ADVANCED SENSORS AND INSTRUMENTATION

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Program Update

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The Advanced Sensors and Instrumentation (ASI) program, soon to close out its seventh fiscal year, continues to address key technology gaps for future nuclear energy systems. Information on the projects can be found in our ASI annual awards summaries, annual review webinars, and newsletters posted at the Office of Nuclear Energy website (energy.gov/ne).

In support the U.S. Department of Energy's FY 2020 Consolidated Innovative Nuclear Research (CINR) Funding Opportunity Announcement (FOA), the ASI program has developed NEET-2 work scopes. These were presented on August 9th, 2019 and can be reviewed at the following website link: https://neup.inl.gov/SitePages/FY19_Webinar_Presentations.aspx The NEET-2 work scope continues to focus on developing advanced sensors and instrumentation technologies that address critical technology gaps for monitoring and controlling advanced reactors and fuel cycle facilities. The goal of this crosscutting technology development is for sustaining the existing fleet, advancing new reactor technology, advancing fuel cycle technology development, and improving U.S. global competitiveness. The ASI program focus for this year's CINR FOA is on advanced technology for semi-autonomous and remote operation. Work scope was developed in three key areas; first -Advanced Control Systems, second – Big Data, Machine Learning, and Artificial Intelligence, and third – Advanced Sensors and Communication.

In the area of Advanced Control Systems, proposals are sought for technology that streamline and simplify the digital design process in a meaningful way. This would include new test methodologies that reduce I&C testing and provide validation and verification of smart digital devices.

The work scope in the area of Big Data, Machine Learning, and Artificial Intelligence looks for proposals that demonstrate advanced analytics that support semi-autonomous and remote monitoring of advanced reactor designs and integrate predictive analytics and risk informed condition monitoring system.

The Advanced Sensors and Communications work scope is focused on technology that enables the deployment of new sensors and instrumentation technology that can survive harsh advanced reactor environments and utilizes wireless communication. The proposed sensors should include performance models for initial calibration, routine operation, radiation degradation, in-situ re-calibration and predictive failure mechanisms for the lifetime of operation.

As the ASI program continues to award projects through different competitive solicitations, we encourage the I&C community to visit the NE website for the current funding opportunity announcements—especially for the industry-focused solicitation entitled, "U.S. Industry Opportunities for Advanced Nuclear Technology Development."

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U.S. DEPARTMENT OF ENERGY

SymPLe Architecture: Achieving Verifiable and High-integrity Instrumentation and Control Systems through Complexity Awareness and Constrained Design

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The Problem of Complexity and Software

Over the past few decades, digital-based instrumentation and control (I&C) technology has advanced more rapidly and more thoroughly than any other discipline important to nuclear power plants (NPPs). Digital-based I&C encompasses embedded digital devices (e.g., programmable logic controllers [PLCs], smart sensors), communication networks, display systems, and actuation devices. As the modernization of NPPs moves forward, the question of realizing safe and cost-effective I&C systems to replace aging analog I&C systems becomes paramount. These new I&C systems must be as trustworthy and safe as their predecessors and function as users and operators expect despite the possibility of disruption, faults, operator errors, vulnerabilities, and cyber attacks. Digital (programmable microprocessor-based) technology is the leading technology replacement choice for older analog I&C due to its widespread dominance in the embedded systems marketplace and its acceptance by other safety critical industries. These economies of scale have predisposed the use of commercial-off-the-shelf (COTS) software-based I&C components wherever possible.

While most process control industries have been able to embrace digital I&C technology to improve performance, reliability, maintainability, and efficiency of production, the nuclear industry has been relatively slow to adopt digital I&C for safety-critical plant functions. There are number of reasons for this, namely, (1) lack of familiarity of these systems by the nuclear community, (2) concerns over Software Common Cause Failures (SCCF) that could adversely affect safety by violating independence criteria. We assert that another deeper underlying reason for not fully realizing digital I&C and automation in nuclear power is associated with the *complexity* that can manifest in these software-based systems that is different from the complexity of their analog predecessors. Software-based technology being very amendable to modification, reuse, and reconfiguration allows users to make almost any functional system from software given a suitable microprocessor platform. Microprocessor technology is almost miraculous in its ability to be flexible and configurable to almost any use or any fix – the same CPU that controls a washing machine can be used (with a different algorithm or instructions) to control a feed-water pump in an NPP - and it does not take a great level of skill to create complex designs in these software (SW)-based devices. These above attributes are positive and negative. One positive is that software is easy to change and mutate, hence the name software – being soft. A negative is that complexity naturally arises. Having no physical limitations (like mass, volume, density), complex software/hardware designs are possible and no real effort to accomplish this complexity is really needed. Complexity is a source for design faults or flaws, arguably the primary cause of serious failure for most safety critical systems [1]. Design faults are often due to the inability to reason or fully consider the extent of interactions in a system with its environment and users. As complexity increases, design faults are more prone to occur when interactions between humans, controller and controlled environment make it challenging to identify rare event erroneous states.

Complexity Awareness for Verifiable Systems

From 2015 to 2019, as part of its crosscutting research to address technology needs and challenges that affect the continued availability of nuclear energy, the Department of Energy (DOE) Nuclear Energy Enabling Technologies (NEET) Advanced Sensor and Instrumentation (ASI) program awarded a research project involving the Electric Power Research Institute (EPRI), and Virginia Commonwealth University (VCU). The project, entitled "Realizing Verifiable I&C and Embedded Digital Devices for Nuclear Power," pursued concepts, design and realization of verifiable I&C architectures as alternatives to SW-based I&C systems that culminated in the *SymPLe* architecture.

The fundamental assertion posed by the SymPLe project is that I&C systems and embedded digital devices in the context of nuclear power may not need to be derivatives of "software intensive" systems and, by extension, not carry the complexity associated with these devices and systems. Reducing complexity and enhancing reasoning about a system provides a solid foundation for justifying the trust in the system. We assert that architectural solutions best address complexity awareness and constrained behavior. SymPLe rethinks digital I&C from a perspective of complexity, awareness, and trust.

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Foundations and Overview of the SymPLe Architecture

The architectural foundations for SymPLe are influenced by three important engineering areas that are supportive of modernized nuclear I&C; (1) principles of real-time safety critical systems, (2) formal model-based design assurance methodologies, and (3) Field Programmable Gate Array (FPGA) overlay architectures for constrained behavior. From these technical foundations, we defined high level design principles which establish the basis of the formulation of operational rules, rules for organization, or rules for composition for the SymPLe architecture. The SymPLe design principles:

1. *Abstraction*. SymPLe uses abstraction to introduce and define the basic units of computations, Function Blocks (FBs). The FB is given its precise interface and functional specifications without any need to understand the internals of the FB operation.
2. *Partitioning*. This principle helps to build simple systems by disentangling functions that are separable so they can be grouped in self-contained architectural units, thus generating stable intermediate forms [31].
3. *Segmentation or Sequentiality*. This principle recommends that hard-to-understand complex concurrent and simultaneous behaviors should be decomposed, wherever possible, into a serial or sequential behavioral structure such that a sequential model of computation or step-by-step analysis of the behavior becomes possible.
4. *Principle of Independence*. This principle suggests that the interdependence of architectural units should be reduced to the necessary minimum that is required by the application.
5. *Principle of Observability*. Non-visible communication channels or states among architectural units pose a severe impediment for the understanding of system behavior. To this extent, non-visible communication or interfaces shall be avoided.
6. *Principle of a Consistent Time*. This principle is crucial in developing deterministic predictable behavior. Consistent time allows agreement and consensus of events by different actors and components in the system.

Referring to Figure 1, at the lowest level is a reconfigurable computing device such as FPGA or Application Specific Integrated Circuit (ASIC). At this level, the capacity of the cell-based architecture is capable of realizing a broad range of functionalities and is highly generalized, commensurate with technology used. In a modern FPGA, it is possible to synthesize designs ranging from simple logic circuits to 32-bit super-scalar microprocessors. The next layer in Figure 1 represents the SymPLe overlay architecture. SymPLe constrains user accessible functionality by only allowing SymPLe defined functions to be used by the designers. From a user's perspective, elementary function blocks allow I&C applications to be built-up into Function Block Diagrams (FBDs) (programs) much like they are in PLC environments. These FBDs are executed in *task lanes* that enforce concurrent and interference-free execution of programs.

The SymPLe architecture is organized into two distinct hierarchal levels: the global sequencer level and the task level. The global sequence level is concerned with managing the executions of and coordination between independent and parallel task lanes. This level enforces the real-time deterministic features of the architecture and directs inputs and outputs to, from, and between components of the architecture. From a control perspective, the global sequencer level is the root of the control tree and has the highest level of control. The major components at the global sequencer level include the global sequencer, N tasks lanes, a bus switch, a point I/O manager, and shared memory I/O.

The task level of the architecture is involved in executing a linear sequence of elementary functions to achieve a desired higher level of functionality. The task level also encompasses the low-level granular fault and error detection capabilities and implements the basic fault tolerance and error resiliency of the architecture. The major components of a task include the task or local sequencer, a function block controller, a set of function blocks, and redundant memory.

SymPLe is designed to enforce deterministic and predictable execution behavior in the task lanes. The operational semantics of the architecture are formally verified to ensure high degree of trust in the deterministic behavior. To assist designers, libraries of formally verified elementary functions are used to compose I&C programs. The final step is to verify and test the I&C application against the specification. Along each layer of SymPLe, verification activities produce evidence to support qualification. This research project follows the IEC 61508 assurance standards. The use of IEC 61508 standard was chosen for several reasons—most notably the nuclear industry is actively investigating the use of IEC 61508 to

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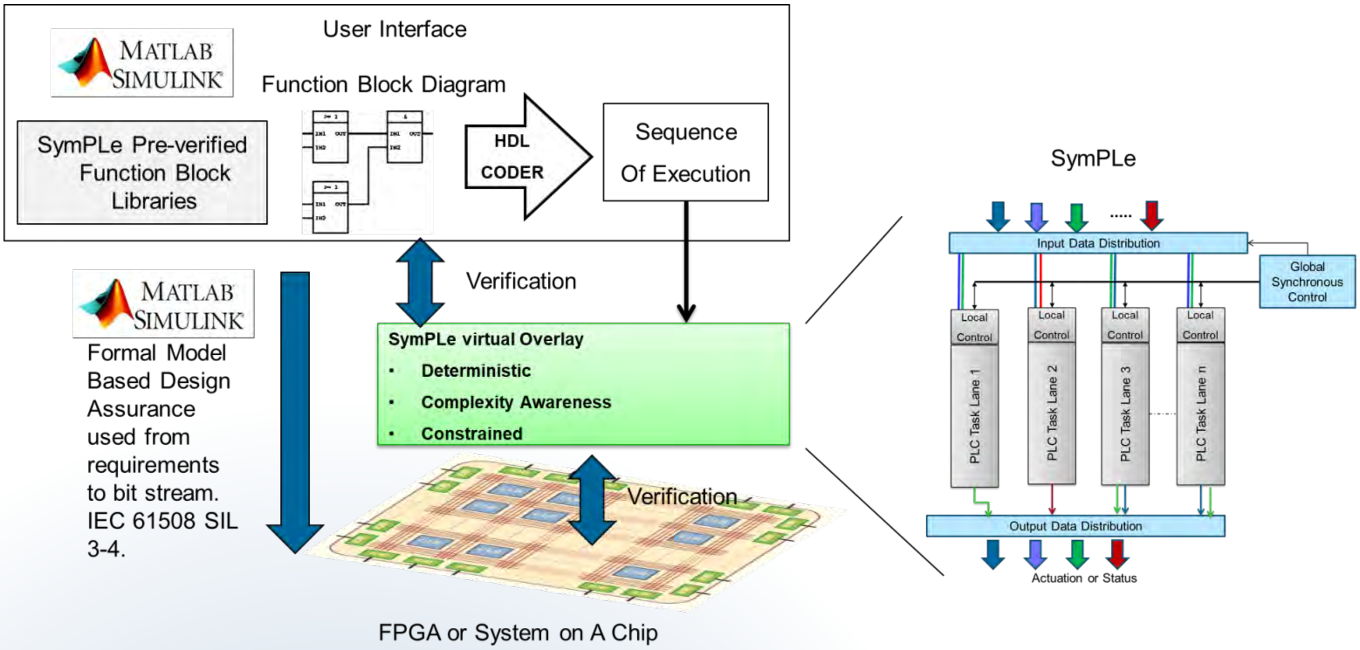

Figure 1. SymPLe architecture concept.

support commercial grade qualification of digital I&C systems—and use of IEC 61508 on this project provides added value to the greater I&C community. The SymPLe architecture is designed to promote "accessible verification" between OEM/utility engineers and the regulatory agencies that review and license NPP I&C systems.

It is important to note, SymPLe is specifically aimed at safety-critical, but low-complexity functions within NPPs and process control applications where constraining device complexity to support verifiability and safety cases arguments can make a significant impact. There are many safety critical and related functions (Safety Integrity Level [SIL] Levels 3- and 4-type systems) in an NPP, but many of these functions are not very complex in functionality or logic. Typical examples include rod control logic, pressure sensors, Proportional, Integral, and Differential (PID) control for pumps, emergency diesel generator startup controllers, etc.

Another added benefit of SymPLe is the complementary nature to design for diversity. Because SymPLe contains functional building blocks that can implement a variety of functions, it is easier to produce functionally different designs than with software processor-based solutions. The SymPLe overlay with formal verification plus selective design diversity provides a very rigorous approach to SCCF. Since formal verification is used extensively in SymPLe, design diversity does not need to be heavily relied upon for every aspect of architectural SCCF mitigation, as it is now with digital I&C systems. These principles provide a sound and well-formed basis for addressing the issue of SCCF in digital I&C in a practical and cost-effective manner.

Key Technologies in SymPLe

SymPLe leveraged two technologies not normally used in the nuclear energy industry. The first of these was *FPGA Overlays or Virtual Machines*. Generally, overlay is an abstraction method that presents a different logical view on the resources of a computer system or architecture than the physically accurate view [2]. It is important to note that overlays are not "fixed" designs or reverse-engineered old designs. They employ a model of computation; these overlays represent a user domain and encode requirements from that user domain. Overlay architectures allow a domain community to decide what is "important" to them. SymPLe overlays are used for two purposes: (1) to constrain behavior with respect to the complexity requirements, and (2) employ a model of computation—

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the PLC function block model of programmability (e.g., IEC 61131). The use of PLC programmability is based on the long legacy of PLCs in nuclear power.

The second major technology is model-based engineering (MBE) and design assurance. MBE elevates models in the engineering process to a central and governing role in the specification, design, integration, validation, certification, and operation of a system [3]. In general, the nuclear industry has been very slow to adopt MBE methods in the digital I&C area. MBE and design are a paradigm shift from traditional nuclear industry document-based, certification, and acquisition lifecycle model approaches. MBE is a "systems engineering" perspective that supports the iterative lifecycle processes that occur between various stakeholders. As such, model-based analysis allows support for decision making by providing reasoning along the various aspects of design, development, and verification and validation. It provides portable executable models to collect insight that could be overlooked early in the requirements and specification phases. Another compelling reason for adopting MBE practices is cost and reduction in design flaws. The safety-critical aerospace and automotive industry has largely embraced MBE for these reasons.

Conclusion

We believe this research has advanced the state-of-the-art in the qualification of advanced instrumentation with embedded digital devices for NPP application by (1) developing a novel and practical architecture solution for constraining behavior and enhancing verification in both design time and runtime, and (2) applying the developed methods to representative embedded digital devices to ascertain the effectiveness of the SymPLe approach. The outcomes of this research provide a technical basis by establishing and demonstrating the efficacy of "verification aware" designs for digital I&C. The research culminated several important milestones for the industry:

- Used comprehensive model-based design and engineering to produce verifiable I&C systems for the nuclear industry with clear findings on the utility of MBE.
- Initially employed a comprehensive use of MBE, testing, and verification in an IEC 61508 workflow in support of design assurance.
- Gathered evidence of difficult to find design flaws (24 design flaws and bugs) found using model-based design and testing methods. Detailed the nature of these SCCFs including where they were introduced, the triggers, and how they were found.
- Gathered evidence on the synergistic use of practical formal methods and testing and how these two methods can be used to significantly increase assurance of reduction and avoidance of design flaws.
- Developed and realized a prototype of SymPLe on a commercial industrial PLC platform National Instruments' cRIO 9049, which was used in an integrated a hardware-in-the-loop testing environment.

Additional reading: Carl Elks, Matt Gibson, Final Technical Report, *Achieving Verifiable and High Integrity Instrumentation and Control Systems through Complexity Awareness and Constrained Design*. Milestone - M2CA-15-CA-EPRI-0703-0221 2019 Work Package ID: CA-15-CA-EPRI-0703-02, NEET-2 Project No. 15-8044.

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An Approach to Model-based Testing of Instrumentation with an Embedded Digital Device

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Research Motivation

The instrumentation and control (I&C) equipment used in currently operating United States nuclear power plants (NPPs) is primarily based on mature analog technologies that are progressing towards obsolescence. The continued reliance on this legacy analog technology, which is also being propagated into new NPP designs, imposes performance penalties and maintenance burdens in comparison with modern digital I&C equipment [1]. Experience in other industries has shown that digital technology can provide substantial benefits in terms of performance, reliability, and maintainability. Nevertheless, the nuclear power industry has been slow to adopt digital technology primarily because of regulatory uncertainty, implementation complexity, and limited availability of nuclear-qualified vendors and products. A specific concern is the potential for common-cause failure (CCF) vulnerability associated with embedded digital devices.

Given the great demand for digital functionality in high-volume industries, the industrial I&C marketplace is dominated by digital technology. Consequentially, it is increasingly difficult to acquire instrumentation that is not equipped with an embedded digital device (EDD). These EDDs serve to enhance the performance, reliability, and flexibility of the equipment. However, the inclusion of an EDD also adds complexity to equipment functionality and increases the potential for latent systematic faults, which, in turn, complicates demonstration of qualification for safety-related applications. Without systematic, science-based methods to resolve concerns about the qualification of digital technology, the nuclear power industry faces a significant challenge in modernizing its safety-related I&C equipment to address obsolescence and enhance performance.

Project Overview

As part of its crosscutting research to address technology needs and challenges that affect the continued availability of nuclear energy, the Department of Energy (DOE) Nuclear Energy Enabling Technologies (NEET) Advanced Sensors and Instrumentation (ASI) program awarded the University of Tennessee Knoxville (UTK), The Ohio State University (OSU), Virginia Commonwealth University (VCU), and Analysis and Measurement Services (AMS) Corporation a focused research project from 2015 through early 2019. The project, entitled “Development and Demonstration of a Model Based Assessment Approach for Qualification of Embedded Digital Devices in Nuclear Power Applications,” involved developing an approach employing model-based testing to help resolve concerns about integrity, quality, and potential CCF vulnerability. An effective demonstration of qualification can minimize uncertainties that serve to inhibit deployment of advanced instrumentation (e.g., sensors, actuators, microcontrollers) with EDDs in nuclear power applications.

The research objectives of the project addressed the challenge of establishing high levels of safety and reliability assurance needed for the qualification of EDDs (e.g., microprocessors, programmable logic devices) that are subject to software design faults, complex failure modes, and CCF vulnerability. Specific objectives were: (1) assess the regulatory context for treatment of CCF vulnerability in embedded digital devices, (2) define a classification scheme for equipment with an EDD to characterize its functional impact and facilitate a graded approach to qualification, (3) develop and extend model-based testing methods to enable effective demonstration of whether devices are subject to CCF, which may arise from vulnerabilities introduced at any stage of the design lifecycle, (4) establish a cost-effective testing framework that incorporates automation and test scenario prioritization, and (5) demonstrate the qualification approach through selection and testing of candidate digital device(s).

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The fundamental technology development for this research involves establishing a cost-effective qualification framework that incorporates model-based testing to support determination of whether equipment with an EDD is vulnerable to CCF. During the course of this research project, an approach for model-based testing was generated, a suitable prototype intelligent device was devised, and capabilities to implement and automate a testing environment were developed and applied through demonstration. This article provides a summary of key findings from the testing methodology development and demonstration performed through this research project.

Model-based Testing Methodology

The model-based testing (MBT) approach developed through this research involves automatic generation of qualification test cases from a set of models of the system under test or its environment [2]. The MBT methodology is based on an extension of a software testing technique known as mutation testing. Mutation testing is a fault-based software testing technique that has been shown to be effective in identifying adequate test data to find faults in the software. While the traditional mutation testing technique can identify defects introduced at the code level, it does not directly treat faults in requirements and design. To cover the full spectrum of faults that may arise during the software development lifecycle, the traditional mutation testing technique is extended to identify requirements and design faults.

Development of the MBT framework involved three main steps: (1) extending the traditional mutation testing technique to the requirements and design level, (2) developing a method to execute the specification documents at the requirements and design level, and (3) developing a method to generate test cases that can detect (i.e., "kill") the mutants generated using the extended mutation testing approach. To extend the mutation testing technique, it was necessary to identify and classify defects introduced at the requirements and design phases of the software development lifecycle, and develop mutation operators for each defect category. To enable this extension, the typical formulation of the software requirements specification (SRS) and the software design description (SDD) for digital equipment were modeled using an Extended Finite State Machine formulation. Some examples of the identified defects and corresponding mutation operators are given in Table 1.

The means for establishing and executing the specification models employs a model-based software reliability assessment tool developed by OSU for safety critical software [3]. The Automated Reliability Prediction System (ARPS) allows the user to enter the information from the SRS/SDD document to construct a High-Level Extended Finite-State Machine (HLEFSM) representation of the requirements and design. The method to execute the resulting HLEFSM model involves four steps: (1) examine the definition of functions, (2) examine the definition of variables in each function, (3) execute the system logic and print the path that the system traverses, and (4) execute

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Table 1. Defects and Mutation Operators in the Requirements and Design Level

Defect name	Mutation Operator
1. Missing (definition of) function: The entire definition of a function is missing from the SRS/SDD.	MF
2. Extra (definition of) function: The entire function definition is extraneous.	EF
3. Incorrect/ambiguous function name: The name of the function is incorrect/ambiguous.	IAFN
4. Function with incorrect logic: The functionality is valid, but the logic is erroneous.	FIL
5. Missing function output: The definition of an output is missing from the SRS/SDD.	MFO
6. Missing instance of function: The definition of a function is correct, but a call to that function is missing	MIF

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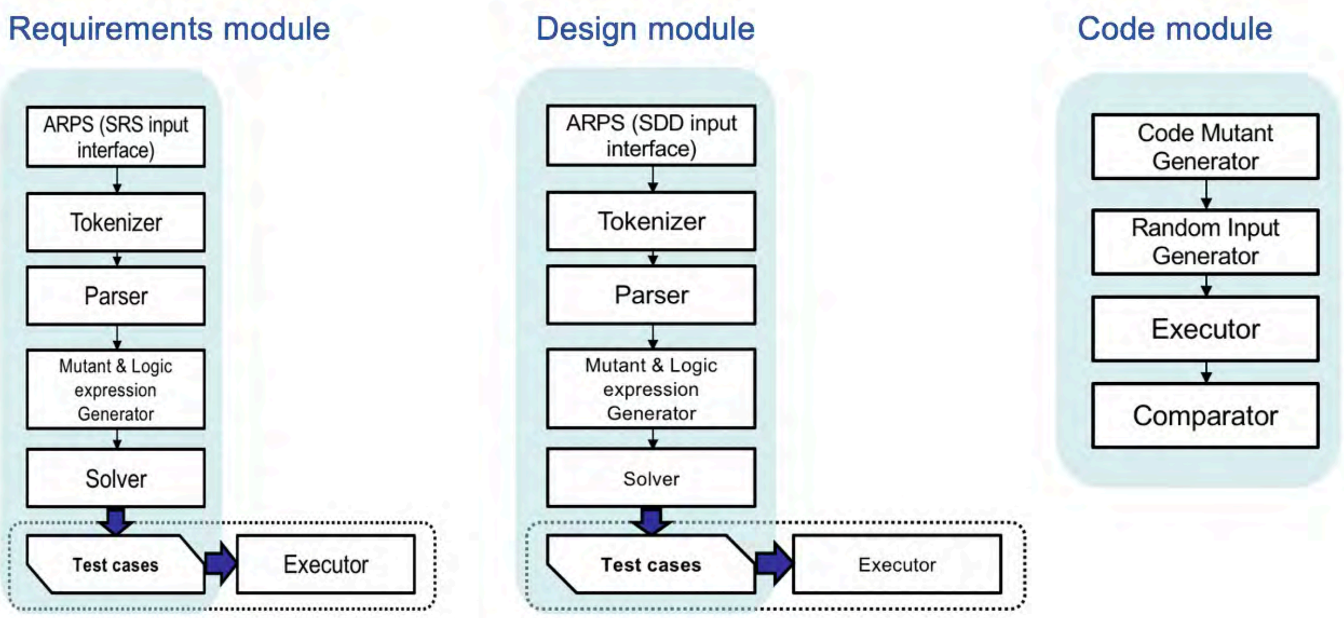

Figure 1. The model of AMuTT

the function logic for each function in the path that the system traverses and print the path. The results of model execution are output in a string by compiling the HLEFSM constructed by ARPS.

The automated generation of test cases within the MBT framework focuses on establishing a suite of tests to detect or kill mutated versions of the software that correspond to defects at the requirements and design levels. Killing a mutant involves the following two steps: (1) identifying the paths that the system needs to traverse to kill the mutant and (2) identifying the test inputs that satisfy the constraints generated during the execution in Step 1. The Automated Mutation Testing Tool (AMuTT) provides the means to generate test cases to detect the individual mutants. The AMuTT consists of three modules, which are the requirements module, design module, and code module as shown in Figure 1. The requirements and design modules consist of six submodules, which are the SRS/SDD Input Interface, Tokenizer, Parser, Mutant Generator, Solver, and Executor. The code module consists of four submodules, which are the Mutant Generator, Random Input Generator, Executor, and Comparator.

Therefore, in the MBT framework established through this research, tests are developed based on hypothesized software faults arising from requirements, design, and coding sources. The objective is to define a test suite that can differentiate/detect the potential existence of each postulated fault. Mutation operators systematically seed faults (i.e., create mutated versions with embedded faults) in either the base software or models of requirements or design documentation, and the test suite is executed on the mutants to determine if the tests are sufficiently comprehensive to detect all of the seeded faults. The mutation testing framework provides a means to demonstrate that the full range of postulated faults are covered and thereby give evidence for the qualification of the software-based device.

Demonstration Approach

An experiment was designed to demonstrate the effectiveness of the MBT framework. The primary elements of the experiment involved the software and physical development of a representative prototype instrument with an EDD, the creation of the software under test (SUT) variants with seeded faults (i.e., mutants), and the execution of experimental testing based on the MBT framework and a black-box random testing baseline approach.

The experimental procedure was organized into four steps, which are: 1) development of the software for the device under testing, 2) generation of variants of the software under testing with seeded defects, 3) defect identification using the black-box baseline method, 4) defect identification using the MBT approach. VCU developed the demonstration target (VCU Smart Sensor) and established multiple variants implementing selected defects from a

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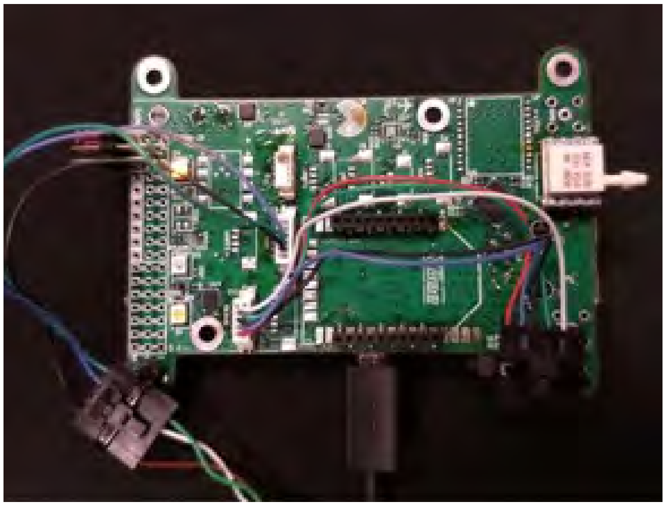

Figure 2. VCU Smart Sensor

compiled library. AMS, with the assistance of UTK, devised and conducted the black-box baseline testing on the demonstration target and its variants. OSU established the MBT Framework and implemented it to perform model-based testing on the demonstration target and its variants.

The selected development and demonstration target for testing, shown in Figure 2, was a prototype smart pressure sensor originally developed in the VCU Unmanned Aerial Vehicle laboratory. The VCU Smart Sensor provides functionality for temperature and pressure measurements, calibration, communication, and filtering and analysis of inputs/outputs. The selected instrument consists of an established design and code that has over 10,000 hours of test time in previous projects. Since this sensor is a research product rather than a commercial item, it was necessary to generate post-development design documentation, (i.e., the SRS and SDD).

As part of the experiment, VCU established a defect library from which to generate faulted versions of the software and design documentation. Each mutated variant contained a set of seeded defects whose types and quantity were only known by the developer. Twenty variants were created for the experiment and served as the subject of qualification using both MBT and black-box baseline testing.

As noted, black-box baseline testing was conducted on mutated versions of the VCU Smart Sensor to serve as the basis for comparing the effectiveness of the MBT methodology. This comparative testing was performed using an automated Software Reliability Test (SRT) system developed by AMS. [4] The SRT, consisting of hardware and software, sends inputs to a device under test, and compares the outputs for a given set of inputs to a software model of the device, known as an oracle. This process is repeated at high speed thousands or millions of times, in order to build a representative picture of how the device will behave over its complete input space. This method for randomized testing represents the current state-of-the-art industry practice and serves as a suitable point of comparison.

Demonstration Results

The experimental demonstration of the MBT Framework was applied to software products for the VCU Smart Sensor at the requirements, design, and implementation levels. At the requirements level, 78 indigenous (or residual) defects were identified for the SRS of the smart sensor. This result was not surprising given that the SRS for the smart sensor was generated in an after-the-fact, ad hoc fashion by researchers rather than as part of a formalized activity concurrent with the development of a commercial product. Nine SRS variants were found to each have a unique seventy-ninth defect. The time costs associated with MBT approach at the requirements level was found to range from 11.79 hours to 2.14 hours. The first few instances required the most time but vast majority of cases took less than 3 hours, benefitting from increased familiarity and expertise of the testers.

At the design level, 62,842 possible mutants were identified for the representative case of the first variant of the demonstration target. Applying cost-reduction techniques developed as part of the research, this number was reduced to 6,284 mutants, which resulted in 52 unique logic expressions to be solved to generate the test cases. Execution of the test cases resulted in 127 indigenous defects in the SDD being identified. Again, given the research-product nature of the SDD for the smart sensor, this result is not unexpected. The total time to execute the MBT approach at the design level for this smart sensor variant was 21.66 hours.

At the implementation level, 209 mutants were generated for each variant based on a selected set of mutation operators. Three test cases were then generated to identify the number of killed (i.e., detected by specific test case) and live (i.e., undetected by specific test case) mutants. The results were analyzed to characterize the remaining live mutants for each test case. Based on that analysis, the remaining mutants were identified as equivalent logic mutants or were classified as dead code mutants. Dead code mutants are the mutants whose mutated code is a dead code (i.e., has no effect). Equivalent logic mutants are the mutants whose logic is equivalent to the logic of the original code. The final set of test cases were then executed

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on the smart sensor variants. The results revealed defects in 16 variants while no defect was found in the other four variants. Potential factors that influence the results include: (1) no defect exists in such code variant; (2) the defects were seeded in the dead code of the code variant; (3) the code variant is equivalent to the original code; and (4) the defect seeded is out of the application boundary of the code variant. The time cost for MBT approach at the implementation level ranged from 11.63 hours to 52.2 hours, with most of the cases taking 16 hours or less.

When a software failure was encountered during test case execution, the source code was examined to identify defects. Then the defects were fixed. Test cases were run again to identify remaining defects in the source code. In the application of MBT framework, defects were identified in all variants either through testing or analysis.

As part of the experimental demonstration, black-box baseline testing of the VCU Smart Sensor was conducted on all 20 variants of the demonstration target, but since the input space is extensive and the speed at which the VCU Smart Sensor can be tested is limited, established techniques were used to generate a subset of the possible input space. The collection of test points began with 25 test cases that investigate the boundary values of the input space. This technique is then followed by multiple sets of randomly generated cases using the uniform-stochastic generation method. In total, there were 116,025 test cases in the collection. Each version of code was tested using the test case collection, but if no unusual outputs were seen, the test case collection was retested again. The results of the testing of all 20 code versions revealed five versions where no errors were detected, four versions that did not return any outputs (i.e., failed execution), and 11 versions where the outputs did not match up with the expected result.

The comparative analysis of the experimental results showed that both methods were able to identify 15 of the 20 defects. For Code Variant 20, software failures were identified only by the MBT framework. Neither of the MBT framework and the black-box baseline testing showed a software failure in four of the code variants through testing. Based on the oracle provided by VCU, the defects were seeded in dead code for those variants. The dead code containing the seeded defects was identified in the equivalent mutant analysis by the MBT framework.

Conclusion

The primary outcome of the experimental demonstration of the MBT framework involves conclusions that can be drawn about the effectiveness and efficiency of the MBT methodology. The objective of MBT is to ensure that equipment with an EDD undergoes suitably comprehensive testing to establish that it is not subject to CCF. The approach by which MBT accomplishes this objective is through development and application of an effective test suite that provides the appropriate coverage to detect the full range of postulated faults that may arise at the requirements, design, and code (implementation) level of the EDD software. The effectiveness of MBT is shown through its capability to detect faults from multiple phases of the software development lifecycle. An unanticipated result is the capability that the MBT methodology provides to assess the SRS and SDD for defects. This suggests that MBT framework can be applied to assess the underlying quality of evidence employed to support commercial grade item dedication (e.g., post-development software documentation).

A comparative analysis of the testing results from MBT and black-box testing demonstrates that the MBT methodology enables detection of faults that are not detectable through the conventional testing approach. Additionally, the MBT framework incorporates automated tools and fault-type equivalence to achieve testing efficiencies. Consequently, the time required for implementing and executing the MBT is comparable or less than that required for the black-box testing and associated failure analysis. The experimental evidence demonstrates this efficiency gain. Thus, the results of the comparative analysis of the experimental demonstration indicates clear benefits that arise from the MBT methodology.

Finally, this research also reaffirmed the value that an automated system, like the SRT, provides in diagnosing system faults, which can supplement the qualification process of digital instrumentation and control in the nuclear industry. Additionally, the prototype VCU Smart Sensor serves as an additional research product that has been fully documented and is now available as a resource to support further investigations and other research projects.

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An Impedance-based Diameter Gauge for In-pile Fuel Deformation Measurements

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Introduction

Significant research has been conducted to develop instrumentation capable of performing in-pile dimensional change measurements. These efforts have largely been driven to improve the existing understanding of pellet cladding mechanical and chemical interaction, which has significant effect on the performance of fuel rodlets. [1,2] These previous efforts are predominately based on Linear Variable Differential Transformers (LVDT) and optical interferometry techniques. There has been substantial development for axial elongation using optical fiber-based interferometry techniques. [3-7] To a greater extent, LVDTs have been used for many decades to measure in-pile axial elongation—an approach refined by the Halden Reactor Project (HRP). [8-9] Electrical impedance-based sensing is a mature measurement field with wide-ranging applications, including many commercially available devices for standard measurements. However, electrical impedance-based measurements have had limited applications in the nuclear field.

The research presented here provides proof of concept for using electrical impedance between two electrodes as a contactless method to measure the in-pile dimensional changes of a sample while minimizing intrusiveness. Researchers envision several measurement configurations based on the principle of measuring impedance between two or more electrodes. This study focuses on two co-axial cylinders for electrode geometry, the inner cylinder representing the specimen (i.e., cladding of nuclear fuel) and the outer cylinder being the diameter gauge sensor.

The purpose of this study is to investigate the accuracy and sensitivity of the sensor to cladding deformation. Benchtop testing of the impedance-based diameter gauge is conducted for known cladding diameters, and the measurement error is derived for "off-design conditions." The research team used uncertainty analysis to determine the impact of each design parameter on the measurement uncertainty, to serve the purpose of optimizing sensor design and understanding its performance and limitations.

Methods

Sensor Design

In general, impedance-based measurements apply an AC voltage, Vac across two electrodes, and measures the AC current, iac, or vice-versa. The electrical impedance is simply Vac/iac. The sensor presented here utilizes this basic measurement principle. The sensor design consists of a conductive tube located concentrically around the nuclear fuel cladding. The two electrodes in this design are the cladding and the concentric conductive tube surrounding the cladding. Figure 1 shows a simple cross-sectional schematic representation of the sensor design.

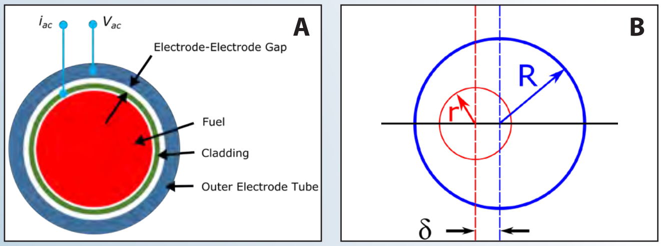

Figure 1. (A) Schematic cross section of radial deformation sensor design. AC voltage is applied to the outer tube electrode while the current is measured from the cladding tube. (B) Diagram showing spatial location definitions for cladding outer radius, inner radius for the electrode, and the offset of their center points.

In the simplest case, the sensor would be used in a dry capsule experiment but with potential to extend to more complicated flowing coolant conditions. In the dry configuration, the measured impedance is dominated by the capacitance component of impedance. Therefore, the sensor electrodes need to be close enough to have significant capacitive coupling, but sufficiently separated to avoid electrical contact when fuel swelling occurs. Based on fuel performance predictions for

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UO2-Zry fuel systems, a maximum diametric range of approximately 100 to 150 µm (50 to 75 µm on the radius) is used for design evaluation with an assumed cladding outer diameter of 9.5 mm. As a result, the desired measurement range necessitates a measurement resolution of less than approximately 10 µm.

Theory

The capacitance between two cylindrical electrodes, as shown in Figure 1, is provided in Claussnitzer's 1968 article [10] as:

$$C = \frac{2\pi\varepsilon L}{\cosh^{-1}\left(\frac{r^2+R^2-\delta^2}{2rR}\right)}$$

where ε is the absolute permittivity, L is the length of the cylinders, r is the outer radius of the inner cylinder (cladding), R is the radius of the outer cylinder (sensor), and δ is the distance between the centers of the sensor and rod.

The Taylor series uncertainty propagation method [11] can be used to estimate the deterministic uncertainty of the measured radius. These results are shown in Figure 2 with the uncertainty from each term plotted in addition to the total uncertainty over a range of values for cladding radius. The uncertainty contribution from that of the measured capacitance decreases monotonically as the cladding radius approaches the sensor radiusThis is a result of the capacitance becoming large compared to the measurement accuracy of the LCR meter. The uncertainty contribution from the measurement of the sensor radius monotonically increases with cladding radius. The uncertainty contribution from the cladding offset remains low until the radius of the rod approaches the radius of the sensor. At that point, the uncertainty from the eccentricity goes asymptotically high. These competing effects result in a minimum plateau for the total uncertainty of approximately 10 µm at a cladding radius of 4.4–4.9 mm.

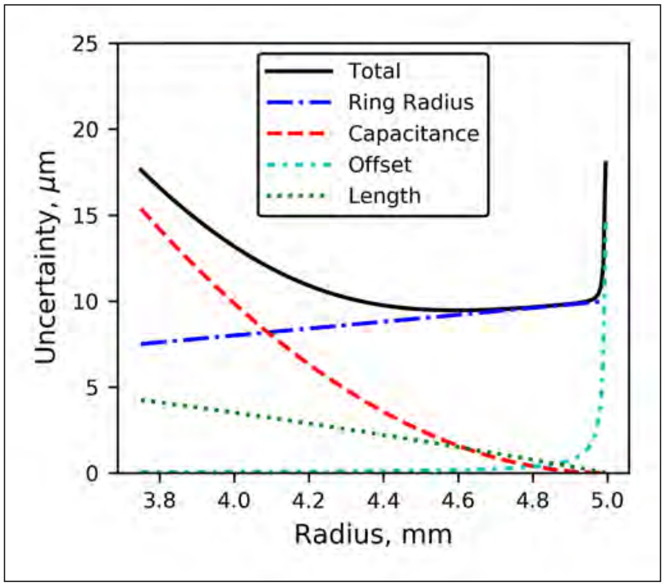

Figure 2. Calculated deterministic uncertainty of measured radius based on capacitance measurement uncertainty of 0.07 pF, ring radius uncertainty of 10 µm, and a length uncertainty of 100 µm.

A minimum measurement uncertainty is clearly observed in Figure 2, which does not occur at the maximum radius. This distinction is important in the design of an experiment incorporating the sensor, and careful consideration should be made to decide the sensor radius based on the needs of the experiment and the associated uncertainties.

Results and Discussion

The experimental test configuration described previously was used to collect experimental measurements for comparison to the analytical and COMSOL modeling of the sensor. The experimentally measured capacitances are given in Table 1 along with the corresponding calculated diameters and measurement error. These results all have an error on the diameter measurement of less than 20 µm, which is within the deterministic uncertainty shown in Figure 2. This provides evidence that the assumptions incorporated in the model are representative of the sensor and experimental setup.

Table 1. Calculated capacitance from COMSOL modeling for different combinations of rod and ring diameters.

		Measured Capacitance (pF)	Calculated Radius (mm)	Error (µm)
Cladding Radius	4.750 mm	28.05	4.7545	4.5
	4.775 mm	31.32	4.7796	4.6
	4.800 mm	36.45	4.8100	10.0

The experimental setup used in this study incorporated precision-controlled stages to adjust the position of the ring relative to the rod. The setup relies on precise fabrication and assembly to ensure the axes of the rod and sensor were parallel. Various measurements were conducted to explore some of the off-design conditions

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that could be encountered during a deployment of the sensor. Specifically, the precision controlled stages were used to offset the rod location from the center of the sensor. In a sensor deployment scenario, it may be impossible to ensure the sensor and rod are concentric and therefore it is important to understand how this misalignment will propagate into measurement error.

Impedance measurements were made for a range of positions of the ring relative to the rod for each rod diameter (Figure 3). The analytical and COMSOL results show the capacitance increasing as the rod approaches either side of the ring, which explains the shape and limits of the curve in Figure 3. By considering the 9.5-mm and 9.55-mm curves, a 9.5-mm rod misaligned by 0.12 mm would be interpreted as a well-aligned 9.55-mm rod, showing the importance of accurate alignment. When the sensor and rod are concentric (Position = 0), the capacitance is at a minimum, and by definition there is no sensitivity to position ($\partial C/\partial \delta=0$). This is an important and enabling fact because it reduces the sensitivity of the measurement to vibrations when in a well-aligned state.

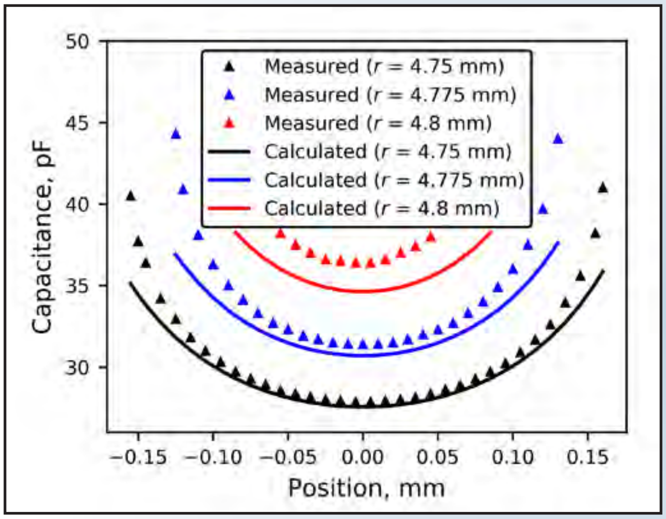

Figure 3. Measured capacitance for various sensor offset, δ. The corresponding solid lines are results from the analytic capacitance solution shown in Equation 1.

The results show the excellent measurement resolution of capacitance and low noise encountered in the system. During measurements, it was observed that capacitance values could be made reliably with a resolution of approximately 0.1 pF, which is consistent with the 0.07 pF accuracy reported by the manufacturer of the LCR meter.

Summary and Conclusions

The sensor design described in this study measures the diameter of a rod through electrical impedance measurement between the rod and a concentric ring. The sensor has the potential to perform contactless measurement of radial expansion of nuclear fuel in a reactor environment, which substantially reduces the intrusiveness of the approach compared to existing methods. Experimentally measured electrical impedances were compared to numerical results using COMSOL Multiphysics and analytic models, all resulted in good agreement. The analytic model was used to interpret the electrical impedance for diameter measurements. Measurements were performed on rod diameters of 9.5 mm, 9.55 mm, and 9.6 mm. Characterization of off-design conditions was done by performing measurements with the rod offset (not concentric) various distances from the center of the sensor. From the experimental results, the following conclusions were reached:

The sensor has a diameter measurement resolution of <1 µm for a sensor diameter of 10 mm and rod diameters ranging from 9.5 to 6 mm.

The sensor is capable of measuring rod diameters of 9.5 mm, 9.55 mm, and 9.6 mm with < 20 µm of error (< 0.2 % error on diameter measurements).

Measured capacitance is a minimum ($\partial C/\partial \delta=0$) when rod and sensor are concentric, resulting in low sensitivity to offset distance when the sensor is well-aligned.

The sensor design has a resolution of an order of magnitude less than targeted for light water reactor fuel

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testing needs. The results provided through analytic models, numerical modeling, and experimental results all indicate sufficient diameter measurement resolution and accuracy for relevancy to fuel cladding deformation. The sensor and similar designs will continue to be explored for such measurements and deformation measurement needs for other specimen types.

Acknowledgment

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Technology-Enabled Risk-Informed Maintenance Strategy to Minimize Operation and Maintenance Costs

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The domestic fleet of nuclear power plants (NPPs) is facing a unique economic sustainability challenge in today's energy market due to high total operating costs. One of the major contributors to the total operating cost of an NPP is the operations and maintenance (O&M) budget, which includes labor-intense preventive maintenance (PM) programs. PM programs involve manually inspecting, calibrating testing, and performing maintenance of plant assets at periodic frequencies, as well as time-based replacement of assets, irrespective of individual asset condition. This approach, combined with the push to achieve high-capacity factors, has resulted in a labor-centric business model. It is time to transition from this labor-centric business model to a technology-centric business model that will enable an optimal maintenance strategy by eliminating unnecessary costs associated with time-based PM activities.

To enable this transition, the commercial nuclear industries are utilizing and developing reliable methodologies, based on available state of the art technologies, which facilitate assessing equipment condition and the dynamic risk of failure. The U.S. Department of Energy's Idaho National Laboratory under the Light Water Reactor Sustainability Program is partnering with PKMJ Technical Services and Public Service Enterprise Group (PSEG) Nuclear, LLC to develop and demonstrate a deployable risk-informed predictive maintenance strategy to eliminate unnecessary O&M costs for an identified plant system, laying the foundation for scale-up to the entire plant. Recently developed technologies such as advanced wireless and wired sensors, data analytics, and risk assessment methodologies will support this transition. The technology-centric O&M model will result in significant automation and lay the foundation for real-time condition assessment of plant assets, thus enabling condition-based maintenance and enhancing plant safety, reliability, and economics of operation.

The project team has identified the circulating water system (CWS) at Salem NPP as the target plant system to achieve project's goal of developing and demonstrating a deployable risk-informed predictive maintenance strategy at a commercial NPP. To support the project goal, three interrelated tasks have been identified:

1. Develop a risk-informed approach using existing plant information to optimize maintenance frequencies for the CWS.
2. Develop diagnostic and prognostic models to understand the health of the CWS and update the risk model to achieve risk-informed condition-based maintenance approach.
3. Develop and demonstrate a digital, automated platform to centralize the capabilities developed in Tasks 1 and 2 to facilitate implementation of these technologies in industry.

Approach

Figure 1 presents a well-defined approach to achieve the primary goals of the project. The approach can be broken into three focal areas: (1) data sources and recommendations; (2) model development; and (3) automation platform. A brief description of each category is provided in this section.

Data Sources and Recommendations

Data collected from plant systems contain metadata related to plant processes, maintenance logs, operator logs, and other relevant items. Typical plant process data relevant to the CWS include gross power, river inlet and outlet temperatures, and motor-related information such as on-off duration, motor current, and temperature measurements at the motor stator and bearings. Data collected for the circulating water pump itself include vibration, discharge header pressure, and ambient air temperature. Additional data sets from relevant items

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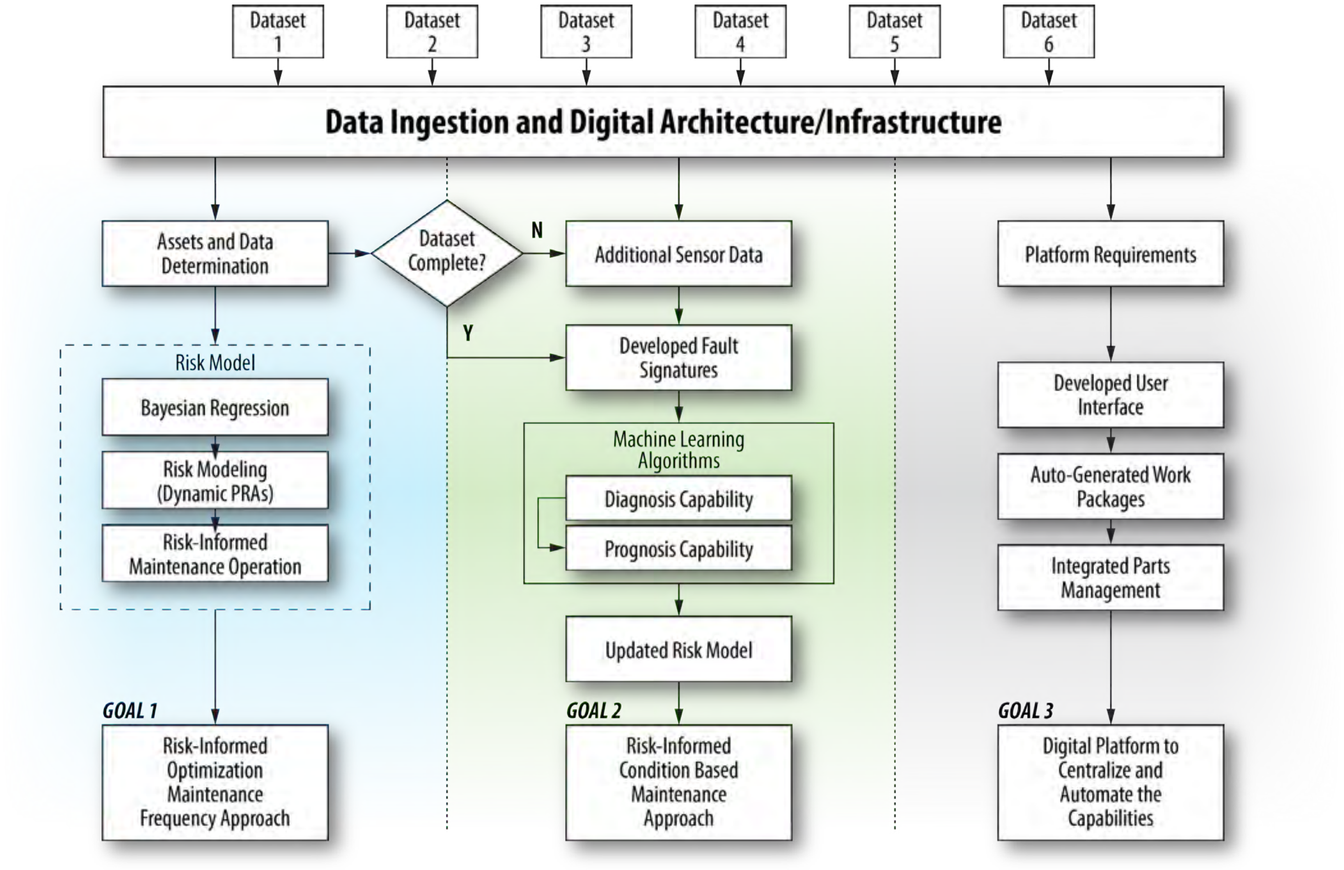

Figure 1. Research scope of integrated risk-informed condition-based predictive maintenance and automated platform.

such as condenser, river inlet, river outlet, and operator actions in the field are extracted and added to the data lake in real time. A data completeness evaluation will be performed and recommendations will be provided to the partner utility. Some examples of recommendations include changing the frequency of data collection, installing additional sensors, or replacing/re-calibrating existing sensors.

Model Development

The research and development activities associated with model development will be performed for risk, diagnostic, and prognostic models, requiring identification of potential failure modes for the target plant system. Risk models calculate component and system risk, utilizing plant-specific historical data obtained in the data sources and recommendation activities. Component failure rates and probability of failure are not fixed in time, but rather evolve, providing a more realistic picture of component and plant risk. For the selected system, Bayesian statistical models are employed to estimate failure rates (λ) and probability of failure (p) for components based on their past performance, failures, repair and maintenance, etc. Bayesian statistical models start with known, fixed values of λ and p for the components and utilize available data to update λ and p based on the most recent information. The models for λ and p will be integrated with existing plant-maintained probabilistic risk assessment models for the specific system and components, creating dynamic probabilistic risk assessment models.

Diagnostic and prognostic models will be developed in a parallel activity, using machine-learning methodologies.

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Machine-learning techniques, including both linear and nonlinear techniques, have shown the ability to correlate the functional relationship present in heterogeneous data and diagnose an evolving fault at an early stage, providing the opportunity to take action and prevent failure. A fault is a particular mode of degradation that can be detected by analyzing plant information. Upon diagnosis of a fault, machine-learning techniques will be further utilized to predict progression of the fault under different operating conditions and estimate the remaining useful life of the system or component. The predicted fault growth path and remaining useful life estimation, along with operating condition information, will be utilized to update λ and p values, which in turn will update the risk model to make a current risk prediction. The risk prediction is mapped to low-, medium-, and high-risk categories to allow system engineers to make risk-informed decisions on asset maintenance activities, enabling both optimization of maintenance activities and auto generation of work orders.

Development of Automated Platform and Validation

This part of the research is focused on developing a platform to enable seamless integration of information from risk, diagnostic, and prognostic models with other plant information. Visualization schemes and an effective user interface will be developed that support automatic generation of the necessary electronic work orders by taking into consideration different plant resources, such as field worker qualifications, optimal work scheduling, and other aspects. Each stage of the project will be validated via demonstration/testing at the plant as it is achieved. This exercise will enable: (1) evaluation of the effectiveness of the techniques and tools, (2) collection of feedback from plant engineers and maintenance staff to enhance the techniques and tools, and (3) introduction of advanced technologies to provide confidence as PM is gradually phased out.

SUMMARY AND PATH FORWARD

The project outlines a comprehensive approach for successful research, development, and demonstration of an integrated risk-informed condition-based maintenance capability. Online monitoring and data analytic techniques with advanced risk assessment methodologies are used to schedule maintenance activities without impacting plant operation. The technology-centric approach is designed to reduce preventive maintenance frequency, drive down costs, enhance safety and reliability, and improve the economics of operation in NPPs. This will ensure the nuclear industry will remain economically competitive and viable in the energy market.

As part of ongoing research, the team is analyzing plant process data, maintenance logs, operator logs, and other relevant data sources to perform a data completeness evaluation for the CWS. The team is also working with a sensor vendor to install wireless vibration sensors on identified locations of the circulating water motors to enable online monitoring capability.

Metamaterial Void Sensor for Fast Transient Testing

Mark Roberson
Goldfinch Sensor Technologies
and Analytics LLC

Nuclear reactor uranium fuel rodlets are assembled in a container rod. The metal cladding of the rod transfers heat for powering the steam turbines. Commercial nuclear reactor fleet companies are developing new claddings for safety and efficiency, and to support new reactor geometries for commercial power production, science experimentation, and space propulsion.

The cladding-coolant interface is critical. The generation of heat within the rod generates internal pressure and cladding stresses. During a reactor accident, voids (bubbles) can form in the cooling fluid on the cladding (see Figure 1). At the void location, the cladding-coolant heat transfer decreases, and the cladding temperature and stresses increase. The voids in the cooling fluid can cause cladding degradation and weakening. Nuclear accidents such as Fukushima Daiichi show the need for better fuels [1]. After the accident the United States Congress placed emphasis on accident-tolerant fuels for reactors, meaning fuel rods that can be operated safely in the presence of thermal excursions and reactor-initiated accidents. In other thermal events, such as a loss of cooling accident, a breach in the coolant-pressure boundary causes a rise in temperature from stored thermal energy. It is important to measure these effects in a controlled test, analogous to car-crash testing, and the test vehicles are a critical component.

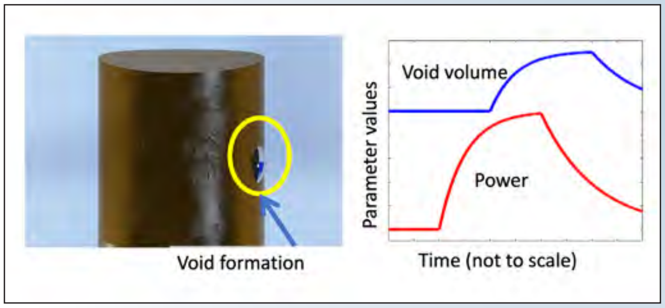

Figure 1. Schematic view of void formation on a rod.

Idaho National Laboratory (INL) operates the Transient Reactor Test (TREAT) facility [2] (see Figure 2). Because of the reactor geometry, the facility can safely create fast reactor transient tests to simulate many reactor accident scenarios. The TREAT facility tests help to optimize Light Water Reactor fuels, and the technologies developed have potential for other reactor designs such as sodium-cooled fast reactors.

Figure 2. INL TREAT facility.

Light-water reactors represent more than 80% of the nuclear energy production in the world [3]. In both the pressurized water reactors and boiling water reactors, power production is constrained by the critical heat flux between cladding and the liquid water. The critical heat flux is a main safety parameter [4,5]; it occurs when bubbles coalesce and a film of vapor is formed on the heater element. Understanding this complex two-phase flow phenomena is a critical step in the safety analysis of the nuclear power plant.

Goal

To develop and license new reactors, fuels, and operational conditions, it is critical to quantify the timing, location, and size distribution of voids. Existing void-sensing methods include capacitive plates, ultrasonic probing, neutron hodoscopy, and gamma ray probing. Neither neutron hodoscopy nor gamma ray probing have the required time resolution, and ultrasonic probing requires contact with the rodlets. The project develops a sensor to measure the voids. The target sensor test vehicle is the INL TREAT Super-Static Environment Rodlet Transient Test Apparatus.

The project conducts applied research and development in order to demonstrate completion at Technology Readiness Level 5, "System/subsystem/component validation in relevant environment." At Goldfinch Sensor Technologies and Analytics LLC, our goal is to validate the ability to perform direct, time-resolved, and multi-position detection and characterization of boiling in high-pressure, high-temperature environments with minimal electrical feedthrough requirements.

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Objectives

Developing extreme environment sensors is a complex process of instrument and software development and qualification. A development spiral has stages of research and development (R&D) input, conceptual formulation, design and demonstration, acceptance, and operation. The project works with the lessons from the first cycle to complete a second spiral and to transfer the second iteration systems for acceptance testing. We found gaps to be addressed before bringing the technology to commercialization, and identified technical areas needing additional modeling and simulation. In talking with potential end-users, we identified testing at high temperatures and pressures as a requirement before testing on operational systems. We are optimizing our physical sensor and establishing a formal software approach to migrate from benchtop to a deployable confirmation. This project is expected to be completed with a system validation task to exit at TRL-5. We plan to demonstrate the proof of concept system in varying conditions that match the INL TREAT environment as closely as possible. The project has six technical objectives.

1. Modeling and Simulation. Perform the theoretical work required to form numerical models and simulations of performance and use the results to develop an operational model of void formation and sensing.
2. Autoclave Operation. Construct and operationalize an autoclave to produce the temperatures and pressures needed and include engineering and safety tasks to reduce the risk of personnel injury or equipment damage.
3. RF and Electronics. Develop the measuring system components and sensors to prepare for commercial application.
4. Device Fabrication. Continue the development of the sensors with emphasis upon the process flow for making sensors of repeatable performance.
5. Software Development. Explore code challenges in void-sensing and bubble-sized characterization and begin migrating from an experimental software set to a commercial product.
6. Subsystem Validation. Validate the system through a design of experiments and system testing.

Current status

The existing method for sensing voids uses capacitive paddles. It is difficult to maintain the isolation of signals from floating grounds and from very low frequency electric and magnetic fields. Our approach to sensing the voids is based on radio frequency (RF) metamaterials. Designing instrumentation for a reactor core presents challenges for the electrical feedthroughs and RF cable because of the high temperatures and pressures. A standard RG-58 coaxial cable is only rated to a maximum temperature of 60°C. so we use dielectric mineral coax cables with stainless steel conductors and create welded electrical connections. These devices are fabricated using ceramic and metal elements suitable for the temperature, pressure, and RF performance. The metamaterial elements are attached to the ceramic before coating the entire device with a water penetration barrier coating (see Figure 3).

Figure 3. Encapsulated metamaterial void sensor.

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Dr. Juliana Pacheco Duarte from Virginia Tech is joining the project with her team for hydraulics modeling and autoclave testing. Thermal-hydraulics subchannel codes can be used to analyze the heat transfer and fluid mechanics parameters of the complex reactor core geometry without the need of the time-consuming 3D computational fluid dynamics models. The codes have been extensively validated for a wide range of two-phase flow experiments for both pool boiling and flow boiling conditions. The modeling includes two-fluid, three field (fluid film, fluid drops, and vapor) models.

Experimentally we use a variety of RF signal waveforms, including a single frequency signal set at around the peak transmission of the sensors. Filling the test chamber (see Figure 4) with water and injecting air simulates voids on the fuel rod. Our results show our ability to detect both single bubbles and multiple bubbles (see Figure 5). We have also demonstrated our ability to determine the position and flow direction of the bubbles.

Value to Nuclear Applications

Rapid high-temperature event detection and void localization technology is of great value to nuclear plant operators in fuel development. The outage time, fuel, and power replacement expenses for a failed rod in a boiling water reactor can easily exceed $1M. In a nuclear reactor, departure from nucleate boiling represents the primary critical safety issue for pressure water reactors. Operators can quickly identify localized material failures of fuel rods and avoid further damage. This technology permits tighter process monitoring needed for upfit scenarios where power output is being increased with higher energy content fuel rods. Beyond core temperature monitoring in active reactors, void temperature sensing is valuable in other phases of the nuclear industry materials lifecycle, including spent fuel waste monitoring and plant decommissioning.

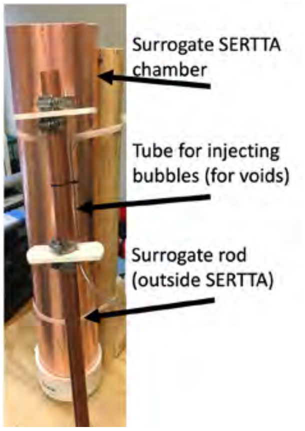

Figure 4. First phase test chamber for void detection testing.

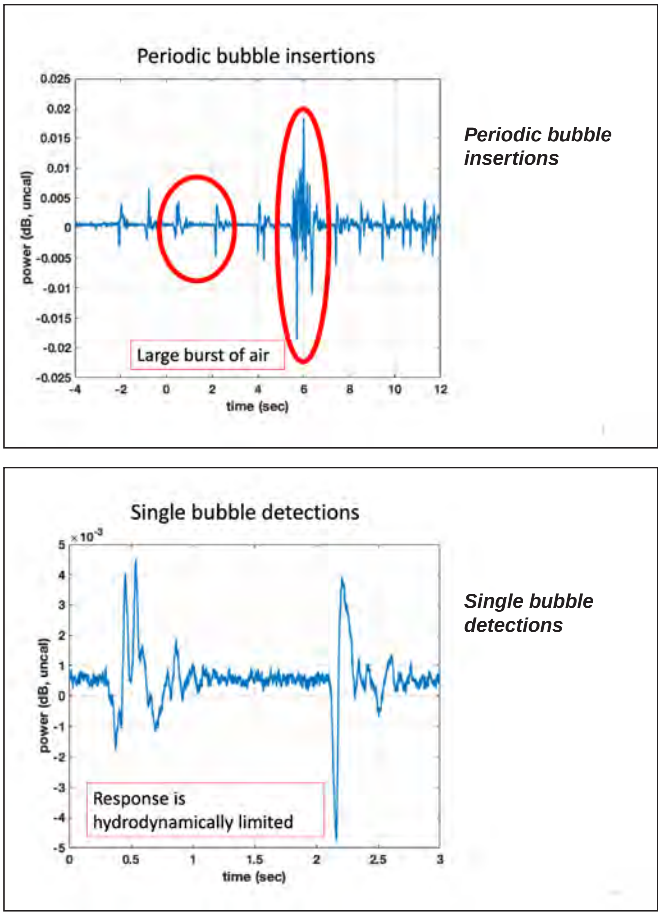

Figure 5. Typical data showing bubbles flowing past the sensor.

Summary

This project is developing an improved void detection and characterization sensor. The effort is a critical part of fuel technology optimization for light water reactors. The benefits include improved fuel safety, fuel burnup, and accident tolerance. Understanding void formation will help develop new, safer nuclear reactor fuel.

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