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Operator Support Technologies for Fault Tolerance and Resilience

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Goals

The Operator Support Technologies for Fault Tolerance and Resilience project develops and evaluates aids for the operator of a nuclear power plant to facilitate a more timely response to plant faults and grid disturbances. The goal is to better manage plant upsets and improve operator performance with the ultimate goal of improving plant safety, production, and cost management. The project takes advantage of unique expertise at each of the two collaborating organizations: Argonne National Laboratory (ANL) and Idaho National Laboratory (INL). ANL has extensive sensor validation and equipment fault diagnosis experience, while INL has strong capabilities in the human factors aspects of assisting operators in monitoring overall plant performance.

Presently, the operator of a commercial nuclear power plant, when responding to an upset caused by an equipment fault, is required to take a symptom-based approach with the goal of stabilizing the reactor, regardless of the cause. The operator is not expected to diagnose the identity of the fault. This is with good reason as the task of scanning many instruments and alarms and then correlating the trends among sensor readings to deduce the identity of the fault is a challenge. To do so requires reasoning how different faults play out through the physics of the plant giving rise to the observed sensor readings with time. This process as performed by a human is time consuming, approximate, and prone to error.

The approach we take recognizes that the identity of the fault can be arrived at by correctly matching expected trends based on the conservation laws with observed sensor trends. In fact, this is what an operator would do left to his or her own resources. In our method, an automated reasoning process takes as input-data the sensed process variables and the conservation laws that govern plant operation to determine through a reasoning process a mutually consistent faulted plant state. The reasoning process is transparent and familiar to the operator as it is very nearly the same qualitative reasoning process by which he or she would make a fault diagnosis given sufficient time and access to instrument readings. The system can then recommend to an operator the actions that can mitigate undesirable plant events and trends and return the plant to a safe operating condition with the least amount of upset possible.

Since the approach is quantitatively based, as opposed to the qualitative reasoning of an operator, it has the potential to provide more accurate and timely diagnosis of component faults. This is important because the longer a transient persists, the larger the degree that the plant is subjected to off-normal conditions and the more of a challenge it is to arrest the plant excursion and return to

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within normal operating parameters. Application of this technology will help minimize the impact of faults on the plant by greatly improving human performance by aiding the timely application of appropriate mitigating actions in response to a fault. This will make it possible to manage many plant transients without incurring reactor trips and plant protection actuation, for which recovery is difficult, prolonged, and costly.

We envision this capability as an integral component of a computer operator support system (COSS), an advisory system to help manage the enormous amount of information an operator must process and integrate to arrive at an understanding of how the plant is operating in an off-normal situation and how its trajectory will unfold. This is a daunting task for even the most experienced operators. This system would assist the human operator with control as opposed to serving as an extension of the control system. Existing automatic control systems lack "awareness" of the plant state and the larger world in which they operate; they simply track a setpoint.

Objectives

To achieve these goals, work is proceeding according to the following objectives and related tasks. Presently, we are in the second year of the project.

- Year 1 - Develop and test fault diagnosis algorithms. The objective is to characterize performance on a simulation test-stand and improve the technical readiness of methods and algorithms.
- Year 1 - Develop and implement computer-enabled control algorithms for simulator-based testing. The objective is to determine technical and human performance requirements for an integrated operator support system and develop a prototype.
- Year 2 - Link fault diagnosis algorithms developed at ANL to the plant simulation software running on the INL full-scale simulator. The objective is to demonstrate fault diagnosis capability for a representative plant subsystem selected in our present work as the chemical and volume control system of a pressurized water reactor.
- Year 2 - Develop a fully integrated COSS for demonstration including fault detection, fault diagnosis, and control actions to mitigate faults. The objective is to support the planned human factors studies for the operator support system in the context of realistic nuclear plant component faults.
- Year 3 - Perform full-scale simulator shakedown tests of integrated fault diagnosis and automated control provided by the COSS for a wide spectrum of faults.

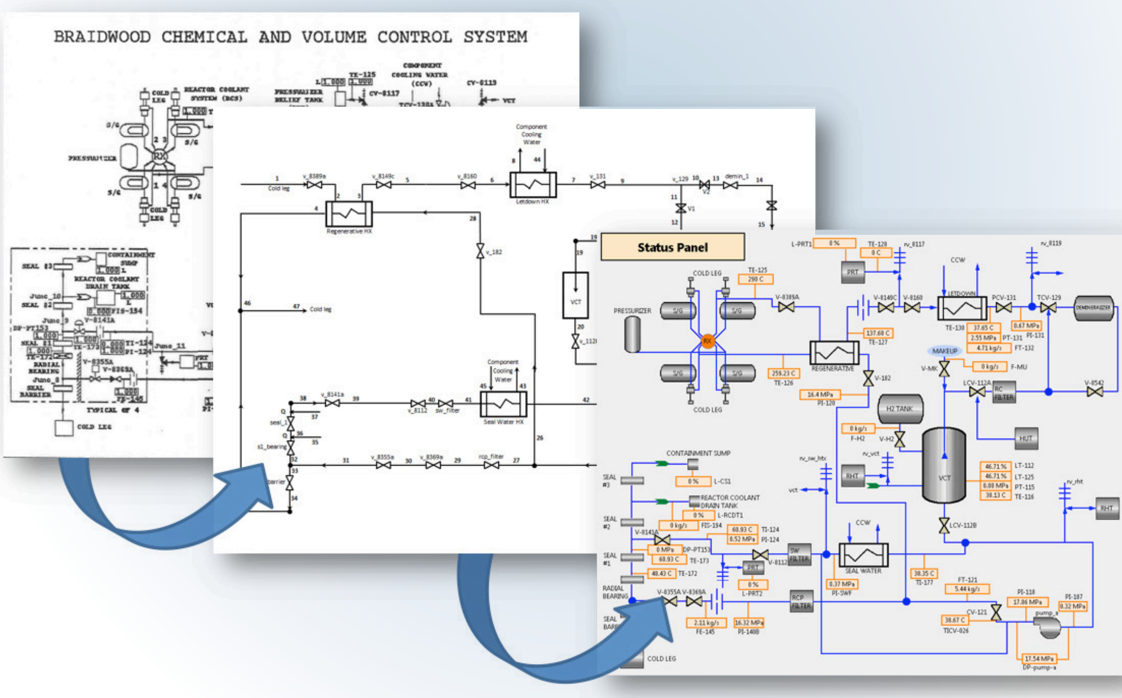

Figure 1. CVCS physical system, the simulation model developed to describe it, and the piping and instrumentation diagram used in the validation of the fault diagnosis algorithms.

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- Year 3 - Develop technical requirements for application of the COSS technology across multiple plant systems.
- Demonstrate the COSS technology to industry with the objective of transitioning the technology into power plants, initially through a follow-on pilot project.

Current Status

Significant work was completed in the first year of this project as we work toward meeting all the objectives over the 3-year length of the project.

The fault diagnosis algorithms were exhaustively tested using computer simulations of 20 different faults introduced into the chemical and volume control system (CVCS) of a pressurized water reactor (PWR) (see Figure 1). The testing approach followed accepted procedures for verifying and validating software. It was shown that the software satisfies its functional requirement, which is to accept sensor information, identify process variable trends based on this sensor information, and then to return an accurate diagnosis based on chains of rules related to these trends. The validation and verification exercise made use of a one-dimensional systems code for simulation of CVCS operation. Plant components were failed and the code generated the resulting plant response. Parametric studies with respect to the severity of the fault, the richness of the plant sensor set, and the accuracy of sensors were performed as part of the validation exercise.

This present COSS includes displays to support the operator during the monitoring task (see Figure 2). These displays provide the operator with contextual information concerning the general plant status in fast transient situations. This contextual information aids the operator's understanding as he or she begins to interact with the COSS during time-sensitive situations. The COSS also includes additional backend development that provides it with the capability to communicate with the gPWR simulator. This communication is a vital factor for supporting future evaluations in which the operator interacts with the COSS during a scenario involving the surrounding simulated control boards. The COSS is able to aggregate information from the simulator into the COSS and display live values during this scenario.

Work in this second year of the project is underway to link the ANL fault diagnosis software with the INL full-scale simulator at the Human System Simulation Laboratory. Interface functional requirements have been defined and the integration task is proceeding according to those requirements.

Ultimately, the goal of our efforts is to demonstrate the benefits of operator aids that improve operator performance by augmenting operator cognitive abilities via alerting the operators to fast transient situations, providing clear success paths to mitigate abnormal plant conditions resulting from faults, and synthesizing information to display to the operator.

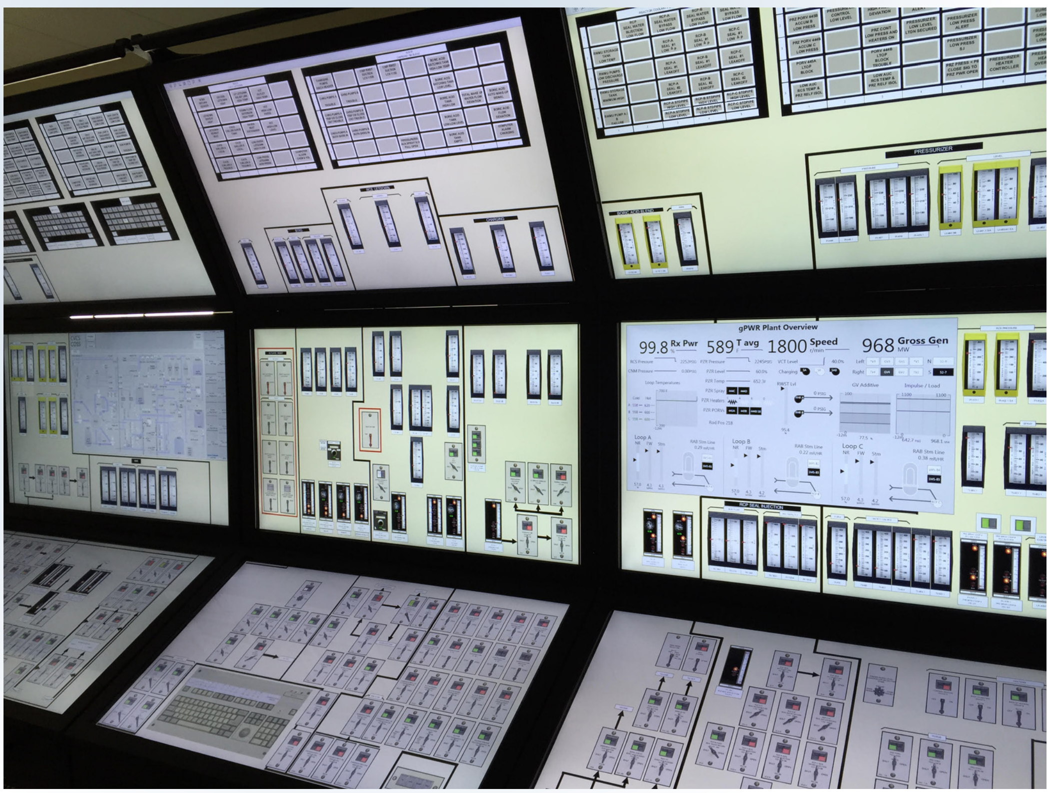

Figure 2. Computer Operator Support System (COSS) prototype embedded in the Human Systems Simulation Laboratory (HSSL).

Smart Electrical Cables Enabled by Optical Fibers to Safeguard Nuclear Energy Systems

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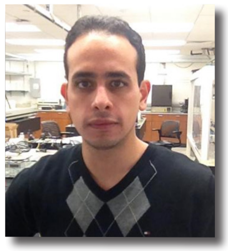

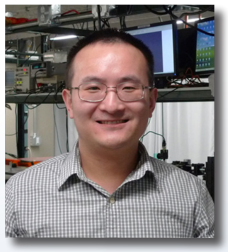

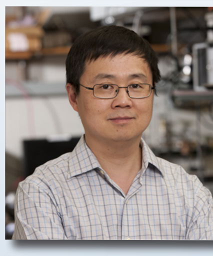

University of Pittsburgh researchers invent smart electrical cable capable of sensing radiation, temperatures, and other parameters with high spatial resolutions.

The safe and efficient operation of nuclear reactors and various fuel cycle processes can be significantly enhanced through information gathered by ubiquitous sensor technology. The deployment of advanced sensors is important to safeguard nuclear energy systems at both component and system levels. For sensor networks used in nuclear energy systems, they must withstand harsh environments and perform proper measurements during both normal operation and in harsh post-accident situations for long periods of times. At the same time, the deployment of a sensor network should not significantly increase engineering complexities and cost for new and existing nuclear power systems, which are already very expensive.

Supported by the Department of Energy's NEET program, researchers from the University of Pittsburgh (Pitt) invented fiber optical sensor network solutions that can be conveniently deployed in radiation environments for a wide array of nuclear energy applications. As radiation resistant sensing technique, fiber optical sensors such as fiber Bragg grating have been studied previously for nuclear energy applications [1-5]. However, their applications in radiation environments are mostly for temperature and strain measurements. The deployment of fiber optical sensors in nuclear power systems are largely unexplored.

Our innovation uses electrical cables, which are ubiquitously deployed in nuclear power systems, as sensor platforms. Speciality optical fibers are seamlessly integrated into electrical cables as sensing devices. Using distributed fiber-sensing schemes, radiation dosage, both physical parameters (i.e., temperature, strain, pressure, liquid levels, and chemical information such as radical chemical species (e.g., hydrogen) concentrations) can be monitored across the entire nuclear power system with 1–10 cm spatial resolution. Since electrical cables are already part of nuclear power systems, no alternation or modification is needed to accommodate new sensors. This will greatly reduce costs and engineering barriers for sensor deployments. It provides a feasible and cost-efficient solution for new and existing nuclear infrastructures.

To develop suitable optical fibers, Pitt researchers collaborated with Corning®, the world leading optical fiber company, to develop a number of new optical fibers for nuclear energy applications. Three different types of optical fibers are being developed with support from the NEET program. This includes an optical fiber that is sensitive to gamma radiation. Through the control of radiation sensitive composition in fiber core, optical fibers are responsive to radiation from 1 Gy to >10,000 Gy. This will address a wide arrange of scenarios, locations, and durations while electrical cables are placed and operated through their operational life spans. The second type of fibers is radiation-resistant fibers, which will be used to measure temperature and strain. Through detailed research on radiation resilience of optical fiber, both silica fiber and fiber coated, need to be optimized to ensure reliable measurements of temperature and physical parameters. The third type of fibers is fibers with diffusive cladding, which allow chemical species to be permeated to interact with fiber cores. Functional coating is developed at Pitt to respond to various chemical species, especially for hydrogen to address monitoring needs during distressed situations. Once these fibers are designed and manufactured, Pitt researchers worked with Westinghouse to incorporate appropriate fibers into electrical cables. Figure 1 shows a close-up photograph of a fiber sensor integrated electric cable.

Figure 1. A photograph of the electrical cable integrated with distributed fiber radiation and temperature sensors. The red arrow shows the inserted fiber protected by polymer tubing.

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Optical fibers responsive to radiation and radiation-resistant fiber for temperature measurements are protected by appropriate polymer tube to reduce friction with other electrical wires. Special gas permeable tubes will be needed for gas species measurements. Functionalities of smart cables were tested in the Westinghouse radiation facility in Pittsburgh. Figure 2 shows a photograph of electrical cable mounted inside a radiation chamber, a mock-up radiation source is placed to be photographed to show the relative locations of the gamma radiation source.

Once the smart cable was mounted in the radiation chamber, a Co-60 source was used to irradiate the cable. Prior to the radiation, relative locations of the fiber and electrical cable were accurately registered using a distributed temperature measurement scheme. The measurement accuracy of the cable location is ~1cm. Using a distributed fiber sensing interrogation scheme, the accumulated radiation dosage was monitored from 50Gy up to 840 Gy at the maximum radiation locations.

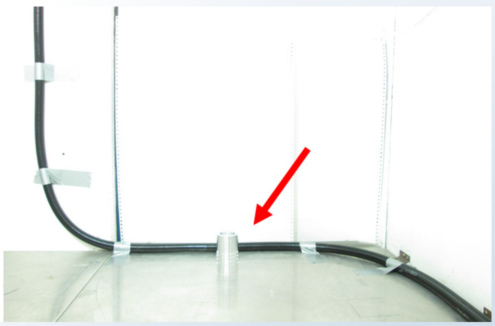

Figure 2. A photograph of the electrical cable mounted in the radiation chamber. The red arrow indicates the mock-up radiation source.

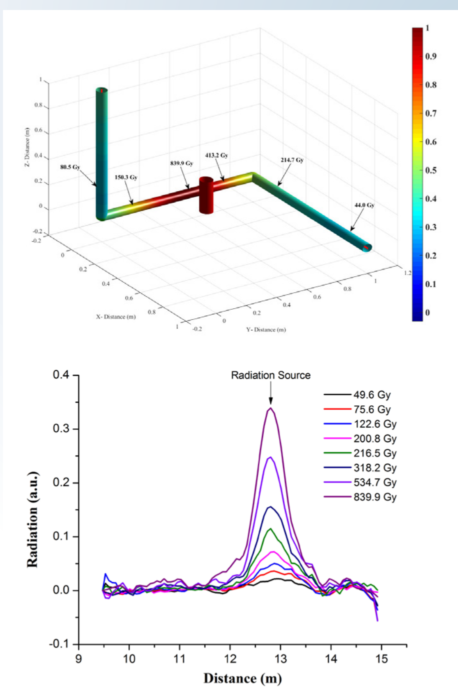

Figure 3. (a) Color-coded accumulated gamma radiation dosage by a Co-60 source after 120-minute radiation. (b) Distributed radiation dosage along the cable with various radiation times.

Figure 3a shows the distributed radiation dosage along the cable with a peak accumulated dosage of 839.9 Gy. The distributed fiber dosage measurement revealed the location where the maximum dosage was incurred, which is consistent with the placement of the Co-60 source. Figure 3b shows the spatially distributed radiation dosage profile as a function of cable length at different gamma radiation dosages. Peaks of radiation dosages are consistent with the location of the source. The symmetrical dosage profiles along the cable are also consistent with the location and gamma ray radiation profile of the source. The peak radiation dosage, which was validated by a standard gamma dosimetry measurement scheme ranges from ~50 Gy to 840 Gy. By changing the composition of the radiation-sensitive fiber core, the measurement sensitivity can be tuned to suit a wide range of scenarios.

The technology demonstrated in article not only provides a feasible way to monitor radiation-induced aging of electrical cables, it also provides a ubiquitous sensing solution to perform other high-resolution measurements for a wide range of physical and chemical parameters.

The University of Pittsburgh and our partners are working diligently to enhance functionalities and to explore avenues to commercialize this technology. The next step for this technology is to demonstrate a smart electrical cable that can respond to hydrogen, which will have significant values to improve safety of nuclear power systems. We believe that smart electrical cables will be part of future nuclear energy systems.

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Wireless In-Core Acoustic Telemetry and Self-Powered Sensing

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Introduction

The core of a nuclear reactor, used for research or for commercial power production, presents a particularly harsh environment for sensors while simultaneously imposing challenging constraints on the transmission of their signals outside the reactor. Although many sensors used in reactors, like thermocouples and charge collection flux sensors (e.g., rhodium wires), are self-powered, each sensor requires at least two signal wires that must penetrate the reactor vessel. The situation for sensors or data transmitters that require even small amounts of electrical power to be provided within the reactor creates further complications as well as additional wiring requirements. Management of those wiring harnesses and pressure vessel feed-throughs make fueling and other inspection and maintenance tasks more difficult, and wire breakage or loss of external electrical power availability under accident conditions can lead to serious problems. Testing with thermocouples has shown that the harsh reactor environment can also cause significant sensor drift and performance degradation with time [1].

The conventional approach to these problems is to "harden" conventional sensors and their associated signal-conditioning electronics against the degradation introduced by intense fluxes of energetic particles. In this article, we will demonstrate a completely different approach to telemetry and sensing that exploits a reactor core's energy-rich environment to generate acoustic signals from self-powered sensors and be detected outside the reactor. These signals produce sounds that can propagate through the reactor's coolant, whether it be gas, water, or liquid metal, and through its mechanical structures (e.g., lattice work, pressure vessel, plumbing).

Many of the articles that appeared in previous issues of the ASI Newsletter have addressed issues related to radiation hardening [2,3,4,5] and in-core electrical power production [6]. A salient grand challenge for a number of Department of Energy Programs is to enhance our fundamental understanding of fuel and material behavior subjected to intense irradiation. These programs consist of Fuel Cycle Research and Development (FCRD), which includes accident tolerant fuel research and the resumption of transient testing of nuclear fuels and materials at Idaho National Laboratory (INL), Light Water Reactor Sustainability, and Advanced Reactor Technologies. FCRD is the initial and major sponsor of in-core wireless sensing. Additionally, the Nuclear Science User Facilities (NSUF) has been a strong supporter of in-pile instrumentation development in general and thermoacoustics specifically. The NSUF provides cost-free access to unique nuclear energy-related research capabilities on a competitive basis. Advanced in-pile instrumentation can be developed through NSUF-access grants and eventually used by the NSUF to support the other DOE programs.

Robust and accurate in-pile measurements will enable development and validation of a computationally predictive, multi-scale understanding of nuclear fuel and materials linking fundamental micro-structural evolution mechanisms to macroscopic degradation. One of the major obstacles to development of practical, robust, and cost effective in-pile sensor systems is instrument lead requirements. If a wireless telemetry infrastructure can be developed for in-pile use, in-core measurements would become more attractive and cost effective.

Figure 1. "Fuel rod" thermoacoustic sensor. (Top) The thermoacoustic resonator is shown at the center of the photograph. (Bottom) The resonator and suspension springs are contained within a "slotted tube" that has the same outer diameter as the reactor's fuel rods. The thermoacoustic sensor can be designed to meet the same geometrical constraints as most fuel rods.

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This article provides a high-level overview of a promising wireless telemetry infrastructure based on acoustic transmission of in-pile measurements (information). This novel approach is being developed and tested by INL, the Pennsylvania State University (PSU), Westinghouse, and IST Mirion. This team of collaborators was assembled to accelerate the transfer of thermoacoustic (TAC) technology from a university and a national laboratory, to both the power and in-core sensor industries. We also present data from the first fission-powered TAC sensor that was tested in the core of PSU's Breazeale Nuclear Reactor in September 2015 and acoustically telemetered data from the Advanced Test Reactor (ATR).

Acoustic Based Telemetry System

When contemplating technologies to transmit information out of a reactor vessel, it is almost self-evident that acoustics would be synergistic with the nuclear reactor environment. Unlike radio-frequency telemetry, requiring an external electrical power source and propagation through the shielding effects of water, acoustic signals take full advantage of the structural components used in the construction of reactors when communicating the measured signals to the outside world. In our initial implementation, the telemetered signal is a resonant acoustic frequency—a pure tone. Most structural components that comprise a reactor, including the cooling fluid, will readily transmit such a continuous acoustic tone. The reactor's volume can literally be filled with sound. Internal structural latticework and piping can act as acoustic wave guides that can be used as "acoustic antennas" that transmit sound directly to receivers. The acoustic signal's frequency is encoded in a similar manner as FM radio transmissions and its amplitude also contains useful information, as long as the amplitude is above the background noise levels within a relatively narrow frequency range of interest. Hydrophones can be placed within the reactor fluid or accelerometers or other vibration sensors can be placed on the exterior of the reactor vessel or piping to receive the signals. Multiple sensors can be frequency multiplexed, thus many sensors can be utilized and monitored simultaneously by a single acoustic receiver. The transmission and detection of signals by the acoustic receiver is completely cable free—a truly wireless technology.

Thermoacoustic Signal Production

The production of sound by heat has been observed as an "acoustical curiosity" since a Buddhist monk reported the loud tone generated by a ceremonial rice-cooker in his diary, in 1568. [7] In 1850, Karl Friedrich Julius Sondhauss documented and investigated an observation made by glassblowers who noticed that when a hot glass bulb

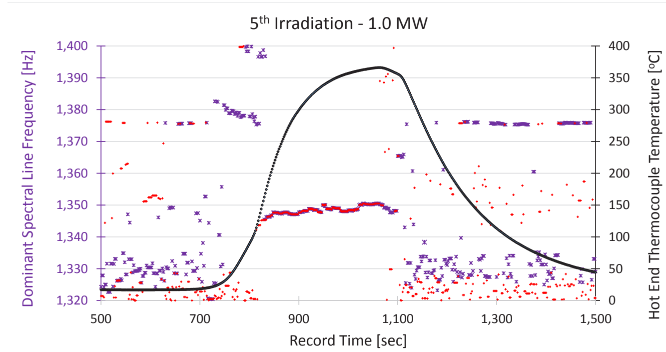

Figure 2. Time record of the resonator's hot-end temperature and the frequency of the largest spectral component received by two hydrophones at different locations. The temperature of a Type-K thermocouple is plotted as the black diamonds. The blue "x" and red "*" symbols are the frequencies of the largest spectral component within the frequency range between 1,320 Hz ≤ f ≤ 1,400 Hz. The reactor reached full power (1.0 MW) at t ≅ 800 s. The reactor power was reduced to 800 kW at t ≅ 1,060 s, then the reactor was shut down at t ≅ 1,100 s. The frequency only gets locked in when there is enough reactor power to energize the TAC engine.

was attached to a cooler glass tubular stem, the stem tip sometimes emitted a pure tone. [8] The Sondhauss tube is the earliest thermoacoustic engine that is a direct antecedent of our fission-powered sensor. [9]

The first qualitative explanation of these acoustical curiosities was provided by Lord Rayleigh: "If heat be given to the air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction, the vibration is encouraged." [10] The standing sound wave created by a temperature gradient transfers heat from a solid substrate to a gas in a manner that is analogous to a four stroke car engine: compression, heat input, expansion, exhausting of heat. The thermoacoustic engine is an extremely simple heat engine when compared to

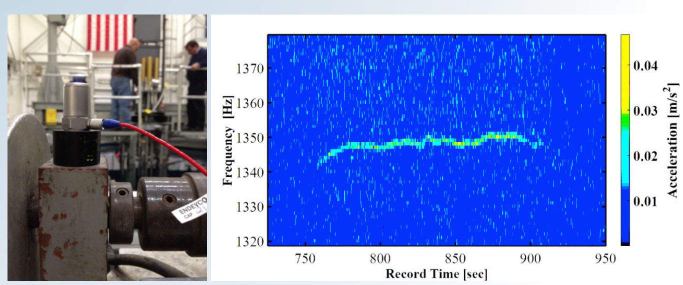

Figure 3. Time record (spectrogram) of the vibration signal received by an accelerometer mounted on a structure outside the reactor pool. (Left) Accelerometer with a magnetic base (black) attached to the motor mount of an instrumentation tower that extends into the reactor pool. (Right) Spectrogram showing the accelerometer's output frequency on the vertical axis as a function of time represented by the horizontal axis. The thermoacoustic sensor's signal is clearly visible above background noise.

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an automobile engine that requires pistons, valves, cams, rocker-arms, flywheel, etc., to ensure that the compressions and expansions are synchronized with the heat input and exhaust at the proper phase in the cycle. The pressure changes induced by the sound wave, synchronizes the strokes in a thermoacoustic engine. The standing-wave thermoacoustic process requires no moving parts other than the oscillation of the gas. The thermoacoustic engine can be constructed from materials found in reactors. The details of the thermoacoustic process for reactor use are found in our 2013 publication. [11]

For the results we report here, we used a nuclear fuel as the heat source for our thermoacoustic engine and the exhaust heat was rejected to the reactor cooling fluid to sustain the necessary thermal gradient. In most circumstances, it would be preferable to provide the engine's heating by gamma-ray absorption, since gamma absorbing materials do not become depleted and are not regulated.

Signal Transduction and Telemetry

The beauty of the thermoacoustic engine is that the transduction mechanism for certain physical phenomena is intrinsic to the heat engine. Changes in temperature, resonator length, and gas composition are encoded in the frequency of the sound. [12] Neutron or gamma absorption are encoded in the amplitude of the sound. [13] Although the intrinsic transduction capabilities of INL-developed TAC heat engine have now been demonstrated, other schemes can be developed to encode the acoustic signals for sensing different parameters. An acoustically transduced sensor, reported by Thompson and Holmes [14], was developed at Oak Ridge National Laboratory. They used acoustics to convert eddy current-induced vibrations within a graphite reactor to telemeter RF signals that characterized microstructure.

The INL-developed TAC sensor is shown in Figure 1. It was designed to be geometrically indistinguishable from the other Training, Research, Isotopes, General Atomics (TRIGA) fuel elements in the Breazeale reactor's core. Heat was produced by fission of two Pathfinder UO_2 fuel pellets contained within a finned heat exchanger produced by additive manufacturing technology.[15]. The sensor's resonance frequency is dependent upon the resonator's length and the gas in the resonator, which is in good thermal contact with the coolant, and thus is a measure of coolant temperature [10], while the radiated sound amplitude can be correlated with reactor power. The acoustic signals from the TAC sensor can be picked up by hydrophones and accelerometers anywhere in the reactor pool and from structures that penetrate the pool. The accelerometers were attached to structures in and out of the water that can couple sound-induced vibrations to the sensors. Most of the signals we acquired had sufficient signal-to-noise ratios even with both the ^{16}N diffusion pump and the pool coolant pump operating.

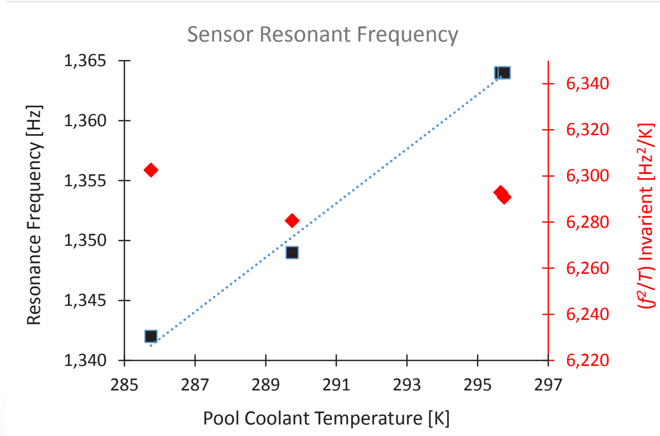

Figure 4. Resonance frequency of the thermoacoustic sensor's standing-wave for different coolant temperatures demonstrating frequency is a function of temperature. The resonance frequencies corresponding to temperatures are plotted as black squares that spans ±1.7%. The right-hand (red) axis has the same relative span, but the value of the f2/T invariant [10], plotted as red diamonds, has a standard deviation of only ±0.12%.

In-Core Test Results

The TAC sensor was tested during eight irradiation runs in the Breazeale Nuclear Reactor over the span of a week. Figure 2 is a time record made during the fifth irradiation. It shows the temperature of the thermocouple that was brazed to the hot-end of the TAC resonator, contained within the insulation space, as well as the output of two hydrophones that were located far from the core in the reactor's coolant pool. Short Time Fast (essentially sliding-average) Fourier transforms of 10-second time records were produced every 2 seconds and the frequency of only the largest-amplitude spectral component is plotted in Figure 2 for both the hydrophones. The TAC sensor achieved onset at about t = 810 s, which is the time the largest amplitude spectral components for both the hydrophones coalesced at the same frequency. Before onset of thermoacoustic oscillations (t < 810 s) and after their cessation (t > 1,100 s), the frequencies of the dominant spectral components from both hydrophones' signals are fairly random and were different due to the proximity of the hydrophones to the sources of pump noises in their respective locations. This is, as would be expected, when the pump noises were received within the displayed bandwidth, Δf = ±40 Hz.

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Figure 3 shows one of several accelerometers that were attached to structures external to the reactor's coolant pool. The spectrogram displays the frequency of the detected vibration as a function of time with the amplitude of the signal coded as color from blue to yellow. Because the characteristic impedance of the water is close to the impedance of the solid structures that penetrate the reactor pool, the sound produced by the TAC sensor coupled well to those structures.

As demonstrated in Figure 4, we were able to show that the frequency of the thermoacoustically generated sound provides an accurate determination of the reactor's coolant temperature. The speed of sound in an ideal gas or gas mixture, c, is pressure independent and related to the acoustically averaged absolute (Kelvin) temperature, T, the mean molecular mass of the gas mixture, M, the mixture's polytropic coefficient, $\gamma = 5/3$, and the Universal Gas Constant, R: $c = (\gamma R T / M)^{1/2}$. Ignoring the small localized changes in the resonator's otherwise uniform cross-sectional area caused by the porous heat exchanger and stack, the fundamental resonance frequency of the thermoacoustic sensor occurs when the wavelength of the sound in the gas mixture, $\lambda = c/f$, is twice the resonator's length, $L \cong \lambda/2$: $f^2 = (c^2/4L^2) = (\gamma R T / 4 M L^2) \propto T$. As is apparent from Figure 4, just forming the ratio of the square of the measured resonance frequency, f^2, to the absolute (Kelvin) temperature of the reactor's coolant, T, produces values of f^2/T that vary by only ±0.12%, while the temperature changes by 3.4%.

ATR Vibroacoustic Infrastructure

As a salient part of the TAC technology transfer to reactor research and industry, an acoustic receiver infrastructure has been installed at the ATR to measure acoustic emissions from within the reactor. The ATR is the next logical venue for testing TAC telemetry and sensing. A TAC sensor has already been designed and is scheduled for insertion in the ATR as part of the 2017 Accident Tolerant Fuel Sensor Experiment.

In preparation for using a TAC sensor in the ATR, the acoustic background signatures in the ATR were characterized. The First Acoustic Baseline Signature of ATR from start-up to shut-down has been generated by the acoustic receiver infrastructure at the ATR, and is shown in Figure 5. Data is being taken, analyzed, and archived so that the various operational states of the ATR can be identified and used for TAC sensor design as well as for diagnostic and prognostic applications. The following are the objectives of the current ATR acoustic monitoring effort:

- Develop an acoustic baseline for the ATR under a variety of operating conditions
- Identify quiescent frequency regions for TAC sensing exploitation
- Develop acoustic signal processing techniques to provided improved signal-to-noise ratios and subtract background signatures
- Identify potential diagnostic and prognostic health monitoring opportunities.

The ability of the ATR acoustic receiver infrastructure to monitor active noise sources emanating from within the

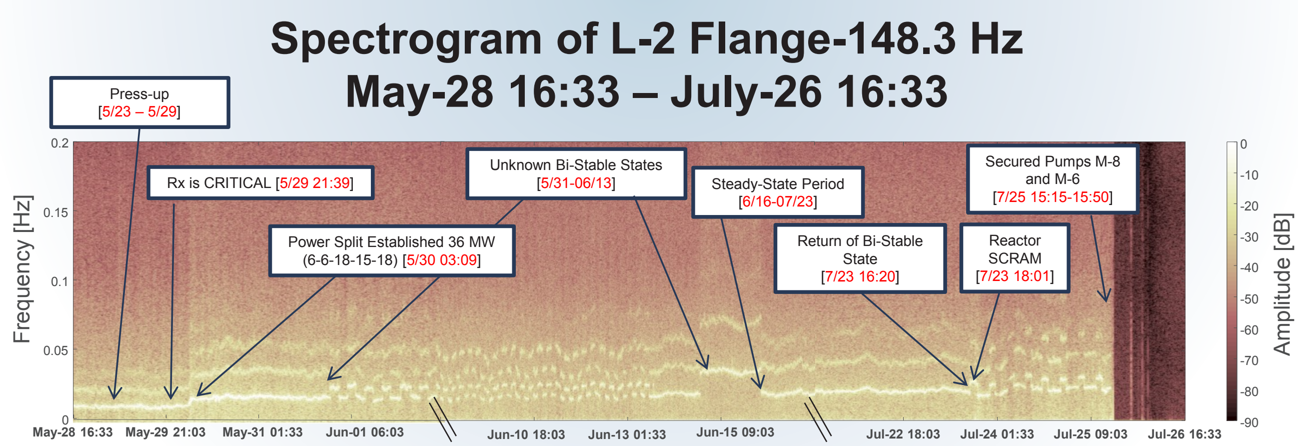

Figure 5. Advanced Test Reactor vibroacoustic environment. Panoramic spectrogram view of a surrogate TAC signal produced by a five-vane pump, at 148.3 Hz, showing different ATR process states during the testing period from May 28 through July 26, 2015.

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reactor has been successful. The periodic pressure pulses from the five-vane pump attached to the rotating shaft of the primary coolant pump makes an excellent "surrogate" TAC signal source. The frequency and harmonics generated by the pump vanes are nearly identical to signals that would be generated by TAC sensors inserted into the reactor core. Surrogate TAC signals allow us to understand and anticipate the changes in frequency, amplitude, and phase of an actual TAC sensor signal.

The surrogate TAC signals generated by the cooling pump provides insight to effectively detect signals from an actual TAC sensor. The data shows that the majority of the ATR reactor noise has frequencies above 2 kHz. TAC sensor signals will be designed to operate within the quiescent frequency range below 2 kHz and produce signal amplitudes well above the noise floor. The receivers have sufficient amplitude sensitivity to monitor three or more harmonics generated by the cooling pumps with a frequency resolution better than 0.02 Hz and a phase resolution below 6 degrees. Thus, the acoustically telemetered technique has the capability of making high-fidelity observations that will allow for sensitive in-core thermal, microstructural, and radiation measurements produced by acoustic sensors. In summary, the ATR reactor makes a surprisingly good signal transmission medium for acoustic signals below 2 kHz.

Conclusions

We have demonstrated the ability to acoustically telemeter temperature and power information from the core of a nuclear reactor to the exterior without requiring external electrical power or wiring. In doing so, we have created a new vibroacoustical paradigm for in-pile telemetry and sensing. Such a sensor strategy might have provided useful information in a reactor accident like that which destroyed the Fukushima complex in March 2011. In a commercial reactor, the flux of gamma radiation could provide sufficient heating that tungsten or stainless steel could be used as a heat source instead of nuclear fuel. This would avoid degradation in the sensor's sensitivity with time (due to fuel depletion) and alleviate the controls imposed for handling of enriched uranium. Multiple sensors in various core locations could also be used to optimize power distribution and improve the reactor's operational efficiency.

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ORNL TRANSFORM Tool Uses Open-Standards Modeling for Collaborative Design of Advanced Nuclear Reactors

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Engineering modeling and simulation is a demanding field. Not many engineers have the specialized skills needed to create models for accurate simulations. Modeling is often limited by the time and training users need to effectively implement proprietary products, but these limitations could be eliminated through large-scale collaborative modeling using open standards.

The Need

Oak Ridge National Laboratory (ORNL) recently completed a project under the Advanced Reactor Technology (ART) program to produce shareable models and an easy-to-use interface for collaborative development of advanced reactor concepts. The biggest benefit of this collaborative paradigm is the potential for shortening the design cycle for new concepts. Design and development has often taken decades due to the complexity of nuclear reactor design and modeling. Reducing this concept design time frame is critical, as the development of reactors often crosses multiple political cycles and can be slowed or stopped by delays in completing a concept that is favorable economically and politically.

ORNL partnered with Modelon, an international supplier of model-based systems engineering tools, libraries, and services, and Xogeny, a start-up exploring ways to integrate engineering models into web-based analysis applications.

Small Modular and Advanced Reactor Development

The project began as a means of developing concepts for small modular reactors. Small modular reactors are about one-third the size of the current generation of nuclear power plants. Key advantages include the ability to fabricate in the factory and deliver by truck or rail to a site, zero carbon emissions, lower initial cost, scalability, and site flexibility. Small modular reactors could also provide better safety and security than their larger counterparts. However, whether the reactor is small or large, modular or full scale, one constant aspect is the need for teamwork on a massive scale. In addition to small modular reactors, other advanced reactor concepts are being investigated that include liquid metal, gas cooled, and molten salt concepts. In these instances, rapid development of models that can be used to perform concept trade studies is needed.

The design and licensing of new nuclear reactor concepts takes hundreds of engineers, many different organizations, and the simulation of these designs for licensing, safety, operations, maintenance, and economics. These efforts require close collaboration among multidisciplinary groups. Traditionally, each of these organizations might rely on different models that ared not necessarily compatible with each other. The need to reduce this redundancy and develop shareable models is a prime driver behind this effort.

Following the lead of several industries that have developed rapid concept and prototype capabilities, ORNL turned to open-standards modeling as embodied by Dymola, Modelica, and FMI. In this effort, ORNL partnered with Modelon and Xogeny to develop the Transient Simulation for Reconfigurable Models (TRANSFORM) architecture (see Figure 1).

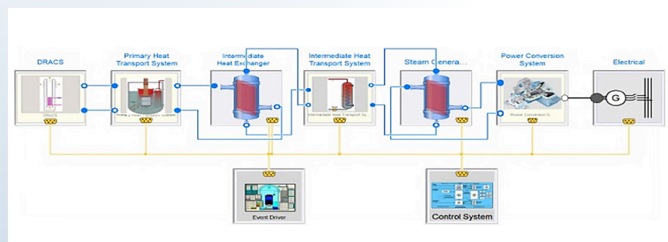

Figure 1. The advanced reactor architecture developed by ORNL serves as the starting point for all modeling work.

Models Tailored to the User

Modeling is becoming a more mainstream engineering activity. Previously, few engineers were capable of developing and using system simulation models. One of the goals of the project is to make the development and use of advanced reactor models more accessible to a broad range of engineering disciplines and skill sets. Interface programs like Dymola are helping to develop models that are user friendly and capable of rapid reconfiguration. Dymola is a proprietary package of software from Dassault Systèmes that uses the open-standard Modelica language to model and simulate the dynamic behavior and performance of systems with complex interactions. Within proprietary packages like Dymola lies the ability to create what are termed functional mockup units (FMUs). FMUs rely on a functional mockup interface (FMI) as an open-standard interface that enables compiled models to be integrated into multiple proprietary or nonproprietary simulation environments. As a result, FMUs can be used outside the original authoring tool or solver, opening the way for wider deployment throughout the enterprise and among qualified partners. In addition to developing a collaborative platform for model development, Modelon

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and Xogengy are also helping ORNL develop interfaces that allow a low threshold of entry for non-modelers to simulate reactor design concepts. Currently these include an Excel interface and a web interface for model simulation and execution (see Figure 2).

Multiple Fidelity Models Needed

Model based systems engineering (MBSE) focuses on interaction among systems in different physical domains such as those between controls and the plant. Models of different fidelities give users the ability to consider many different variants and topologies for concept assessment and system optimization. These types of analysis can be performed in the very early stages of the design process, often before detailed geometry is available.

From the modeling and simulation standpoint, models are easier to build and modify using MBSE. They also provide a more convenient environment from which to establish specifications.

In the current architecture and simulation framework developed by ORNL, models are developed in Modelica/Dymola, configured on a web interface, and then they are either run in Dymola, through a web browser, or downloaded for local simulation on a user's computer. This approach allows users to easily set parameters, download models (FMUs) created in Modelica, and automatically set up cases and run them within the Excel add-in or other commonly used simulation programs.

The combination of a dynamic modeling interface, supported libraries, the modeling language, and the FMI Add-in for Excel enables novice modelers to run parametric cases across a wide suite of models. It is a powerful combination that did not exist previously for modeling and simulating reactor designs.

Development in the Cloud

The next major step in the ORNL project was to transition from a local application to a web-based simulation and development platform. This is where the dual expertise of Modelon and Xogeny is helpful. Using Modelica and FMI, along with software collaboration and development platforms like GitHub, ORNL is bringing an advanced approach using cloud software development and computing, as well as web-based user interfaces for advanced reactor system modeling. Deployment of models and access to them is being made as easy as possible for multidisciplinary engineering teams.

A large team may still be needed to design and simulate advanced nuclear reactors, but the ORNL TRANSFORM tool will provide a smoother, faster process for a wide range of team members to make their contributions.

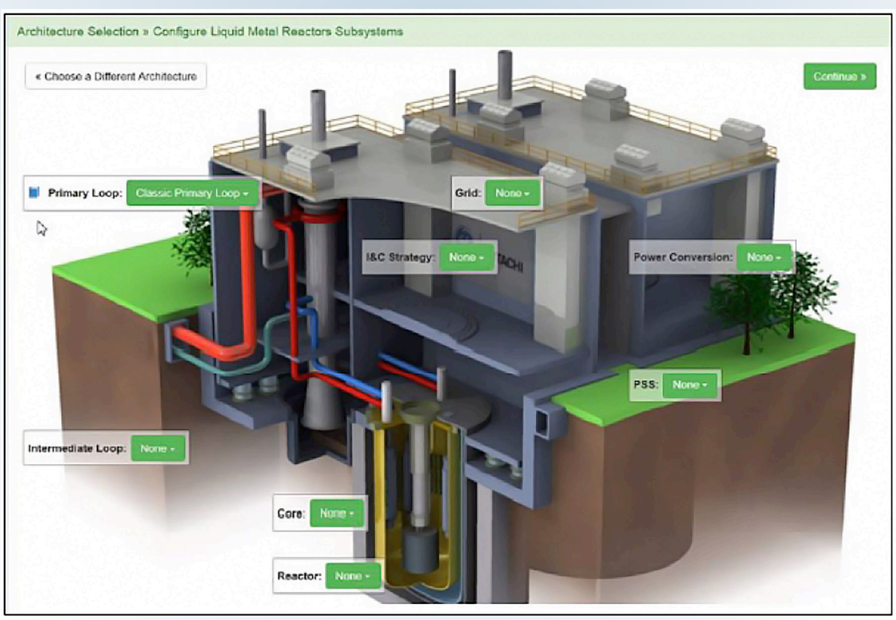

Figure 2. A version of the web application developed by Modelon/Xogeny. The web platform allows for a advanced reactor concept configuration and parameter setting, which leads to a downloadable Excel and/or browser execution and simulation.

Commercialization of Products of DOE Research Grants

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The Department of Energy (DOE) grants under the Small Business Innovation Research (SBIR) program awarded to Analysis and Measurement Services Corporation (AMS) Corporation over the last 10 years have resulted in a number of commercial products already implemented and working in nuclear power plants. These products are generating a recurring annual revenue of $5 million in return for a one-time investment of a little over $10 million by DOE. Four examples of these products are introduced in this paper:

1. Rod control system performance verification technology
2. Equipment and techniques for cable condition monitoring
3. Online monitoring to optimize instrumentation and control (I&C) system maintenance
4. Digital I&C qualification.

Collectively, these and other AMS products developed with SBIR funding are saving the nuclear industry over 100 days of outage time per year, which corresponds to nearly $100 million in annual revenues for the nuclear industry.

Introduction

AMS has conducted a number of research and development (R&D) projects with grants from DOE under the SBIR program. The goal of the SBIR program is to subsidize research and development (R&D) efforts in small companies (less than 500 employees) to stimulate innovation in the private sector and yield commercial products for science and industry. This paper presents four examples of products that have been developed by AMS under the SBIR program of DOE and commercialized in the nuclear industry. We have focused here on the cost/benefit description of these developments as opposed to their technical details, which are found in numerous publications by AMS and others.

Rod Control System Performance Verification Technology

In pressurized water reactors (PWRs), the drop time of control and shutdown rods must be measured after each refueling outage to verify that there is no obstruction impeding the rods. The requirement is for each rod to drop from the top to the bottom of the reactor in less than 2 seconds.

To shut the reactor down, the rods are dropped by gravity, but normal manipulation of the rods for reactor control is accomplished by the control rod drive mechanisms (CRDMs). In PWRs, CRDMs are typically made of three coils that must work together in timely sequences to move the rods. To verify the timing and sequencing of CRDMs, plants must track the activation and deactivation of the three CRDM coils as they work together to operate the grippers and lift mechanisms that hold and move the rods. This is accomplished by recording and analyzing the electrical current signals that energize the coils. This must be done after each refueling cycle or whenever the reactor vessel head is removed.

Through SBIR projects, AMS has developed advanced technologies to perform rod drop time measurements and CRDM testing enabling plants to complete the tests in less than 1 hour compared to 12 to 24 hours that it would take to perform the tests using conventional procedures. At over $50,000 per hour of power generation revenue, this saves a plant between $550,000 and $1,150,000 at each refueling cycle of 14 to 24 months.

In addition, R&D efforts performed under more recent SBIR projects have resulted in new techniques to track the performance of rod control electronics. For example, by measuring the current and voltage of CRDM coils, we can calculate the coil resistance and monitor the value for overheating, degradation, and other changes that can interfere with proper movement of the rods. The same principles have been used to verify the health of digital rod position indication (DRPI) coils, perform online condition monitoring on DRPI power supplies, improve the resolution of DRPI systems, and more.

One of the recent SBIR projects of AMS was performed in partnership with a host utility on a PWR plant who worked closely with AMS to develop what the plant calls a "Rod Control Adjustment Automation and Analysis Recorder." This system has already helped the plant avoid a forced shutdown in 2015 by detecting a fault in a rod control system coil. More specifically, the AMS system gave the plant early warning of an impending coil failure and clued them to switch to the spare coil soon enough to prevent a forced shutdown. In fall 2014, prior to the installation of the new rod control analysis recorder, a failed rod control system coil forced the same plant to shut down for 7 days.

Overall, DOE has awarded AMS about $3,500,000 in R&D grants, which so far have resulted in almost $1,500,000

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of recurring revenue. This revenue stream is expected to continue for as long as the clients' plants are operating and should increase as more plants are added to the current client base.

Cable Condition Monitoring

In simple terms, a nuclear power plant cable is made of a metallic conductor covered by a polymer insulation. During routine plant operation, conductor and connector problems arise and are identified, located, and resolved using an array of existing electrical testing technologies. These include insulation resistance (IR) checks, time domain reflectometry (TDR) tests, and loop resistance, capacitance, and inductance (LCR) measurements. Fortunately, these measurements can all be performed in-situ on installed cables while the plant is operating. Through an SBIR project, AMS integrated these measurements and developed a cable characterization unit, referred to as "CHAR," that includes all the electrical in-situ measurements in one compact and portable test unit. This product has so far generated nearly $6 million of commercial revenue for a little over $2 million, the amount that DOE has invested in R&D grants leading to development of CHAR (Figure 1).

Online Monitoring to Optimize I&C Maintenance

Online Monitoring (OLM) has a wide spectrum of applications in nuclear power plants and much has already been done to outfit U.S. plants with OLM capabilities. For example, online vibration monitoring, which encompasses essentially all the rotating systems of a nuclear power plant, is widespread. Numerous national and international firms have been providing the nuclear industry with vibration monitoring capabilities for four decades. At AMS, OLM development has been focused mostly on verifying the calibration and response time of process I&C systems.

To date, the commercial OLM projects of AMS have been implemented at the Sizewell B nuclear power station in the United Kingdom and in the Advanced Test Reactor (ATR) located at Idaho National Laboratory in the United States. Both commercialization projects encompass calibration monitoring and response time verification of temperature, pressure, level, and flow sensors. The work involves retrieving the normal output of the sensors from existing plant computers and analyzing them for evidence of drift. For response time testing, a set of test equipment is deployed in the plant for the duration of the tests to record the data, which is then analyzed to yield the sensor response time.

A common complaint about online calibration monitoring is that it is a one-point calibration check rather than a full-span calibration verification tool. To overcome this concern, OLM data must be retrieved from not only periods of normal plant operation, but also during startup and shutdown episodes. At Sizewell B, AMS has taken OLM data during startup, normal operation, and shutdown, and successfully demonstrated that this data can help verify

Figure 1. CHAR System

the calibration of a sensor over its entire operating range. As a result of OLM implementation, the Sizewell B plant has reported that it is saving about 5 days of outage per each operating cycle of about 14 months. This amounts to nearly $5 million of generation revenues plus all the indirect benefits of OLM implementation such as reduced radiation exposure to technicians, less damage to plant equipment from potential mistakes during calibration, reduced potential for calibration-induced alarms, and much more.

The ATR plant implemented OLM in 2015, and the actual savings are not yet realized. However, AMS and ATR personnel developed a business case ahead of time that showed that OLM can save ATR over $100,000 per year in direct benefits in reducing manual calibration workload and response time testing using the conventional method.

Overall, AMS has so far generated nearly $7 million in commercial revenue from the $3 million in grants that it has received from DOE for various OLM developments.

Digital I&C Qualification

An important aspect of digital I&C qualification is electromagnetic compatibility (EMC) testing. With DOE grants under the SBIR program, AMS developed new equipment, technology, and procedures to streamline EMC qualification of digital I&C systems for nuclear power plants. The goal of EMC qualification is to guarantee that the digital equipment to be installed in a nuclear plant will be immune to the EMC environment of the plant. Conversely, it must be verified through EMC testing that the digital equipment to be installed in a plant will not emit electromagnetic radiation that disturbs nearby plant equipment.

The EMC testing capabilities that AMS has developed through the SBIR projects of DOE have to date generated over $3 million of commercial revenues for the nearly $3 million that DOE invested. This revenue stream is expected to continue and to grow as more plants replace their analog equipment with digital systems.

Conclusion

AMS has successfully commercialized the product of much of its R&D projects funded by DOE grants under the SBIR program. Over the past 10 years, we have generated nearly $20 million of recurring commercial revenue in return for a one-time investment of a little over $10 million by DOE. Four examples of DOE-funded R&D products at AMS were introduced in this paper in terms of their applications in nuclear power plants and the revenue that they have generated. Figure 2 shows the revenue for each of these examples compared to the dollar amount of the DOE grants spent to design, develop, test, and market the products.

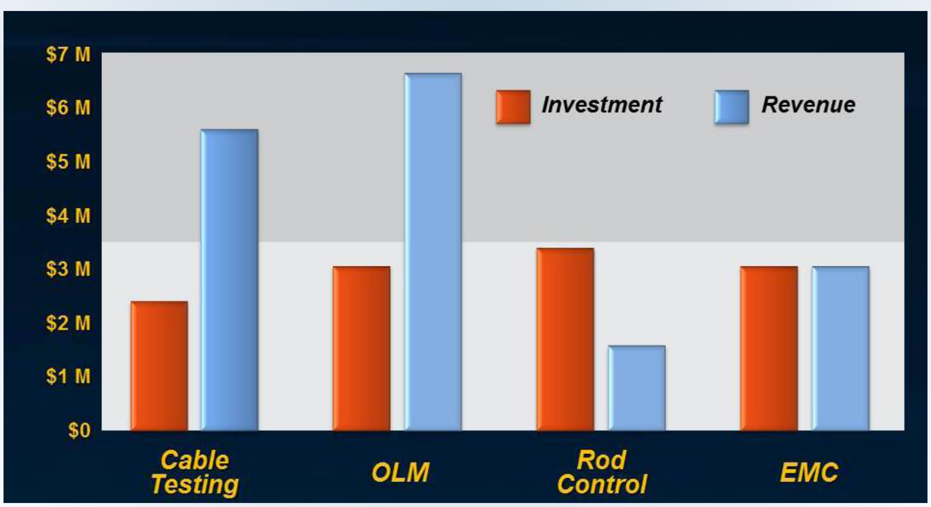

Figure 2. DOE Investments versus Revenue Generated to Date for the Four Examples Presented in this Paper