded to universities, national laboratories and industry through NEET CTD and the Nuclear Energy University Programs (NEUP) via the annual Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA). For more information on this FOA, visit www.neup.gov. Furthermore, NE engages the small business community for targeted I&C RD&D through its participation in the Small Business Innovation Research / Small Business Technology Transfer (SBIR/STTR) programs. Information related to SBIR/STTR opportunities can be found at www.science.energy.gob/sbir under the nuclear energy topics.

In this newsletter, we hope to cover a wide range of I&C topics relevant to NE and to the reader. We welcome your feedback on this newsletter or any other aspect of the ASI program. You can reach me by phone at (301) 903-1652 or via e-mail at suibel.schuppner@nuclear.energy.gov.



INSIDE ARTICLES

Power Harvesting for Sensor Networks in Nuclear Power Plants

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Wireless Sensor Nodes

A primary issue of using power harvesting technologies currently available is the limited generation capacity. Matching a compact and efficient energy conversion device with an adequate energy source is an engineering challenge, as well as minimizing energy consumption by other circuitry in the WSN (Figure 1). Fortunately, the demand for smaller packages and longer battery life in consumer electronics has driven the development of ultra-low power circuitry for the last decade; self-powered WSN technology will benefit from these advances.

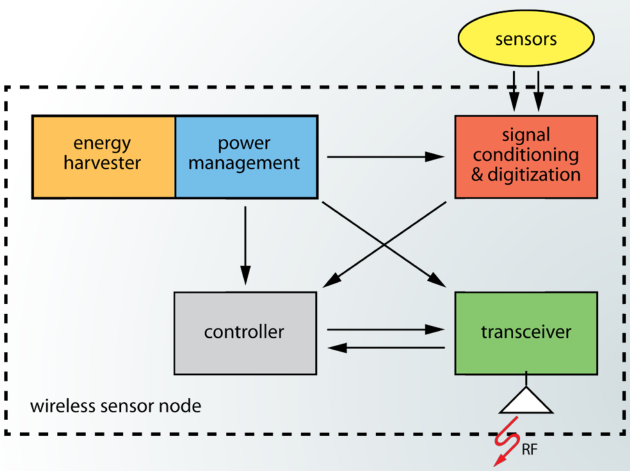

Figure 1. A functional block diagram of a WSN.

The architecture of a self-powered wireless sensor node will be largely independent of the harvesting technology employed and the wireless communications method used—assuming low power consumption is kept as a key feature. Specifically, the power management block would vary slightly according to the type of harvester used, but circuitry implementing the remaining functions would not be radically modified.

To arrive at a baseline power estimate for a hypothetical wireless sensor node, signal conditioning and digitization electronics for four thermocouples, a small microprocessor, and a radio transceiver was considered. We assume one transmission of data from this node every 30 seconds as well as several relays of data from other nodes every second. We also assume that low-power, commercial off-the-shelf components are used and that power to the thermocouple cold-junction compensation (CJC) subcircuits can be turned off between measurements.

Ambient Energy Sources

The focus of an ongoing research project has been to consider the potential for harvesting energy sources gathered from the ambient environment as opposed to energy intentionally introduced for the purpose of power generation. These energy sources can be organized into three main categories:

- Kinetic – energy from motion or force
- Thermal – energy from spatial temperature gradients or temporal temperature gradients
- Radiated – electromagnetic energy (including light that is transmitted through space.

Kinetic Sources

Human bodies, vehicles, bodies of water, machines, seismic activity, weather, and a multitude of other sources create motion and changing forces that provide opportunities for energy harvesting. Sources can be continuous, periodic, or intermittent. In addition, sources can provide energy impulses, energy in narrow frequency bands, or energy that is more random (wide spectrum) in nature. Motions and forces can be linear or rotational or a combination of the two. Each presents its own challenges and opportunities.

Thermal Energy Sources

Thermal energy sources are abundant in many environments including factories, vehicles, etc. In many cases, the heat is an unneeded (and often undesired) by-product of the generation or utilization of other types of energy. Thermal energy is useful for harvesting if spatial temperature gradients exist (by using thermoelectric materials) or temperatures change with time (by using pyroelectric materials). Most naturally occurring temporal temperature changes are so slow that their thermal cycle times (minutes, hours, days, or even longer) are too long to be useful for power harvesting. Temperature changes that are large enough and fast enough to generate substantial amounts of electricity are usually created artificially.

Radiated Energy Sources

Our environment is literally flooded with radiated electromagnetic energy from natural and man-made sources. The sun is a major source—solar insolation exceeds 1 kW/m2 at prime times in prime locations on the earth's surface. Intensities of other ambient sources pale in comparison unless locations very close to power

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transmission equipment or radio transmitters or intense artificial light sources are considered.

Kinetic Energy Harvesters

Four distinct methods exist for harnessing waste vibrational energy: piezoelectric generation, electromagnetic generation, electrostatic generation, and triboelectric. The first relies on the piezoelectric effect—certain materials will generate an electrical current when placed under mechanical strain. This method lends itself to generating high voltages, but low currents. Piezoelectric generators have been demonstrated in Microelectromechanical Systems (MEMS) devices, and performance does not suffer significantly on the microscale. Clearly, the piezoelectric properties of the chosen material directly influence the performance of the generator. However, the mechanical properties of the piezoelectric materials are also nontrivial for this generation method, as the piezoelectric elements must be directly stressed.

The second method relies on traditional induction—a magnet is moved relative to a coil of wire, producing a current. Electromagnetic generation lends itself to relatively high-current, low-voltage output. This method does not scale well; microscale implementations perform poorly in comparison to their larger counterparts. The effectiveness of electromagnetic generators heavily relies on the properties of both the magnet and the coil that are used.

The third method, electrostatic generation, relies on a variable capacitor ("varactor"). Mechanical motion can be used to change the distance between, or degree of overlap of, the plates of a capacitor. This method requires a preexisting voltage source, as an uncharged capacitor will be useless for power generation in this way. Electrostatic generation lends itself to high-voltage, low-current output. This method scales well; MEMS devices have been created that utilize it. However, electrostatic generation methods are immature in comparison with piezoelectric and electromagnetic methods.

A fourth method for harvesting mechanical energy is generation based on the triboelectric effect. This describes the tendency for some materials to become electrically charged when brought into contact with one another by pressing or rubbing. A common example of this effect is the static electricity encountered in everyday activities. Researchers are beginning to cultivate triboelectricity as a potential source of energy for harvesting, but again this method is immature compared to piezoelectric and electromagnetic methods.

Thermal Energy Harvesters

Thermal energy harvesters capture heat energy flowing from a warm surface to a cooler surface and convert it to electricity. Familiar examples are in commercially available electronic wristwatches that consume only a couple of microwatts and can be powered by heat from the wearer's arm. However, our hypothetical WSN requires several orders of magnitude more power than these watches. The majority of thermal harvesting devices feature no moving parts and relatively long effective life spans, if they are not subjected to severe environmental stresses.

The maximum achievable efficiency for any thermodynamic device is limited to its theoretical Carnot efficiency, which is determined by the difference in temperatures of the heat source and the heat sink (T_h is the hot side temperature, and T_c is the cold side temperature).

$$\eta_{carnot} = \frac{T_h - T_c}{T_h}.$$

Greater temperature differentials yield greater theoretical efficiencies. The two prominent thermal energy harvesting technologies are thermoelectric generators and pyroelectric generators. Thermoelectric generation is a well-established technique; however, pyroelectric generation, while immature, offers the possibility of significantly greater conversion efficiency.

Radiated Energy Harvesters

Ambient electromagnetic fields from natural and man-made sources permeate our environment, and they span the frequency spectrum from DC (e.g., Earth's magnetic field) to 1019 Hz (e.g., gamma rays) and beyond. Current R&D efforts focus on three technology areas for capturing this energy and converting it into electricity: electric field antennas, magnetic field antennas, and photovoltaic cells.

Electric-field (E-field) Antennas. Electric fields in typical industrial or residential environments are simply too weak to power the target sensor node. Radio Frequency (RF) energy inside a nuclear power plant is usually problematic due to its interference with sensitive electronics. Hence, it is not desirable to have or increase energy in the RF spectra. Exclusion zones around instrument stations keep sensitive electronics separated from walkie-talkies and cell phones unless detailed site-specific electromagnetic compatibility (EMC) surveys have demonstrated that such measures are not required. The availability of RF fields during some plant conditions is questionable, especially those involving interruption of power. Even though E-field

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harvesting is a fairly popular subject of current research efforts, it is not likely to produce technology useful for powering WSNs, especially in NPPs, in the foreseeable future.

Magnetic-field (B-field) Antennas. The two issues that plague E-field collectors, low field strengths and lack of source continuity, also apply to magnetic field devices. Magnetic fields can interfere with pacemaker operation, corrupt data stored on the stripes on credit cards, and induce "hum" in microphone cables; but fields strong enough for use in energy harvesting are rarely encountered. Even if the conductor is carrying hundreds of amps, it is not possible to gather sufficient energy from the surrounding field unless the receiving coil is in such intimate proximity to the power conductor that the wire loops actually surround it, as in the case of a current transformer.

Photovoltaic cells. Technology for indoor photovoltaic (IPV) energy convertTechnology for indoor photovoltaic (IPV) energy converters is maturing and being used to power wireless sensor networks, HVAC and lighting controls, and novelty items. However, compared to a solar cell in direct sunlight, IPV harvesters typically exhibit only 0.1% of the output power per unit area. This dramatic difference is the result of reduced illumination levels (typically 500 lux versus 100,000 lux) and illumination-dependent conversion efficiencies.

IPV cells typically produce only 10 µW·cm-2 when exposed to typical office-level lighting, so a square cell array with sufficient capacity for our hypothetical WSN module would be almost a half-meter on a side. Availability of ambient light is a serious limitation in a NPP environment, especially during off-grid or SBO conditions. No direct sunlight is available inside secondary or primary containment, and artificial lighting levels are often reduced when operating on backup power. Although photovoltaics are among the most mature of power harvesting technologies, the obstacles to using IPV technology for self-powered sensor nodes seem insurmountable—even without considering radiation-tolerance issues.

CONCLUSIONS

Many industries are beginning to utilize mesh networks to replace conventional point-to-point wiring, reaping the cost savings associated with eliminating the communications cabling. In addition to these cost savings, these mesh networks open the potential for greater expansion in instrumentation in the plant that could augment human performance, provide additional data on plant equipment and component status, and facilitate online assessment of the material condition of plants.

The combination of wireless communications and power harvesting enables the implementation of truly WSNs. Development of methods to couple low-drift, high-accuracy, low-power transducers with ambient power harvesting to produce a transducer that is capable of being installed during construction of the plant and operating reliably for many years and possibly until the plant is decommissioned is possible.

Fortunately, NPP facilities are abounding with environmental energy sources having potential to power wireless sensor nodes. Of the harvesting technologies considered, all except thermal energy harvesting have known issues that make them unsuitable for use in the NPP environment—especially if operation through extended SBOs is desired. Thermal harvesting seems to be an attractive approach because of the abundance of waste heat at NPPs. This heat continues to be produced when the reactor is shut down and even when the fuel assemblies are removed from service and placed in spent fuel storage pools. In SBO scenarios, heat is the one form of energy most likely to persist until grid or backup power can be restored.

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Continued on page 19

Advanced Small Modular Reactor Research and Development Program: Instrumentation, Control, and Human Machine Interface Technical Area

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Energy security and the reduction of greenhouse gas emissions are two key national energy objectives that can be met in a sustainable manner through nuclear power. The development of deployable small modular reactors (SMRs) can provide the United States with another economically viable energy option, diversify the available nuclear power alternatives for the country, and enhance U.S. economic competitiveness by ensuring a domestic capability to supply demonstrated reactor technology to a growing global market for clean and affordable energy sources. An SMR is generally characterized by (1) an electrical generating capacity of less than 300 MWe, (2) a primary system that is entirely or substantially fabricated within a factory, and (3) a primary system that can be transported by truck or rail to the plant site. These reactors can result in lower capital costs than large reactors, allow for replacement of smaller aging fossil plants to sustain the current power generation capacity, and readily adapt to support multiple energy applications (e.g., process heat, electricity). Additionally, SMRs can be introduced through phased construction of modules at a plant site to incrementally achieve a large-scale power park.

SMR Program Description and Objectives

The overall program for supporting the development, demonstration, and deployment of SMRs consists two distinct elements: the SMR Licensing and Technical Support (LTS) Program and the Advanced SMR (AdvSMR) Research and Development (R&D) Program. The SMR LTS Program's focus is on certification and licensing of the most mature light-water-cooled SMR designs (i.e., integral primary system reactors [IPSRs]) through cost-shared partnerships with reactor vendor/licensee teams. The AdvSMR R&D Program's focus is on non-light-water-cooled designs (e.g., liquid metal, liquid salt, gas) through activities to provide for the development of next-generation, AdvSMR concepts.

The primary goal of the AdvSMR R&D Program is the development of AdvSMR designs that can provide safe, simple, and robust sources of energy to meet expanding needs for electricity, process heat, or other applications at an affordable price. To fulfill this goal, the AdvSMR R&D Program supports nuclear technology research that enables the development of innovative SMR technologies. The research program is organized into technical areas, among which is the subject of this article—the AdvSMR Instrumentation, Control, and Human-Machine Interface (ICHMI) technical area.

Drivers for AdvSMR ICHMI Research

The benefits of AdvSMRs can include reduced financial risk, increased operational flexibility, and lower capital cost due to modular construction. Achieving these benefits can lead to a new paradigm for plant design, construction, and management to address multi-unit, multi-product-stream generating stations and to offset the reduced economy-of-scale associated with smaller plants. Fulfilling the objective of AdvSMR technology development also depends on the resolution of technical challenges related to the unique characteristics of these reactor concepts. ICHMI technologies provide the foundation for what is the equivalent of the central nervous system of a nuclear power plant. Therefore, ICHMI RD&D can play a significant role in resolving challenges and realizing benefits specific to SMRs.

ICHMI research drivers arise to resolve outstanding challenges and realize the prospective benefits posed by development of AdvSMRs. These drivers translate into technology needs and innovation opportunities. The basis for identifying ICHMI challenges and the resulting RD&D needs can be categorized into three major elements. These three major elements are (1) ICHMI issues that arise from the unique operational and process characteristics that are the consequence of fundamental design differences between AdvSMRs and previous or current large plants, (2) ICHMI technologies that can ensure and then further enhance the affordability of AdvSMR plants, and (3) ICHMI technologies that can further expand the functionality of SMRs.

AdvSMR ICHMI Research Projects

Current research under the AdvSMR ICHMI technical area is composed of eight projects being conducted at five national laboratories. The objectives of the collective research activities are to address identified technology gaps, resolve challenges that constrain the development of AdvSMR concepts, and expand technical capabilities to enable enhanced benefits to be realized from innovative applications. The selection of the projects was based on a rational prioritization approach that emphasized R&D into specific technology needs that are unique to SMRs (e.g., multi-modular plant management, highly automated control, and specific measurement and monitoring

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techniques that enable optimal staffing, efficient operation, and effective asset usage).

The ongoing AdvSMR ICHMI projects address specific technology development activities. Each project is described below in terms of the motivating technical issue and specified research focus. The eight projects are as follows:

1. Johnson Noise Thermometry for Drift-free Temperature Measurements
2. Concepts of Operation for Multi-Modular SMR Plants
3. Framework for Human-Automation Collaboration
4. Supervisory Control of Multi-Modular SMR Plants
5. Impact of Active Control on Passive Safety Characteristics of Advanced SMRs
6. Modeling Tools for Dynamic Behavior Simulations of SMRs
7. Prototypic Prognostic Technique Demonstration for SMR Passive Components
8. Enhanced Risk Monitors with Integrated Equipment Condition Assessment.

The Johnson Noise Thermometry (JNT) project involves development of a prototype self-calibrating temperature measurement. Periodic maintenance demands associated with sensor calibration are a significant source of operations and maintenance (O&M) burden and cost. Developing a fundamental measurement of a critical parameter (temperature) can enhance operational efficiency and reduce maintenance demands. Johnson noise does not drift over time so it can provide a dependable, accurate temperature measurement that minimizes the need to perform periodic maintenance.

The Concepts of Operation project contributes to establishing the technical basis for innovative modes of operation, levels of staffing, and allocation of function. To ensure economic viability through containment of O&M costs, multi-modular AdvSMR plants require definition of nontraditional concepts of operation to address unique operational scenarios. These scenarios can involve considerations such as distribution of load-following demand among multiple units, transition among different product streams, and high levels of automation with humans in supervisory roles. The issues and implications of innovative operational concepts for multi-modular plant configurations have not been evaluated in detail. Alternate concepts of operation and staffing models need to be developed and demonstrated to enable multiunit AdvSMR plant concepts to achieve flexible, efficient operations. In addition, an investigation of the impact of these concepts on human roles and responsibilities is needed to resolve regulatory uncertainty about licensability.

Current regulations that establish minimum staffing requirements for each unit provide a driver for the Human-Automation Collaboration project. These requirements are based on traditional operational models and limited automation. High staffing levels pose the threat of unsustainable O&M costs for AdvSMRs on a per megawatt basis. To enable optimal staffing, the focus of this research is a framework that balances automation and human involvement to support situational awareness of operators. A key consideration is the identification and demonstration of innovative approaches to automation, such as adaptive automation. More flexible automation can lead to effective integrated human-automation teams, which can support staffing goals and unique operational scenarios for AdvSMRs.

Highly automated, intelligent control capabilities have not been demonstrated for nuclear power plant operations and there is limited experience in other safety-critical application domains. The objective of the Supervisory Control project is to provide the means for the integration of control, decision, and diagnostics to support extensive automation. The targets for automation include operational management of highly complex plants, dynamic management and control of multiple product streams from a plant, and coordinated management of multiple modules. Specifically, control strategies and methods need to be developed within a flexible functional architecture to supervise multiunit plants, accommodate shared systems or resources, and enable flexible co-generation operational regimes.

AdvSMR concepts offer the potential to enhance safety through passive characteristics based on intrinsic design features. Passive features can perform more reliability than active systems because of their reliance on intrinsic phenomena. The presence of active systems, whether due to design or regulatory requirements, poses the potential that their action could affect the behavior of passive characteristics. The impact of active control on passive safety characteristics has not been adequately investigated and requires integrated treatment. The project on the Impact of Active Control provides evaluation of the potential for active control actions to compromise the performance of passive safety features and investigates prospective approaches for inherently controlling AdvSMRs.

The Modeling Tools project provides simulation resources and a library of models that can be used by projects within this technical area. AdvSMR concepts likely will go through a great variety of configurations of reactors and heat loads to explore useful and cost effective applications of modular plants designs. The safety and control evaluations of various concepts depend on an understanding of system dynamics, necessitating a number of mathematical models.

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Several different organizations and researchers may be involved in evaluating the concepts and developing advanced technology and methods. A basic library of models and common simulation environment is needed to facilitate efficient research, establish a common basis for comparison, and minimize the potential for duplicative modeling efforts. Thus, this project effectively supports a range of research activities requiring dynamic behavior simulation by developing modeling tools to provide easily reconfigurable modules, employ a commonly available and familiar simulation environment, and reduce data input to typically available system-level plant data.

The basis for the Prognostics project arises because traditional in-service inspection approaches used in existing light-water reactor (LWR) plants are difficult to apply for assessment of AdvSMR component degradation given the different coolant environments, temperatures, and accessibility. Physics-based prognostics facilitate estimation of the remaining lifetime of generally inaccessible AdvSMR structures and components, some of which may reach a degraded condition during extended operational cycles. There is a need to demonstrate methods to determine the remaining lifetime of passive internal components and thereby avoid unnecessary component replacement while contributing to a science-based justification for extended plant lifetime. Development of prognostic methods requires that issues specific to AdvSMRs are addressed, such as monitoring in-pool or in-vessel components to reduce the requirement for in-service inspection, accounting for uncertainties in advanced material behavior by detecting high-temperature degradation phenomena, and resolving measurement challenges associated with extreme coolant environments.

The Enhanced Risk Monitor project is based on employing condition monitoring techniques to provide condition indicators for key active equipment. Such indicators can reflect evolving degradation and support identification of incipient failure. These capabilities are especially important for hard-to-access, in-vessel active components that would otherwise require time-consuming, labor-intensive inspection during outages. Incorporation of condition knowledge into operational risk monitors can enable real-time decisions about stress relief for susceptible equipment while supporting effective maintenance planning. The capability to actively address the normal, abnormal and deteriorating states of plant equipment through degradation-based reliability models can permit AdvSMRs to meet aggressive availability, safety, and economic goals.

Relationship with NEET ASI

The projects identified for the AdvSMR ICHMI technical area were prioritized based on the exigency of the technology need to be resolved and the perceived benefit of the research product. A technology neutral approach was employed for the AdvSMR R&D Program so the RD&D emphasis focuses on ICHMI issues that affect multiple AdvSMRs or, at least, classes of AdvSMR concepts. Thus, crosscut characteristics are considered in the prioritization of research activities. In many cases, other reactor classes (e.g., LWRs, IPSRs) can benefit from the RD&D outcome. Where a desired research outcome had applicability beyond AdvSMRs, the decision on whether the specific technology issue should be treated under the AdvSMR ICHMI technical area or the Nuclear Energy Enabling Technology (NEET) Program's Advanced Sensor and Instrumentation (ASI) pathway was based on determination of the relative importance of the research within the two programs. If the outcome was considered to be critical to achieving the goals of the AdvSMR R&D program, then the activity was given high priority and, therefore, was retained by the program. Close coordination between the AdvSMR ICHMI technical area and NEET ASI pathway is ensured by frequent interaction between the two programs.

Assessment of Ultrasonic Transducers Survivability under Irradiation Project

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INTRODUCTION

Many Department of Energy-Office of Nuclear Energy (DOE-NE) programs are investigating the long duration irradiation performance of candidate new fuels and materials for use in existing and advanced nuclear reactors. Ultrasonic measurements have a long and successful history of use for materials characterization, including detection and characterization of degradation and damage, measurement of various physical parameters used for process control, such as temperature and fluid flow rate, and in non-destructive evaluation (NDE). Although many types of ultrasonic sensors can be used to measure different properties of interest, all ultrasonic sensors incorporate a transducer, which can limit the survivability of the sensor in an irradiation test. The development of ultrasonic tools to perform different in-pile measurements requires a fundamental understanding of the behavior of ultrasonic-transducer materials in high-radiation environments. Irradiation studies of ultrasonic transducers have been described in the literature, but a one-to-one comparison of these studies is difficult because materials and test conditions often differ. Additionally, tests to date are generally at lower flux/fluences than what might be seen in U.S. Material Testing Reactors (MTRs).

Nuclear Energy Enabling Technologies (NEET) is leveraging DOE-NE funding to enable the use of ultrasound based sensors by collaborating on a Pennsylvania State University (PSU)-led effort that was selected by the Advanced Test Reactor National Scientific User Facility (ATR NSUF) for an irradiation of ultrasonic transducers in the Massachusetts Institute of Technology Nuclear Research Reactor (MITR). This test is an instrumented-lead test, allowing real-time signals to be received from the transducers. The test is unique because it is the first irradiation to include both piezoelectric transducers, which rely on the electric charge that builds within certain crystals or ceramics under mechanical stress, and magnetostrictive transducers, which rely on the tendency of ferromagnetic materials to change shape or dimension as they are magnetized. Additionally, it will expose transducers to higher fluences than were achieved in prior irradiations. This test will enable accurate measurement of the degradation of candidate transducer materials under irradiation. It has been designed to provide fundamental data on piezoelectric and magnetostrictive material performance in irradiation environments; hence, these data will be directly comparable to results of prior irradiations. Collaborators (Figure 1) in this endeavor include PSU, the Massachusetts Institute of Technology (MIT), Idaho National Laboratory (INL), Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL), and the French Commissariat à l'énergie atomique et aux énergies alternatives (CEA), who are assisting at their own cost with design review and signal analysis.

Figure 1. Collaborators from PNNL, PSU, MIT, INL, and ANL discussing preliminary capsule design at MIT.

BACKGROUND

Several U.S. DOE-NE programs are investigating new fuels and materials for advanced and existing reactors, including sodium fast reactors (SFRs), high-temperature gas reactors (HTGRs), and light-water reactor (LWRs). Significant portions of these programs focus on characterizing the irradiation performance of these fuels and materials.

Some key parameters needed to evaluate fuel performance, which were identified in the first year NEET project report (Daw et al. 2012a), are listed in Table 1. Ultrasonic sensors could potentially measure these parameters with the accuracies and resolutions desired by developers of new modeling and simulation tools. Similar measurement parameters exist for structural material tests.

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Table 1. Summary of desired fuel measurement parameters for irradiation testing.

Parameter	Representative Peak Value
Fuel Temperature	Ceramic LWR: 1400°C
	Ceramic SFR: 2600°C
	Metallic SFR: 1100°C
	Tristructural-isotropic (TRISO) High-Temperature Gas Reactor: 1250°C
Cladding Temperature	Ceramic LWR: <400°C
	Ceramic SFR: 650° C
	Metallic SFR: 650° C
Fuel Rod Pressure	Ceramic LWR: 5.5 MPa
	Ceramic SFR: 8.6 MPa
	Metallic SFR: 8.6 MPa
Fission Gas Release	0-100% of Inventory
Fuel and Cladding Dimensions and Density	Initial Length: 1 cm
	Outer Diameter/Strain: 0.5 cm/5-10%
	Fuel-Cladding Gap: 0-0.1 mm
	Density:
	Ceramic: < 11 g/cm^3; Metallic: < 50 g/cm^3;
	TRISO pebble/compact: 2.25 g/cm^3
Fuel Microstructure	Grain size,10 mm
	Swelling/Porosity: 5-20%
	Crack formation and growth

However, the use of ultrasound sensors requires that ultrasonic transducers survive irradiation test conditions. For high-accuracy measurements, most of these applications will likely require the high-frequency capabilities of piezoelectric transducers, but some measurements can be made with magnetostrictive transducers as well. For example, post-irradiation examinations (PIEs) show that fuel-microstructure parameters, such as porosity and grain size, can be correlated to ultrasonic velocity (and, therefore, detected by ultrasonic methods). As noted by Villard et al. (2011), frequency requirements for such measurements are typically restricted to greater than 10 MHz. However, lower frequencies can be used for some applications, such as ultrasonic thermometry, where frequency requirements may be 100–150 kHz or lower (such as magnetostrictive transducer-based ultrasonic thermometry).

Ultrasonic Transducers

To generate and receive ultrasonic pulses and signals, two of the most commonly used technologies are piezoelectric and magnetostrictive transducers. Ultrasonic measurements using piezoelectric transducers have been demonstrated over a wide frequency range, from kHz to GHz. Since most non-destructive examination (NDE), materials characterization, and process monitoring are performed in the range from 1 to 20 MHz, piezoelectric transducers are ideal. The current capabilities of magnetostrictive transducers are typically limited to operation at frequencies up to about 200 kHz, although recent research suggests that higher frequencies may be possible for small magnetostrictive transducers (Daw et al. 2012b). Mechanical coupling, as well as enhanced guided-wave mode generation, makes magnetostrictive transduction ideal for low-frequency measurements, such as ultrasonic thermometry. At this time, radiation-tolerant sensors using piezoelectric and magnetostrictive materials are under consideration as candidate instrumentation for use in U.S. MTRs. The PSU-led MITR irradiation test is unique because it includes both piezoelectric and magnetostrictive transducers and because it is planned to expose candidate materials to higher fluences than prior irradiations.

Piezoelectric Transducers

The piezoelectric transducer design used in this irradiation test was based on research by Parks and Tittmann (2011) and information from early ultrasonic sensors developed at the Hanford Engineering Development Laboratory (HEDL) for under-sodium viewing (Ord and Smith 1972). They share similar constraints with respect to thermal and neutron-radiation tolerance. These transducers rely on pressure for coupling the piezoelectric element to the waveguide. Electrical contact with the piezoelectric element is achieved by application of pressure. A backing layer behind the piezoelectric sensor provides damping and prevents excessive ringing of the transducer. A schematic of the piezoelectric transducer design is shown in Figure 2.

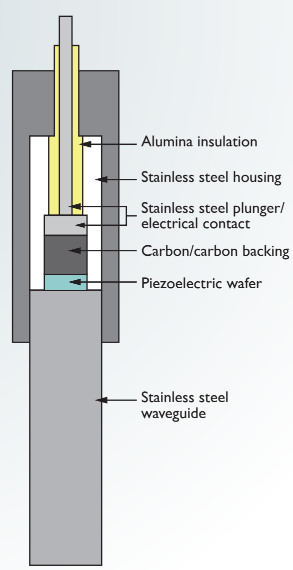

Figure 2. Schematic of piezoelectric transducer design.

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The irradiation volume available in this test limits the number of piezoelectric transducer materials that can be included. As documented in Daw et al.'s 2012 report (2012a), the piezoelectric transducer materials, which are listed in Table 2, were selected based on prior irradiation-test results, anticipated radiation tolerance, transition temperature, and ease of incorporation into sensor designs.

Table 2. Piezoelectric transducer materials selected for irradiation.

Transducer Material	Composition	Transition Temperature, °C	Transition Type
Bismuth Titanate	Bi3TiO9	909	Curie Temperature
Aluminum Nitride	AIN	2200	Melt
Zinc Oxide	ZnO	>1500	Melt

Magnetostrictive Transducers

The magnetostrictive transducer design proposed for this test was selected based on research by Lynnworth et al. (1968) and Daw et al. (2010). The transducer designs consist of a small driving/sensing coil and a magnetostrictive waveguide. The ultrasonic signal is generated when a radio-frequency alternating-current pulse is driven through the coil. The induced magnetic field causes magnetic domains within the material to oscillate. Received echoes of the oscillations are sensed through the coil via the reciprocal effect. A schematic of the magnetostrictive transducer design is shown in Figure 3.

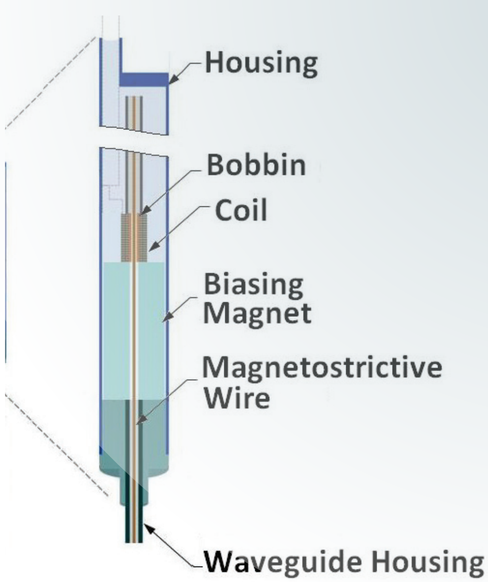

Figure 3. Schematic of magnetostrictive transducer design.

As documented in Daw et al.'s 2012 report (2012a), the magnetostrictive transducer materials (see Table 3) were selected based on previous use in radiation environments, amounts of neutron sensitive materials, Curie temperature, and saturation magnetostriction.

Table 3. Magnetostrictive transducer materials selected for irradiation.

Transducer Material	Composition	Curie Temperature, °C
Remendur	49Fe-49Co-2Va	950
Galfenol	Fe-14Ga-NbC	700
Arnokrome 4 and 5 (Loose Samples Only)	95Fe-5Cr, 92Fe-8Mn	770

EXPERIMENT DESIGN

Capsule

The MITR configuration restricts the test capsule to a cylinder 42 mm in diameter and 152.4 mm in length (see Figure 4). The capsule uses structural graphite as a holder material. Graphite is an ideal material as it has low density (for reduced gamma heating). In addition, graphite is thermally conductive (to produce a uniform predictable temperature), exhibits low neutron activation, and can be used at very high temperatures.

To ensure that irradiation conditions are well characterized, the sensors listed in Table 4 were included in the irradiation capsule.

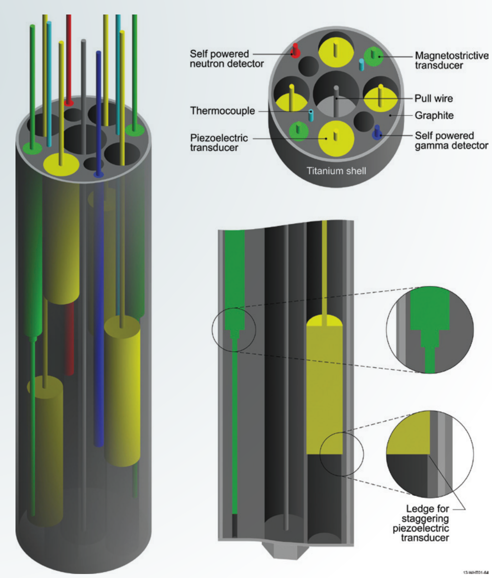

Figure 4. Schematic of test capsule design showing positions of test transducers and sensors.

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Table 4. Sensors included for monitoring irradiation conditions.

Sensor	Parameter Monitored
Type-K Thermocouples	Real Time Temperature
Melt Wires	Maximum Temperature
Self-Powered Neutron Detector	Thermal Neutron Flux
Self-Powered Gamma Detector	Gamma Flux
Flux Wires	Integrated Thermal and Fast Neutron Fluence

Irradiation Conditions

Transducer temperature is adjusted by controlling the composition of the gas in the gap between the capsule and the experiment guide tube. The steady state test temperature is approximately 450°C. It is planned that the test will continue for at least 310 calendar days, allowing the transducers to be exposed to higher fast-neutron fluences than prior piezoelectric transducer irradiations (e.g., greater than 1 × 1021 n/cm2 [Augereau et al. 2008]).

RESULTS TO DATE

The ULTRA test capsule was inserted into the MITR on February 19, 2014. To observe rapid changes at relatively low fluences, the test was started with the reactor slowly ascending to power. Figures 5 and 6 compare the transducer performance with the power history (green trace) for this irradiation. The vertical lines on the power history curves represent MITR shutdowns for refueling and maintenance.

Unfortunately, the ZnO and one of the AIN transducers failed prior to the reactor reaching full power. It is suspected that these failures are due to problems with the electrical connections. However, all other transducers and sensors continue to operate. At the time of this publication, the test has reached a total fast fluence of over 2.0 × 1020 n/cm2.

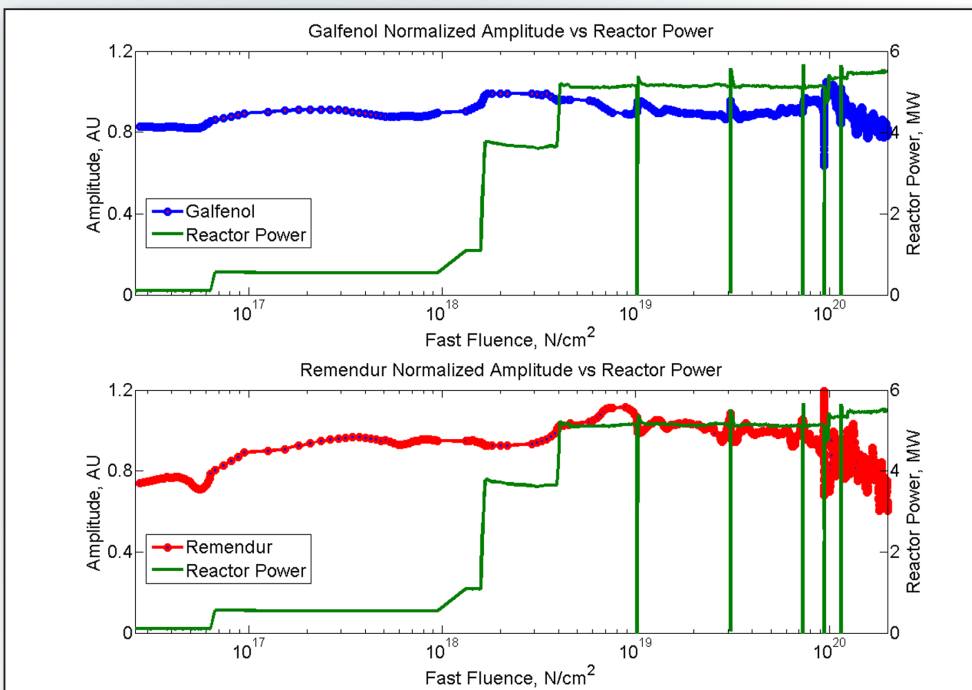

Figure 5. Normalized amplitude of magnetostrictive transducers as a function of total fluence.

The Galfenol magnetostrictive transducer (blue trace in upper Figure 5 plot) continues to operate with little apparent degradation due to irradiation. The Remendur transducer (red trace in lower Figure 5 plot) has shown changes in signal strength, at least some of which appears to be temporary and temperature related.

The AIN transducer (dotted trace in upper Figure 6 plot) continues to operate with little obvious degradation (erratic signal behavior is suspected to be caused by inconsistency in coupling between the crystal and the waveguide and associated with thermal effects). The BiTiO transducer (dotted trace in lower Figure 6 plot) has shown steady degradation over the course of the test. This behavior is similar to degradation observed in prior tests.

CONCLUSION

Ultrasonic measurements have a long and successful history of use in materials characterization, measurement of various physical parameters used for process control, and NDE. To develop advanced in-core sensors based on ultrasonic technologies, a fundamental understanding of the behavior of ultrasonic transducer materials in high-radiation environments is needed. While a number of irradiation studies of ultrasonic transducers have been performed, a direct comparison of these studies is difficult due to differences in the included materials and test conditions. In addition, tests to date have generally been

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performed at lower flux/fluences than what might be required for U.S. MTRs.

A NEET supported, PSU-led effort to perform an ultrasonic transducer irradiation is being performed in the MITR. The test is unique because it is the first irradiation to include both piezoelectric and magnetostrictive transducers and because it is planned to expose transducers to higher fluences than prior irradiations. This test is an instrumented lead test; real-time signals will be received from the transducers. Such a test will enable an accurate measurement of the performance and degradation of candidate piezoelectric and magnetostrictive transducer materials under irradiation and, ideally, identify an appropriate ultrasonic transducer material to enable development of new ultrasonic sensors capable of monitoring many physical parameters in-core.

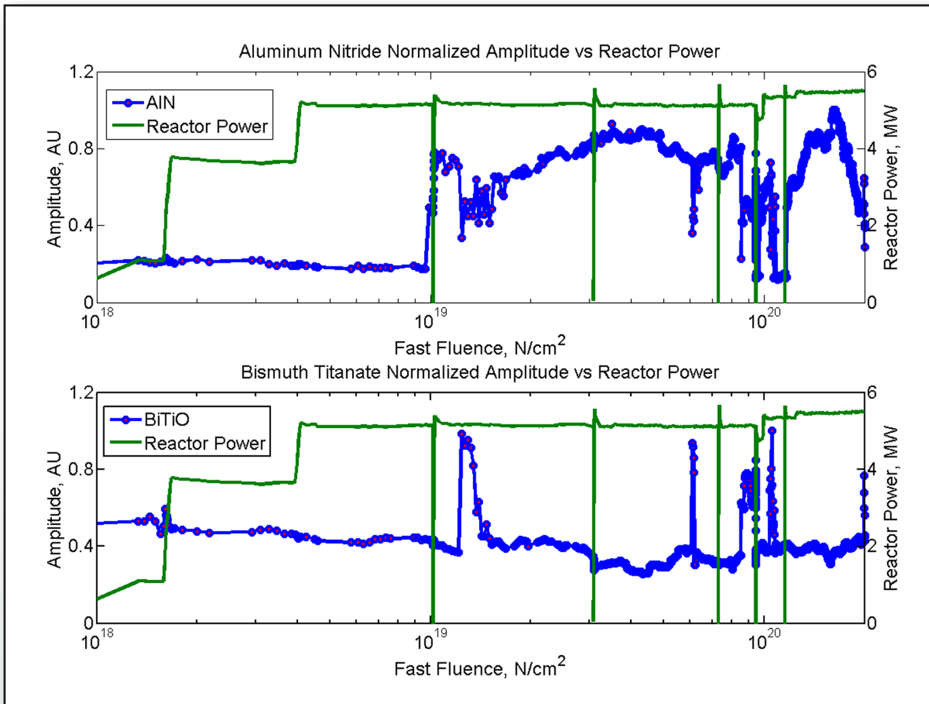

Figure 6. Amplitude of piezoelectric transducers as a function of total fluence.

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Concrete Structural Health Monitoring in Nuclear Power Plants

Advanced Instrumentation, Information, and Control Systems Pathway

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The existing fleets of nuclear power plants (NPPs) in the United States have initial operating licenses of 40 years, though most these plants have applied for and received license extensions. As plant structures, systems, and components age, their useful life—considering both structural integrity and performance—is reduced as a result of deterioration of the materials.

Concrete structures are present in all NPPs and are grouped into four categories: primary containments, containment internal structures, secondary containments/reactor buildings, and other structures, such as spent fuel pools and cooling towers (Naus 2007). The age-related deterioration of concrete results in continuing microstructural changes (slow hydration, crystallization of amorphous constituents, reactions between cement paste and aggregates, etc.). Changes over long periods of time may not be detrimental to the point that reinforced concrete will not be able to meet its functional and performance requirements. However, such changes may be measured, monitored, and analyzed to best support long-term operation and maintenance decisions.

Assessment and management of aging concrete structures in nuclear plants require a more systematic approach than simple reliance on existing code margins of safety (Christensen 1990). Current knowledge and ongoing national and international research efforts need to be leveraged and synthesized to advance the state-of-the-art in full-field, multi-physics assessment of concrete structures, particularly with regard to monitoring of its performance in-situ.

Through the Light Water Reactor Sustainability (LWRS) Program, several national laboratories, and Vanderbilt University have begun to develop a framework of research activities for the health monitoring of NPP concrete structures that includes the following four elements, as shown in Figure 1:

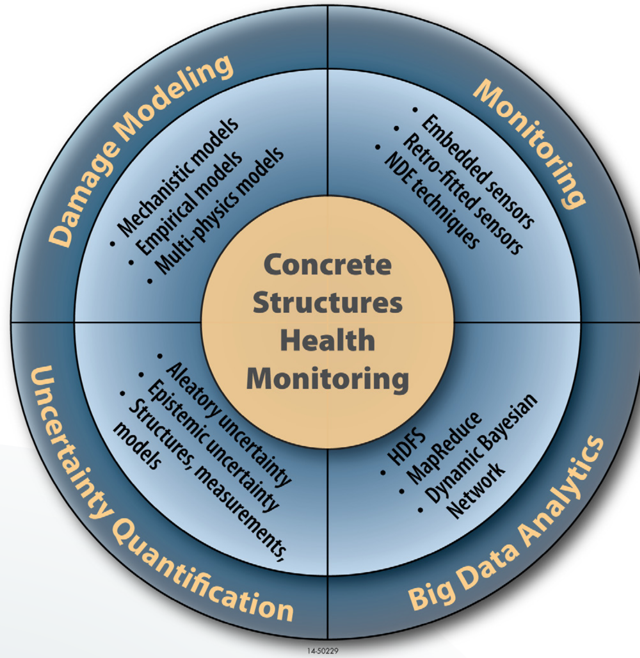

Figure 1. Elements of concrete structural health monitoring.

- Damage modeling
- Monitoring
- Big data analytics
- Uncertainty quantification.

The goal of this framework is to enable plant operators to make risk-informed decisions on structural integrity, remaining useful life, and performance of concrete structures across the nuclear fleet.

Damage Modeling

As plant structures age, incidences of degradation of concrete structures may increase due to a variety of degradation modes. The conventional classification of concrete degradation in NPPs (acknowledging that the degradation modes may be coupled) is physical, chemical, mechanical, and irradiation with an increase in temperature. Extensive research on modeling different concrete damage mechanisms has been reported in the literature and is currently ongoing under material degradation research. The focus of this element in the overall health monitoring framework is to leverage existing knowledge, and use damage models to develop signatures that can be used in monitoring for damage inference.

Monitoring

A variety of monitoring techniques have been studied for concrete structures, including embedded sensors

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in concrete, retrofitted sensors, manual inspection, and external NDE techniques.

Oak Ridge National Laboratory (ORNL), via the Light Water Reactor Sustainability Program's Materials Aging and Degradation Pathway, has been researching and evaluating current nondestructive examination (NDE) techniques to identify types of defects that could occur in thick heavily reinforce concrete structures. ORNL assessed five NDE techniques (Clayton 2014):

- Shear-Wave Ultrasound
- Ground-Penetrating Radar
- Impact Echo
- Ultrasonic Surface Wave
- Ultrasonic Tomography.

These techniques were compared in terms of ease of use, time consumption, and defect detection capability. It was concluded that no single technique can cover the spectrum of defect detection, and each technique had advantages and disadvantages.

In this research, INL and Vanderbilt University collaborate with ORNL to advance NDE-based monitoring techniques. The concrete samples prepared by ORNL with different age-related defects will be used to test promising monitoring techniques and collect information on the concrete structure. Different types of techniques—optical, thermal, acoustic, and radiation-based—are available, and practically feasible and useful combinations of these techniques for NPP concrete structures need to be identified. When data from multiple techniques is combined for damage inference, the information is expected to be heterogeneous in nature.

Big Data Analytics

The information gathered from health monitoring results in high volume, velocity, and variety (heterogeneity) of data, which are the three main characteristics of *Big Data*, as shown in Figure 2.

Data (big or small) is of little value without proper analytic tools. Therefore, *Big Data Analytics*, a combination of big data and analytic tools, presents an opportunity to store, process, and access heterogeneous (structured, unstructured, and binary) data. The effective application of big data analytics would support decisions related to operations, maintenance, and risk reduction. Owing to the advancements in data storage and processing power, big data analytics have a wide range of applications in science and technology, health care, transportation, education, and other consumer industries.

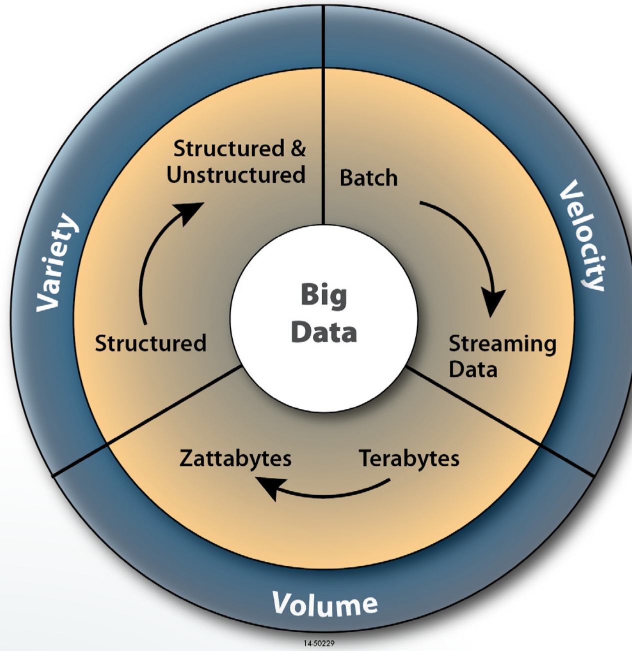

Figure 2. Characteristics of big data.

The development of the concrete structural health-monitoring framework would require tools to store, process, and access the data. Some of the tools developed to date and studied for other applications are as follows:

- ***NoSQL.*** Database MongoDB, CouchDB, Cassandra, BigTable, Hypertable, Voldemort, and Hbase
- ***MapReduce.*** Hadoop, Hive, Pig, Cascading, Cascalog, S4, MapR, Greenplum
- ***Storage.*** S3, Hadoop Distributed File System (HDFS)
- ***Servers.*** EC2, Google App Engine, Elastic, Beanstalk, Heroku
- ***Processing.*** R, Yahoo! Pipes, ElasticSearch, Datameer, BigSheets, and Tinkerpop.

This research activity will initially focus on the Hadoop distributed file storage system (HDFS) and MapReduce, and Dynamic Bayesian networks (DBNs). As shown in Figure 3, the Hadoop distributed file system has master/slave architecture and is suitable for large data sets. HDFS is scalable, fault tolerant, and provides high throughput access to application data. MapReduce is a parallel processing framework that has two functional routines: *Map and Reduce*. Map accesses large data sets, subdivides the data sets, and assigns them to slave nodes. The Reduce routine aggregates the results from slave nodes to obtain the final result.

Probabilistic graphical models for machine learning such as Bayesian networks (Jensen 1996) have shown much effectiveness in the integration of information across

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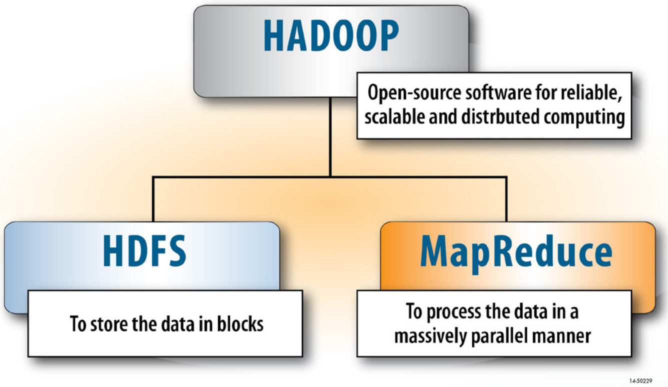

Figure 3. Big data analytics via Hadoop.

multiple components and physics in several application domains. The DBN have been used for systems evolving in time, and recent work has extended DBNs to include heterogeneous information in diagnosis and prognosis (Bartram and Mahadevan 2014). The Bayesian network is able to include asynchronous information from different sources. Also, Bayesian networks can be built in a hierarchical manner, by composing component-level networks to form a system-level network.

Big data presents many issues such as data quality, relevance, re-use, decision support, etc. In particular, uncertainty of inference due to data quality, data sparseness and incompleteness, as well as due to the approximations and assumptions in the models used for inference, needs to be addressed. This leads naturally to the next element of this research: uncertainty quantification.

Uncertainty Quantification

Uncertainty sources in health monitoring may broadly be classified into three categories: natural variability in the system properties and operating environments (*aleatory uncertainty*); information uncertainty due to inadequate, qualitative, missing, or erroneous data (*epistemic uncertainty*); and modeling uncertainty induced by assumptions and approximations (*epistemic uncertainty*). Considerable previous work has focused on variability, but a systematic approach to include data and model uncertainty sources in structural health monitoring still awaits development.

Data Uncertainty. Sensor information may be inadequate, due to sparse, imprecise, qualitative, subjective, faulty, or missing data. Alternatively, one may be confronted with a large volume of heterogeneous data (big data), involving significant uncertainty in data quality, relevance, and data processing. In the context of a probabilistic framework, both situations may lead to uncertainty in the distribution parameters and distribution types of the variables being studied, and the Bayesian approach is naturally suited to handle such data cases and update the description with new information. Flexible parametric or non-parametric representations can be developed within the Bayesian framework to handle such epistemic uncertainty (Sankararaman and Mahadevan 2011). An important recent development is the extension of global sensitivity analysis to quantify and distinguish the relative contributions of aleatory uncertainty versus epistemic uncertainty (Sankararaman and Mahadevan 2013) to the overall uncertainty in the analysis output.

Model Uncertainty. There are significant challenges in developing a multi-physics computational framework for concrete degradation modeling that mathematically represents the interactions among the multiple degradation processes and their effect on to the quantities being measured by sensors. The models for various processes could be based on first principles or regression of empirical data. For some components there may not even be any mathematical models available, but perhaps reliability data from past experience or literature. Quantification of the model uncertainty resulting from such heterogeneous information could be studied with respect to three categories, namely, model parameters, model form, and solution approximations; and the corresponding activities to quantify them are calibration, validation, and verification, respectively. Model parameters are estimated using calibration data, and Bayesian calibration constructs probability distributions for the model parameters. Model form uncertainty may be quantified through either a validation metric, based on validation data, or as model form error (also referred to as model discrepancy or model inadequacy). Model form error can be estimated along with the model parameters using calibration and/or validation data, based on the comparison of model prediction against physical observation, and after accounting for solution approximation errors, uncertainty quantification errors, and measurement errors in the inputs and outputs (Liang and Mahadevan 2011). The Bayesian network offers a systematic approach to integrate the information from various data and modeling sources and to compute the overall uncertainty in diagnosis and prognosis.

SUMMARY

This research and development activity will:

- Advance the state-of-the-art in each of the four elements to overcome challenges such as feasibility, complexity, and scalability to develop an effective concrete structural health monitoring framework

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- Enable collaboration across different LWRS pathways, universities, utilities, and vendors
- Leverage current knowledge and ongoing national and international research efforts (i.e., the application of knowledge and science from LWRS's Material Aging and Degradation Pathway, Electric Power Research Institute's NDE research initiatives, and other sources) to the science of data analysis, integration of heterogeneous data, development of diagnostic and prognostic models, and uncertainty quantification.

Based on the initial review of literature on different concrete degradation modes and models, research performed by ORNL on NDE techniques, and other external references, this research will investigate monitoring of chemical-mechanical coupled degradation in concrete via full-field imaging techniques (thermal, optical, and vibratory) and acoustic measurements. Possible full-field techniques include infrared imaging, digital image correlation, and velocimetry. Effective combinations of full-field techniques need to be identified for different types of concrete structures. Dynamic operating conditions (cycle loading, pressure variations, humidity, etc.) may lead to coupled chemical-mechanical degradation such as alkali-silica, reaction, fracture, corrosion, and internal swelling. The forward analysis of the evolution of concrete degradation is a challenging task in itself, which requires the combination of reactive transport modeling with mechanical degradation models. The inverse problem of damage inference in the presence of multiple damage mechanisms is even more challenging, and requires development of damage signatures that have to be effectively connected to monitoring data.

Going forward, this research will focus on data analysis and development of uncertainty-quantified diagnostic and prognostics models that will support continuous assessment of concrete performance. The resulting comprehensive approach will facilitate the development of a quantitative, risk-informed framework that would be generalizable for a variety of concrete structures and can be adapted for other passive structures.

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MICROCALORIMETER DETECTORS FOR NUCLEAR SAFEGUARDS

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A variety of analytical methods are available for the measurement of nuclear materials in support of safeguards and nonproliferation efforts. For several decades, high-purity germanium (HPGe) detectors have been the technology of choice for non-destructive analysis (NDA) methods for nuclear material characterization via gamma-ray spectroscopy. A team of researchers from Los Alamos National Laboratory (LANL) and the National Institute of Standards and Technology (NIST) is developing new instrumentation technology to improve the performance of NDA gamma-spectroscopy analysis of plutonium-bearing materials, and close the long-standing performance gap between NDA and destructive analysis (DA). The new technology has applications for fuel-cycle safeguards, and material accountancy and control.

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The energy resolution of a conventional semiconductor gamma-ray detector is fundamentally limited by the statistics of electron-hole pair generation. In contrast, cryogenic microcalorimeters are fundamentally limited by thermal noise processes. At very low temperatures (near 100 mK), microcalorimeter spectral energy resolution can be over an order of magnitude better than HPGe. Depending on detector design parameters, energy resolution as good as 22 eV FWHM at 100 keV has been achieved.

Modern cryogenic refrigeration technology allows for routine operation at temperatures below 100 mK without any liquid cryogens. A microcalorimeter converts the energy of an incident x ray or gamma-ray to heat in an absorber (tin is commonly used). The absorber is attached to a thermometer, which itself is weakly connected to a heat bath by a silicon nitride membrane. The temperature rise, as measured by the thermometer, is proportional to the energy deposited in the absorber, and thus to the energy of the incident photon. After the initial temperature rise, the energy flows into the heat bath, and the temperature returns to its steady-state level until the next event.

The most sensitive cryogenic calorimeters are those that use a superconducting transition-edge sensor (TES) as a thermometer. TES calorimeters are based on a superconducting film biased in the transition region between its superconducting and normal states. In this narrow transition region, the resistance of the film is sensitively dependent on temperature, and it can be used to measure the energy deposited by a photon interaction. The temperature is measured by biasing the TES with a constant voltage. The current flowing through the TES changes with the increased temperature when a photon is absorbed. The current is measured using a Superconducting Quantum Interference Device (SQUID).

The energy resolution of a microcalorimeter is proportional to the square root of its heat capacity. This dependence prevents the use of arbitrarily large detector elements. Achieving reasonable counting efficiency demands the use of multi-pixel detector arrays, where individual detectors are small but the total collection area is relatively large. The LANL/NIST team is now working with a 256-pixel microcalorimeter array, shown in Figure 1. Each detector consists of a 1.5 mm by 1.5 mm by 0.38 mm thick tin absorber thermally connected to a TES thermometer. The total collection area is 5.76 cm2, which compares favorably to typical planar HPGe crystal sizes commonly available. The microcalorimeter dynamic range falls off more rapidly at higher energies compared to HPGe, but is sufficient to measure up to at least 210 keV. Using a carbon-fiber entrance window in the cryostat, energies down to 30 keV can be measured. This energy range contains gamma-ray lines from all of the isotopes commonly considered in plutonium isotopic analysis.

With typical planar HPGe energy resolution (400–500 eV FWHM at 100 keV), there are still many overlapping photopeaks in energy spectra acquired from a plutonium

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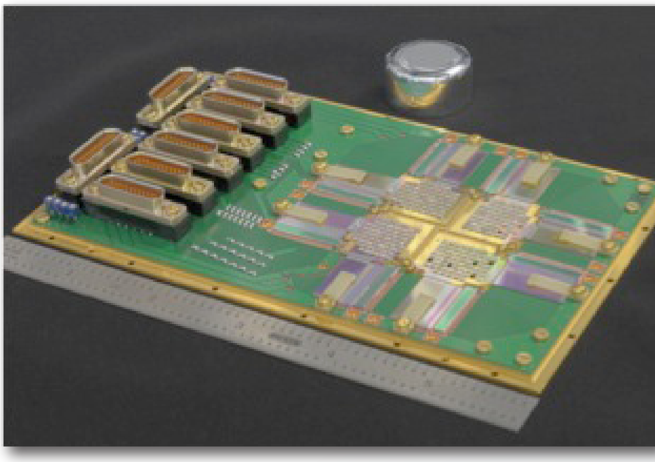

Figure 1. A 256-pixel microcalorimeter array for ultra-high resolution gamma-ray spectroscopy. Individual pixels are 1.5 mm square by 0.58 mm thick. A typical planar germanium crystal is shown at top for size comparison

sample. The data in Figure 2 show the impressive resolving power of the microcalorimeter detector in the 100 keV region of a Pu sample where peak overlap is especially problematic. The figure shows HPGe and microcalorimeter data collected from the same plutonium isotopic standard. Notice the considerable peak overlap in the HPGe data, and greatly reduced overlap in the microcalorimeter data. For this particular sample, we observe a factor of 2.2 improvement in the 240Pu 104 keV peak area statistical error compared to HPGe for equal total peak counts. For the weaker 240Pu 160 keV peak (not shown), we observed a factor of 6.4 improvement in the peak area statistical error due to resolving an interference from a 241Pu peak only 360 eV away.

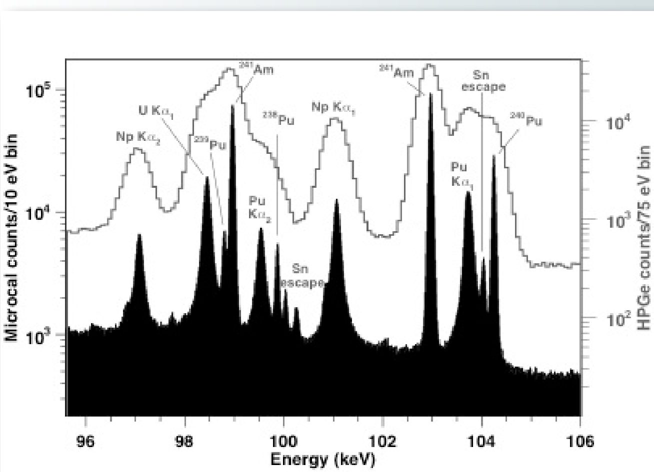

Figure 2. The 100 keV spectral region of a plutonium item measured with planar HPGe (gray) and a microcalorimeter array (black). Note the greatly improved resolution and peak separation in the microcalorimeter data, leading to improved plutonium isotopic content analysis.

By reducing or removing peak overlaps and improving signal to background, measurement uncertainties of extracted above-background peak areas can be reduced. This translates into improved precision and accuracy in the plutonium isotopic content values determined from the spectral analysis. Systematic errors present a limit to achievable measurement uncertainty that cannot be reduced by increasing spectral statistics. One source of uncertainty is the nuclear data required to perform spectral analysis and extract isotopic composition. These data include gamma-ray branching fractions, gamma-ray energies, and isotope half-lives, among others. In addition to the development of new instrumentation, improving knowledge of these constants of nature, possibly combined with reformulating long-standing spectral inverse analysis methods, is seen as important work necessary to reduce present uncertainty limits of NDA.

From validation and intercomparison exercises, the systematic error of plutonium isotopic measurements with HPGe detectors is seen to be around $\sigma = 1\%$ relative uncertainty. This level of measurement uncertainty is insufficient to achieve desired safeguards goals for large reprocessing plants having throughput of hundreds of metric tons per year of irradiated fuel. To replace or reduce time and resource intensive DA (mass spectrometry) and enable the safeguarding of such facilities using primarily NDA methods requires smaller total measurement uncertainty than is presently achievable with HPGe. For nuclear material control and accounting applications, microcalorimeter technology can offer improvement over current capabilities of NDA measurements using HPGe.

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