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Experimental Design for Evaluating Selected Nondestructive Measurement Technologies

Advanced Reactor Technology Milestone: M3AT-16PN2301043

July 2016

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U.S. DEPARTMENT OF ENERGY

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Abstract

The harsh environments in advanced reactors (AdvRx) increase the possibility of degradation of safety-critical passive components and therefore pose a particular challenge for deployment and extended operation of these concepts. Nondestructive evaluation technologies are an essential element for obtaining information on passive component condition in AdvRx, with the development of sensor technologies for nondestructively inspecting AdvRx passive components identified as a key need. Given the challenges posed by AdvRx environments and the potential needs for reducing the burden posed by periodic in-service inspection of hard-to-access and hard-to-replace components, a viable solution may be provided by online condition monitoring of components. This report identifies the key challenges that will need to be overcome for sensor development in this context and documents an experimental plan for sensor development, test, and evaluation. The focus of initial research and development is on sodium fast reactors with the eventual goal of the research being developing the necessary sensor technology, quantifying sensor survivability and long-term measurement reliability for nondestructively inspecting critical components. Materials for sensor development that are likely to withstand the harsh environments are described, along with a status on the fabrication of reference specimens, and the planned approach for design and evaluation of the sensor and measurement technology.

Executive Summary

Passive components in advanced reactors (AdvRx), especially those within the primary and intermediate loops, are exposed to high temperatures (in excess of 500°C), fast spectrum neutron radiation (in fast reactors), and potentially corrosive coolant chemistry. These environments increase the possibility of degradation of safety-critical components and therefore pose a particular challenge for deployment and extended operation of these concepts. Nondestructive evaluation (NDE) technologies are an essential element for obtaining information on passive component condition in AdvRx, with the development of sensor technologies for nondestructively inspecting AdvRx passive components identified as a key need.

In general, condition assessment of passive components will be required for in-vessel components as well as components outside the reactor vessel. In regions where the sensor is not in contact with the coolant, and possibly not at elevated temperatures (such as in parts of the secondary power conversion systems), conventional NDE technology applied periodically (e.g., during refueling outages) may suffice, particularly if materials and structural research indicates that any cracking in these locations is unlikely to see rapid growth between inspections.

Given the challenges posed by AdvRx environments and the potential needs for reducing the burden posed by periodic in-service inspection of hard-to-access and hard-to-replace components, a viable solution may be provided by online condition monitoring (CM) of components. CM also provides opportunities for detecting materials degradation early in the degradation growth lifecycle. Online CM based on NDE technologies are of most value in scenarios where the component is in-vessel and/or in hard-to access areas. Given the potential for long-term sensor exposure to elevated temperatures in these scenarios, online CM will require the development of sensors that are capable of tolerating the environmental conditions imposed by AdvRx.

This report identifies the key challenges that will need to be overcome for sensor development in this context and documents an experimental plan for sensor development, test, and evaluation with the eventual goal of quantifying sensor survivability and long-term measurement reliability for nondestructively inspecting critical components. The focus of the initial research is on online monitoring sensor technology for nondestructive evaluation of components in sodium fast reactors.

A number of NDE methods exist that may be adapted to online monitoring, including ultrasonic measurements (linear and nonlinear ultrasonics, applied using guided wave methodologies), acoustic emission (AE) monitoring that passively listens for initiation and growth of cracking, magnetic Barkhausen noise measurements that are sensitive to magnetic changes in ferromagnetic materials, and eddy current measurements that are sensitive to electrical conductivity and magnetic permeability changes caused by materials degradation (including cracking). Of these, ultrasonic wave-based methods (including AE) enable wide area monitoring while magnetic and eddy current methods enable localized measurements, generally at high-risk locations.

A number of other NDE technologies are available (such as visual examinations and radiography). However, these are usually not applicable for online monitoring of components and may require draining the coolant or other actions to provide access to the component under test. As a result, though these techniques are useful for periodic in-service inspections, they are not considered for this stage of the research.

The research activities follow a phased approach, with the first step comprising identification of sensor materials that can survive in-vessel. Given the likely requirement to minimize the number of sensors in-vessel and the consequent requirement for monitoring of larger regions by a single sensor in-vessel, this

step is restricted to the identification of sensor materials that enable ultrasonic/AE monitoring. A limited set of piezoelectric materials are useful under conditions likely in operating sodium-cooled fast reactors, and include aluminum nitride, bismuth titanate, lithium tetraborate, and lithium niobate. Samples of these materials have been obtained and are being used, in combination with a robust sensor design that leverages prior work, for fabricating in-situ online monitoring sensors. Simulation models of ultrasonic wave propagation were developed for use in sensor design and measurement data interpretation, particularly for measurements from in-situ online monitoring.

Several specimens were also fabricated for use in bench-top, room-temperature experiments. These experiments are focused on obtaining baseline data on sensor performance in mild environmental conditions (i.e., at room temperature). Measurements being acquired from these specimens include ultrasonic and eddy current data on cracking of various dimensions. These measurements also provide an opportunity to fine-tune sensor designs for increasing signal-to-noise ratios. Similar data on sensors operating in elevated temperature and liquid sodium will help quantify the degradation of measurement capabilities due to sensor aging.

A number of additional specimens with known flaws (length, through-thickness depth) are also being fabricated for generating empirical data on sensor sensitivity to relevant flaw parameters. The data will be used, along with the simulation models, to quantify NDE measurement reliability when performing in-situ, online monitoring and to optimize sensor design for increasing reliability. Specifically, the simulation capabilities will be applied, along with the empirical data, to extract information on probability of detection and false call rates. Results of these studies will be documented in future reports in this series.

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Acronyms and Abbreviations

AdvRx	advanced reactor(s)
AdvSMR	advanced small modular reactor
AE	acoustic emission
ART	Advanced Rector Technologies
ASME	American Society of Mechanical Engineers
CDF	core damage frequency
CM	condition monitoring
ASME Code	ASME Boiler and Pressure Vessel Code
EMAT	electromagnetic acoustic transducer
HTGR	high-temperature gas reactor(s)
HTR	high-temperature reactor(s)
I&C	instrumentation and control
ISI	in-service inspection
IHX	intermediate heat exchanger
LWR	light-water-cooled reactor
MBN	magnetic Barkhausen noise
NDE	nondestructive evaluation/examination
NLU	nonlinear ultrasonics
O&M	operations and maintenance
PHM	prognostic health management
SCC	stress corrosion cracking
SFR	sodium-cooled fast reactor
SSC	systems, structures, and components
STAAR	Sensor Technology Assessment for Advanced Reactors (project)
USV	under-sodium viewing
VHTR	very-high-temperature gas reactor

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1.0 Introduction

A key characteristic of advanced reactor (AdvRx) concepts, which include sodium-cooled fast reactors (SFRs) and high-temperature gas reactors (HTGR) (Abram and Ion 2008), are the harsh environments within the primary and intermediate loops, and include high temperatures (in excess of 500°C), potential for fast spectrum neutrons, and corrosive coolant chemistry. These environments in proposed AdvRx concepts increase the possibility of degradation of safety-critical components and therefore pose a particular challenge for deployment and extended operation of these concepts. The relatively lower level of operational experience with AdvRx concepts (when compared with light-water-cooled reactors [LWR]), and the consequent limited knowledge of physics-of-failure mechanisms of materials and components in AdvRx environments, when combined with the potential for increased degradation rates, point to the need for enhanced situational awareness with respect to critical passive systems. Information on component condition and failure probability is considered critical to maintaining adequate safety margins and avoiding unplanned shutdowns, both of which have regulatory and economic consequences.

Nondestructive evaluation (NDE) technologies are an essential element for obtaining information on passive component condition in AdvRx, with the development of sensor technologies for nondestructively inspecting AdvRx passive components identified as a key need. This report identifies the key challenges that will need to be overcome for sensor development in this context and documents an experimental plan for sensor development, test, and evaluation with the eventual goal of quantifying sensor survivability and long-term measurement reliability for nondestructively inspecting critical components.

1.1 Research Objectives

This project involves development of sensor technologies for diagnostics and physics-based prognostics to facilitate detection of materials degradation in generally inaccessible AdvRx components in harsh environments (high temperatures, high fluence, and potentially corrosive coolant chemistry). This research supports the AdvRx goals for improved safety through asset protection and lifetime degradation management, improved economics through optimized operations and maintenance (O&M) activities, and extended operating cycles and reactor life. The focus of the activities described in this report is to support inspection and monitoring of SFR passive components, with the goal being to adapt the technology for high-temperature reactor (HTR) components at a later date.

The objective of the research is reliable detection of early stages of degradation in inaccessible AdvRx passive component and reactor internals materials, with the measurement technologies providing prognostic indicators of damage that, if necessary, support assessment of the residual life of these components. In developing the methods, issues specific to AdvRx will need to be addressed, such as monitoring in-pool or in-vessel components to reduce the requirement for in-service inspection (ISI) during infrequent refueling/maintenance outages, detection of cracking from relevant degradation phenomena in materials being considered for AdvRx, measurement challenges associated with extreme environments, and supporting extended operation of critical components during longer intervals between refueling.

The overall research objectives are to:

- Identify in-situ measurement technologies that support early detection of degradation modes of interest to advanced reactors
- Develop sensors that enable in-situ, online monitoring for passive component degradation detection in hard-to-replace components in AdvRx

- Design and conduct experiments that enable quantitative assessment of sensitivity and reliability of selected in-situ NDE measurement technologies applied to selected AdvRx passive component degradation modes, especially in hard-to-replace components
- Assess selected in-situ nondestructive measurements for their ability to provide prognostic indicators for these degradation modes, and optimize sensor design and measurement methodology to maximize detection capability.

Previous research in this project focused on the analytic tools necessary to provide high-confidence predictive assessments of remaining life of passive components, given NDE measurements of component condition. The context for this work was the reduction of O&M costs in advanced small modular reactors (AdvSMRs), and the need to tie in predictive assessments of component condition to plant control technologies. Given the potential need to provide prognostic health management (PHM) for several systems within the hierarchy of an AdvRx design (Meyer et al. 2013a; Meyer et al. 2013c), a hierarchy of PHM systems was proposed (Meyer et al. 2013b), with information at one or more levels of this hierarchy being supplied to a supervisory plant control system for optimizing plant operations with respect to O&M requirements. This hierarchy corresponds to PHM systems operating on localized measurements, PHM systems operating on component-wide measurements, and global PHM systems that integrate diagnostics and prognostics information across multiple components.

Previous research performed a gaps assessment, and focused on the development of a framework for prognostic health monitoring PHM at the localized scale. Meyer et al. (2013a) discussed a number of technical gaps that limit the applicability of current PHM systems in AdvRx. The major limiting factors identified were: 1) advanced sensor technology for operating under harsh environments; 2) accurate models for material degradation accumulation and subsequent progression; 3) prognostics under different sources of uncertainty such as measurements noise, temperature variations, fluctuations in pressure and loading profiles, and model uncertainties; 4) sensor data fusion; and 5) verification and validation of the PHM systems. A number of technical requirements for PHM systems in AdvRx were identified based on these gaps, and technologies were developed to address several of these requirements. These technologies are documented in several previous reports in this series (Meyer et al. 2013a; Meyer et al. 2013c; Ramuhalli et al. 2014b; Ramuhalli et al. 2015).

Activities described in this report focus on addressing several of the challenges implicit in the first of the major limiting factors identified above—advanced sensor technology for material degradation detection in harsh environments. Specifically, the focus is on experimental measurements of prognostic indicators for AdvRx candidate materials and components. Initially, the research focus is on defining in-situ measurement requirements and developing the technical bases for transitioning bench-scale in-situ NDE measurements to field-deployment within the context of sodium fast reactors. Ex-situ measurements are used as necessary for preliminary evaluation and supporting the selection of measurement technologies, appropriate sensors, and preliminary quantification of sensor sensitivity and reliability.

The research described in this report, as well as in the previous reports in this series, provides some of the essential instrumentation and control (I&C) technologies that are vital to safe, cost-effective operation of nuclear power plants. The research, development, and demonstration described in this report (and related reports) resolves gaps in technology capabilities, and enables these advanced technologies to be matured to the appropriate readiness level in a timely manner while ensuring the associated capabilities can be incorporated into reactor designs at an appropriate early stage.

1.2 Organization of Report

This technical report is organized as follows. Section 2 includes background information on AdvRx and briefly summarizes previous research in this project and the research assumptions being made in this research. Section 3 describes the experimental design for evaluation of select nondestructive measurement techniques. Section 4 summarizes the status of research to date and briefly outlines ongoing research as well as the next steps in the execution of the experimental plan.

2.0 Background

This section briefly describes background information on AdvRx, summarizes previous research in this project, and provides the research assumptions being made in this research. We begin by briefly describing recent findings from a project focused on sensors technology assessment for advanced reactors within the Advanced Reactors Technology (ART) program.

2.1 Sensors Technology Assessment for Advanced Reactors

During FY2016 there was an assessment of sensor technologies and a determination of measurement needs for AdvRx under the "Sensor Technology Assessment for Advanced Reactors" or STAAR project. This assessment, jointly conducted by Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, and Pacific Northwest National Laboratory, was conducted to provide the technical basis for identifying and prioritizing research targets within the I&C Technology Area within the ART program and contribute to the design and implementation of AdvRx concepts. Figure 2.1 shows the high-level relationship between the findings from STAAR to date (unpublished as of the publication date of this present document, but expected to be published within the next month) and the broader program, with the information obtained from this study, along with other studies under the ART program, expected to be a key part of the technical development effort needed to successfully license an AdvRx nuclear power plant.

Highlighted within this study was the importance of I&C technologies, such as measurement and monitoring capabilities, which provide information on plant processes, support operations, and provide indications of component health. This included factors that influence measurement requirements, limitations of past measurement techniques, and the state-of-the-art of sensor technologies and technology gaps for high-temperature gas and sodium-cooled fast reactors.

Key research needs that are being identified include sensor technologies for reliable process measurements (flow, temperature, pressure, power) in SFRs and HTRs, sensor technologies for reliable plant CM (for conditions such as loose parts monitoring, coolant contamination, etc.), and sensor technologies for nondestructive plant component inspection.

The research described in this report addresses this last need.

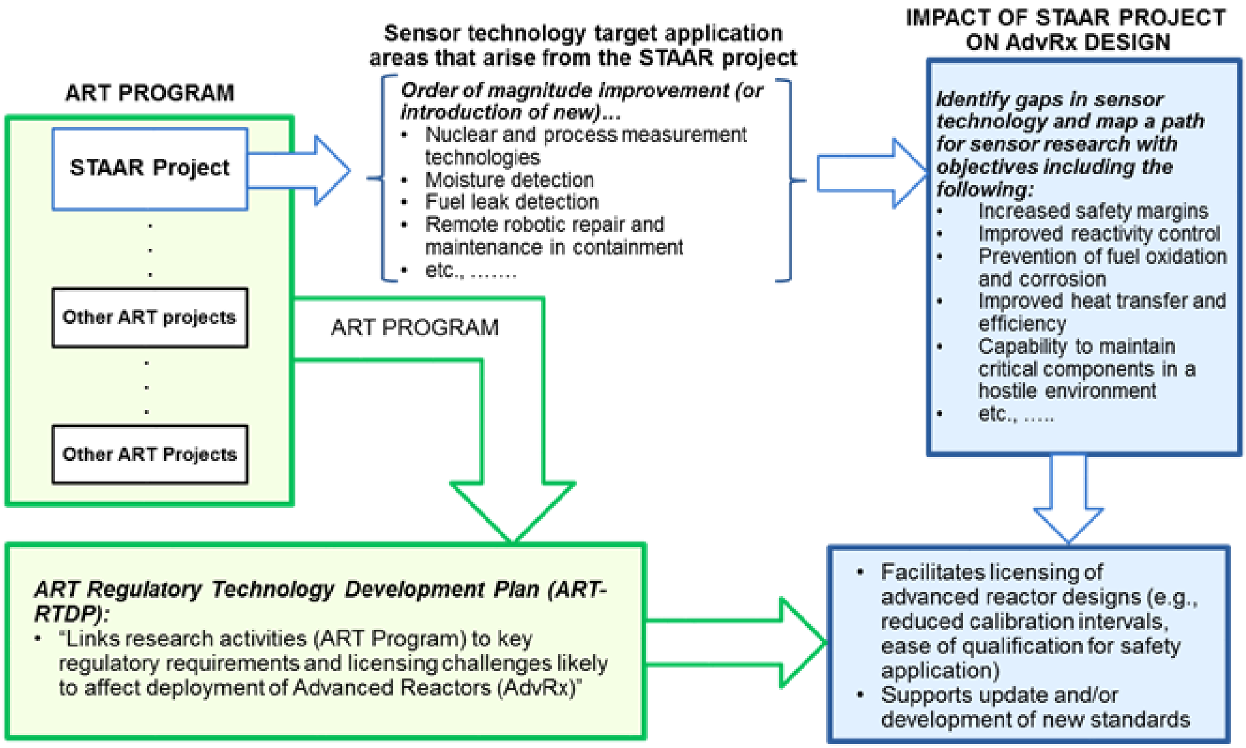

Figure 2.1. Relationships between STAAR Findings and the ART Regulatory Technology Development Plan[a]

2.2 Overview and Operational Characteristics for Advanced Reactors

Advanced reactors generally encompass all non–LWR concepts, and are being considered as a longer-term option for meeting electrical generation and process heat needs in the United States (Abram and Ion 2008). Among the concepts being considered are SFRs and HTFRs, both of which have some operational history in the United States and elsewhere. A detailed description of these concepts is available in previous reports in this series (Meyer et al. 2013a). Additional details of AdvRx concepts as they apply to advanced small modular reactors (AdvSMRs) and likely O&M approaches are provided in the previous reports in this series associated with AdvSMR prognostics and enhanced risk monitor research (Coble et al. 2013; Meyer et al. 2013a; Ramuhalli et al. 2013; Ramuhalli et al. 2014a).

Degradation and failure of materials that make up passive components in AdvRx are likely to be key factors impacting safety and economics of AdvRx. The challenges associated with materials operating under conditions likely to be encountered in SFRs and VHTRs (very-high-temperature gas reactors) (Meyer et al. 2013a) include degradation mechanisms not encountered in LWRs, and potentially unexpected materials performance under the expected complex loading conditions in advanced reactors. The limited knowledge of physics-of-failure mechanisms of materials used in structural components in AdvRx environments (high temperatures, fast neutron fluxes, potentially corrosive chemistry due to the coolant), and longer exposure times due to extended periods between maintenance and refueling outages are likely to challenge available inspection and maintenance technologies.

[a] An ORNL STAAR draft document.

Material damage accumulation in structural components of AdvRx can be monitored by employing a combination of several NDE techniques (Bond et al. 2008) such as eddy current inspection, ultrasound, acoustic emission (AE), magnetic Barkhausen noise (MBN) measurements, etc., with the selection of specific techniques dependent on the material, degradation mechanism, location within the reactor system, availability of mitigation and repair approaches, and required frequency of inspection relative to plant refueling frequency. Meyer et al. (2013a) discussed a number of technical gaps that limit the applicability of current inspection and predictive maintenance approaches in advanced reactors. Among the major limiting factors identified were:

- Advanced sensor technology for operating under harsh environments
- Accurate models for material degradation accumulation and subsequent progression
- Predictive maintenance under different sources of uncertainty such as measurements noise, temperature variations, fluctuations in pressure and loading profiles, and model uncertainties
- Sensor data fusion to assess material degradation state.

2.2.1 Prototypic AdvRx Materials

Given that the operating environment in AdvRx and design concepts (such as integral intermediate heat exchangers [IHX]) differ from those in LWRs, the materials of construction of these critical components are expected to differ as well. Structural materials being considered for use in these concepts will need to meet performance requirements over the design lifetimes for components in different regions (pressure boundary, internals, etc.). Various structural materials are being actively researched with the ART program and in other research programs, and include alloys such as modified 9Cr-1Mo, Alloy 709, and Alloy 617. These materials are in addition to austenitic stainless steels (grades 304 and 316), and are qualified for elevated temperature operation (ASME 2015), and graphite and ceramic composite materials for some of the internals and core support structures (Corwin 2016). However, a number of research questions remain as these materials are considered for higher temperature applications.

Degradation mechanisms that are of concern in these materials include aging and environmental issues such as irradiation and corrosion damage, creep and fatigue, and issues associated with weldments. These are areas of active research as well as work to update the relevant codes and standards.

2.2.2 Prototypical AdvRx Passive Components

From the perspective of NDE of SFR AdvRx passive components, a number of critical safety-related components may be identified. These include the reactor and containment vessel, the IHX, direct reactor auxiliary cooling system, and the reactor closure/stationary deck in addition to the primary electromagnetic (EM) pump. Figure 2.2 shows a summary of ISI and condition monitoring (CM) requirements for major components, as specified in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (ASME Code) Section XI, Division 3 (2003) (Chang et al. 2005).

Major Components	ISI		Maintenance		
	Scheduled Inspection	Access	Preventive	Corrective	Access
Control Rod System					
- Control Rod Drive Mechanism	Not Required	N/A	TBD	Replace part	Port [6]
- Control Rod Drive Line	Not Required	N/A	TBD	Replace	Port [6]
Reactor Internals					
Integrally Welded Structures -Core Support Structure -Core Barrel -Passive Core Restraint -Coolant Flow Ducts & Plenum -Thermal Barrier (Redan)	Visual (VTM3) [1]	Ports[3]	Not planned	Not planned	N/A
Internals attached by other than welding	Visual (VTM3) [1]				
Reactor Support - Support Skirt Welds & Bolts	Visual (VTM3) [2]	Ports & Pit [4]	NA	NA	
Reactor & Containment Vessel	Visual (VTM2) [2] CM	7" gap, Ports[5]	NA	NA	NA
Primary EM Pump	CM	N/A	TBD yrs	Replace	Port [6]
IHX	CM	N/A	Not planned	Replace	Port [6]
DRACS	CM	N/A	Not planned	Replace	Port [6]
Reactor Closure - Stationary Deck	CM,Visual(VTM3)		NA	NA	

(1) Primarily dimensional gauging and under-sodium scanning. Maybe supplemented with readily available information from continuous monitoring.
(2) Conducted using a remote operated vehicle with camera and light
(3) Access port in the reactor enclosure head for in-vessel inspection machine access.
(4) Inspection pit around the reactor support skirt
(5) Access port in the upper outer skirt of reactor containment vessel
(6) Plant design shall include provision to permit access for removal of large components. Provisions include ports in the reactor enclosure shield deck hatch and containment, and an extension to the roof to accommodate the handling and removal of large components.

Figure 2.2. Summary of ISI and Maintenance Requirements for Major Components in SFRs (from Chang et al. 2005)

Note that, as specified, basic NDE techniques (visual, for the most part) are proposed for these components. The technique typically requires draining the coolant from the vessel. Alternatively (and especially for gross structural deformation), under-sodium viewing technology may be applicable. However, condition monitoring (CM, in Figure 2.2) is a likely approach for many of these components. Though the basic CM approaches defined above generally relate to leak monitoring, alternative CM approaches based on NDE technologies can provide early warning of degradation prior to the appearance of a leak, giving increased time for maintenance or repair activities to be performed.

The development of NDE (and online CM based on NDE measurements—hereafter referred to as simply "condition monitoring") for these components is challenging due to the variation in materials and failure modes, and diversity in locations (welds, joints, bends/elbows, etc.). In-vessel monitoring brings additional challenges, with the need to deploy robust long-lasting sensors while limiting the number of sensors that can be deployed (both for cost purposes as well as to limit the number of penetrations for cabling).

In addition to these safety-related passive components, other components in SFRs (and potentially HTRs) may require the development of sensors and measurement methods for NDE. For components that are readily accessible and where the inspection process is not challenged with sensor immersion in the coolant, classically applied NDE methods are usually sufficient. Technologies for these methods are available commercially, are being applied to inspect nuclear components, and may require only minimal modifications for use in SFRs.

New technology (whether it be sensors, or methods that take advantage of novel phenomena) are likely to be necessary in cases where new component designs are planned. A specific example is the printed circuit heat exchanger that is being evaluated for use in Brayton cycle power conversion systems, with supercritical CO_2 (SCO_2) as the working fluid. The large number of small-diameter heat exchanger tubes, combined with the integrated fabrication methods used, make inspection of these tubes for delamination of layers and clogging of tubes due to the accumulation of corrosion or other impurities difficult.

2.3 Prognostic Health Management for Advanced Reactors

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

PHM technologies are expected to play a vital role in the deployment and safe, cost-effective operation of advanced reactors. Diagnostics and prognostics provide the technical means for enhancing affordability and safe operation of AdvRx over their lifetime by enabling lifetime management of significant passive components and reactor internals. In particular, when combined with condition information of passive components, these technologies can provide information on failure probability that is considered critical to maintaining adequate safety margins and avoiding unplanned outages, both of which have regulatory and economic consequences.

Under these conditions, PHM is a key enabling technology for providing dependable, high-fidelity assessments of component conditions and incipient failure detection in AdvRx SSC. Periodic ISI technologies already exist and are used in operating nuclear power plants to provide an assessment of passive component condition, including whether significant cracking exists that could compromise structural integrity. However, the applicability of existing technologies may be limited in AdvRx, because of their compact design, restricted access to key in-vessel and in-containment components, and extended periods between inspection and maintenance opportunities. PHM systems, with their emphasis on increased in-situ structural health monitoring and prognostics to assess remaining service life (also referred to as remaining useful life) provide a mechanism to address the limitations of current ISI approaches for use with AdvRx. PHM technologies provide improved awareness of system condition, and when integrated during design of the AdvRx, can provide the tools necessary for quantifying the operational envelope for safe economic O&M, and in coordination with supervisory control algorithms, enable these reactors to stay within the operational envelope while maintaining adequate safety margins.

Advanced reactors are expected to benefit by the use of PHM systems through:

- Providing early warning of potential degradation in inaccessible passive components leading to failure in AdvRx environments. Such early warning can inform operational planning and maintenance scheduling decisions during infrequent refueling outages.
- Reducing risks by providing enhanced situational awareness of plant equipment and component conditions and margins to failure, particularly in conditions where knowledge of physics of failure in the AdvRx environment is limited
- Enhanced affordability and safe operation during their lifetime by enabling lifetime management of significant passive components and reactor internals (especially for critical passive safety components) in harsh environments (high-temperature, fast flux, and corrosive coolant chemistry)
- Relieving the cost and labor burden of currently required periodic ISI during refueling outages, especially for components in hard-to-access areas such as those in-vessel/in-containment

- Supporting a science-based justification for extended plant lifetime by ensuring reliable component operation.

To predict failure, PHM systems require some type of input (data) about the state of the component(s) of interest. These inputs could be in the form of information on stressors to which the system or component is exposed, or information on the condition of a specific system or component. Consequently, measurements and diagnostics, in addition to prognostics, are key elements to a PHM system, and are the topic of this document.

2.4 Research Assumptions

As discussed previously, the research described in this report relates to the development of sensor technologies for NDE of critical passive components.

The following assumptions are being made in the experimental design and approach described in this report:

- The research focus will be on developing solutions that are applicable to the monitoring of inaccessible passive components key to the safe operation of AdvRx designs.
- The research will initially focus on passive components in SFR concepts.
- Background information about representative AdvRx designs, components, and concepts of operations for these designs is assumed to be available. Where applicable, the research team will collaborate with researchers from other technical areas within the ART program.
- The laboratory-scale test bed for degradation assessment of a prototypical AdvRx passive component will only simulate conditions and features necessary for proof-of-principle demonstration for target degradation mechanism and the associated in-situ measurement technology.
- Operational experience with materials degradation in previous AdvRx are assumed to be relevant for this research.

3.0 Experimental Design for Evaluation of Select Nondestructive Measurement Technologies

The ability to assess passive component integrity will be critical to ensuring the safety of AdvRx components. Detecting and characterizing degradation reasonably early in the lifecycle of passive components is potentially important for deploying timely maintenance and mitigation actions. The assessment of passive component integrity is typically performed through direct nondestructive measurements on the components using one or more NDE sensors, either during refueling/maintenance outages of the plant or through in-situ CM of the component.

In this section, we discuss initial requirements for NDE measurement technologies for use in AdvRx; provide an overview of various NDE methods that may be deployable in AdvRx for periodic ISI and in-situ monitoring; and describe an experimental plan for design, test, and evaluation of NDE technologies for AdvRx. The initial experimental design will focus on SFR environments (operating temperatures around 550°C or lower, with long-term immersion in sodium a possibility), with modifications to address HTR environments as the next major phase of research and development.

3.1 Initial Requirements for Nondestructive Measurement Technologies in AdvRx

Because opportunities to perform inspections and maintenance of passive components when the plant is off-line will be limited in many AdvRx concepts, there is a need to monitor risk-significant passive components during plant operation for degradation. In addition, there may be a need to monitor the stressors (time at temperature, fluence, mechanical loads, etc.) that contribute to degradation of these components. Requirements for NDE measurement sensors (whether for online or off-line condition assessment or for stressor monitoring) include:

- Ability to tolerate the harsh operating conditions in-vessel in AdvRx over extended periods of time. Anticipated conditions include high temperatures (> 550°C during operation), potentially corrosive coolants, and fast neutron spectra (in some designs). For ISI, when the reactor is not operational, the temperatures can vary depending on the reactor type, with the temperature in SFR in-vessel being around 250°C. Note that the actual conditions faced by the sensors will be a function of their specific location (in-vessel vs. ex-vessel), and whether the sensor location allows for the possibility of active cooling.
- High reliability, to ensure that detection of degradation occurs as early as possible in the degradation lifecycle in the presence of other factors that may influence the measurement. For cracking, this implies the ability to detect small cracks with a high confidence in the presence of factors such as material anisotropies and geometric variations in the specimen. Measurements that are sensitive to pre-crack forms of degradation may be useful as well, as they can potentially provide sufficient early warning of impending failure of the component.
- Capability to quantify the amount of degradation from the measurements. This requirement ensures the ability to accurately estimate the present state of damage in the material and/or component from the measurement. The ability to accurately quantify the amount of damage may require algorithms that can integrate information from multiple sources.

A number of factors will influence the ability to make reliable measurements in AdvRx environments. These include sensor effects (such as aging of the sensors and bonding issues between the sensor and the component), component issues (location of the flaw relative to the sensor, component geometry that may preclude ready access to the region of interest, and location of the component in the plant), and environmental issues (for instance, temperature and stress loads on the component affect the response of electromagnetic and ultrasonic sensors).

3.2 Measurements State-of-the-Art

(Meyer et al. 2013a) described a state of the art assessment of measurements that may provide information on passive component condition. According to Meyer et al. (2013a), “the health of a passive component or system may be inferred from measurements of the current extent of active degradation and degradation drivers.” NDE measurements are typically applied to estimate the current extent of active degradation (i.e., measurements of component condition) in these components. Degradation drivers are sometimes referred to as stressors, and typical measurements will include measurements of environmental or process variables in a nuclear plant. In some cases, environmental and process variables may change in response to degradation of a passive component (for instance, steam generator exit temperature and heat exchanger fouling (Coble et al. 2010; Hines et al. 2011)), and may be used to compute condition indicators for component degradation.

Meyer et al. (2013a) also distinguished component condition measurements as being global or local (Figure 3.1). Global measurements normally interrogate a significant portion of a component while local measurements interrogate smaller regions of the component in the immediate vicinity of a sensor. Global measurements are often collected during reactor operation (i.e., online), and generally are collected more frequently than local measurements. Local measurements, on the other hand, are typically obtained periodically, such as during plant outages. Local measurement approaches are often coupled with mechanical scanners or other deployment technologies (such as robotic deployment platforms) to provide detailed condition measurements over a larger portion of the component. Generally, local measurements are typically deployed for inspecting high-risk areas such as weld joints between components.

In general, a process measurement or global condition measurement is considered applicable to the entirety or a significant region of the component to which the sensor is mounted. Therefore, symbols for process measurements and global condition measurements in Figure 3.1 are only meant to associate measurements with a component and are not meant to accurately depict sensor placement. In practice, an assessment may be performed to prioritize sensor placement to ensure maximum coverage while minimizing the possibility of surprise failures.

A detailed assessment of advances in process monitoring, global and local condition measurements, and harsh-environment measurements was provided in Meyer et al. (2013a). Below, we describe an overview of NDE methods that are widely used in nuclear power plant ISI, and advances in NDE that are likely to be of relevance to the problems of ISI and in-situ online CM in AdvRx.

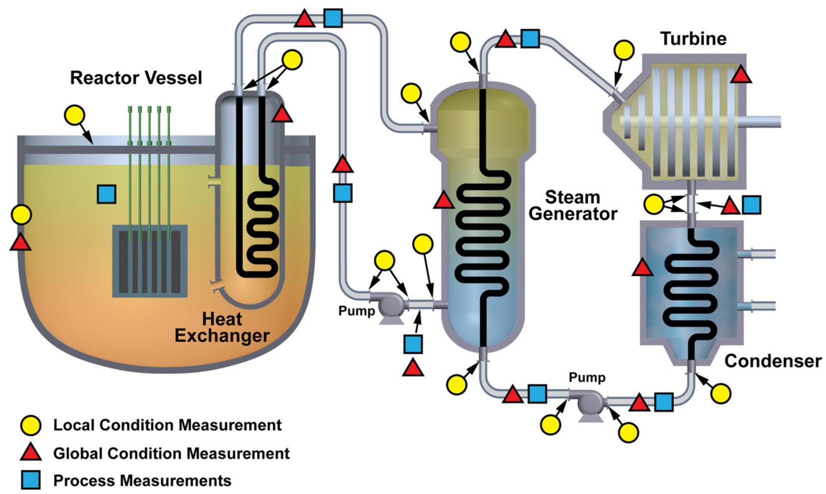

Figure 3.1. Notional Illustration of Candidate Sensor Locations in AdvRx for Performing Local Condition, Global Condition, and Process Measurements (Meyer et al. 2013a)

3.3 Nondestructive Measurement Techniques

Standard NDE technologies exist to detect gross deformation (cracking and material loss) in materials; for example, ultrasonic, eddy current, and visual techniques. Ultrasonic techniques are typically applied to the detection and sizing of flaws in components requiring a volumetric examination, such as pressure boundary components. Visual techniques are applied to examine many core internal components. Eddy current techniques are employed for the inspection of steam generator tubes. These technologies are used routinely during refueling outages for inspections. The performance of several of these techniques is summarized in Bond et al. (2008) in terms of ultimate detection limits and in terms of statistical performance metrics that provide an indication of probable detection limits. Studies (Bond 1988) indicate sub-millimeter performance for detectability of surface-breaking cracks under well-controlled laboratory conditions and a performance limit of several millimeters for surface-breaking cracks under field conditions.

Current ISI practices for LWRs are based on requirements in the ASME Code, which were originally developed in the 1960s. ASME Code requirements for ISI were initially developed for the management of fatigue degradation (Doctor 2008), and in recent years, have been expanded to address diverse and challenging degradation mechanisms in nuclear power plants, such as stress corrosion cracking (SCC).

AdvRx, with their higher operating temperatures and corrosive coolant chemistry, can be expected to experience mechanisms not commonly seen in LWRs (O'Donnell et al. 2008). In recent years, there has been activity around updating portions of the ASME Code relevant to liquid metal reactors and high-temperature reactors, with a focus on materials and degradation mechanisms. For SFR in particular, degradation of concern includes crack initiation and propagation through mechanisms such as thermal and vibration fatigue and high-temperature degradation (such as creep and creep-fatigue). Mitigation of such degradation mechanisms will require the ability to detect crack initiation and propagation sufficiently early in the process to ensure that appropriate actions can be taken before significant degradation accumulates to the point where the only possible mitigating action is to replace the component.

It is likely that traditional ISI methods are capable of detecting and characterizing cracking in SFR. These methods include volumetric (ultrasonic NDE) and surface (eddy current and visual) examination methods. However, challenges exist in translating these methods to SFRs. Specifically,

- Visual techniques have limited applicability in liquid metal coolants, which are optically opaque.
- Many of the components of concern (such as the IHX and primary pump tanks) may not be readily accessible, being submerged in liquid coolant. ISI will require draining the coolant to provide access, or require high-temperature-tolerant sensors that can locate the component and perform the inspection under sodium. Under-sodium viewing (USV) probes may enable accurate visualization under sodium but may not be capable of inspecting for cracking that initiates on surfaces where the probe does not have direct access.
- The electrical conductivity of liquid metal may limit the ability to perform certain types of measurements (such as eddy current inspections) under sodium.

To address these issues and to provide alternatives to the currently proposed approach for examination (essentially continuous monitoring outside the vessel using leak detectors), it is likely that a combination of online, in-situ monitoring with periodic off-line measurements of component or material condition will be needed (Meyer et al. 2013a). The intent of real-time monitoring of materials degradation is to provide early warning of crack initiation and monitor crack growth, with additional ISI techniques brought to bear as needed for increasing the confidence in characterization. By detecting the presence of cracking mechanisms early in the process, better insights are gained about the state of the material that can be used to understand the precise margins to failure. A brief state-of-the-art assessment for real-time monitoring of early degradation in materials used in the production of nuclear power is covered in McCloy et al. (2013).

Several NDE technologies have emerged as potential candidates to meet the requirements for early detection of cracking and other materials degradation. These include ultrasonic birefringence, ultrasonic velocity and attenuation, ultrasonic backscatter, acousto-ultrasonics, nonlinear ultrasonics, MBN, magnetic AE, and magnetic loop measurements (coercivity, remanence, and permeability).

Raj et al. (2003) discuss the response of several techniques, including micromagnetic and ultrasonic techniques, to several basic microstructural changes such as grain growth, reorientation, and the precipitation of second phases, that occur as a result of different degradation mechanisms. Dobmann (2006) have investigated micromagnetic techniques for characterizing aging in nuclear power materials caused by thermal embrittlement, neutron radiation, and fatigue. These techniques are sensitive to the creation of conductive or magnetic regions caused by precipitation or phase transformations. The sensitivity of many of the techniques to microstructural changes as a consequence of degradation has been verified in well-controlled laboratory investigations, although the sensitivity is impacted by a number of factors such as surface-roughness, second-phase microstructures and precipitates, and the presence of other degradation mechanisms.

Further work is required to characterize the performance of these techniques under applicable field conditions. In general, the expectation is that techniques based on ultrasound would be deployed in-vessel or under sodium while magnetic, electromagnetic, and visual methods would be deployed outside the vessel at key locations (weld and base metal) that are considered to be at high risk of failure.

However, the use of sensors for online CM in harsh environments is likely to result in a gradual change in the sensor response and sensitivity because of aging and degradation especially in regions of high temperatures and irradiation (neutron and gamma) according to Daw et al. (2012). While recent advances (Coble et al. 2012) may be used to monitor and compensate for sensor drift, improved sensor materials and sensor designs may be needed to maintain the ability to monitor the materials/components over the long term.

The following sections briefly describe methods that are being considered for the initial phase of sensor development and evaluation for use in monitoring and inspecting AdvRx, specifically SFR, passive components.

3.3.1 Magnetic Barkhausen Noise

The magnetic Barkhausen effect is a result of the magnetic hysteresis of ferromagnetic materials (Jiles 2000; Stupakov et al. 2008). The magnetic flux density (B) in ferromagnetic materials placed in an external applied magnetic field is a function of the applied magnetic field *(H)* and the magnetic permeability (μ): $B = \mu H$, with larger numbers of magnetic domains within the material aligning with the applied field direction as the field strength increases. This realignment is, however, not a continuous process, because the presence of dislocations or other damage precursors results in domain wall pinning. Increasing the applied field strength results in abrupt realignment of some domains, and is accompanied by a release of energy that may be detected using a sensing coil (Figure 3.2). Studies indicate that the magnetic Barkhausen effect in many materials is primarily from the motion of 180° domains, and its interactions with dislocation tangles (Krause et al. 1994; Ranjan et al. 1987a). The number of Barkhausen counts is given by Ranjan et al. (1987b).

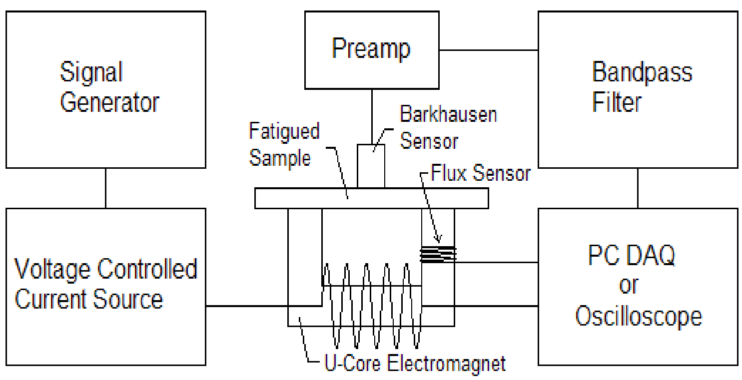

Figure 3.2. Schematic of Magnetic Barkhausen Noise Measurement System

In general, two Barkhausen bursts are present—one for positive magnetization and the other for negative magnetization. Numerous models have been developed to predict Barkhausen response to microstructural defects in steels such as grain boundaries and second-phase precipitates (Kameda and Ranjan 1987; Moorthy et al. 1997; Perez-Benitez et al. 2005).

Like all electromagnetic methods, the magnetic Barkhausen method is predominantly a near-surface measurement, with the standard depth of penetration (the distance into the material where the induced current density decreases to 37% of its value at the surface) decreasing with increasing frequency (ASNT 2004). For non-ferritic steel (such as 304 or 316L), the skin depth at 1 kHz is about 13.1 mm.

In many stainless steels, the effect of increasing damage is an increase in dislocation density and/or a change in phase (from austenitic to ferritic). These phenomena combine to impact the Barkhausen noise measurement from steels subjected to aging and degradation. However, the correlation between the measured parameters and the amount of damage is not linear, and is a function of several other variables (such as hardness). The Barkhausen noise measurement method has been applied to determine residual stresses in ferritic steels, the amount of hardening or cold work, and other forms of mechanical damage in materials (Gorkunov et al. 2000; Hakan Gur and Cam 2007; Parakka et al. 1997; Sagar et al. 2005; Sullivan et al. 2004).

Sposito et al. (2010) summarize the results of several efforts to correlate the Barkhausen emission with level of creep damage in ferritic steels. The studies did indicate sensitivity to creep damage through changes in the amplitude of the peak in the Barkhausen emission signal and the value of the magnetic field at which this peak occurs. The Barkhausen response was attributed to several material phenomena such as the formation of precipitates and cavities, the coarsening of precipitates, and grains in the material. It is noted that the formation of oxides on the surface of the material can impact the magnetic Barkhausen response.

In spite of the documented sensitivity of this technique to many forms of degradation, there are multiple sources of uncertainty that impact the interpretation of the resulting measurement. Some of these sources of uncertainty include:

- Location of the measurement relative to the location and orientation of the external stressors.
- Orientation of tensile strain direction, relative to the applied external field direction and the magnetic easy axis (Krause et al. 1995).
- Specimen fabrication variability and residual stress in the specimen (Krause et al. 1995; Lindgren and Lepistö 2001).
- Number, location, and orientation of magnetic domains. In two-phase steels, the volume fraction and distribution of the ferromagnetic phase will affect the measurement (Csikor et al. 2007).
- Probe coupling and tilt relative to the surface of the specimen. Changes in surface condition with degradation can result in improper probe contact with the specimen and lower the overall measurement.

All of these sources are likely to affect the measurement from ferromagnetic materials being considered in AdvRx in general and SFR in particular.

3.3.2 Ultrasonic Measurements

Acoustic wave propagation in solids is a function of the mechanical properties of the solid (such as density) and is affected by the macro and microstructure. Details of wave propagation in solids, and the impacts of microstructural changes on the measured parameters, are given elsewhere (for instance, Doctor et al. 1989; Ensminger and Bond 2011; Goebbels 1994; Krautkrämer and Krautkrämer 1990; Raj et al. 2000). Traditionally, changes in bulk or guided wave ultrasonic velocity and attenuation have been correlated with microstructural changes from various forms of degradation. Material discontinuities such as cracks provide high acoustic impedance contrast and a change in the measured signal amplitude; as a result, this is a commonly used approach for in-service inspection for cracking in operating LWRs. Techniques included in ultrasonic inspection employ:

- Bulk measurements (Cantrell and Yost 2001)
- Rayleigh wave measurements (Shui et al. 2008)
- Guided wave measurements (Bermes et al. 2008).

Nonlinear ultrasonics (NLU) techniques are significantly more sensitive to early stages of material damage than conventional linear ultrasonic measurements (Nagy 1998). Conventional ultrasonic methods apply high-frequency (in excess of 500 kHz, typically between 2.25 MHz and 10 MHz) energy and measure the resulting response from scattering and reflection of the energy at interfaces such as crack faces or grain boundaries. The presence of cracking is detected by means of a reflection from the crack surface, or diffraction from crack tips. Other forms of damage (such as creep damage) may be detected by making use of velocity and attenuation measurements through one or more measurement configurations. However, such measurements are not as sensitive to earlier stages of damage. NLU methods rely on the generation of harmonics from a monochromatic input. The generation of harmonics is from nonlinearities in the elastic constants associated with the material (Zarembo and Krasil'nikov 1971). The second harmonic is of particular interest, and the resulting nonlinear material parameter is represented by β (Kyung-Young 2000).

A schematic of a typical single-sided measurement setup for linear and nonlinear acoustics measurements is shown in Figure 3.3. Alternative setups use a transmitting probe to transmit acoustic energy through the specimen and a receiving probe on the opposite side of the specimen (through-transmission mode), or rely on the generation of Rayleigh surface waves.

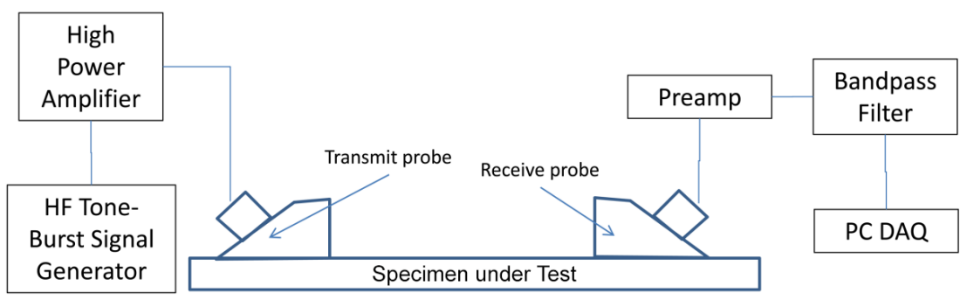

Figure 3.3. Schematic of Simple Pitch-Catch Ultrasonic Measurement System

NLU has been applied to the characterization of a range of damage mechanisms, including fatigue (Cantrell and Yost 2001; Kyung-Young 2000), irradiation embrittlement (Matlack et al. 2012b), SCC (Matlack et al. 2012a; Shintaku et al. 2010), and corrosion pitting (De et al. 2010). Sposito et al. (2010) indicate that the nonlinear parameter exhibits greater sensitivity to creep damage accumulation than ultrasonic velocity measurements.

AE is a related passive monitoring technique. Crack detection and monitoring has been one of the main applications considered for AE monitoring in the nuclear power industry. However, the noise generated by reactor coolant loops and the attenuation of AE signals as they propagate through large structures limits this capability. Experiences applicable to continuous flaw monitoring in nuclear reactor structural components suggests that quantification of flaw size from AE signals in large complex structures can be difficult and that cracks must grow at a sufficient rate to be detected reliably (Bentley 1981; Jax and Ruthrof 1989; Runow 1985). A demonstration of AE for monitoring the growth of intergranular stress corrosion cracking flaws on a reactor pressure vessel nozzle-to-safe end dissimilar metal weld was performed at Limerick Unit 1 using waveguides (Hutton et al. 1993) after initial detection using other NDE methods. Some sensor degradation was observed during the two fuel cycles. Currently, AE is the only online monitoring technique sanctioned by the ASME Code for performing in-service monitoring of components important to safety.

3.3.3 Eddy Currents

Eddy currents are generated in a conducting material by the principle of electromagnetic induction. A coil of wire produces a varying magnetic field when an alternating current is applied to it. The magnetic field of the coil (the primary magnetic field) induces eddy currents in the conducting specimen, which creates a secondary magnetic field in opposition to the primary magnetic field. Because the coil and the conducting specimen are a magnetically coupled system, the electrical impedance of the coil is altered by the electrical properties of the conducting specimen and distance from the coil. The presence of discontinuities in the specimen alters the induced eddy current pattern, further changing the electrical impedance of the coil as measured by the eddy current instrument. Both electrical and magnetic characteristics of the test object are of importance (Libby 1971). Eddy current flow within the test object results in a skin effect, which is a concentration of the current toward the surfaces adjacent to the exciting test coils. The skin depth is a function of the frequency of the exciting field, and electrical conductivity and magnetic permeability of the test material (ASNT 2004), and also governs the measurement of MBN (Section 3.3.1).

Figure 3.4 provides a graphical representation of a typical eddy current examination. There are many variations to both coil configurations and coil geometry (ASNT 2004). Probe parameters that influence the depth of penetration of the eddy currents and the impedance of the coil include the wire and coil diameter, number of turns in the coil, and the type of core and shielding material.

Eddy current measurements have been used extensively in the nuclear power industry to examine components such as steam generator tubing and reactor internals for cracking, corrosion, and other forms of degradation. Because the measurement is a function of test specimen conductivity, eddy current measurements have been applied to also determine the electrical conductivity of specimens.

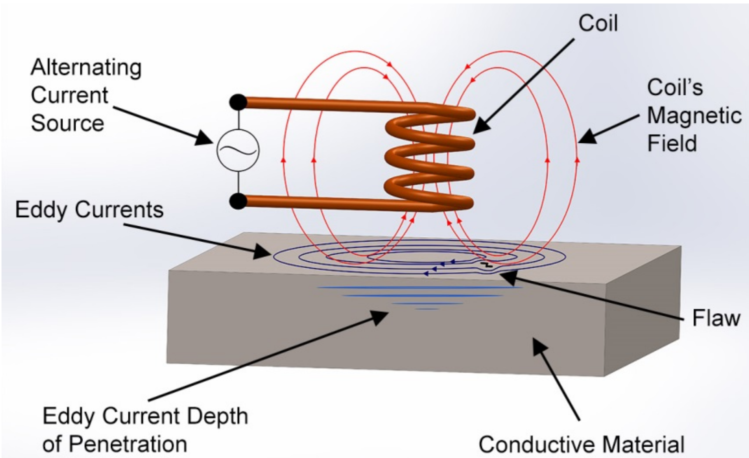

Figure 3.4. Graphical Representation of a Typical Eddy Current Examination

3.3.4 Other NDE Methods

A number of other NDE measurements are applicable to detect cracking (Raj et al. 2003). These include potential drop measurements, digital image correlation, x-ray diffraction, small-angle neutron scattering, acoustic birefringence, acoustic backscatter, etc. Each of these approaches is sensitive to different aspects of material microstructural changes, although the level of sensitivity varies by technique. Many of these methods are either unsuitable for online monitoring or require additional development for field deployment.

3.4 Experimental Plan

As discussed earlier, several NDE methods may be applicable to detecting degradation in AdvRx passive components. In general, such methods may be used to periodically inspect components, or used to continuously monitor them. Each of these brings its own challenges, and the experimental design described here attempts to address these in a phased manner.

3.4.1 Objectives and Design Goals

The objectives of the planned series of experiments are:

- Advanced reactor operational environment tolerant probe design and fabrication for reliable detection of cracking in hard-to-access and hard-to-replace components.
- Quantitative assessment of cracking detection and characterization reliability in representative environments.
- Assessment of detection capability for earlier stages of degradation (pre-crack and crack-initiation) in representative environments.
- Demonstration of NDE sensor technology in a suitable test facility.

The design goal for in-situ, online sensors is survivability in-sodium up to 600°C. Survivability in the context of this work is assumed to mean that functionality of the sensors (including a signal-to-noise ratio greater than 1) is maintained for an extended period of time, with one of the objectives of the experiments being to quantify the amount of time the sensor functionality can be maintained in relevant conditions.

3.4.2 Overview of Approach

The objectives listed above will be addressed using a phased approach, focused on sensor design and testing for NDE sensors capable of tolerating the operational environments in AdvRx. The initial focus will be on SFR environments (operating temperatures around 550°C or lower), with modifications to address HTR environments as the next major phase of research and development. While much of the issues being discussed apply equally to pool-type and loop-type SFR designs, the specific inspection requirements are expected to vary depending on whether the component being examined (such as the IHX) is in-vessel or outside the reactor vessel. Consequently, the base probe design may need to be adapted as the inspection requirements and locations are identified.

The experimental plan distinguishes between NDE sensors used for periodic inspections of in-vessel and ex-vessel components, and online monitoring of in-vessel and ex-vessel components. The requirements for these cases are quite different, in terms of operating temperature, inspection goals, and sensor characteristics.

Periodic ISI of in-vessel components is expected to require sensors that are capable of being deployed during refueling or other maintenance outages. In these instances, ISI of primary system components may be conducted either after draining the sodium coolant or by using ultrasonic inspection probes that are similar to those developed within the USV projects. The expectation is that ultrasonic inspection provides the best arrangement for cracking detection under these conditions, with the electrical conductivity of liquid sodium or sodium deposits on components (when the coolant is drained) interfering with other NDE methods (such as eddy current approaches). There is some evidence that eddy current-based techniques for IHX tubes may be feasible (although access challenges remain, especially with helical tubing), while steam generator tubing can be inspected using eddy current or other electromagnetic methods (Sasaka et al. 2015). However, this fundamental research needs to be further matured before it can be adapted for robust sensor development and reliability assessment. Within this work, adapting such research on eddy current NDE will be conducted during the next major phase.

For ex-vessel components and inspections conducted from outside the vessel during periodic outages, it is likely that currently used technologies (identified in the ASME Code) will be sufficient to reliably detect cracking. Technical gaps that will need to be addressed in this context include procedure development and the development of acceptance criteria; this is not addressed in this present work as this will rely on advances that are currently being made in the Materials technical area.

For both in-vessel and ex-vessel components, in-situ CM provides an attractive arrangement that enables monitoring and screening of large components. By identifying components with no significant degradation development, online CM helps limit the need for labor- and cost-intensive periodic ISI while helping maintain the necessary confidence in structural integrity. The focus of the research described below is on NDE sensors for online in-situ CM.

In general, in-vessel and a large proportion of ex-vessel monitoring may be conducted with ultrasonic probes. This is because of the ability to monitor large structures for degradation initiation and growth using both active (by applying ultrasonic energy to the component and measuring the response) and passive (used in a “listen-only” mode) methods. Passive methods (AE), in particular, have been shown to be sensitive to stress waves released by crack initiation and crack growth; however, the effects of acoustic noise (such as from coolant flow or pump vibration) may limit sensitivity. For this reason, the bulk of the experimental efforts are concentrated on ultrasonic probe design, testing, and performance evaluation for improving sensitivity and measurement reliability.

However, electromagnetic probes (such as eddy current probes) will have some applicability for online CM of specific (high-risk) locations on ex-vessel components (minimizing the effects of liquid metal coolants on the measurement). Examples include dissimilar welds near nozzles and welds in the reactor vessel, and for this reason, ongoing sensor survivability and reliability tests have been augmented with limited survivability and reliability tests of electromagnetic sensors.

The first step in the experimental approach is focused on sensor design and high-temperature survivability tests. These tests are focused on measuring changes (degradation) in signals measured from cracking in representative specimens as the sensors are aged at temperature. Signal degradation on bench-top specimens as well as from in-situ measurements will be quantified. This will be followed by quantifying long-term aging characteristics for sensors due to combined temperature and sodium exposure. The final step in this phase of research (conducted in parallel with sensor aging in-sodium) will focus on gathering data on crack detection reliability in-sodium. The intent is to begin gathering the necessary data that, over time, can be adapted to supporting codes and standards development for the NDE and online monitoring of AdvRx components. Note that, given the distinctions identified above, reliability data will need to be generated for both periodic ISI as well as in-situ online CM from crack initiation to failure.

3.5 Progress on Experimental Plan

3.5.1 Sensor Materials Selection and Design

Meyer et al. (2013a) discuss various probes that may be used for measurements in harsh environments. For ultrasonic NDE measurements, piezoelectric and electromagnetic acoustic transducer probes are the most common form, with piezoelectric sensing used to measure vibration, AE, guided ultrasonic waves, nonlinear ultrasonic, ultrasonic velocity and attenuation, ultrasonic backscatter, diffuse fields ultrasonic testing, etc. However, the most common piezoelectric material used in ultrasonic probes (lead-zirconate-titanate or PZT) has limited applicability in high-temperature and irradiation environments, with its use (such as in USV) limited to refueling outages where the temperature of the coolant is below about 250°C. Materials considered more suitable for higher-temperature transducers include bismuth titanate, modified bismuth titanate, and lead metaniobate (Daw et al. 2012; Ensminger and Bond 2011). Other considerations for design of high-temperature piezoelectric transducers include the choice of materials for the faceplate and sensor body, techniques for bonding the material to the transducer faceplate and damping material, and techniques for coupling transducers to the test component.

A discussion of in-sodium ultrasonic measurements is provided by Bond et al. (2012) for in-sodium applications during outages at temperatures up to 250°C. A review of ultrasonic transducers for high-temperature applications, specifically lead-bismuth applications at temperature up to 600°C, is provided by Kazys et al. (2008). The advantages of sol-gel processing are highlighted with respect to sensor bonding and coupling. An exhaustive review of piezoelectric materials for high-temperature sensing applications is provided by Zhang and Yu (2011). The authors make note that the properties of oxyborate single crystals make it a good candidate for development of sensors to tolerate high temperatures and harsh environments. In other work, Zhang et al. (2010) describes testing of a prototype accelerometer fabricated from $YCa_4O(BO_3)_3$ single crystals at temperatures up to 1000°C. Parks et al. (2010) have tested single crystal aluminum nitride (AlN) crystals at temperatures in excess of 1100°C.

Alternatives to piezoelectric sensors include electromagnetic acoustic transducers (EMATs) (Alers et al. 1988; Wilcox et al. 2005), magnetostrictive sensors (MsS) (Kwun and Bartels 1998), and laser-based ultrasonic techniques (Scruby 1989). In general, EMAT and MsS probes rely on permanent magnets, and their use at high temperatures is limited by the choice of the magnet material (if any). As with piezoelectric materials, high-temperature applicability may be limited if the Curie temperature of the magnet (at which the magnet loses the ability to be magnetic) is lower than the operational temperature. This impacts measurements such as the MBN measurement, as well as magnetostrictive probes that are used for measuring temperature and EMAT probes. In irradiation environments, the activation of elements in typical magnets is a concern. Materials such as cobalt and samarium are readily activated by neutron irradiation and can result in difficulties in handling post-irradiation (such as during probe change-out). However, through careful probe design and materials selection, such probes can be used at higher temperatures. Boyd et al. (1988) and Iizuka and Awajiya (2014) describe high-temperature EMAT probes demonstrated in excess of 1000°C. These sensing techniques are generally less sensitive than piezoelectric-based sensors but enable non-contact sensing of components. In the case of laser-based techniques, the standoff distance can be substantial. However, laser ultrasound techniques are very sensitive to surface conditions.

Given the sensor material selection challenges, we are leveraging ongoing research in this area (Daw et al. 2013; Parks and Tittmann 2011; Parks et al. 2010; Veilleux et al. 2013; Zhang et al. 2010) to assist in material selection and probe design. A summary of high-temperature piezoelectric materials is given in Table 3.1, and where available, the sensitivity (in terms of the piezoelectric modulus d33 in pico-Coulombs per Newton (pC/N), and the electromechanical coupling coefficient) are provided. In the present application (in-situ detection of cracking and monitoring of crack growth), assuming a maximum operating temperature of 550°C, four commonly available materials are candidates for probe design and detection sensitivity studies due to their higher d33 and electromechanical coupling coefficients—lithium tetraborate (LTB), bismuth titanate (BiT), lithium niobate (LN), and AlN. These materials are being procured for use in sensor fabrication.

The probe design for in-vessel use will require sealing it against intrusion from the coolant. We are leveraging the ultrasonic probe designs developed for the USV sensor, with adaptations to support longer-term measurements in-sodium. Materials selection for the probe body, backing material, and bonding materials are ongoing, with the design using pressure-coupling of mineral-insulated cables to limit the degradation of cables as well as potential degradation of the solder. The challenge will be coupling the probe to the component under test, with pressure coupling (i.e., clamping) the probe to the component the most likely possibility. Initial bench-scale experiments will use pressure coupling of the probe to the specimens for testing, with other choices (such as welding the probe to the component) being deferred until the sensor design activity reaches a higher technical readiness level.

Table 3.1. Summary of High-Temperature Piezoelectric Material Properties

Material	Acronym	d33 (pC/N)	Curie Temp. (°C)	Highest Operational Temperature (°C)	Electro-mechanical Coupling Coefficient
Aluminum Nitride (film)	AlN	5.1	>2000	1100 (in CO_2 atmosphere, 700 w/o)	0.2
Lithium Niobate	LN	6	1142	1000	0.17
Bismuth Titanate (K-15)	BiT	18	650	550	0.45–0.47
Calcium Bismuth Niobate (KCe sub)	CBN	16	868	…	kp 8.6% kt 23.8%
Lithium Tetraborate (Li2B4O7)	LTB	19.5	917	…	24
Langasite (La3Ga5SiO14)	LGS	6.0–7.0	1400	1400	0.16
La3Ta0.5Ga5.5-xAlxO14	LTGA	d11 = 6.94	1500	…	0.17
Ca3Ta(Al0.9Ga0.1)3Si2O14	CTAGS	5.67	900 (+?)	900	0.163
Gallium Nitride (film)	GaN	3.7	>700	1000 (in CO_2 atmosphere, 700 without)	…
Ca0.9(NaCe)0.05Bi2Nb2O9	…	16	900	…	kp 8.8% kt 22.3%
CaBi2Nb2O9 (textured)	…	19	943	…	…
Gallium Orthophosphate	GaPO4	d11 = 4.1	970	700–900	0.2

3.5.2 Specimen Design for Ex-Situ Tests

A set of specimens with known crack lengths are necessary to calibrate the performance of the sensors being fabricated under room-temperature conditions. The data provides a reference set of measurements. By performing similar measurements after sensor aging at temperature, and in-situ (where the effects of sensor aging and any material property changes due to temperature and sodium effects are combined), quantitative data on crack detection performance changes as a result of long-term exposure to harsh environments in advanced reactors may be obtained.

For this purpose, a series of specimens was created by subjecting them to fatigue loading. The specimens were fabricated of 304 stainless steel, with a tapered gage section and a small groove on each side to assure that crack growth would occur at the intended location.

The specimens were held in hydraulic wedge grips, and axial alignment of the specimens was maintained as closely as possible to avoid the imposition of bending stresses. A closed-loop servohydraulic test machine was used to apply cyclic stresses under load control, and crack growth was determined by visual examination. In addition, interlocks were used to assure that changes in the applied displacement, for example, from crack growth, would stop the cyclic loading to avoid excessive crack growth.

Each specimen, except the control specimen, was subjected to different levels of fatigue loading. A sinusoidal waveform was applied, with the maximum load at 13,000 lbs. (57826 N) and minimum load of 1200 lbs. (5338 N). A frequency of 6 Hz was used.

Figure 3.5. and Figure 3.6 show the region around the center of the gage section for the control specimen and a specimen with a visible crack, respectively. In the example shown in Figure 3.6, the specimen was loaded for 91,190 cycles, resulting in a crack about 3 mm long.

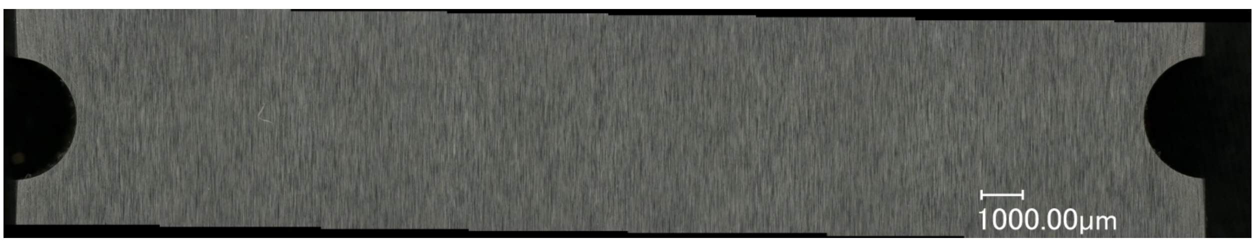

Figure 3.5. Specimen 1. Control specimen, with no cyclic loading.

(a)

(b)

Figure 3.6. (a) Specimen after 91,190 Cycles. Crack growth is shown from notches at each side of specimen. Extensive plastic zone deformation is apparent ahead of the crack tip. (b) Detail of crack tip.

Additional specimens are being designed for use in in-situ sensor aging studies and details of these specimens will be documented in future reports.

3.5.3 Laboratory-Scale Testbeds for NDE Sensor Assessment

Two laboratory-scale testbeds were fabricated previously for the purpose of generating specimens for ex-situ measurements and for in-situ measurement assessments at elevated temperatures (up to 650°C). These testbeds, described in previous reports (for instance, Ramuhalli et al. 2015), were adapted to provide the necessary capability for testing and evaluation of NDE sensors at elevated temperatures under load. These are briefly described below.

Both testbeds (and Figures 3.7 and 3.8) consist of mechanical load frames, furnaces, 5-ton actuator, power supply enclosure, and control system enclosure. The control system enclosure houses the electronics that run the system, including the motor drive for the stepper motor that is used in conjunction with the 5-ton actuator. The load frame is the base that all components are mounted to, and is based off a 20-ton shop press. The furnace, actuator, and both electrical boxes mount to the load frame. The machine allows the user to specify a force to be applied to the specimen, as well as a temperature for testing. During a test, the machine logs the date, stepper position, sensor position, temperatures, and force applied to a file for future analysis.

A programmable logic controller is used to control the operation of the testbed, and enables independent control of temperature and load. Heating is controlled by means of three control circuits for the heater, with a 5-point thermocouple to control the heat independently in each of the three heater circuits. The load is controlled by means of a 5-ton actuator with a 24:1 gear reduction ball screw, which allows the system to apply a force of 5 tons to the specimen. A stepper motor with a 100:1 gear reduction allows for very precise control of the actuator. A separate position sensor is mounted to the actuator to monitor the position of the actuator.

Figure 3.9 shows a close-up of the specimen and in-situ probes mounted at either end of specimens outside the furnace, within specially modified specimen grips that are cooled using chilled water to keep the probes within their temperature limits. Measurement data is periodically acquired using an automated data acquisition system. Figure 3.10 shows the user interface for this automated data acquisition system.

These testbeds, initially designed for monitoring of high-temperature creep damage, have been modified to use arbitrarily programmed loads that can simulate low-cycle fatigue damage and creep-fatigue damage. Additional sensors (specifically acoustic emission sensors with waveguides providing access to the high-temperature regions on the specimen) have been added, along with the necessary data acquisition system for logging and analyzing acoustic emission data. The furnace is also being modified to accommodate additional NDE sensors (specifically high-temperature piezoelectric sensors) inside the furnace, to be used on specimens with pre-fabricated cracking, to gather empirical data on sensor survivability and sensitivity as a function of time-at-temperature. A detailed test-plan has been developed for this purpose, and will be included in future reports describing the results of these experiments.

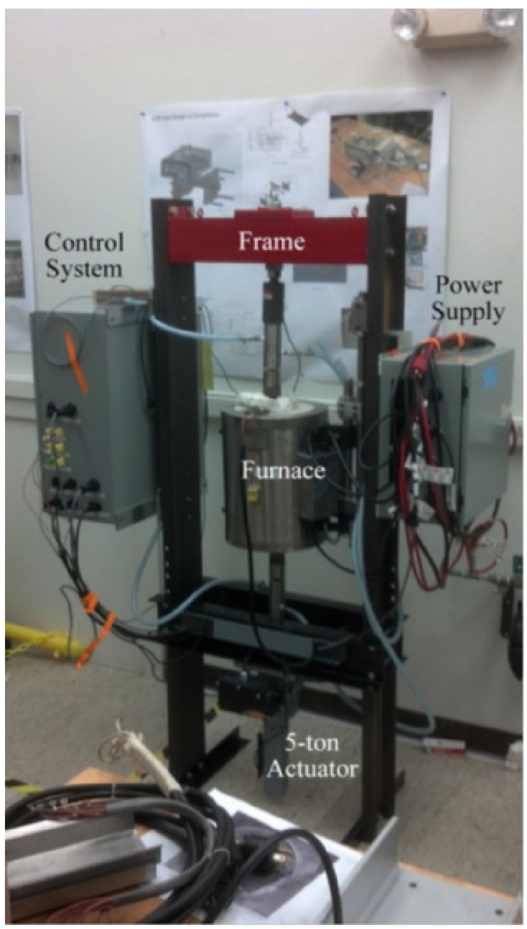

Figure 3.7. Creep-Test System for Validating Prognostic Algorithms

Figure 3.8. In-Situ Creep Test Frame

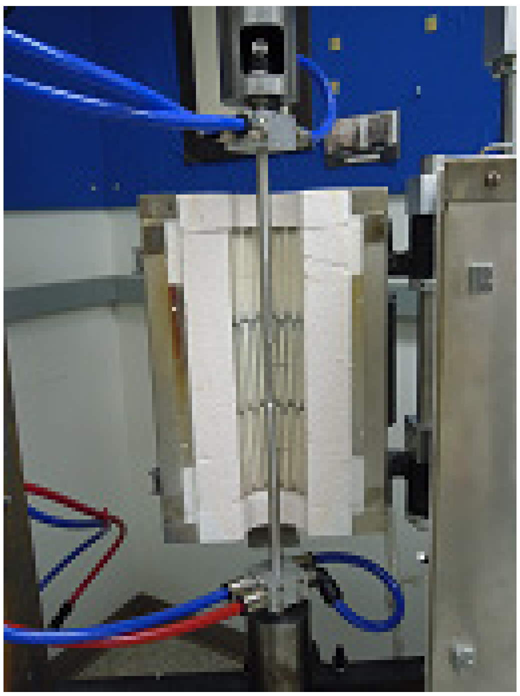

Figure 3.9. In-Situ Creep Test Frame Specimen Chamber

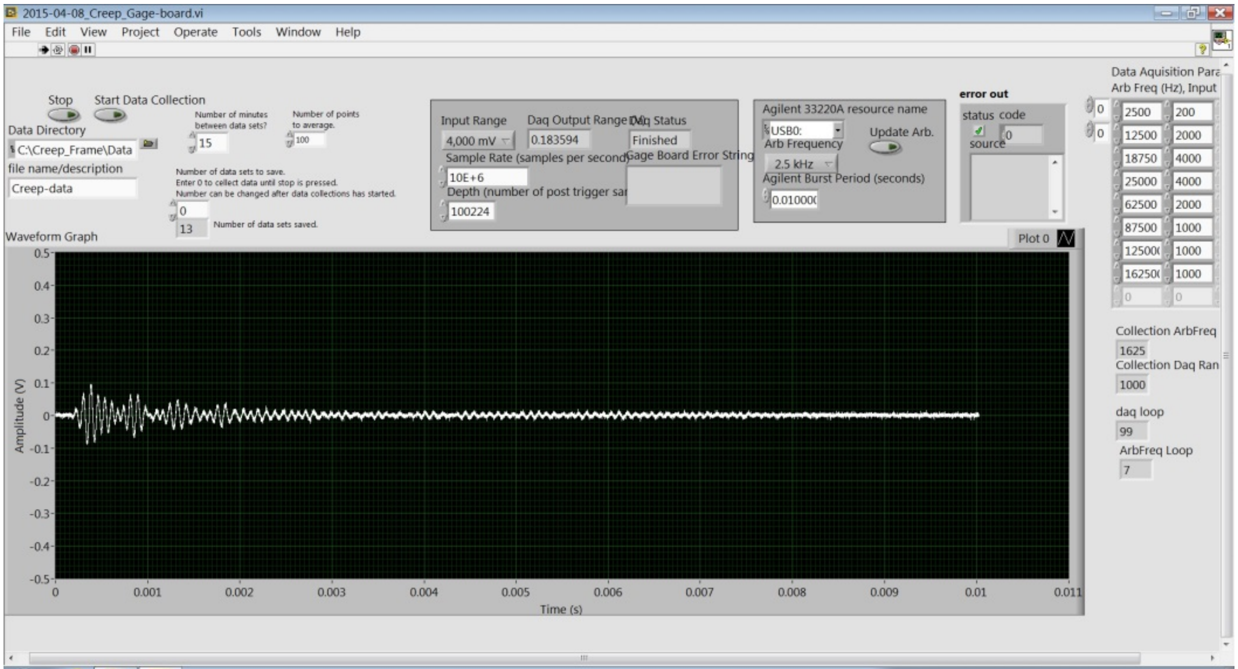

Figure 3.10. Interface for In-situ Creep Testbed Automated Measurement Data Acquisition System

3.5.4 Quantification of Measurement Reliability and Sensitivity

The detection of flaws in materials is subject to uncertainty from measurement noise, material microstructure, surface condition and access, instrument calibration errors, environmental conditions, and human factors, among other factors. Studies to evaluate the reliability of different (off-line, local) NDE measurement methods have resulted in information about the probability of detection (POD) (Berens and Hovey 1981, 1983) of a flaw of specified size (length or depth of penetration of the crack), false call probability, and associated confidence bounds based on flaw type, material, and inspection technique (Singh 2000). For nuclear power applications, NDE reliability studies have resulted in performance demonstration requirements codified in the ASME Code (Section XI, Appendix VIII) that are used to qualify equipment, procedures, and personnel prior to allowing their use in ISI. The use of automated analysis methods for flaw detection and diagnostics adds a layer of complexity to the assessment of reliability. Techniques for the qualification of such tools are being evaluated (EPRI 2009).

Most studies for reliability assessment of an NDE method (such as ultrasound) have typically utilized a statistical approach, where detection and characterization performance of measurements on a standard set of flaws (cracks) is used. Multiple replicates of the measurement are typically acquired, to account for variability in instrumentation, procedures, and human factors. The standard set of cracks generally contains cracks that span the range of variables being tested, with the population size of cracks chosen to ensure statistical relevance. Data on detection performance is usually analyzed by determining, for each crack, the number of replicate measurements that resulted in a correct detection. This hit-miss data is then used with a regression analysis to estimate the POD. An alternative analysis methodology (â vs. a POD model) uses regression analysis to identify the relationship between the flaw variable and the measured signal response.

The approaches described above for estimating reliability of NDE methods require a large population of flaws, with multiple independent measurement replicates. Each replicate may be, for instance, measurements taken by a single inspection team. This approach, while robust, takes time and significant resources for fabricating multiple flaws and administering the measurement process for each replicate measurement.

An alternate approach has focused on using a combination of simulation models and limited measurement data to estimate NDE measurement reliability. In this approach, physics-based simulation models of the NDE measurement are first developed and validated using a set of empirical data. An example of the simulations on specimens with geometrical variations is shown in Figure 3.11. The figure shows expected ultrasonic NDE responses at different locations on a specimen, given a modulated tone-burst excitation applied at the top of the specimen. These changes in arrival time, amplitude, and shape of the measured signal are primarily due to the wave propagation characteristics within the specimen. These are further modulated by the presence of damage such as cracking, as well as the other factors described above, and may be used (after validation of the simulations) to study the effects of small variations in experimental parameters (such as temperature or specimen dimensions).

The approach to using a combination of experiment and simulation to computing reliability uses experimental measurements on several flaws that span the range of variables of interest with the NDE measurement instrumentation, to generate bounding empirical data on detection and characterization performance. Through a careful design of experiments, factors that are expected to influence the NDE reliability are then identified and the expected changes in the detection performance due to random variability in these factors computed using the physics-based simulation model. The resulting data set (hit-miss, or â vs. a) is then used to generate the POD and probability of false alarm information. Clearly, this approach for estimating reliability is faster and less resource-intensive than a fully empirical approach. However, this method relies on the availability of well-validated simulation models.

The computation of NDE reliability information requires identification of the independent variables, as a function of which the reliability information is necessary. In most NDE approaches (and for ultrasonic and eddy current methods in particular), the independent variable is usually a crack parameter (length, or depth of penetration of the crack in the through-thickness direction). These variables are sufficient for assessing the reliability of NDE methods for crack detection in AdvRx components, for periodic ISI as well as in online CM focused on crack detection. However, these variables are invalid when dealing with the ability to detect cracking at early stages (pre-crack material changes or crack initiation and early stages of crack growth), and other variables will need to be defined.

As a part of this experimental plan for NDE reliability assessment of online monitoring in advanced reactor components, simulation models developed under this project for sensor design and optimization are being validated using empirical measurements. These simulation models will be used in concert with empirical measurements to estimate the POD. Initial simulation models of online monitoring using ultrasound are being adapted to provide the necessary information on crack detection capability. The information, if combined with structural mechanics information on critical flaw sizes, can form the basis for generating acceptance criteria for use in codes and standards.

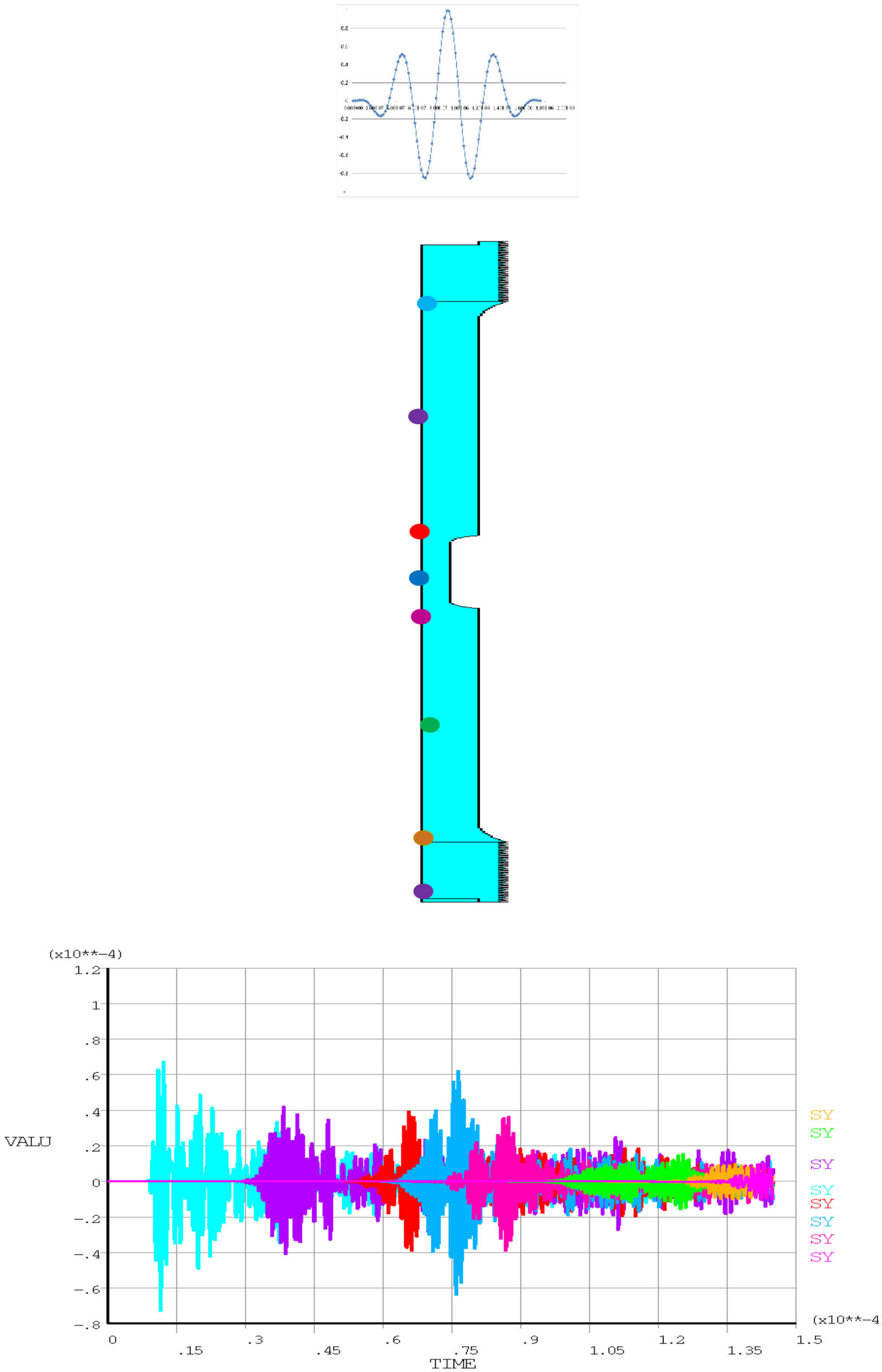

Figure 3.11. Example of Ultrasonic NDE Simulation, Showing Expected Response at Several Locations on a Test Specimen with a Single-Frequency Tone-Burst Excitation at the Upper End of the Specimen.

4.0 Summary

Nondestructive evaluation technologies are an essential element for obtaining information on passive component condition in AdvRx, with the development of sensor technologies for nondestructively inspecting AdvRx passive components identified as a key need. Given the challenges posed by AdvRx environments and the potential needs for reducing the burden posed by periodic ISI of hard-to-access and hard-to-replace components, a viable solution may be provided by online CM of components.

Online CM based on NDE technologies will require the development of sensors that are capable of tolerating the environmental conditions imposed by AdvRx, especially in-vessel, while providing reliable measurements that are capable of detecting and characterizing cracking and other forms of materials degradation relatively early in the degradation growth lifecycle. A number of NDE methods exist that may be adapted to online monitoring, including ultrasonic measurements (linear and nonlinear ultrasonics, applied using guided wave methodologies), AE monitoring that passively listens for initiation and growth of cracking, magnetic Barkhausen measurements that are sensitive to magnetic changes in ferromagnetic materials, and eddy current measurements that are sensitive to electrical conductivity and magnetic permeability changes caused by materials degradation (including cracking). Of these, ultrasonic wave-based methods (including AE) enable wide area monitoring while magnetic and eddy current methods enable localized measurements, generally at high-risk locations.

A further distinction may be made for measurements obtained in-vessel vs. measurements needed on components outside the reactor vessel. In regions where the sensor is not in contact with the coolant, and possibly not at elevated temperatures (such as in parts of the secondary power conversion systems), conventional NDE technology applied periodically (during refueling outages) may suffice, particularly if materials and structural research indicates that any cracking in these locations is unlikely to see rapid growth between inspections.

A number of other NDE technologies are available (such as visual examinations and radiography). However, these are usually not applicable for online monitoring of components and may require draining the coolant or other actions to provide access to the component under test. As a result, these techniques are not considered for this stage of the research.

The research activities follow a phased approach, with the first step comprising identification of sensor materials (including materials used for fabricating the sensor housing) that can survive in-vessel. Given the likely requirement to minimize the number of sensors in-vessel and the consequent requirement for monitoring of larger regions by a single sensor in-vessel, this step is restricted to the identification of sensor materials that enable ultrasonic/AE monitoring. A limited set of piezoelectric materials are useful under conditions likely in operating SFRs, and include aluminum nitride, bismuth titanate, lithium tetraborate, and lithium niobate. Samples of these materials have been obtained and are being used, in combination with a robust sensor design that leverages prior work, for fabricating in-situ online monitoring sensors.

In parallel, several specimens were fabricated for use in bench-top, room-temperature experiments. These experiments serve to provide baseline data on sensor performance in mild environmental conditions. Similar data on sensors operating in elevated temperature and liquid sodium will help quantify the degradation of measurement capabilities due to sensor aging, and provide quantitative measures of the resulting changes in efficiency and reliability of the measurement methods.

A number of additional specimens with known flaws (length, through-thickness depth) are also being fabricated for generating empirical data on sensor sensitivity to relevant flaw parameters. The data will be used to seed studies on NDE measurement reliability when performing in-situ, online monitoring. Previously developed simulation capabilities will be applied, along with the empirical data, to extract information on probability of detection and false call rates. Results of these studies will be documented in future reports in this series.

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