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ANL/NE-12/43

Light Water Reactor Sustainability (LWRS) Program – R&D Roadmap for Non-Destructive Evaluation (NDE) of Fatigue Damage in Piping

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Nuclear Engineering Division

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Light Water Reactor Sustainability (LWRS) Program – R&D Roadmap for Non-Destructive Evaluation (NDE) of Fatigue Damage in Piping

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September 2012

Executive Summary

Light water reactor sustainability (LWRS) nondestructive evaluation (NDE) Workshops were held at Oak Ridge National Laboratory (ORNL) during July 30th to August 2nd, 2012. This activity was conducted to help develop the content of the NDE R&D roadmap for the materials aging and degradation (MAaD) pathway of the LWRS program. The workshops focused on identifying NDE R&D needs in four areas: cables, concrete, reactor pressure vessel, and piping. A selected group of subject matter experts (SMEs) from DOE national laboratories, academia, vendors, EPRI, and NRC were invited to each workshop. The LWRS NDE workshop on piping fatigue was held on August 2nd, 2012 with twenty one SMEs attending that particular workshop.

Fatigue (caused by mechanical, thermal, or environmental factors) is the number one cause of failure in metallic components. Examples of past experience with this form of degradation in reactor coolant system (RCS) include cracking at: BWR feedwater nozzle; BWR steam dryer support bracket; BWR recirculation pipe welds; PWR surge line to hot leg weld; PWR pressurizer relief valve nozzle welds; PWR cold leg drainline; PWR surge, relief, and safety nozzle-to-safe-end dissimilar metal butt welds; PWR decay heat removal drop line weld; PWR weld joins at decay heat removal system drop line to a reactor coolant system hot leg. The effects of environment on the fatigue resistance of materials used in operating PWR and BWR plants are uncertain. There is a need to assess the current state of knowledge in environmentally assisted fatigue of materials in LWRs under extended service conditions. It is also important to develop a mechanistic understanding of the role of water chemistry on the microstructural changes in the materials and on their fatigue properties. In parallel, implementation of effective inspection and monitoring programs (i.e., NDE techniques, sensors and systems for surveillance and monitoring, improved condition monitoring and operational assessment strategies, etc.) for timely detection and mitigation of fatigue damage to safety critical components is of vital importance to achieving safe and economical long term operation (LTO) of the existing fleet of LWRs.

The first presentation at the piping fatigue NDE workshop was made to help identify material degradation issues associated with environmentally assisted fatigue. Dr. S. Majumdar, a senior mechanical engineer at Argonne National Laboratory (ANL), with extensive expertise in this area gave an overview of that subject. In summary, the presentation identified locations in LWRs where problems are more likely to occur. Those locations include: weld heat affected zones; vulnerable spots associated with dead flow zones or places where the local chemistry is different from bulk chemistry; thermal stratification and thermal striping zones; locations affected by off-design transients; initiation sites caused by manufacturing flaws (e.g., scratches and dings). The presentation also identified certain gaps in the ability to detect and monitor environmentally assisted fatigue damage that needs special attention. Those include measurement of oxygen/hydrogen content in the water during transients (start up, shut down, etc.), wide-area sensors and instruments for detection of cracks that initiate from places not identified during design as high stress regions (i.e., surprise failure incidents), and novel NDE techniques for early detection of cracks (microcracks) and for loss of protective oxides in view of the fact that the actual degradation locations are often hard to predict.

A series of presentations were made subsequently on promising NDE and monitoring techniques for detection, diagnostics and prognostics of fatigue damage. The talks – S. Bakhtiari (ANL), J. Wall (EPRI), B. Regez/S. Krishnaswamy (Northwestern Univ.), and A. Chattopadhyay (Arizona State Univ.) – covered a wide range of conventional NDE and monitoring methods as well as emerging sensors and techniques, many of which are currently being evaluated for non-nuclear applications. A brainstorming session was conducted next during which the SMEs were asked to provide their input to help define R&D actions needed to address the gaps discussed earlier. A major objective of the brainstorming session was to identify those sensors and techniques that have the most promising commercial viability and fill a critical inspection or monitoring need.

Some common themes regarding R&D needs identified by the working groups included techniques for early (pre-cursor) detection, fatigue crack initiation and growth monitoring (below current conventional NDE limits and for welds, base metals, bends/elbows, and long pipe sections), sensors for in situ materials characterization and for feature sizes usually examined by laboratory techniques (e.g., oxide coating assessment), global screening —as opposed to local examination methods—for early detection of damage, robust sensors for harsh environments (elevated temperatures – >200°C), and development of improved signal processing, data analysis, and sensor fusion algorithms for better sensitivity to detection of incipient degradation. It was also noted that a critical challenge in damage detection is the fact that damage at the microscale may not be detected by conventional sensors. Although considerable research has been conducted on developing different sensing techniques, existing sensors pose considerable limitation on the size of detectable damage. A viable approach proposed to overcome this problem is to develop a hybrid framework that integrates physics based model with data from physical sensors, resulting in a robust framework for damage detection and remaining useful life prediction.

Following the brainstorming session, the proposed NDE R&D needs were prioritized and ranked based on an open voting process. The top three proposed R&D needs are as follows:

1. NDE capability to detect and characterize damage/degradation (fatigue and stress corrosion cracking) at an early stage. The efforts should address the physics of measurement–sensitivity to early degradation and extraction of "real" signals from noise (unwanted signals) associated with structural features. New sensor technologies may be needed to measure material property changes of interest (i.e., size and dimension of grain boundaries, commonly measured in tens of microns).

2. Measurement capability for fatigue crack initiation and growth monitoring in welds, base metals, bends and elbows, and along long sections of piping. Sensors and systems are needed to measure below the current conventional NDE detection limits for macrocracks. It is also imperative to ensure that the defined detection limits are adequate for LTO.

3. Measurement capability for in situ material characterization for features of the size usually studied in the laboratory. Of particular interest are sensors that provide material state awareness for selected early degradation modes (e.g., oxide coating assessment).

A common theme among all the proposed R&D needs was the development of a sample library for the evaluation of all NDE and monitoring techniques (i.e., design of experiments to define numbers and classes). A number of NDE and monitoring techniques employing acoustic/ultrasonic, thermal, electromagnetic, micromagnetic, and optical (visual, laser) sensors were also identified as viable candidates for further evaluation. An overview of the proposed NDE and monitoring techniques is presented in this report. The NDE data will ultimately serve as input to mechanistic models to help more accurately predict the remaining useful life of components and in turn increase confidence in LTO of the existing fleet LWRs.

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1.0 Introduction

The Department of Energy's (DOE) Light Water Reactor Sustainability (LWRS) Program is developing the fundamental scientific basis to understand, predict, and measure changes in materials and systems, structures, and components as they age in environments associated with continued long-term operations (LTO) of existing commercial nuclear power plants (NPPs). Research under the LWRS Program is being conducted within four pathways:

1) Materials Aging and Degradation
2) Advanced Light Water Reactor Nuclear Fuels
3) Advanced Instrumentation, Information, and Control Systems
4) Risk-Informed Safety Margins Characterization.

A key element of LTO of LWRs is expected to be the management of aging and degradation in materials that make up the passive safety system components (SSC). Understanding the likely degradation mechanisms in these materials under LTO is essential. At the same time, approaches to assess the condition of these materials in a nondestructive fashion will also be necessary to assure adequate safety margins and ensure that an effective aging management program can be set up for LTO. The objective of the Materials Aging and Degradation R&D pathway is to create a greater level of safety through application of increased knowledge and an enhanced economic understanding of plant operational risk beyond the first license extension period. R&D is being conducted to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in NPPs. Data and methods to assess the performance of SSCs essential to safe and sustained nuclear power plant (NPP) operations are being developed. These R&D products will be used to define operational limits and aging mitigation approaches for materials in NPP SSCs that are subject to long-term operating conditions.

License extensions for extended-LTO [i.e., 60–80 years] will require a shift to a more proactive approach to aging management in addition to updated approaches to periodic in-service inspection (ISI). Three overarching elements of research are necessary to develop a proactive aging management philosophy and these include:

- Integration of materials science understanding of degradation accumulation, with nondestructive measurement science for early detection of materials degradation
- Development of robust sensors and instrumentation, as well as deployment tools, to enable extensive condition assessment of passive NPP components
- Analysis systems for condition assessment and remaining life estimation from measurement data

It is likely that tackling these research elements in parallel will be necessary to address anticipated near-term deadlines for life extension decision-making (1st of the second round license extension packets may be received by the NRC 2014/15, with decision needed by 2019 or 2020).

To address the research needs, the Materials Aging and Degradation (MAaD) Pathway of the LWRS program supported a series of workshops in the summer of 2012, with the objective of identifying technical gaps and prioritizing research in Non-Destructive Evaluation (NDE) methods. This document summarizes the findings of the workshop addressing NDE R&D for Fatigue Damage in Piping.

1.1 Background

The US fleet of commercial nuclear power reactors has an average age of more than 30 years, and most of the fleet has either applied for or received an extension of the operating license from 40 years to 60 years (NRC 2011). Attention is now turning to the potential for a second round of license extensions (Chockie et al. 1991; Bond 1999; Gregor and Chockie 2006; Bond et al. 2008a). A challenge to safe long-term operations is the life-limiting nature of materials aging and degradation, as such aging and associated degradation in the structural response of the material can limit safety margins. Replacement of a subset of components (such as the steam generator) may be possible, though the costs associated with the replacement (including the time offline) may be challenging. Moreover, it is economically prohibitive to replace several of the larger components, including the reactor pressure vessel and primary piping. Thus, management and mitigation of aging-related degradation in these critical components becomes important to maintaining safety margins.

One class of components whose aging may impact the safe extended operation is metallic Class 1 piping. In the context of long term operations, the increased exposure to time-at-temperature, along with the effects of extended irradiation and accumulated operational stresses, is expected to result in a fatigue and cracking of Class 1 piping. Fatigue damage caused by mechanical, thermal, and environmental factors is the main cause of failure in metallic components. The long term effects of environment in particular on the fatigue resistance of materials used in operating PWR and BWR plants remain uncertain. The primary locations of concern are in the heat-affected zones around welds. These types of degradation, if left undetected, have the potential for coolant leaks from cracking.

From a regulatory perspective, commercial nuclear power plants (NPPs) are required to demonstrate adequate safety margins through multiple, independent, and redundant layers of protection (Diaz 2004). Regulatory guidance towards the management and mitigation of the effects of passive SSC aging in this regard is contained in the Generic Aging Lessons Learned (GALL) reports (NRC 2001, 2005a, b, 2010d). These reports provide the technical basis for determining whether plant aging management programs (AMPs) at operating reactors are adequate or need modification as plants enter extended operation. The AMP applies to all SSCs that are safety-related or whose failure could affect safety-related functions, as well as those SSCs relied on for compliance with fire protection, environmental qualification, pressurized thermal shock, anticipated transients without scram, or station blackout regulations. Specific programs that need modification are also identified, and the information in these reports are also included in the NRC’s Standard Review Plan for Review of License Renewal Applications (NRC 2010c).

One component of the AMP is the scheduled ISI of passive components, codified in 10 CRF 50.55a (2007), which specify the requirements for nondestructive inspection (such as inspection periodicity, inspection techniques, and qualification procedures). These elements are contained in the American Society for Mechanical Engineers (ASME) Boiler & Pressure Vessel (BPV) Code, which the Code of Federal Regulations incorporates by reference. The ASME Code specifies the minimum requirements for nondestructive examination (NDE). Specifically, Section XI of the Code defines the acceptable volumetric and surface examination techniques, minimum requirements for acceptable procedures, and the acceptance criteria for flaws that are detected. In addition, requirements for qualification of the procedures, equipment, and personnel are specified to ensure reliable inspections. Currently, degradation in the reactor pressure vessel (RPV) (and Class 1) components is managed through periodic ISI as mandated by the ASME BPV Code, with risk-based principles used to determine ISI intervals and the components for inspection in any given interval.

In the United States, for certain inspection techniques and components, the nuclear industry has developed additional examination guidelines, such as those developed under the Boiling Water Reactor Owners Group's Vessel and Internals Project (BWRVIP) program, and the Materials Reliability Program (MRP) (for instance, EPRI 2008c; EPRI 2011b). A number of studies have also examined the reliability of NDE techniques (Chockie 1981; Doctor 1984; Fong 1986; Bates et al. 1987; Nichols and McDonald 1987; Willetts and Ammirato 1987; Doctor et al. 1995; Doctor 2007; Miller 2008; Singh 2000) and determined that several sources of variability were present that impacted the reliability of NDE. These results were codified in Section IX, Appendix VIII of the ASME BPV Code, and are the basis for performance demonstration procedures for NDE techniques (Chockie 1985).

While the ISI program for metallic components (particularly Class 1 components) has been in existence for a number of years, there are still gaps associated with the reliable detection of cracking, particularly the detection of incipient cracking. This report is the outcome of a workshop on environmental fatigue in Class 1 piping that examined the measurement and inspection needs and the current state of the art with respect to NDE for crack detection (especially incipient crack detection), with the objective to identify technical challenges in the application of NDE methods for fatigue detection and characterization, and to define a research roadmap to address these challenges. The objective of the proposed research is the development of the scientific basis for reliably detecting and characterizing aging and degradation in piping components, to serve as input to licensing decisions for long-term operations.

1.2 **Report Organization**

The document is organized as follows. Section 2 discusses the measurement needs from a materials science perspective. Specifically, the impact of degradation mechanisms of concern on materials microstructure, and the key measurements that are needed for assessment of impact on structural integrity are summarized. Section 3 summarizes the state of the art in nondestructive measurements that may be applicable to the problem at hand. Section 4 discusses the gaps (as identified at the workshop) in NDE measurements for LTO, and a research roadmap to address high priority gaps. Finally Section 5 concludes the report and identifies a timeline for follow-on R&D. In addition, a series of Appendices are included, that provide details of the workshop process, outcomes of the workshop, and list the attendees.

2.0 Problem Statement

Fatigue is a cumulative aging damage mechanism that will become increasingly important as reactor life is extended [NET. 2009]. Although it was recognized as a factor in the original design of plants, the problem has been aggravated by the recognition that the initial estimates of fatigue life were based on the behavior of materials in air, and fatigue lives can be significantly decreased in LWR coolant environments. Acceptable fatigue aging management programs have been developed for plants undergoing license renewal. These programs, however, could involve inspection, repair, and replacement activities that are expensive and involve significant worker exposure to radiation. A review conducted in 2009 by the Steering Committee of the LWRS program made up of experts from academia, industry, NRC and the national laboratories identified fatigue damage to RCS piping as one of the areas of concern to LTO of current fleet of LWRs. Consequently, the committee recommended that work in the area of fatigue should be considered to increase confidence in the estimates of environment on fatigue life and minimize the likelihood of unnecessary repairs and replacements or inspections.

Environmental fatigue research being conducted under the MAaD pathway of the LWRS program is expected to provide mechanistic understanding of the key variables in environmental fatigue to help predict service-life of components affected by this mechanism [INL.2012]. Environmentally assisted fatigue is a growing problem within LWR components and will grow more severe with extended service, even though there is not agreement on mechanisms or directions between regulators and industry. The objective of this task is to develop a model of environmentally assisted fatigue mechanisms to predict life for this mechanism. This will be supported by experimental studies to provide data for identification of mechanisms and key variables and provide valuable data for model validation. The experimental data will inform regulatory and operational decisions, while the model will provide a capability to extrapolate the severity of this mode of degradation to extended-life conditions. A final report will be delivered in the 2017 to 2021 timeframe, providing both the model of fatigue mechanisms and the supporting experimental data.

In parallel with research on long-term performance of reactor metals, techniques for NDE of key reactor metals are needed toward development of technologies to monitor material and component performance. This task will deliver an R&D plan in 2012 for sensor development to monitor reactor metal performance. An initial step in this R&D plan is to examine the key issues including those associated with fatigue, environmental fatigue, and crack initiation, and available technologies. Expert panels will develop the R&D plan, ensuring broad input and discussion. In future years, sensor development will be performed with a demonstration of key prototypes by 2016. This ambitious date will require collaboration with other tasks within the LWRS Program and other programs and critical assessment and use of technologies from other industries. Validation and qualification of the sensors will be established and documented in the 2017 to 2021 timeframe.

The following section addresses the materials aging and degradation problems of primary concern to LWRS including the mechanisms at play. The specific problem of fatigue damage in RCS piping and the associated aging related issues are described. The measurements needs from a materials science perspective are also discussed. The current state of the art as well as some emerging in NDE techniques in application to detection and characterization of fatigue damage in RCS piping are discussed in the subsequent section.

2.1 Fatigue Damage in RCS Components

The 104 light-water reactors (LWRs) in the United States generate approximately 20% of total US electricity production. Most of the US reactors were built before 1970 and the initial design lives of most of the reactors are 40 years. It is expected that by 2030, even those reactors that have received 20-year life extension license from the US Nuclear Regulatory Commission (NRC) will begin to reach the end of their licensed periods of operation. For economic reasons, the licenses for the existing fleet of LWRs could be extended beyond 60yeras to perhaps beyond. Ensuring safe operation of existing NPPs beyond their initial design life is of vital importance. Environmental assisted damage and aging issues are some of the major concerns for long-term viability of these nuclear reactors. Despite regular maintenance and tightly regulated operating procedures, aging related failures do occur in US nuclear power plants (NPP).

Different forms of aging might be active in the NPP components [Shah. 1993, INL. 2009, Busby. 2008, Allen 2009, Chopra. 2011]. They include pure irradiation-induced hardening and softening, irradiation-induced swelling, phase transformation, creep, thermal aging such as thermal hardening and softening of material properties, thermally induced high-cycle and low-cycle fatigue, and high-cycle mechanical fatigue due to flow-induced vibration, chemical corrosion related damage such as flow-assisted general corrosion, crevice corrosion, and stress corrosion cracking (SCC). These mechanisms can act individually in combination to accelerate the aging processes. Different NPP components are subjected to different damage mechanisms depending on the type of material used, the way it is manufactured, and the exposure environments.

Fatigue is the number one cause of failure in metallic components. Fatigue is a form of degradation of material leading to fracture caused by repeated cyclic loading. The types of fatigue damage are generally categorized as mechanical thermal and environmental [EPRI. 2005]. Mechanical fatigue is due to cyclic stresses that result from application of pressure or other mechanical loads. Of special significance in nuclear plants is fatigue resulting from vibration of components and/or piping systems due to equipment motion or fluid induced forces. It is generally observed as a high-cycle fatigue phenomenon. Thermal fatigue is due to cyclic stresses that result due to changing temperature conditions in a component or in the piping attached to the component. Thermal fatigue may involve a relatively low number of cycles at a higher stress (e.g., plant operational cycles or injection of cold water into a hot nozzle) or be due to a high number of cycles at low stress amplitude (e.g. local leakage effects with cyclic stratification). The environmentally enhanced fatigue effect is the reduction in fatigue life in a reactor water environment compared to that in a room temperature air environment. Environmental fatigue involves two primary elements: the effects of a reactor water environment on fatigue crack initiation and the potential accelerated growth of an identified defect due to reactor water environments.

Typically, mechanical fatigue is independent of cyclic frequency or strain rate. Corrosion fatigue (CF) is a non-environment specific mechanical fatigue aggravated by corrosion. Corrosion fatigue, on the other hand, is strongly dependent on cyclic frequency or strain rate. In specific environments (e.g., BWR and PWR water) corrosion fatigue is also referred to as environmentally assisted fatigue. Environmentally assisted fatigue should be distinguished from SCC which is also environmentally assisted but occurs under constant stress.

Examples of past experience with this form of degradation in reactor coolant system (RCS) include cracking at: BWR feedwater nozzle; BWR steam dryer support bracket; BWR recirculation pipe welds; PWR surge line to hot leg weld; PWR pressurizer relief valve nozzle welds; PWR cold leg drainline;

PWR surge, relief, and safety nozzle-to-safe-end dissimilar metal butt welds; PWR decay heat removal drop line weld; PWR weld joins at decay heat removal system drop line to a reactor coolant system hot leg. The effects of environment on the fatigue resistance of materials used in operating PWR and BWR plants are uncertain. There is a need to assess the current state of knowledge in environmentally assisted fatigue of materials in LWRs under extended service conditions. It is also important to develop a mechanistic understanding of the role of water chemistry on the microstructural changes in the materials and on their fatigue properties. In parallel, implementation of effective inspection and monitoring programs (i.e., NDE techniques, sensors and systems for surveillance and monitoring, improved condition monitoring and operational assessment strategies, etc.) for timely detection and mitigation of fatigue damage to safety critical components is of vital importance to achieving safe and economical long term operation (LTO) of the existing fleet of LWRs.

2.2 Aging and Degradation Mechanisms in RCS Components

In addition to the RPV and internal structures, the reactor cooling system (RCS) pipes are part of the reactor coolant pressure boundary whose structural integrity affects the overall functionality of NPP. RCS cooling system pipes include hot leg and cold leg pipes and steam generator tubes for PWR plants and steam, feed water and recirculation pipes for BWR plants, all of which are critical for the overall safety of the reactors. Besides SCC, pressure and thermal stress-induced low-cycle fatigue is also a major concern for the RCS. Pressure and thermal stress are created during system transients including heat up and cool down that could cause low-cycle fatigue damage. This fatigue along with SCC leads to corrosion fatigue. For example, SCC/CF can occur in PWR coolant systems nozzles, dissimilar metal welds, and elbows [Shah. 1993]. Stress corrosion cracking and corrosion fatigue in RCS components depends on the material, its associated exposure environment, and the sources of stress. Figure 2.1 show the parameters that affect the severity of SCC/CF.

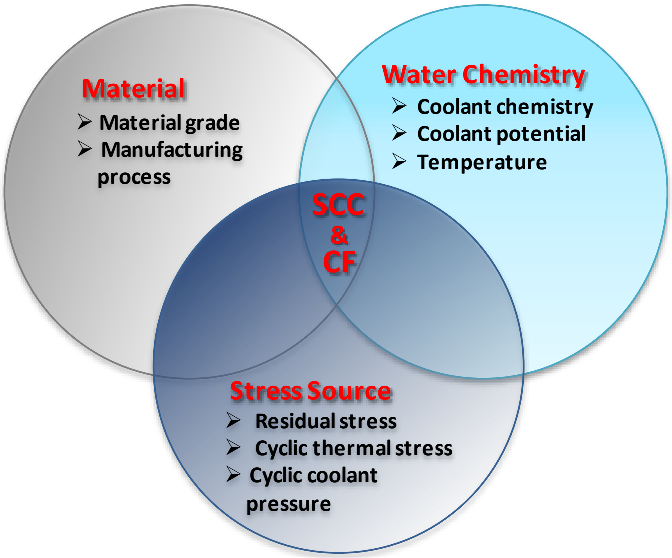


Figure 2.1 Susceptible material, right water chemistry, and stress source are the factors that control environmentally assisted fatigue.

The reactor cooling system typically includes part of the RPV shell, the RCS piping in or out of the RPV, and the associated nozzles and welds. For PWRs, the major RCS pipes are hot and cold leg pipes and for BWRs the major RCS pipes are steam, feed water, and recirculation pipes. In the US, the PWR primary system piping is fabricated mostly by three manufacturers –Babcock & Wilcox, Combustion Engineering, and Westinghouse. All these fabricators used different materials for the RCS piping. For example, the main coolant piping material used by Babcock & Wilcox and Combustion Engineering is wrought ferritic steel. Westinghouse-design used austenitic stainless steel. The combustion engineering piping is constructed of roll-bonded clad plates, whereas Babcock & Wilcox used weld-deposited cladding on the piping inside surface. In the Westinghouse-design, the RCS piping and fitting materials were constructed using both wrought stainless steel and cast stainless steels, such as, Types 304 and 316 wrought stainless steels and CF-8 cast stainless steel grades, respectively. It is to be noted that these grades have similar chemical composition. The piping used in Westinghouse plants is seamless, and because it is fabricated from stainless steel, requires no cladding for corrosion protection. Table C.1.1 shows the details on RCS piping material grades for a typical Westinghouse design PWR. In the US BWRs, both carbon and low alloy steel material are used for the RCS piping. The information about typical piping material is summarized in Table C.1.2.

Table 2.1 PWR primary RCS piping material [Shah. 1993].

Main piping system			
RPV nozzle forging	Low alloy steel (SA 508-2)		
RPV nozzle safe end forging	Wrought stainless steel (316 SS)		
Piping connected to safe end	Wrought stainless steel (316 SS, 304N SS) & cast stainless steel (CF-8A, CF-8M)		
Safe end to nozzle (dissimilar metal weld)	Weld material	Nozzle butter	Safe end butter
	Stainless steel	Stainless steel	None
	NiCrFe alloy	NiCrFe alloy	None

Table 2.2 BWR RCS piping material [Shah. 1993].

Main steam piping system			
RPV nozzle forging	Low alloy steel (SA 508-2)		
RPV nozzle safe end	Low alloy steel (SA 541-1)		
Piping connected to safe end	Carbon steel (SA 155 grade KFC60, cl-1)		
Feed water piping system			
RPV nozzle forging	Low alloy steel (SA 508-2) with stainless steel (308 L SS) clad		
RPV nozzle safe end	Low alloy steel (SA 541-1) with stainless steel (308 L SS) clad		
Piping connected to safe end	Carbon steel (SA 333 grade 6)		
Recirculation piping system			
RPV nozzle forging	LAS (SA 508-2)		
RPV nozzle safe end	Stainless steel (304 or 316 SS) or Nickel alloy (Alloy 600)		
Piping	SS (304 or 316 SS)		
Safe end to nozzle (dissimilar metal weld)	Weld material	Nozzle butter	Safe end butter
	308 SS or 308L SS	309/308/308L SS	None
	Alloy 82/182	Alloy 182	None or Alloy 182

In addition to material properties and manufacturing practice, water chemistry of light water reactor plays a key role in initiation and propagation of environmental fatigue damage. Growth of SCC/CF is also highly dependent on the presence of mechanical/thermal stress in the component. The stress could be due to residual stress generated during manufacturing process or could be due to applied loading. It is well known that stresses are generated during welding of dissimilar metals. Residual stresses are generated during forming of steam generator tubes. It is necessary to model these manufacturing processes for developing predictive models for SCC/CF. In RCS components, the stress could also be due to thermal loading and coolant pressure. Coolant pressure and temperature cycles during normal operating condition and maintenance/emergency outage transients, the RCS components undergo low cycle mechanical/thermal fatigue.

Fatigue crack initiation and crack growth may be governed by a number of material, structural and environmental factors, such as stress range, temperature, fluid oxygen content, mean stress, loading frequency (strain rate), surface roughness and number of cycles. Cracks typically initiate at local geometric stress concentrations, such as welds, notches, other surface defects, metallurgical anomalies and structural discontinuities. The presence of an oxidizing environment or other chemical species can accelerate the fatigue crack initiation and propagation process [EPRI. 2005]. Typical sequence of crack initiation and growth is shown in Fig.2.2. The initiation interval during which cracking is considered microstructurally small is denoted by “ainit”. Linear elastic fracture mechanics (LEFM) can be applied to predict fatigue crack growth once a main crack is formed. Prior to that state, “initiation tests” using smooth specimens need to be employed. Typically, initiation involves cracks ≤300 µm (25% load drop). As noted previously, the environment affects both the initiation and propagation of cracks.

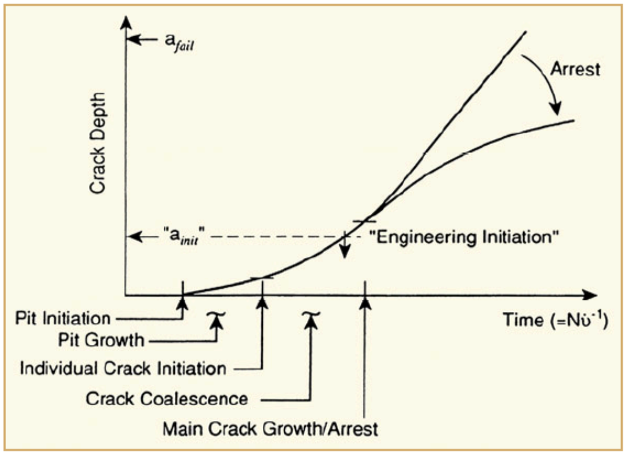


Figure 2.2 Susceptible material, right water chemistry, and stress source are the factors that control environmentally assisted fatigue.

Many common operating system parameters (pressure, temperature, vibration, flow, etc.) are already being monitored during plant operation. Water chemistry parameters (pH, DO, etc.) are also being monitored at inlet/outlet during NO, steam generator (SG) blow-down. Special attention, however, should be paid to such operating parameters oxygen and hydrogen content in the water during transients (start up, shut down, etc.). As noted earlier, problems associated with environmentally assisted fatigue usually occur at: weld heat affected zones; dead flow zone or places where the local chemistry is different from bulk chemistry – thus the need to identify such vulnerable spots; thermal stratification, hot/cold water mixing and thermal striping zones; off-design transients – flow-induced vibration; manufacturing flaw sites such as scratches and dings. In many surprise failure incidents, cracks initiate from places not identified during design as high stress regions. More extensive ISI procedures or more elaborate monitoring methods may have to be put in place for extended operation of existing LWRs. Novel NDE techniques are needed to detect incipient cracks and damage precursors such as microstructural changes associated with loss of protective oxides as early as possible, understanding that the actual damage initiation locations are often hard to predict.

3.0 NDE for RCS Piping: Current State of the Art

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, "Inservice Inspection of Nuclear Power Plant Components" specifies the requirements for periodic examination of RCS components including piping and welds (similar/dissimilar metal welds). The results of ISIs employing various NDE techniques serve as a key input to management of fatigue in RCS piping. Other principal inputs include monitoring of plant cyclic operation and operational experience by the industry [EPRI. 2005]. Inspection and monitoring is conducted on safety critical components for which fatigue damage is of potential concern. Inspection is an integral part of a program to assure that fatigue cracks do not grow to a size that would challenge the structural integrity of a component. The frequency of inspections for selected components is determined on a site-specific basis and is included in the plant's ISI plan. In-service inspections are commonly implemented on a risk-informed basis and thus are focused on locations where component failure is of higher significance to operational safety. It is worth noting that conventional NDE methods employed during ISIs are qualified to detect degradation beyond engineering initiation stage (e.g., macrostructural degradation). Furthermore, risk informed inspections applied on a selective and localized basis do not necessarily guarantee that all flaws would be detected before they pose a challenge to the structural integrity. More reliable detection of damage at an early stage would require implementation of global NDE and monitoring methods. Ideally, the NDE probing method should provide information about microstructural changes in the material indicative of the state of degradation of mechanical properties of a component.

Nondestructive evaluation techniques may be used for either material characterization or for ISI of NPP components. When employed for characterization of materials, the most accurate method is commonly selected for a particular application. Alternative NDE methods and destructive examinations may additionally be used for validation and verification of the results. Furthermore, for such applications the efficiency of the examination method is often not a major constraint. For ISI applications, on the other hand, the efficiency (speed of inspection) and cost are often among the main factors that influence adaptation of a NDE method for field deployment. The NDE techniques used for ISI in general provide the means to assess the present condition of a component (i.e., integrity and fitness for service) and to further help predict its performance during the subsequent operating cycle (i.e., meet safety margins). As such, ISI techniques are routinely qualified based on their ability to reliably detect – high probability of detection (POD) – limiting flaws that could become a safety concern to the structural integrity of a component, determined based on mechanistic assessments. In view of the above discussion, it is therefore important to make the distinction between NDE methods used for material characterization (correlation of NDE parameters with change in material microstructure) and those employed for ISI applications (detection of macrostructural degradation). Accordingly, promising NDE techniques used for accurate characterization of materials in many cases may not be practical for field deployment.

Conventional NDE methods in their various forms that are used for ISI of RCS piping and associated components include remote Visual/Video testing (VT), dye penetrant testing (PT), Magnetic particle testing (MPT), ultrasonic testing (UT), magnetic flux leakage (MFL), eddy current testing (ECT), and radiography testing (RT) with portable instruments. Phased array and angle-beam UT methods are used primarily for inspection of welds. Time-of-flight diffraction UT method on the other hand is used for detection of cracking through the entire pipe wall. Ultrasonic testing using normal beam angle is used for detection of wall thinning. Axial and circumferential guided-wave UT (GW-UT) methods are employed for volumetric examinations over long sections of piping and for inspection of buried pipes. For surface and near-surface examinations, conventional ECT using single element or array probe configurations are used for detection of localized degradation. Deeper penetration can be achieved with by employing pulsed (PEC) and remote field eddy current techniques. Techniques such as vibro-modulation – a vibro-acoustic technique used for large area detection of craze cracks– have also been used for specialized applications. A comparison of various NDE methods evaluated for detection of thermal fatigue damage in piping is provided in [EPRI. 2000a]. Acoustic emission (AE) monitoring is currently the only method approved by the ASME code for detection of cracks and leaks. The AE technique, however, is not routinely used in existing LWR plants.

Modern NDE equipment has evolved significantly over the past two decades as a direct result of major advancements in microelectronic and computer technology. Some common features of modern NDE equipment include:

- Higher degree of inspection automation (hardware and software)
  - More prevalent use of compact and efficient robotic and remotely operated scanners, crawlers, and vehicles for better access in confined spaces
  - Advanced visualization and automated data analysis tools
- Faster inspections through employment of linear and matrix array sensor configurations
- Increased accuracy and quantification capability
  - Improved signal-to-noise ratio (S/N) as a result of improved probe design and on-board signal conditioning electronics
  - Use of advanced and efficient algorithms for real-time analysis of large amounts of data
- Greater penetration depth and higher spatial resolution
- More flexible and modular tools allowing incorporation of multiple sensors in the probe assembly
- Compact systems (integrated inspection units for rapid deployment)
- Rugged probes for operation in harsh environments (elevated temperature and pressure, radiation, moisture, and corrosive media)
- Inspection techniques that are less affected by the surface condition of components

It should be noted that the term “emerging” technology here refers to any technique that has not yet gained widespread acceptance for routine field use by the NPP industry, even though the technique itself may have been originally developed for other applications and demonstrated in the past. Emerging NDE and monitoring technologies in their various forms that can potentially be employed for in situ inspection of RCS components include:

- Advances in eddy current testing (ECT) include
  - Pulsed eddy current (PEC) technique
  - Remote-field eddy current testing (RFECT)
  - High spatial resolution arrays
  - Thin-film sensors
  - Solid-state sensors including giant and anisotropic magnetoresitive (GMR and AMR) probes
  - Magneto-optic imager (MOI)
  - Superconducting quantum interference device (SQUID)
- Advances in ultrasonic Testing (UT) include

    - Time-of-flight diffraction (TOFD),
    - Advances in phased array UT (PA-UT) such as full-matrix capture,
    - Ultrasonic leaky Raleigh wave technique,
    - Ultrasonic scattering (diffuse field),
    - Non-linear acoustics/ultrasonics
    - Laser UT (LUT),
    - Ultrasonic camera (Acoustocam® imager)
    - Electromagnetic Acoustic Transducer (EMAT),
- Infrared (IR) thermal imaging
    - Pulsed thermal imaging,
    - Thermal tomography,
    - Vibrothermography,
- Enhanced visual testing (VT)
- Radiographic testing (RT) with portable instruments
- Radio frequency (RF) and Microwave remote vibrometry methods
- Micromagnetic techniques (for microstructural material characterization and monitoring)
    - GMR and AMR sensors for impedance measurement
    - Magnetic Barkhausen noise (MBN) measurement or Barkhausen noise analysis (BNS),
    - Magnetic Susceptibility sensors
    - Magneto-static sensors
- In-situ residual stress (RS) measurement
    - X-ray diffraction (XRD) with portable instruments
    - Thermoelastic measurement using IR camera
    - Photoelastic measurement using two-dimensional epoxy resin
    - Eddy current impedance
    - UT using critically refracted longitudinal (L_{CR}) waves.
- Monitoring technologies
    - Acoustic emission (AE)
    - Active sensing using distributed sensors
        - Inductive, capacitive and strain gauge probes
        - PZT transducers
        - Fiber optic sensors
    - Electric potential drop (electrical resistivity probes–DC/AC potential drop (DCPD/ACPD))
    - Digital speckle correlation technique (DSCT) for contact and non-contact measurement of creep, creep-fatigue and strain

A brief description of a subset of the emerging NDE technologies listed above with potential application to in-situ inspection and/or monitoring of damage and degradation in passive SSCs is presented next.

Figure 3.1 Industrial MOI system for inspection of aging aircrafts. [*Shih et al*]

Eddy current testing in its various forms is among the most widely used NDE methods for examination of electrically conducting materials. A number of emerging ECT methods with the potential to provide improvements over conventional ECT method are noted here. Magneto-optic imaging (MOI) technique combines eddy current excitation with optical imaging techniques to provide real-time visualization of eddy current distribution over a relatively large area. Although the technology has been in use by the aerospace industry for many years (see Fig. 3.1), its application to the NDE of NPP components has been limited mostly to laboratory tests. Perturbation of induced currents due to surface and subsurface material discontinuities are detected by a magneto-optic sensor in response to the external magnetic fields. The images produced by earlier MOI systems were considered qualitative in nature and with limited quantitative characterization capability. Detection of cracks under protective coating in steel components (e.g., reactor pressure vessel) with a specialized MOI system that uses rotating in-plane magnetization has also been reported in the literature [Fitzpatric. 1996]. Detection of cracks in steel plates which were imaged through 0.125 inches of stainless-steel cladding has also been reported. Furthermore, it is noted that the rotating in-plane magnetization method allows detection of cracks of arbitrary orientation.

Deeper penetration depths can be achieved by operating at lower excitation. The sensitivity of coil-type probes on the other hand decreases significantly at lower test frequencies. Magneto-resistors, Hall elements, flux gate sensors and superconducting quantum interference device (SQUID) sensors are potential alternatives to increase sensitivity at lower frequencies. Inspection systems based on some of these promising technologies, however, have not yet been developed for field applications. Further research and development is needed to reduce the complexity and costs of such systems and to further demonstrate their robustness and spatial resolution for practical applications.

Commercially available AMR and GMR sensors have been used in eddy current probes for low frequency testing [Mook. 2006]. It has been demonstrated that the read out electronics for these MR type sensing elements can be placed into the sensor housing together with the power supply necessary for sensor excitation and read out electronics. Magnetic field Sensors can effectively sense the magnetic field generated by a current carrying conductor or the secondary fields generated by induced currents in a test piece. Unlike coil type probes, the output of their GMR sensors is relatively flat over a wide frequency range. A number of publications are available on the use of GMR technology for detection of corrosion and fatigue in infrastructure components. For example, the use of magnetic sensing approach employing GMR gradiometers is reported for measuring both the rate and the extent of corrosion in metal samples. The technique has the potential to overcome some of the difficulties faced by traditional NDE techniques. Active and passive configurations may be used for remote monitoring.

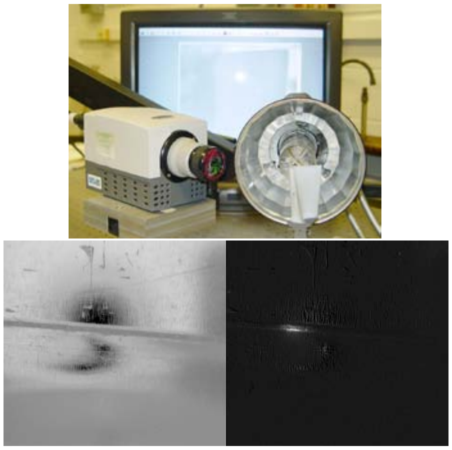
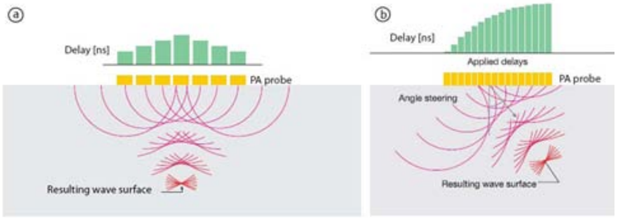


Figure 3.2 (top) Vibrothermography system at ANL for inspection of welds. (bottom) Raw thermal image of the weld zone (left) and differential image (right) displaying only the reflection from an embedded crack.

The discontinuities in solid materials can change the heat flow pattern and in turn result in the fluctuation of the temperature on the surface of the material. Thermal imaging techniques use this principle to measure the change of the surface temperature, which could be related to the condition of discontinuities present in the material. Infrared (IR) tomography (pulsed thermal imaging, thermal tomography, and vibrothermography) have been used an NDE method in a wide range of on-line inspection applications for condition monitoring of electrical equipment, power plant machinery and high-temperature equipment [Shen. 2010]. An infrared camera is commonly used as the detector device. Reported applications include monitoring the condition of insulation and heat loss for high-temperature pressure pipes, heat transfer in heat exchangers, detection of defects in composite pipes, leakage test for underground concrete pipes, assessment of steel plates using pulsed phase thermography, etc. Limited investigations have also been conducted on the use of IR tomography for detection of wall loss defects in steel pipes. Transient thermography uses inductive heating of electrically conducting materials to detect flaws (disbonds, delaminations and cracks). Compared to conventional flash thermography, the equipment is typically more compact and provides higher efficiency in energy delivery. Commercial systems are available that deliver up to 2 kilowatts of RF energy in a pulsed mode. Vibrothermography is another promising technique for detection of defects in welded joints (see Fig. 3.2). Reported applications of this technique have been primarily in the automotive and in the aerospace industry. Limited number of investigations, however, has been reported on the application of vibrothermography to detrection of damage and degradation in NPP components.

Probably 75% of all ultrasonic examinations performed in power plants involve conventional shear wave or longitudinal wave techniques [EPRI. 2007a]. The term “conventional” is used as a descriptive term for pulse-echo or pitch-catch examination using broad beams. However, these techniques have been found to be unsuitable for certain applications—in some cases even for detection, but more often because of unacceptable sizing error. In certain instances, flaw detection is inadequate because sufficient beam intensity cannot be produced in a conventional examination mode to detect the flaw of interest. This is normally attributable to flaw orientation (misorientation) relative to the achievable beam angle and/or is simply because detection requirements are beyond the detection capabilities of this type of examination, as affected by certain material characteristics including material attenuation. To address these detection and sizing limitations, a number of application-specific techniques and special transducers are required. Three types of transducers, focused, phased array, and EMAT, are briefly described below.

Focused beam examination provides both improved detection and improved size determination. Specifically, increased beam intensity, achieved by focusing the otherwise widely distributed energy into a small focal spot, provides increased reflection energy and therefore enhanced detection. If properly focused, backscatter from facets and other flaw surface irregularities can be sufficient for detection, even for flaws whose major orientation causes the specular reflection to be directed well away from the transducer. A focused transducer, as shown in Fig. 3.3, is used for operation within a fluid (e.g., water). A focusing lens is normally attached to the face of the transducer. The liquid is required to provide coupling between the shaped lens and the component surface geometry.



(a) Normal incidence **(b)** Angled incidence

Figure 3.3 Synthetic focusing with beamforming.

Phased array UT (PA-UT) is another method that is gaining more widespread applicability for inspection of NPP components. Advances in phased array UT (PA-UT) technology such as full-matrix capture are continuously being made. An array transducer contains a number of separate elements in a single housing, and phasing refers to how those elements are sequentially pulsed. Each of these elements (typically from 16 to 256) is connected to a separate pulser, receiver, and analog-to-digital converter. These elements are pulsed in such a way as to cause multiple beam components to combine with each other and form a single wave front traveling in the desired direction. Similarly, the receiver function combines the input from multiple elements into a single presentation. Because phasing technology permits electronic beam shaping and steering, it is possible to generate a vast number of different ultrasonic beam profiles from a single probe assembly. Among these, beam steering and focusing are the two basic profiles. The beam steering is achieved when a linearly varying time delay is applied along the array for both the excitation (pulsing) and reception, the array then produces an angled sound beam. The angle of the beam is controlled by the delay between adjacent elements and by the acoustic velocity in the propagation medium. On the other hand, if a nonlinear delay function is applied, the sound beam may be caused to focus at a specified distance. Other forms of beam shapes can be produced by the combination of these two basic profiles.

The benefits of phased array technology over conventional UT emanate from its ability to use multiple elements to steer, focus and scan beams with a single transducer assembly. Beam steering, commonly referred to as sectorial scanning, can be used for mapping components at appropriate angles (This type of image is already familiar to most people; the familiar wedge-shaped, black-and-white ultrasound images of fetuses are sector scans). This can greatly simplify the inspection of components with complex geometry. The small footprint of the transducer and the ability to sweep the beam without moving the probe allows for high-speed inspection as well as aids inspection of such components in situations where there is limited access for mechanical scanning. Electronic focusing permits optimizing the beam shape and size at the expected defect location, as well as further optimizing the POD. The ability to focus at multiple depths also improves the ability for sizing critical defects for volumetric inspections. Focusing can significantly improve signal-to-noise ratio in challenging applications, and electronic scanning across many groups of elements allows for C-Scan images to be produced very rapidly. While significant advancements have been made in this area over the past two decades, it is expected that the emerging PA-UT systems will provide enhanced capability for an increasing number of inspection and monitoring applications for SSCs in the nuclear power industry.

The EMAT method is essentially a variation of the UT method. In conventional ultrasonic examination, the ultrasonic wave in the component is generated by a form of electromechanical conversion, usually piezoelectricity. This is a highly efficient method of generating ultrasound, but it requires a fluid couplant to mechanically transfer ultrasound into and out of the component. The EMAT

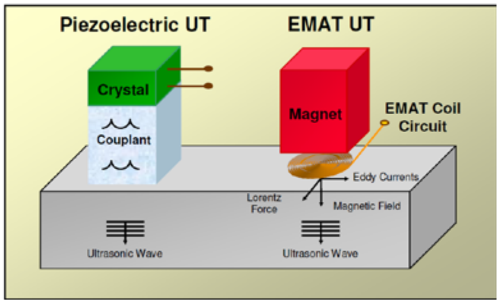


Figure 3.4 An EMAT shown alongside a conventional piezoelectric UT transducer.

technique uses electromagnetic acoustic interaction for elastic wave generation. It generates the sound in the part being inspected instead of the transducer. An inductive element close to the metal surface induces a mechanical disturbance in the metal, which produces the ultrasonic wave. In electromagnetic acoustic generation, the electromagnetic conversion takes place directly within the eddy current skin depth; therefore, no mechanical coupling with the component is needed. The metal surface of the component is its own transducer and the reception of the reflected signal is accomplished in a reciprocal way. This is a major advantage over ultrasonic transducers made with piezoelectric materials that require a coupling medium (typically water). Another advantage of EMAT over UT is that it can tolerate some variation in probe lift-off, so a thorough cleaning of the contacted surface is not necessary. A schematic diagram of an EMAT is shown in Fig. 3.4 [Innerspec Technologies, Inc.]. There are other advantages to the use of the EMAT technique. First, it is a nondestructive method with a very high speed and the possibility of being an automated system. It is well suited for large area scans as well as limited access areas where couplant application would be difficult. Also, errors due to couplant variation are eliminated. As no surface contact is required, minimal surface preparation is required and uniform scale layers do not have to be removed. The degree of reproducibility is also high. For the EMAT technique, available special wave modes include surface waves, vertically polarized shear waves, and horizontally polarized shear waves. It is also the only feasible ultrasonic examination method in areas where fluid couplant is prohibited to prevent component contamination. The disadvantages associated with the EMAT technique are that there is a very high insertion loss (as much as 50 dB) compared to conventional ultrasonic examination. This high insertion loss makes instrumentation design critical. The EMATs receivers are therefore specially designed and expensive units. Also, a substantial power supply is required and the cabling from the power supply to the probe defines the limits of the inspection area.

The Acoustocam® is a real-time, full-field, ultrasonic imaging system that has been developed by Imperium Inc.. The system operates by exciting a large area unfocused ultrasound transducer (used only as a source) which generates a plane pressure wave that strikes the target and is scattered. An acoustic lens in the Acoustocam collects the scattered energy and focuses it onto an ultrasound sensitive detector array, which is basically a piezoelectric array that has been deposited on to a conventional CCD array. The generating transducer is a PZT single crystal element such as Panametrics part # V307 driven with a high voltage (up to 1000V) pulse. Currently, the Acoustocam can be used either in immersion mode or with ultrasonic gel to image acoustic fields from the test structure onto the CCD array. Figure 3.5 shows a handheld Acoustocam and control/display unit at Northwestern University (NU). This is the I-500 with 120x120 pixels (each 0.080mm in size) resolution, which can provide full-field ultrasonic images at standard video rates of 30 frames/sec. The Acoustocam can be used to image cracks on the far side of a structure using shear waves. The adjustable extension tube permits the manipulation of the incidence angle in order to

Figure 3.5 Acoustocam® I-500 from Imperium. [www.imperiuminc.com]

obtain an efficient longitudinal-to-shear wave conversion. . Northwestern University's Center for Quality Engineering and Failure Prevention has successfully imaged second layer fastener cracks with this system [Zhou et al].

Laser ultrasonic testing (LUT) is another remote, noncontact extension of conventional UT. Conventional ultrasonic flaw detection techniques are based on the generation of an ultrasonic wave packet that travels through a structure and interacts with existing flaws within the structure. Either reflected or transmitted signals may be detected in pulse-echo or pitch-catch modes of operation. As might be expected, small flaws give rise to weak reflections or small changes in the amplitude of transmitted signals. These small variations are often too weak to be detected with existing laser detectors. For such cases, at NU we have proposed an alternate approach for ultrasonic detection of small surface-breaking cracks using laser-based techniques [Kromine et al, Sohn et al]. This approach does not measure the interaction of a well-established surface ultrasonic wave with a flaw, but rather monitors the changes in the generated ultrasonic signal as the laser source passes over a defect (see Fig. 3.6). Changes in amplitude and frequency of the generated ultrasound are observed which result from the changed constraints under which the ultrasound is generated when the laser beam passes over a defect.

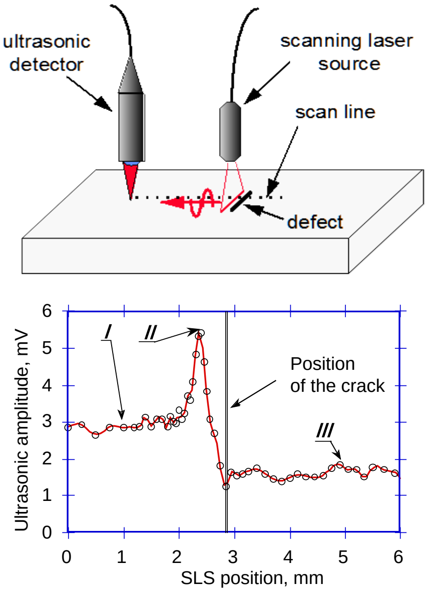


Figure 3.6 (top) Schematic illustration of SLS approach, and (bottom) Typical characteristic signature of ultrasonic amplitude versus SLS location as the source is scanned over a defect.

The SLS approach has been experimentally verified by testing of an aluminum specimen with a surface-breaking fatigue crack of 4 mm length and 50 μm width. The SLS was formed by focusing a pulsed Nd:YAG laser beam (pulse duration – 10 ns, energy – 3 mJ) into a line of 5 mm length and 0.4 mm width. A plot of the ultrasonic amplitude of the generated signal versus the SLS position as the latter was scanned over the crack is presented in Fig. 3.6. The SLS method was developed at NU, and the equipment is shown in Fig. 3.7 [Krishnaswamy. 2003]. We have demonstrated that the SLS technique allows the detection of surface breaking cracks as small as 0.125 mm in length, 0.063 mm in depth and 0.05 mm in width [Sohn et al]. The SLS method can also be used to size crack depths. The method has also been demonstrated for inspection of complex geometries.

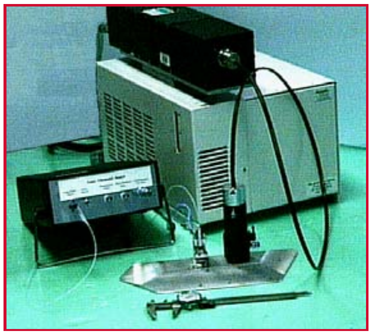


Figure 3.7 The SLS set up at NU consists of both fiberized generating lasers and optical or piezoelectric receivers.

Nonlinear acoustics/ ultrasonics technique holds promise as a viable quantitative means to characterize fatigue state in materials as the method is capable of probing the processes of crack nucleation and growth and of dislocation movement. Its sensitivity to microstructural attributes during the incubation period is often higher than that of the linear properties (velocity and attenuation). Higher order harmonics of the frequency spectrum, rather than the base frequency, are analyzed in order to extract nonlinear effects on the propagation of elastic waves in the material. For example, a number of studies have demonstrated that the second-harmonic amplitude generated by the opening and closing effect of an interface subjected to bias pressure by a passing acoustic wave can be used to estimate the state of fatigue damage. In those cases, the second-harmonic amplitudes exhibited maxima in presence of low external compressive stress. Small fatigue cracks essentially act as harmonic generators and the nonlinear signal in turn exhibits a maximum during crack growth process. Acoustic nonlinearity in many metals appears to increase monotonically with fatigue cycle (see Fig. 3.8). This correlation can be used to predict fatigue damage accumulation in the material.

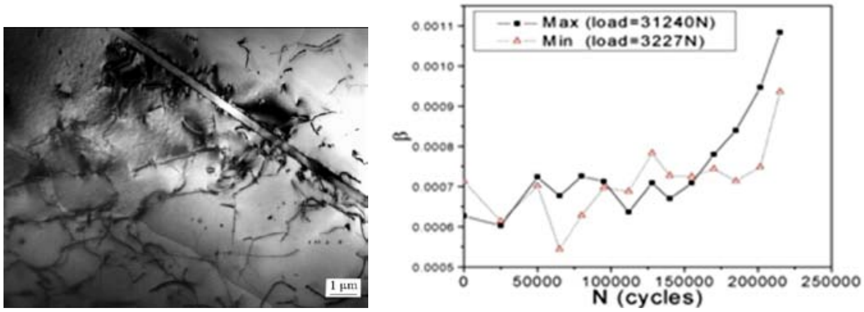


Figure 3.8 Nonlinear acoustics/ ultrasonics: acoustic nonlinearity in steel as a function of fatigue cycle [Cantrell. 1994].

Wave modes such as Shear Horizontal (SH)- waves and the wide class of guided waves offer new solutions for UT [Salzburger. 2009]. For pipelines, Ultrasonic inspection tools are not yet wide spread due to the difficulties of dry coupling using conventional piezoelectric probes. Limited inspections have been done using wheel probes. The dry-coupled EMAT technology offers the potential for high-speed inspection of pipelines. The operability of such systems for field applications is currently under investigation. Within a feasibility study it was shown that guided SH-waves propagating in the pipe wall in circumferential direction have a very high sensitivity for longitudinal crack-like defects and crack fields (SCC) independent from their location (outside or inside). Furthermore it was shown that by proper selection of the frequency the whole circumference of a pipe (36-in. diameter) can be covered by few SH-wave probes. By additional use of Rayleigh waves propagating at the inside surface as well discrimination between inside and outside defects as a defect sizing based on amplitude criteria is possible. Based on these results the concept of the EmatScan CD was developed. In close cooperation with the customer the pig was manufactured and tested. The completed pig can be seen in Fig. 3.9 during the preparation of a test-run. Also shown in that figure is the final version of the SH-wave probe with optimized wear protection together with a spring loaded suspension.

Figure 3.9 Prototype EmatScan CD pig for inspection of pipelines. Also shown (top corner) is the SH-wave probe in a spring loaded suspension [*Salzburger. 2009*].

Remote-field eddy current (RFEC) testing is another NDE method that is deployed with pigs (see Fig. 3.10). A typical RFEC probe consists of a circumferentially wounded single exciter coil and either single or multiple pickup elements placed at a fixed distance from the exciter. In principal, the presence of any discontinuity in the pipe wall results in perturbation of induced fields which may then be detected by the sensing elements. The use of multiple exciter and sensing elements allows deduction of circumferential position of flaws within the pipe wall. The main advantages of RFEC include the non-contact nature of the technique, its insensitivity to the presence of deposits, coatings, and liners, its ability to inspect tight bends, and light-weight instruments. The main limitations of the technology include slow speed of inspection and inability of RFEC method to discriminate between internal and external defects.

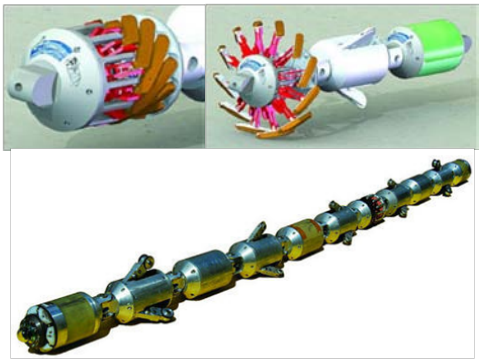


Figure 3.10 (top) Schematic showing the SwRI-developed RFEC modules consisting of excitation coil and sensing elements for inspection of 6-8 in.-diameter natural gas pipelines. (bottom) Explorer II robotic transport tool for RFEC probe developed by Carnegie Mellon University [*www.swri.org/4org/d18/nde/eddycurrent.htm*].

In-situ monitoring of extent and rate of corrosion can be performed using electrical resistance (ER) techniques including DCPD and ACPD and, when applicable, using electrochemical techniques such as linear polarization resistance (LPR). The use of guided waves in their various forms for NDE of piping is currently an active area of research. For insulated piping, employment of attachable piezoelectric transducers allows inspections to be carried out with minimal damage to the insulation material. Ultrasonic guided wave technology offers the potential to rapidly detect, locate, and characterize different flaw types and at different regions along the pipe (straight sections, bends, weldments). The emerging ER probe technology also has the potential to provide further improvement for in-situ and continuous monitoring of corrosion in metallic piping and other buried components and structures.

The ER technique is an on-line method of monitoring the rate of corrosion and the extent of total metal loss for any metallic equipment or structure. The ER technique measures the effects of both the electrochemical and the mechanical components of corrosion such as erosion or cavitation. It is considered as the only on-line, instrumented technique applicable to virtually all types of corrosive environments. An ER monitoring system consists of an instrument connected to a probe. The instrument may be permanently installed to provide continuous information, or may be portable to gather periodic data from a number of locations. Conventional ER probes are commonly equipped with a sensing element having a composition similar to that of the process equipment of interest. Reduction (metal loss) in the element's cross section due to corrosion will be accompanied by a proportionate increase in the element's electrical resistance. Practical measurement is achieved using ER probes equipped with an element that is freely exposed to the corrosive fluid, and a reference element sealed within the probe body. Measurement of the resistance ratio of the exposed to protected element is used to deduce information about material loss. Since temperature changes affect the resistance of both the exposed and protected element equally, measuring the resistance ratio minimizes the influence of changes in the ambient temperature. Therefore, any net change in the resistance ratio is solely attributable to metal loss from the exposed element once temperature equilibrium is established.

Measurement of wall thinning in piping has, in the past, required the removal of all the heat insulation used to clad the pipes [Odakura. 2009]. Hitachi has developed a guided wave inspection system that can screen several tens of meters of pipe for wall thinning at a time but only requires a small amount of heat insulation to be removed (see Fig. 3.11). Key features of the system are that a sensor containing a piezoelectric element can be attached directly to the piping and that use of proprietary signal processing significantly improves detection performance. The system can detect cross-section area change only 1%, not only in straight piping but also in small-diameter curved pipes. For large-diameter pipes, a partially attached guided wave sensor is currently under development with the aim of identifying the location of wall thinning within a comparatively small range from the sensor.

Figure 3.11 A guided wave sensor that can perform wall thinning inspection of piping [Odakura. 2009].

Residual stresses can have a profound effect on the performance of materials and the structural integrity of components. The measurement of RS is normally complicated by the superimposed and typically less important in service stresses. Therefore, it is important for the measurement method to be able to distinguish between the two types of stressors. The level of information provided by different RS measurement techniques can vary significantly. The selection of a particular measurement method should thus be made in view of its capability under specific set of test conditions. In some cases complementary techniques may have to be used to increase the measurement accuracy and reliability. Portable XRD instruments have been developed for in situ measurement of RS. Automated systems are commercially available for measurement of RS distributions [LAMBDA Research. 2001]. One common application of the technique is to quantify subsurface residual stress distributions resulting from the shot peening process that is introduced deliberately to relieve build up of stresses in a component. Alternatively, non-destructive monitoring of RS may be done by performing XRD on coupons (identical material and heat treatment as the component) placed at strategic positions on the component. Residual surface stresses induced by welding and other manufacturing operations play a critical role in the stress corrosion cracking (SCC) of many power plant components.

Conventional X-ray equipments are bulky and use high power X-ray tubes. Furthermore, the solid-state X-ray detector leads limit access to confined locations. Research sponsored by EPRI toward development of a compact X-ray system for situ measurement of surface RS is described in various technical reports [EPRI. 2000b, 2004]. In-situ non-destructive measurement of RS by a photothermal method is described in an EPRI technical report [EPRI. 2000c]. The report describes a procedure to measure RS in type 304 stainless steel components. The method involves measurement of deformation by laser shearography before and after local stress relief. Detecting these regions of tensile RS in power plant equipment can identify locations of potential SCC. Processing of the data for the system developed in that program was done by using multiple neural network (NN) algorithms. The system requires capturing of two images of the surface before and after the application of a local thermal input. A trained NN evaluates the residual stress sign and magnitude and can be trained to measure surface RS for different material types and surface conditions. Further research efforts are under way to develop practical photothermal systems for field use.

Ultrasonic techniques have also been investigated extensively for in-situ NDE of RS. As noted earlier, the technique is based on measuring the effect of stress fields on the propagation speed of ultrasonic waves. The residual stress is then calculated by using the acoustoelastic constant to compare the measured velocity to the known value of an unstressed part. Ultrasonic techniques have the potential of providing three-dimensional measurements. The primary disadvantage of this technique is the fact that the velocity of the ultrasonic wave is affected by other factors (e.g., surface condition, texture, and temperature) than the stress present in the material. The possibility of mapping of the stress fields in wall and welds in a mock-up pressure vessel was demonstrated using critically refracted longitudinal (LCR) waves [Bray. 2002]. The use of LCR waves for characterization of hydrogen induced stress in pipelines is described in another article [Bray. 2010]. The authors, however, point to the fact that each application is unique and material properties such as the acoustoelastic constant are critical. Also, unique probe designs and pressure application systems may have to be designed for different test conditions. Examples of other applications of LCR waves for mapping of stress fields in different components have also been reported by different groups. Further studies, however, are needed to fully demonstrate the applicability of this technology for field use.

The use of an electromagnetic acoustic transducer (EMAT) based system for subsurface measurement of RS was investigated. An important advantage of EMAT over conventional piezoelectric ultrasonic transducers is that the former does not require the use of couplants for excitation and detection of ultrasonic waves. The non-contact nature of EMAT allows measurements to be performed on components under actual operating conditions. The technique is also less sensitive to the surface condition of the part allowing measurements to be performed without surface preparations. The measurements were performed on sheet specimens made of Alloy 600 material. The coupons were subjected to chemical, thermal, and/or mechanical loading. To assess the capability of EMAT, surface characterizations of the in-plane residual stress components were performed using both XRD and ND methods. Investigations under this EPRI sponsored project are associated with measurement of the stress levels to assist with the weld mitigation process. Project results showed that use of an EMAT offers an alternative technique to XRD for obtaining stress measurements in a laboratory environment. Further research efforts are needed toward development of EMAT systems for field use.

The use of EC techniques for mapping of stress in various conducting materials has also been investigated. Eddy current measurements are capable of mapping the near-surface depth profile of the electrical conductivity. It has been demonstrated that EC conductivity measurements can be exploited for near-surface residual stress assessment in surface-treated nickel-base superalloy components [Yu. 2005]. To quantitatively assess the prevailing RS from EC conductivity measurements, the piezoresistivity coefficients of the material must be first determined using known external applied stresses. It is demonstrated in this paper that such dynamic calibration measurements should be corrected for the thermoelastic effect, which is always positive, i.e., it increases the conductivity in tension, when the material cools down, and reduces it in compression, when the material heats up. It was found that the electroelastic coefficients measured by the circular probe were equal to the average of those measured by the directional racetrack probe at parallel and normal orientations. It was noted that although the EC frequency could affect the accuracy of electroelastic measurements, the parallel and normal electroelastic coefficients are essentially frequency independent. Specialized probes for rapid imaging of conductivity and permeability using directional surface-conforming inductive, magnetoresistive, and EC sensors have also been developed. The results of past investigations in general have not clearly established the applicability of EC technique as a general purpose method for RS measurement. It is plausible that EC methods can be adapted to in situ or on-line monitoring of electrical property variations that are indirectly correlated with RS and in service stresses. Further investigations, however, are needed to establish such correlations for practical applications.

In-situ detection and monitoring of stress corrosion cracking (SCC) initiation and growth in LWRs have been investigated by a number of authors. The IAEA-TECDOC-1303 report provides the results of the Coordinated Research Project (CRP) on high-temperature (HT) on-line monitoring of water chemistry and corrosion in PWRs, BWRs and in research reactors [IAEA. 2002]. The report presents an overview of the state-of-the-art with regard to OLM of water chemistry and corrosion in operating reactors and on the development and qualification of promising monitoring techniques. In-situ HT measurements—without changing the physical and chemical state of the reactor water—can potentially overcome known disadvantages associated with conventional sampling procedures. The results of laboratory and field experiments by a number of international participants on the application of electrochemical corrosion potential (ECP), electric current noise (ECN), electrochemical noise (EN), and electric potential Noise (EPN) is presented. Although no clear consensus is provided on the status of the technology, some general remarks are made regarding future directions in HT OLM of water chemistry and corrosion. High-temperature OLM is needed primarily for secondary side measurements in PWRs. Despite their long history, ECP measurements used for such applications have not attained a widespread use. Also, it is not yet clear whether direct measurement of corrosion phenomena (corrosion rate, oxide-film characteristics, cracking susceptibility, etc.) will lead to plant implementation.

Monitoring the behavior of SCC in pressure-retaining and reactor-internal components in BWRs has been studied extensively using ECP measurements. No standard NDE method is currently available for in-situ monitoring of crack initiation through SCC. Various methods for in-situ determination of the tendency for crack growth have been used in commercial reactors both in recirculation piping and side-stream autoclaves and in-core to monitor irradiation assisted stress corrosion cracking (IASCC). Such crack-growth monitors are able to provide valuable real-time information. Optical methods and advanced electrochemical techniques (thin-film, contact electrical resistance, EN, etc.) are proving very useful for mechanistic studies. Further development of these sensor technologies, however, is required before they can be considered for field use. In-core crack-growth-rate measurements are in use for IASCC studies at various test reactors and have also been performed in commercial plants, but they cannot yet be regarded as a routine monitoring tool. In-situ monitoring can provide new and valuable information to plant operators. As stated in the report, full benefit from using OLM sensors will only be obtained if the data can be processed in real time using computer-aided diagnosis systems.

Early detection of significant microstructural change can prevent potential unexpected leakage. Evaluation of a number of innovative NDE techniques for monitoring of microstructural change associated with fatigue damage has been reported in [GRETE. 2004]. The micromagnetic NDE methods considered in that study included GMR magnetometry, MBN analysis, magnetic susceptibility (χ) measurement using a commercially available instrument (Ferromaster®), eddy current impedance using GMR sensor, remanence field measurements using Fluxgate- and SQUID-sensors. Specimens from three different austenite steel grades with adapted geometry were tested under low cycle fatigue (LCF). The microstructural changes related to fatigue damage (dislocation network and martensitic phase) were characterized using quantitative laboratory techniques (REM, ND, and XRD methods). Clear quantification of the influence of individual microstructure parameters on the measured NDE signals was noted as the main challenge in the analysis of the NDE results. The NDE methods evaluated included GMR sensors used as a magnetometer or to measure eddy current transfer impedance. All the NDE techniques that were used for testing the LCF specimens had high spatial resolution and by this the potential to detect strongly localized martensitic phases.

In general, good results were achieved by all electromagnetic NDE techniques. The NDE techniques based on magnetic properties and magnetic Barkhausen noise achieved only partially acceptable results. The MBN method in particular exhibited high sensitivy to internal stresses in the martensite phase, which is considered as a disadvantage for measuring martensite content. On the other hand, this sensitivity was shown to be useful for characterizing other parameters such as internal stresses. The other three NDE methods achieved only partially acceptable results due both to the limitations of the technique as well as unfavorable test conditions. In most cases the low martensite contents was identified as the primary limiting factor in determination of the fatigue state of the LCF-specimens. The comparison of both GMR measurements, carried out by IZFP and PSI, show differences in the results that have to be investigated. The test results generally demonstrated that while no single NDT technique was able to achieve satisfactory results for all different categories of fatigue, at least one NDT technique was able to determine the state of fatigue in each category. The best results were achieved by GMR based techniques. The same techniques were able to perform the measurements online and at elevated temperatures under controlled laboratory conditions. The MBN measurement technique, in addition to being sensitive to martensite content, was also shown to be sensitive to residual stresses in the steel. Thus it was recognized that its use would be most effective for fatigue monitoring when employed in combination with other complementary techniques. Finally, it was noted that the tests did not demonstrate the capabilities of the NDE techniques to monitor the accumulation of fatigue damage directly in a single specimen or specific location on a plant component. Further studies are needed to assess the performance of the NDE techniques under realistic field conditions.

Nondestructive methods for in-situ structural health monitoring are expected to play an increasingly greater role in the nuclear power industry because of a) more stringent safety requirements for critical structures, b) the need to reduce the cost of periodic inspections and maintenance, and c) advancements in distributed sensor technologies and on-board signal processing and data analysis capability. In an online structural health monitoring approach the overall structure to be interrogated can be divided into multiple safety critical zones. A critical zone is defined as the zone or area in which some unwanted events (e.g., structural damage) is initiated and the growth of which could eventually undermine the overall structural integrity of the system. For example, the welding area of a pipe can be an example of a critical zone. Each critical area can be monitored by a group of permanently bonded sensors of same or of different kind. Each group of sensors can be referred as a sensor node. To monitor the overall structure depending on the number of critical zones multiple numbers of such sensor nodes can be permanently bonded to the structure. The sensor nodes all together can be referred as sensor network. An unanticipated loading and changes in environmental condition can lead to unanticipated damage state in a system. The goal of the on-line damage estimator is to determine the state of the structure at a particular structural hot spot monitored by a particular sensor node. A particular sensor node can include single or multiple sensors of the same or of different type. For example to monitor a weld zone both active and passive sensors can be used. The passive sensors such as bonded foil strain gauges (e.g., resistive, capacitive, fiber optic) and thermocouples can be used for monitoring of mechanical and temperature load. A current state estimator algorithm can run in a local micro-processor attached to the sensor node or can run in a remotely placed computer with the sensor data transmitted via a wireless network.

Analogous to the passive sensing approach, active sensing can be employed for online estimation of damage states. Unlike passive sensing, the active sensing approach use an actuation device (transducer) bonded to the structure [Mohanty 2009 & 2010, Bakhtiari 2012]. These devices transmit predetermined narrow or broadband signals to the structure that is being interrogated. The corresponding sensor signals are acquired and used for estimation of the damage state. The detection and quantification capability of an active sensing system depends on the frequency band of the input signal. For example, high frequency ultrasonic and electromagnetic excitation signals could be used for detecting small defects or damage at an early stage (see Fig. 3.12). The current states information at a typical sensor node can be fed to an online predictor to forecast the future state of the structure. The predictor algorithm has to work in real-time. Nonlinear pattern reorganization techniques can be used to forecast the future damage states based on the current estimated states. The results of studies to date suggest that nonlinear pattern recognition in conjunction with machine learning approach could be used to identify complex fault trends and to further help more accurately forecast such events. The emergence of reconfigurable "smart sensors" that measure, process, self-calibrate, and wirelessly transmit (RF/microwave transmission bands) information is expected to significantly improve the ability to monitor the condition of critical components and structures in many industries. Integrated sensing systems are being developed and marketed for monitoring a wide range of physical and process parameters. Adaptation of smart sensor networks to structural health monitoring in the nuclear power industry is an active area of multidisciplinary research and development. Extensive performance demonstrations must be conducted and new codes and regulatory guidelines need to be developed before any such new technology gains widespread acceptability for monitoring of SSCs in the nuclear power industry.

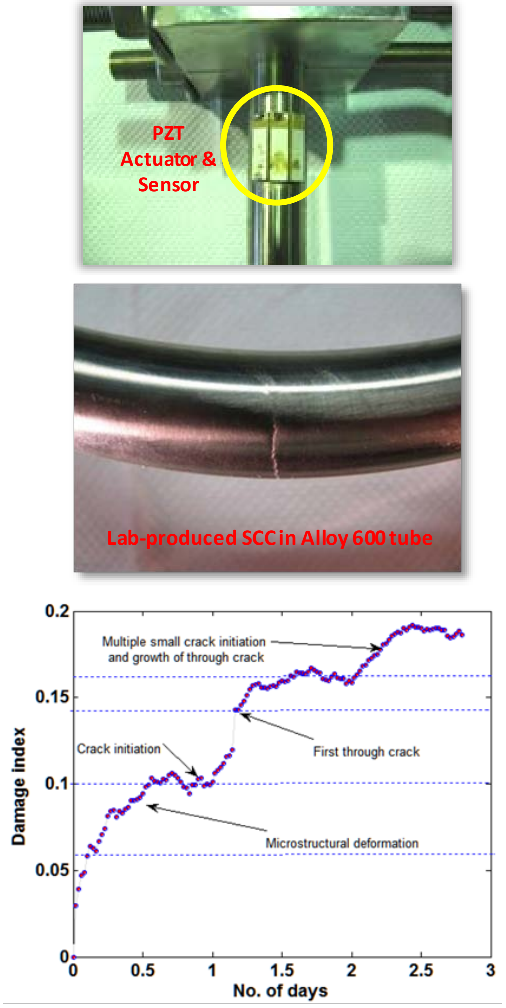


Figure 3.12 Monitoring of crack initiation and growth using broadband active sensing; (top) PZT sensor developed at ANL (middle) circumferential crack developed in U-bend apex region and (bottom) time-series damage state.

A critical challenge in damage detection is the fact that damage at the microscale cannot be detected by off-the-shelf sensors (see Fig. 3.13) . Although considerable research has been conducted on developing different sensing techniques, existing sensors pose considerable limitation on the size of detectable damage. This problem can be overcome by developing a hybrid framework that integrates physics based model with data from physical sensors, resulting in a robust framework for damage detection. The physics based multiscale models will provide useful information for identifying the presence of micro cracks, which are the precursors to macro level damage. The decision making component can use the hybrid data base to isolate, quantify and classify damage. Finally, the information can be fed to the prognosis module for predicting damage evolution and most importantly to estimate the residual useful life of a system. The development of efficient multiscale modeling techniques will eliminate the need to test every conceivable damage scenario for every system. This will result in improved state estimation and robust prognosis procedures capable of assessing system performance under a broad range of future loading conditions.

Multiscale models that span from material microstructure to macrostructure must consider major uncertainties, such as grain orientation and size at the microscale. Ultrasonic techniques can provide information on the defect structure in the bulk of the materials of interest, via the characterization of the dynamic behavior of grain boundaries and interfaces under ultrasonic waves. Treating the microstructure as the evolving state variable in the model will eliminate the need to test every conceivable damage scenario for every system. Specific objectives include: (i) identify system susceptibility to damage through material characterization and evaluate weak links in the microstructure as potential sites for damage nucleation; (ii) develop multiscale modeling for stochastic simulation of metallic microstructures including: constitutive models to predict the initiation and growth of damage and methodologies to characterize threshold crack growth behavior. The proposed procedure will also allow the calibration of the ultrasonic and other NDE techniques to quantify their capability to measure a material "state" that allows a better quantification of damage and better estimations of the potential for failure.

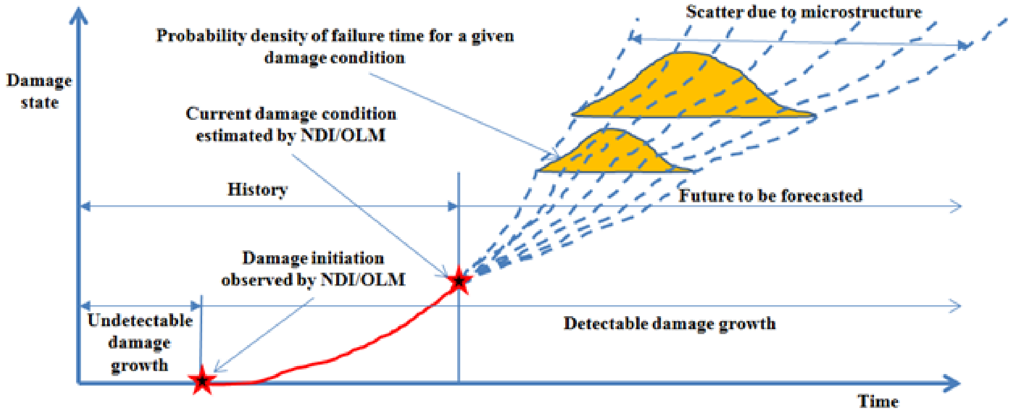


Figure 3.13 Schematic of degradation time-line of any structural system.

4.0 NDE Research & Development Roadmap for Detection of Fatigue Damage in Piping

The purpose of the non-destructive evaluation (NDE) R&D Roadmap for detection of Fatigue Damage in Piping is to support the Materials Aging and Degradation (MAaD) R&D pathway for the Light Water Reactor Sustainability (LWRS) program.

4.1 Fatigue NDE Workshop

A workshop was conducted to help identify the primary technical gaps and needs in detecting fatigue damage in RCS piping and in turn to predict the remaining useful life. The workshop was held at ORNL on August 2nd, 2012. The workshop was attended by subject matter experts (SMEs) from DOE national laboratories (ANL, INL, ORNL, and PNNL), academia, NDE equipment vendors, EPRI, and NRC (see Appendix A for the list of participants).

4.2 NDE Capabilities – Gaps and Needs

A brainstorming session was conducted next during which the SMEs were asked to provide their input to help define R&D actions needed to address the gaps discussed earlier. A major objective of the brainstorming session was to identify those sensors and techniques that have the most promising commercial viability and fill a critical inspection or monitoring need. The gaps identified by the working groups are listed in Table 4.1.

Some common themes regarding R&D needs identified by the working groups included techniques for early (pre-cursor) detection, fatigue crack initiation and growth monitoring (below current conventional NDE limits and for welds, base metals, bends/elbows, and long pipe sections), sensors for in situ materials characterization and for feature sizes usually examined by laboratory techniques (e.g., oxide coating assessment), global screening —as opposed to local examination methods—for early detection of damage, robust sensors for harsh environments (elevated temperatures – >200^{o}C), and development of improved signal processing, data analysis, and sensor fusion algorithms for better sensitivity to detection of incipient degradation.

A common theme among all the proposed R&D needs was the development of a sample library for the evaluation of all NDE and monitoring techniques (i.e., design of experiments to define numbers and classes). A number of NDE and monitoring techniques employing acoustic/ultrasonic, thermal, electromagnetic, micromagnetic, and optical (visual, laser) sensors were also identified as viable candidates for further evaluation. An overview of the proposed NDE and monitoring techniques is presented in this report. The NDE data will ultimately serve as input to mechanistic models to help more accurately predict the remaining useful life of components and in turn increase confidence in LTO of the existing fleet LWRs.

It was also noted at the workshop that a critical challenge in damage detection is the fact that damage at the microscale may not be detected by conventional sensors. Although considerable research has been conducted on developing different sensing techniques, existing sensors pose considerable limitation on the size of detectable damage. A viable approach proposed to overcome this problem is to develop a hybrid framework that integrates physics based model with data from physical sensors, resulting in a robust framework for damage detection and remaining useful life prediction.

Table 4.1 A summary of the main gaps (see App. C for details)

Gap	Wanted
• Sensitivity to early detection of fatigue damage • In-situ or on-line material characterization • Detection limit/sensitivity issues for existing NDE techniques • Detection and identification of real signals from among microstructure noise • Capability to measure below current detection limits of conventional NDE methods. • Need to determine size and dimension that needs to be detected • There are currently no methods that can reliably inspect CASS materials • PA-UT systems for reliable target discrimination from background/ microstructural noise in CASS • Global screening techniques (i.e., not point/localized sensing), and know what, where and how to measure. It is further essential to determine in advance what needs to be found. • Ability to assess the state of the material • Robust sensors for LTO in harsh environments • Maintain sensitivity under hostile environmental conditions (temperature, pressure, moisture, radiation, vibration, and corrosive environments) • Fundamental understanding of the correlation between measurable NDE parameters and changes in material properties and structure due to aging damage • Access to statistically significant library of samples (field and laboratory specimens)	• Early precursor detection (Grain boundary to tens of microns) for reliable RUL prediction. • The ability to perform in-situ in-plant measurement of material properties with comparable sensitivity to laboratory techniques (e.g., measurement of oxide coating to assess the stage of fatigue damage) • Capability to measure and monitor flaw initiation and growth below current conventional NDT limits for cracks in welds, base metals, bends, elbows, and along long pipe sections. • Phased array ultrasonic testing (PA-UT) system to provide improved target discrimination for more reliable inspection of cast stainless steel (CASS) piping – systems employing improved software-based tools for data acquisition, signal processing and data analysis • Global screening technique for early detection of damage • Data fusion and analysis techniques for material state assessment (effective algorithms for processing of large amount of data collected using different probing/inspection parameters that are correlated with different states of damage precursors (not geared for crack detection). • Sensors for harsh environments (i.e., elevated temperature, pressure, moisture, radiation, vibration, and corrosive environments) • Sensors that maintain sensitivity under hostile environmental conditions • Merging of NDE science and materials science through first principle physical study to understand what needs to be measured. Identify parameters measurable by NDE method that can be used to quantify aging effects (e.g., thermal aging) of nuclear reactor materials. • Provide appropriate set of samples – design of experiments to define numbers and classes needed

4.3 NDE R&D Roadmap for Environmental Fatigue Damage in Piping

Fatigue (caused by mechanical, thermal, or environmental factors) is the number one cause of failure in metallic components. The effects of environment on the fatigue resistance of materials used in operating PWR and BWR plants are uncertain. There is a need to assess the current state of knowledge in environmentally assisted fatigue of materials in LWRs under extended service conditions. It is also important to develop a mechanistic understanding of the role of water chemistry on the microstructural changes in the materials and on their fatigue properties. In parallel, implementation of effective inspection and monitoring programs (i.e., NDE techniques, sensors and systems for surveillance and monitoring, improved condition monitoring and operational assessment strategies, etc.) for timely detection and mitigation of fatigue damage to passive safety systems is of vital importance to achieving safe and economical long term operation (LTO) of the existing fleet of LWRs. Figure 4.1 depicts the role of NDE (sensors, inspection, and monitoring) in a synergistic R&D program for reliable assessment of RUL in RCS piping and associated components.

Improved sensors and NDE techniques are needed for inspection and monitoring of locations in LWRs where fatigue damage is more likely to occur. The locations include: weld heat affected zones; vulnerable spots associated with dead flow zones or places where the local chemistry is different from bulk chemistry; thermal stratification and thermal striping zones; locations affected by off-design transients; initiation sites caused by manufacturing flaws (e.g., scratches and dings). Some major technical gaps in the ability to detect and characterize environmentally assisted fatigue that needs special attention include measurement of oxygen/hydrogen content in the water during transients, wide-area sensors and instruments for detection of cracks that initiate from places not identified during design as high stress regions, and novel NDE techniques for early detection of cracks and for loss of protective oxides in view of the fact that the actual degradation locations are often hard to predict.

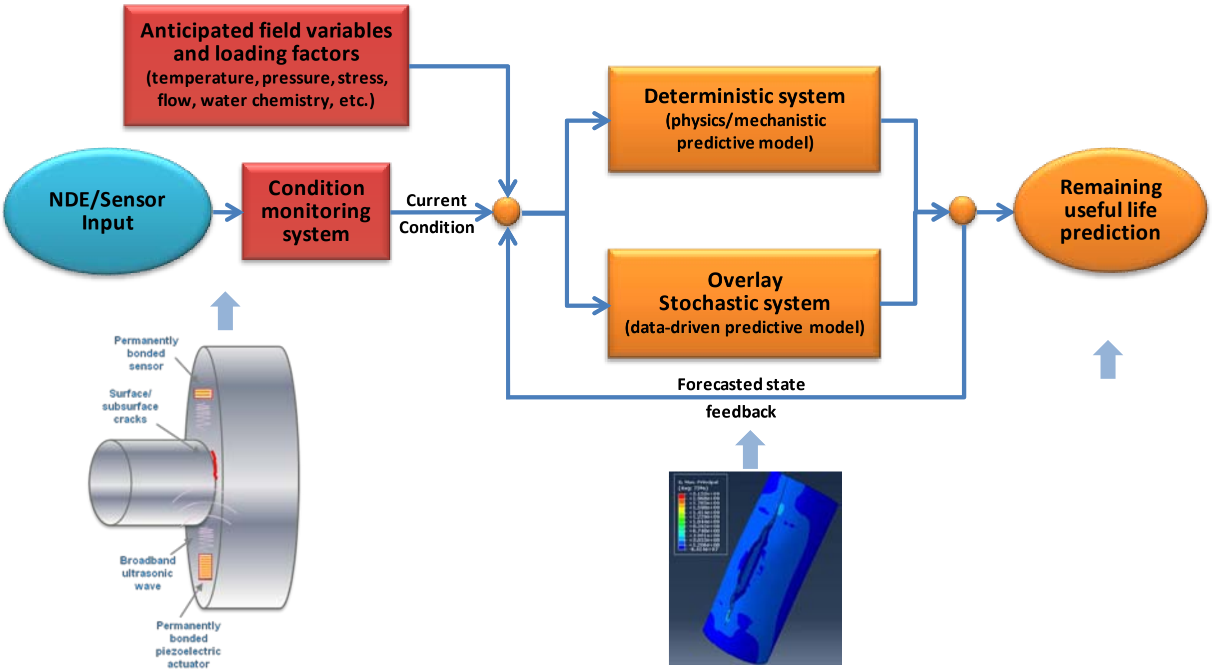


Figure 4.1 The role of NDE (inspection and monitoring) in predicting fatigue life.

As noted earlier, a brainstorming session was conducted at the LWRS NDE workshop on fatigue damage in piping based on which a number of core R&D needs were established. A major objective of that exercise was to identify those sensors and techniques that have the most promising commercial viability and fill a critical inspection or monitoring need. As a result, nine concept proposals for NDE of fatigue damage in RCS piping were developed. The ranking of the proposed R&D concepts are shown in Fig. 4.2. A more detailed description of the voting results on the proposed R&D needs is provided in Appendix C.

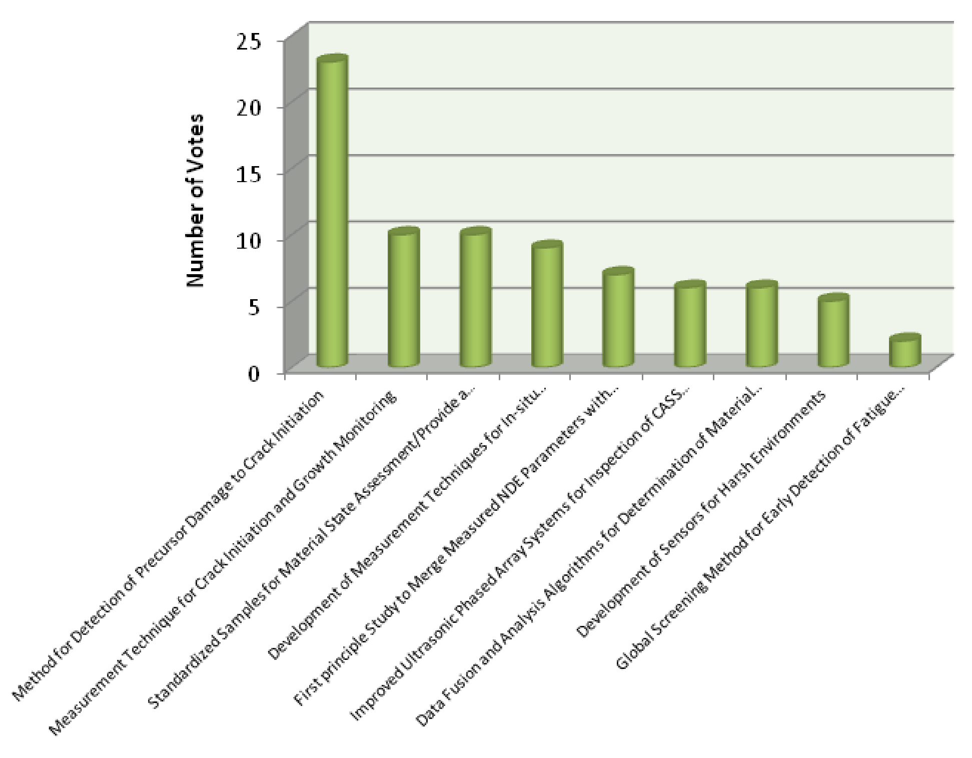


Figure 4.2. Proposal ranking by the working groups (see Table C.4.1 for details).

The following tables list the primary tasks and the associated milestones under the highest priority R&D concepts for NDE of fatigue damage in RCS piping. It is worth noting that the proposed NDE and monitoring technologies here in most part do not constitute an evolutionary improvement over the current state of the art. Instead, the proposed R&D areas identified in this roadmap address critical technology gaps that are important to long term management of fatigue in RCS components. The R&D proposals listed below in most part address the short term goals under the MAaD pathway of the LWRS program. The more fundamental R&D concepts (see Fig. 4.2 and Table C.4.1) that address longer term strategies could be added in the future as the need arises. Those R&D concepts will have to be refined over time based on the results of ongoing investigations and any emerging issues that could arise from LTO experience by the industry.

Project: Assemble library of fatigue specimens.
Note: this project must be initiated first before other programs can proceed

Task	Milestone	Budget
Assemble statistically viable library of sample for NDE technique Evaluation (common inventory of samples)	4Q, FY13	1 FTE
Design of experiments to define the numbers (statistically acceptable for POD studies) and classes (pre-programmed material and damage state) of samples needed		
Determine accessibility of existing inventories (seek to leverage existing samples)		
Obtain/manufacture specimens as needed	4Q, FY15	TBD

Project: Fatigue damage precursor detection.

Task	Milestone	Budget
NDE capability to detect and characterize damage/degradation (environmental fatigue) precursors.		$2.5M
Screen various sensing modalities and identify one or two of the most promising NDE techniques for early detection of fatigue damage (microcrack detection and characterization)	1Q, FY13	
Develop sensors and systems for laboratory testing	2Q, FY13	
Perform studies to address the physics of measurement–sensitivity to early degradation	4Q, FY13	
Develop appropriate signal processing algorithms for extraction of “real” signals from noise (unwanted signals) associated with structural features	2Q, FY14	
Implement appropriate coupling mechanism and sensor placement strategy	4Q, FY15	
Conduct capability demonstration tests on laboratory specimens	4Q, FY15	
Develop prototype system for field test	4Q, FY16	

Project: Environmental fatigue crack initiation and growth monitoring.

Task	Milestone	Budget
NDE capability for environmental fatigue crack initiation and growth monitoring in welds, base metals, bends and elbows, and along long sections of piping.		$2.5M
Screen and evaluate sensor systems and measurement methods (temperature, stress, strain, electrical conductivity, electrical permeability/magnetic susceptibility, etc.)	1Q, FY14	
Down select and optimize one or two of the most promising techniques based on the ability to ensure that defined detection limits are adequate	1Q, FY15	
Develop appropriate signal processing and data analysis algorithms	2Q, FY15	
Conduct sensitivity studies and optimize the test parameters including appropriate coupling mechanism and sensor placement and coverage	3Q, FY15	
Conduct tests on manufactured specimens acquired for parallel fracture mechanics studies	4Q, FY15	
Conduct capability demonstration tests	4Q, FY16	
Develop prototype system for field test	4Q, FY17	

Project: Sensor and system for in-situ material characterization (oxide coating assessment).

Task	Milestone	Budget
Develop measurement capability for in situ material characterization for features of the size usually studied in the laboratory. Of particular interest are sensors that provide material state awareness for key indicators of fatigue damage/degradation state (e.g., oxide coating assessment).		$1.5M
Identify sensors and NDE techniques with comparable sensitivity to laboratory material characterization techniques (e.g., XRD, DCPD/ACPD, etc.)	1Q, FY16	
Down select and optimize the most promising technique based on the prescribed sensitivity requirements obtained with laboratory techniques	4Q, FY16	
Conduct tests on manufactured specimens acquired for parallel fracture mechanics studies	1Q, FY17	
Develop appropriate empirical correlation models and compare with results from predictive mechanistic models	2Q, FY17	
Conduct sensitivity studies and optimize the test parameters including appropriate coupling mechanism	4Q, FY17	
Conduct capability demonstration tests	1Q, FY18	
Develop prototype system for field test	4Q, FY18	

Project: First principle study to merge measured NDE probing parameters with materials science.

Task	Milestone	Budget
First principle study to merge measured NDE parameters with materials science. The research will address fundamental understanding of the correlation between measurable NDE parameters (stress, strain, conductivity, permeability, microstructural change, etc.) and changes in material properties and structure due to aging. The work will constitute a synergistic approach involving NDE and materials science		$2.5M
Identify parameters measurable by NDE method that can be used to quantify aging effects (e.g., thermal, mechanical, and environmental aging) of nuclear reactor materials.	4Q, FY14	
First principle modeling of correlation between material properties (stress, strain, conductivity, permeability, microstructural change, etc.) with parameters measured by NDE (through acoustic/ ultrasonic, electromagnetic, thermal, optical, or radiographic probing methods)	4Q, FY15	
Experimental validation/verification of model predictions and refinement of models based on feedback from experiments	4Q, FY16	
Detailed technical report and modeling tool	4Q, FY17	

5.0 Conclusions

A key element of LTO of LWRs is expected to be the management of aging and degradation in materials that make up the passive safety system components. Understanding the likely degradation mechanisms in these materials under LTO is essential. At the same time, approaches to assess the condition of these materials in a nondestructive fashion will also be necessary to assure adequate safety margins and ensure that an effective aging management program can be set up for LTO. The objective of the MAaD R&D pathway is to create a greater level of safety through application of increased knowledge and an enhanced economic understanding of plant operational risk beyond the first license extension period. R&D is being conducted to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in NPPs. Data and methods to assess the performance of SSCs essential to safe and sustained nuclear power plant (NPP) operations are being developed. These R&D products will be used to define operational limits and aging mitigation approaches for materials in NPP SSCs that are subject to long-term operating conditions.

Integration of materials science understanding of degradation accumulation, with nondestructive measurement science for early detection of materials degradation is one of key concept identified in this roadmap document.

The purpose of the R&D Roadmap for NDE of fatigue damage in piping is to support the MAaD R&D pathway for the LWRS program. Furthermore, development of robust sensors for early detection and monitoring of damage is needed to enable extensive condition assessment of passive NPP components under LTO. One class of components whose aging may impact the safe extended operation is metallic Class 1 piping. In the context of LTO, the increased exposure to time-at-temperature, along with the effects of extended irradiation and accumulated operational stresses, is expected to result in a fatigue and cracking of Class 1 piping. Fatigue damage caused by mechanical, thermal, and environmental factors is the main cause of failure in metallic components. The long term effects of environment in particular on the fatigue resistance of materials used in operating PWR and BWR plants remain uncertain. The primary locations of concern are in the heat-affected zones around welds. These types of degradation, if left undetected, have the potential for coolant leaks from cracking.

In parallel with research on long-term performance of reactor metals, techniques for NDE of key reactor metals are needed toward development of technologies to monitor material and component performance. This R&D plan addresses the need for sensor development to monitor reactor metal performance. An initial step in this R&D plan is to examine the key issues including those associated with fatigue, environmental fatigue, and crack initiation, and available technologies. To address the research needs, the MAaD Pathway of the LWRS program supported a series of workshops with the objective of identifying technical gaps and prioritizing research in NDE methods. This document summarizes the findings of the workshop addressing NDE R&D for Fatigue Damage in Piping.

In summary, several core R&D concepts that address NDE technology gaps for long term management of fatigue damage in RCS piping have been identified in this report. The top four concept proposals are as follows:

1. NDE capability to detect and characterize damage/degradation (fatigue and SCC) at an early stage. The efforts should address the physics of measurement–sensitivity to early degradation and extraction

of “real” signals from noise (unwanted signals) associated with structural features. New sensor technologies may be needed to measure material property changes of interest (i.e., size and dimension of grain boundaries, commonly measured in tens of microns).

2. Measurement capability for fatigue crack initiation and growth monitoring in welds, base metals, bends and elbows, and along long sections of piping. Sensors and systems are needed to measure below the current conventional NDE detection limits for macrocracks. It is also imperative to ensure that the defined detection limits are adequate for LTO.

3. Measurement capability for in situ material characterization for features of the size usually studied in the laboratory. Of particular interest are sensors that provide material state awareness for selected early degradation modes (e.g., oxide coating assessment).

4. First principle study to merge measured NDE parameters with materials science. The research will address fundamental understanding of the correlation between measurable NDE parameters (stress, strain, conductivity, permeability, microstructural change, etc.) and changes in material properties and structure due to aging.

Although not listed above, a major common theme among all the proposed R&D needs was the development of a sample library for the evaluation of all NDE and monitoring techniques (i.e., design of experiments to define numbers and classes). It is expected that this task will be initiated first before other R&D programs could proceed. Finally, it should be noted that the NDE R&D activities under the MAaD pathway should be coordinated with activities being conducted in parallel under the other LWRS pathways. In particular, coordination between the MAaD and the II&C pathway will be necessary to ensure that the results of these activities could be appropriately included in the plant operation and maintenance activities.

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Appendix A.

LWRS NDE Workshops
Piping Fatigue Workshop Attendee List

August 2, 2012

Table A.1: Piping Fatigue Workshop Participants

Name	Affiliation
Sasan Bakhtiari	Argonne National Laboratory
Leonard Bond	Iowa State University
Cy Smith	Oak Ridge National Laboratory
Dwight Clayton	Oak Ridge National Laboratory
Pradeep Ramuhalli	Pacific Northwest National Laboratory
David Brenchley	Pacific Northwest National Laboratory
Wes Hines	University of Tennessee, Knoxville
John Lareau	WesDyne
James Wall	Electric Power Research Institute
Venu Varma	Oak Ridge National Laboratory
Thomas Rosseel	Oak Ridge National Laboratory
John Burke	Nuclear Regulatory Commission
Jamie Coble	Pacific Northwest National Laboratory
Richard Wright	Idaho National Laboratory
Mike Anderson	Pacific Northwest National Laboratory
Kevin Newell	Zetec, Inc.
Glenn Light	Southwest Research Institute
Saurin Majumdar	Argonne National Laboratory
Aditi Chattopadhyay	Arizona State University
Bradley A. Regez	Northwestern University
Carol Nove	Nuclear Regulatory Commission

Appendix B.

LWRS Piping Fatigue NDE Workshop Agenda
August 2, 2012

The purpose of this workshop is to develop content for the LWRS NDE R&D roadmap. The focus of this workshop will be on NDE techniques for detecting fatigue damage in piping.

7:30 am	**Registration**	
8:00 am	**Welcome & Workshop Overview**	Sasan Bakhtiari (ANL)
8:10 am	**Introductions**	David Brenchley (PNNL)
8:30 am	**Definition of the Problem**	
	Environmentally Assisted Fatigue in LWRs – A Review	Saurin Majumdar (ANL)
9:00 am	**Promising NDE Technologies & Methodologies**	
	Overview of Inspection and Monitoring Technologies	Sasan Bakhtiari (ANL)
	Small Bore Socket Weld Examination for Thermal and Vibration Fatigue	James Wall (EPRI)
	Emerging Ultrasonic NDE Methods to Detect Fatigue Damage in Pipes	Bradley A. Regez (Northwestern University)
	A Hybrid Approach to Fatigue Damage Monitoring and Prognosis	Aditi Chattopadhyay (Arizona State University)
10:15 am	***Break***	
10: 30 am	**Brainstorming Session**	Brenchley
11:15 am	**Define R&D Actions to Address Gaps**	Brenchley
WORKING LUNCH		
1:30 pm	**Group Reports & Discussion**	Brenchley
2:30 pm	**Prioritize R&D Action**	Brenchley
3:30 pm	**Break**	
4:00 pm	**What Next and Assignments**	Bakhtiari
4:30 pm	**Check-out**	Brenchley
5:00 pm	**Thank You & Adjourn**	Bakhtiari

Appendix C.
Workshop Process

C.1 Workshop Summary

The first presentation at the piping fatigue NDE workshop was made to help identify material degradation issues associated with environmentally assisted fatigue. Dr. S. Majumdar, a senior mechanical engineer at ANL, with extensive expertise in this area gave an overview of that subject. In summary, the presentation identified locations in LWRs where problems are more likely to occur. Those locations include: weld heat affected zones; vulnerable spots associated with dead flow zones or places where the local chemistry is different from bulk chemistry; thermal stratification and thermal striping zones; locations affected by off-design transients; initiation sites caused by manufacturing flaws (e.g., scratches and dings). The presentation also identified certain gaps in the ability to detect and monitor environmentally assisted fatigue cracking that needs special attention. Those include measurement of oxygen/hydrogen content in the water during transients (start up, shut down, etc.), wide-area sensors and instruments for detection of cracks that initiate from places not identified during design as high stress regions (i.e., surprise failure incidents), and novel NDE techniques for early detection of cracks and for loss of protective oxides in view of the fact that the actual degradation locations are often hard to predict.

A series of presentations were made subsequently on promising NDE and monitoring techniques for detection, diagnostics and prognostics of fatigue damage. The talks – S. Bakhtiari (ANL), J. Wall (EPRI), B. Regez/S. Krishnaswamy (Northwestern Univ.), and A. Chattopadhyay (Arizona State Univ.) – covered a wide range of conventional NDE and monitoring methods as well as emerging sensors and techniques, many of which are currently being evaluated for non-nuclear applications. A brainstorming session was conducted next during which the SMEs were asked to provide their input to help define R&D actions needed to address the gaps discussed earlier. Following the brainstorming and discussion session, the participants were divided into two groups. Each group was given the assignment to arrive at a proposal for R&D to address the NDE gaps in detecting damage and degradation associated with piping fatigue. Table 1.1 shows the three groups and their respective members:

C.2 Identify Gaps

What are the GAPS between the "measurements wanted" by materials experts and the "current NDE capabilities?" What do we need to be able to do with NDE that we can't do now? Gaps are the difference between NDE can do now versus what materials experts want it to do. The following GAPS were identified through brainstorming; the GAPS were assigned to one of three working groups.

Table C.2.1. Brainstorming Gaps Assigned to Group 1.

Group 1 – Piping Fatigue	
LEONARD BOND	
Measurements wanted:	Early Detection and screening for damage – How to get global scan? What, where and how to measure and what needs finding.
Current NDE Capability:	If you know where to look, NDT (eg. UT, EC, etc.) can size many cracks.
The GAP:	Global screening to find early degradation.
DWIGHT CLAYTON	
Measurement wanted:	Identification & characterization of cracks during early formation.
Current NDE Capability	Volumetric examination using ultrasonic phased array with characterization into "relevant" and "non-relevant".
The GAP:	These measurements need to be made easier & less time consuming.
JOE WALL	
Measurements wanted:	A method to inspect cracks & defects in cast stainless components.
Current NDE Capability	UT phased array – not adequate for many components.
The GAP:	There is currently no method to unambiguously inspect cast stainless for defects due to its microstructures.
SAURIN MAJUMDAR	
Measurements wanted:	Precursor to cracking, nucleated crack (micro-crack), state of material prior to cracking, state of oxide coating.
Current NDE Capability:	
The GAP:	
JACK LAREAU	
Measurements wanted:	Unknown fatigue loading in service.
Current NDE Capability	Monitoring techniques are generally indirect. Bragg grating etched on pipe surface could allow multiplexed fiber laser monitoring of multiple locations.
The GAP:	
SASAN BAKHTIARI	
Measurement wanted:	1. NDE techniques to detect incipient/precursors to fatigue damage (in-situ crack initiation and growth measurement). 2. OLM sensors and systems.
Current NDE Capability:	Mainly UT, VT, thermal, ECT (surface breaking flaws) done on periodic basis.

Group 1 – Piping Fatigue	
The GAP:	1. NDE methods for early detection of fatigue damage in welds, base metal, bends/elbows, and long lengths of tubing. GW-UT, Deep penetrating ECT, non-linear UT, Ultrasonic camera, Fiber optics. 2. OLM systems for diagnostics/prognostics of passive components with fatigue damage history. Active sensing (piezoelectric, strain gauge, EM, Fiber optic). Advanced OLM/OLP algorithms for early detection and residual life prediction.
MIKE ANDERSON	
Measurements wanted:	Early or precursor indications for detecting cracking.
Current NDE Capability:	Electromagnetics can be used for surface-generated flaws, ultrasonics for deep flaws.
The GAP:	Very small (precursor) information may not produce discrete signals for current NDE. Need to de-convolute these small signals from surrounding material noise.

Table C.2.2. Brainstorming Gaps Assigned to Group 2.

Group 2 – Piping Fatigue	
PRADEEP RAMUHALLI	
Measurements wanted:	Early indicators for cracking –where to measure.
Current NDE Capability:	Many potential NDE methods seem to work in lab setting.
The GAP:	Limited mechanistic (physics-based)/understanding of how precursor develop & how they influence measurements. For instance, how do stress, inclusions etc. at micro scale change the response (UT, EM, tec.) at macro scale. Fundamental (model-based) studies coupled to measurements are needed.
Measurements wanted:	Early indicators for cracking –where to measure.
Current NDE Capability:	Lab capabilities, sensitive to sensor placement.
The GAP:	1. Methodology for global sensor placement strategy that minimize number of sensors while providing sufficient information for global condition extraction from a small number of local measurements. 2. Sensor hardening issues also need to be addressed for deployment.
Measurements wanted:	Early indicators for cracking –what to do with data?
Current NDE Capability:	Same NDE in lab setting.
The GAP:	Analysis methods – what does NDE measurement mean at pre-macrocrack stage? 1. Need models of damage evolution, lab studies, to develop fundamental understanding of sensing behavior – help drive both sensor design & analysis. 2. Metric (damage index) based acceptability criteria for field apps. 3. Prognosis – what does data (time history) mean for component? How does small scale damage (local) affect large component (global) condition over long time history with uncertain sensor state information?
JOE WALL	

Group 2 – Piping Fatigue	
Measurements wanted:	A method to characterize/quantify the amount of fatigue damage a component has incurred prior to cracking to determine susceptibility.
Current NDE Capability	EM methods, nonlinear UT.
The GAP:	Current inspection practices focus on crack detection and sizing. A method to inspect for susceptibility of a material to crack would allow early detection of damage.
JAMIE COBLE	
Measurements wanted:	Non-destructive measurement of changes in microstructure that correlate to crack initiation (incipient fault detection).
Current NDE Capability:	Acoustic/UT methods? Eddy current? Laser source? (Not sure what methods are applicable).
The GAP:	1. Need to understand the underlying physical mechanisms that cause crack s to form. 2. Identify measurable changes in the microstructure. 3. Develop a sensor (suite) to measure these changes in operating environment. 4. Evaluate the measureable features for critical threshold values that would indicate incipient faults and associated probability/uncertainty.
CY SMITH	
Measurements wanted:	Modeling of physical characteristics of crack growth relative to NDE measurements.
Current NDE Capability	Limited
The GAP:	Lack of understanding of what NDE is trying to measure (micro-crack characteristics). Need evolutionary NDE methods supported by modeling.
VENU VARMA	
Measurement wanted:	How to better predict at initiation (< 3mm).
Current NDE Capability:	Able to detect larger cracks.
The GAP:	1. Better predictive NDE methods for determining when an initiation develops into a crack. 2. Better couplant, positioning & orientation capability, to reduce noise in NDE deployment .
GLENN LIGHT	
Measurements wanted:	Early stage crack damage caused by coalescence of small corrosion pit.
Current NDE Capability:	Ultrasonics using frequency spectrum analysis.
The GAP:	1. Knowing where to look – most are in HAZ, but some are in parent material – Need on-line monitoring to cover entire pipe loop. 2. Guide wave might work, but small crack sensitivity is not available – to find cracks in welds monitoring must begin with weld assumed to be in good condition.
BRAD REGEZ	
Measurement wanted:	Detection of early fatigue cracking in pipes and nozzles. Detection of stress corrosion cracking in pipes and pitting corrosion.
Current NDE Capability	Eddy current, Ultrasonics, Dye penetration testing, Radiography testing & Visual testing, Magnetic particle (Ferrous materials).
The GAP:	1. Develop a suite of sensors to be placed on pipes to detect and monitor both

Group 2 – Piping Fatigue	
	internal and external cracking events (acoustic emission). 2. Have an in-situ NDE system that can do periodic testing of pipes (guided waves?). 3. Develop a new inspection technology that is able to image the pipe both inner diameter and outer diameter.
ADITI CHATTOPADHYAY	
Measurements wanted:	Precursor to damage crack initiation, nucleation and growth.
Current NDE Capability	1. Ultrasonics 2. Thermography 3. Non contact CT 4. AE 5. Laser vibrometry 1-5 for meso-level crack, 5 applicable on specific
The GAP:	1. Merging developments in NDE with SHM techniques for real on-line monitoring 2. Fusion of mechanistic models with on-line SHM & prognosis 3. Sensors – extreme temperature, harsh environment 4. Self-sensing material 5. Self-healing? 6. Robust & efficient prognosis tools for life estimation.
KEVIN NEWELL	
Measurements wanted:	Identification of highly susceptible areas. Precursors of susceptibility. Areas of the material.
Current NDE Capability:	Subsurface: Dual channel UT imaging – promising? Non-linear UT? Guided Wave? Surface: ET
The GAP:	Identification of relevant precursors. Detection of critical flaw size. Ability to create representative test samples.

C.3 Develop Proposed NDE R&D Activities

Working groups were instructed to develop proposals that address specific gaps. They identified the research objectives, scope, schedule, budget, and outcomes for each proposed R&D effort. They also indicated the relative priority of each NDE R&D proposal.

C.3.1 Working Group Assignments

Following a brainstorming activity two working groups were formed. Each group was given the assignment to develop R&D proposals to address the gaps in NDE, sensors, and monitoring technology for aging management of fatigue in RCS piping.

C.3.2 Working Group Instructions

The working groups discussed the GAPS and then set about creating NDE R&D proposals to address the GAPS. For each proposal the group addressed the following elements:

- Measurement wanted:
- Current NDE Capability:
- The GAP:
- Research Objective:
- Scope of Work:
- Expected Outcomes:
- Schedule:
- Budget:
- Ranking:

The group ranked the relative priority of each NDE R&D proposal (high, medium or low) according to three criteria:

1. ***Relative importance*** in "filling a NDE Technology and methodology gap." Solving a big problem for MADD or a tiny one?
2. ***Achievability*** within the constraints of 3-4 years to do a field demonstration.
3. ***Acceptability***—likelihood that stakeholders will support its use. Is it mature enough to be accepted and put to use?

C.3.3 Working Group Reports

The results from the two working groups follow:

C.3.3.1 Group 1 (Head of the Group: Leonard Bond & Sasan Bakhtiari)

This group addressed seven combined areas of R&D needs. The topics are summarized in the following tables.

Topic 1. Develop and Evaluate Methods for Early Detection of Damage/Degradation Precursors	
Measurements wanted:	Early precursor detection
Current NDE Capability:	Electromagnetic induction techniques can be used for surface and near-surface measurements and UT techniques for deep flaws (discrete indications – relatively “large” flaws – cracks etc). Detection limit issues exist for all techniques. Identification of real signals from among microstructure noise is always a challenge.
The GAP:	Sensitivity to early detection Detection limit issues for existing NDE techniques Detection and identification of real signals from among microstructure noise
Research Objective:	Need to address the physics of measurement Demonstrate sensitivity to early detection of degradation and extraction of “real” signals from among structural features generated by background noise.
Scope of Work:	• Define a sample set • Screen various sensing modalities for possible application, • Address issues regarding detection of signals in presence noise • Down select technique(s) – one or more of the most promising approaches • Demonstrate proof of concept
Expected Outcomes:	Capability to detect and monitor early stage damage
Schedule:	4 years
Budget:	2.5 FTE/yr + Equipment ($50K) + Samples – use existing samples where possible
Ranking:	High

Topic 2. Measurement Technique for Crack Initiation and Growth Monitoring	
Measurements wanted:	Fatigue damage – crack initiation and growth monitoring
Current NDE Capability:	UT, visual, dye penetrant, and thermal imaging methods employed for periodic measurements to inspect welds, base metals, bends/elbows, and pipe sections. Emerging techniques based on guided wave and volume material UT, and near surface eddy current testing.
The GAP:	Capability to measure below current detection limits of conventional NDE methods (primarily for detection of macro-cracks). Reliable inspection of welds, base metals, bends/elbows, and long pipe sections. Ensure that defined detection limits are adequate under LTO
Research Objective:	Provide capability to measure and monitor flaw initiation and growth below current conventional NDT limits for cracks in welds, base metals, bends, elbows, and along long pipe sections.
Scope of Work:	• Define, develop samples and environmental test rigs • Evaluate sensor systems and measurement methods (e.g., temp, stress, strain, etc.) • Down select and optimize most promising techniques based on the ability to ensure that defined detection limits are adequate (under LTO) • Demonstrate technique performance
Expected Outcomes:	Sensors and new measurement modality for detection of incipient cracks and monitoring crack growth
Schedule:	3 years
Budget:	3 FTE/yr + Equipment ($150K) + Samples – use existing samples where possible
Ranking:	Medium–High

Topic 3. Development of Sensors for Harsh Environments	
Measurements wanted:	Sensors for harsh environments (e.g., elevated temp – 200^{o}C)
Current NDE Capability:	Piezoelectric, induction (eddy current/EM), optical fiber, and video/visual probes with limited temperature range.
The GAP:	More robust sensors for LTO Maintain sensitivity under hostile environmental conditions (temperature, pressure, moisture, radiation, vibration, and corrosive environments)
Research Objective:	Improve sensitivity of existing sensors Develop robust sensors for operation in harsh environments Ensure long term operation
Scope of Work:	• Need to assess the current state-of-the-art and identify gaps – Adaptation of existing sensors developed for non-nuclear applications – Assess technology maturity for nuclear applications (what is commercially available and what needs further R&D) – Select modalities and sensors with optimum sensitivity • Design and build sensor systems based on the results of initial evaluations • Develop coupling mechanism (non-contact, permanent bonding, detachable/clamp on, etc.) • Proof of concept demonstration
Expected Outcomes:	More robust sensors with improved sensitivity for LTO in harsh environments
Schedule:	4 years
Budget:	4 FTE/yr + Equipment ($200K) – new materials for sensors need to be first determined
Ranking:	High

Topic 4. Development of Measurement Techniques for In-situ Characterization of Materials	
Measurements wanted:	In-situ or on-line material characterization
Current NDE Capability:	Existing techniques can perform materials characterization for early degradation (e.g., oxide scale) under lab (SEM, XRD, DCPD/ACPD, etc.) and on mostly small scale samples.
The GAP:	The ability to perform in-situ in-plant measurements with comparable sensitivity to laboratory techniques
Research Objective:	Provide capability to perform in situ/ on-line materials characterization on site and for features of the size usually examined in laboratory).
Scope of Work:	• Identify techniques with required sensitivity for potential field deployment – Of particular interest is a technique for assessment of oxide coating as an indicator of fatigue damage state • Manufacture/acquire appropriate set of samples • Screen and rank methods • Down-select the most promising techniques for further development and demonstration/testing on realistic test rig
Expected Outcomes:	To demonstrate a sensor that can provide in-situ material state awareness for selected degradation modes (e.g., measurement of oxide coating to assess the stage of fatigue damage)
Schedule:	2 years
Budget:	2 FTE/yr + Equipment ($200K) + $50k (samples) – seek to obtain samples from industry
Ranking:	Very High

Topic 5. Improved Ultrasonic Phased Array Systems for Inspection of CASS Components	
Measurements wanted:	Phased array ultrasonic testing (PA-UT) system to provide improved target discrimination for more reliable inspection of cast stainless steel (CASS) piping – systems employing improved software-based tools for data acquisition, signal processing and data analysis
Current NDE Capability:	Commercial PA-UT products are available, however, their performance/capability needs to be improved for certain materials and applications – better arrays and drive software, more efficient analysis of large amount of data (3-D data sets/full-matrix capture) and enhanced signal interpretation software.
The GAP:	There are currently no methods that can reliably inspect CASS materials. PA-UT systems that give better target discrimination (background/microstructural noise suppression) in CASS, including improved signal analysis
Research Objective:	Provide PA-UT systems that give better target (damage/degradation) discrimination in CASS
Scope of Work:	• Compare capabilities/limits of current PA-UT systems (e.g., piezoelectric vs EMAT) for inspection of CASS • Seek to improve performance/capability using better arrays and drive software, data analysis (3-D data sets) and enhanced interpretation • Testing and performance demonstration
Expected Outcomes:	An ultrasonic PA-UT system that give better target discrimination in CASS components
Schedule:	3 years
Budget:	2 FTE/yr + Equipment (leverage current main units) + Samples – leverage existing CASS samples (if not cost prohibitive)
Ranking:	High

Topic 6. Global Screening Method for Early Detection of Fatigue Damage/Degradation	
Measurements wanted:	Global screening technique for early detection of damage
Current NDE Capability:	Conventional NDE works IF one knows where to look. The detection capability is technique dependent.
The GAP:	The need to have global screening techniques (i.e., not point/localized sensing), and know what, where and how to measure. It is further essential to determine in advance what needs to be found.
Research Objective:	Provide screening techniques, and know what, where and how to measure, and what needs to be found in order to give time to predict the remaining fatigue life.
Scope of Work:	• Evaluate promising global screening methods (e.g., diffuse field, GW-UT, non-linear UT, AE, etc.) • Define what parameters to measure • Determine sensitivity requirements and volume coverage/ measurement, which in turn dictates the number of sensors (sensor network) needed • Generate data needed for prognostics
Expected Outcomes:	New methods that provide long-term structural health monitoring.
Schedule:	3-4 years
Budget:	3 FTE/yr + Equipment ($50K/yr) + Samples – seek to leverage existing samples
Ranking:	Medium

Topic 7. Assemble Statistically Viable Sample Sets for Technique Evaluation	
Measurements wanted:	
Current NDE Capability:	
The GAP:	
Research Objective:	Provide appropriate set of samples – design of experiments to define numbers and classes needed
Scope of Work:	
Expected Outcomes:	Common inventory of sample sets
Schedule:	
Budget:	
Ranking:	

C.3.3.2 Group 2 (Head of the Group: Pradeep Ramuhalli)

This group addressed four combined areas of R&D needs. The topics, some of which overlap with those addressed by Group 1, are summarized in the following tables.

Topic 1. NDE Method for Detection of Precursor Damage to Crack Initiation	
Measurements wanted:	Precursor damage to crack initiation (Grain boundary to tens of microns) Applicable to different types of cracking – SCC and fatigue
Current NDE Capability:	Laboratory techniques are available for detection of micro cracks, some of which may not be truly nondestructive (require surface preparation and stringent coupling/probing requirements). A wide range of electromagnetic, acoustic/ultrasonic, and optical inspection techniques are available for detection of macro cracks.
The GAP:	Need to determine the sizes and dimensions of damage that needs to be detected. Spatial resolution (tens of microns), signal attenuation, and accessibility to the part pose major challenges.
Research Objective:	Improved defect detection sensitivity by improving sensors and the associated signal processing and data analysis algorithms
Scope of Work:	• Determine the change in the material property that needs to be measured. • Evaluate whether existing sensors are capable of measuring those indicators of damage or whether new sensors are needed. The effect of such test parameters as frequency, attenuation, grain structure, and probe access needs to be evaluated. • Post acquisition signal processing • Performance demonstration – Evaluation of NDE technique on standard set of samples
Expected Outcomes:	Robust sensor capable of detecting precursors to cracking
Schedule:	2-3 years
Budget:	2 FTE/yr + Equipment ($100K/yr) + Samples – seek to leverage existing samples where possible
Ranking:	High

Topic 2. Data Fusion and Analysis Algorithms for Determination of Material State	
Measurements wanted:	Data fusion and analysis techniques for material state assessment (effective algorithms for processing of large amount of data collected using different probing/inspection parameters that are correlated with different states of damage precursors (not geared for crack detection). The effort should rely on direct input from materials experts as to what information should be deduced from NDE data.
Current NDE Capability:	Large crack detection and small crack detection on surface. Unreliable crack detection. Algorithms exist for data fusion and analysis, but not applied to precursor NDE problem.
The GAP:	Ability to assess the state of the material.
Research Objective:	Develop data fusion for material state assessment
Scope of Work:	• Evaluate existing or develop multi-sensor data fusion algorithms • Develop new techniques for classification as needed
Expected Outcomes:	Algorithms to assess material state from NDE measurements
Schedule:	3 years
Budget:	2 FTE/yr + Computer hardware/software ($50K)
Ranking:	High – need, however, to defer until sensors are identified and/or developed and data is made available

Topic 3. Standardized Samples for Material State Assessment	
What is needed:	A library of standardized samples to evaluate NDE techniques for material state assessment
Current NDE Capability:	
The GAP:	Sample availability – perform design of experiments to determine numbers and classes needed
Research Objective:	Develop a standardized set of samples with pre-programmed material state
Scope of Work:	• Determine what samples are available and what additional samples are needed. • Identify test parameters and bounds • Define acceptable sample sizes and types (statistically acceptable number of each type for POD studies) • Fabricate samples as needed
Expected Outcomes:	Standard set of samples for material state assessment
Schedule:	2 years
Budget:	1 FTE/yr + Manufacturing cost ($2M – depends on the availability and accessibility of existing inventories)
Ranking:	High – need to be initiated first before certain other programs could proceed

Topic 4. First principle Study to Merge Measured NDE Parameters with Materials Science	
What is needed:	Merging of NDE science and materials science through first principle physical study to understand what needs to be measured. Identify parameters measurable by NDE method that can be used to quantify aging effects (e.g., thermal aging) of nuclear reactor materials.
Current NDE Capability:	
The GAP:	Fundamental understanding of the correlation between measurable NDE parameters and changes in material properties and structure due to aging
Research Objective:	First principle understanding of NDE measurements that are indicative of material susceptibility caused by in-service aging
Scope of Work:	• Synergistic approach involving NDE and materials science • First principle modeling of correlation between material properties (stress, strain, conductivity, permeability, microstructural change, etc.) with parameters measured by NDE (through acoustic/ ultrasonic, electromagnetic, thermal, optical, or radiographic probing methods) • Experimental validation/verification of model predictions
Expected Outcomes:	First principle understanding of material susceptibility in relation to NDE measurements
Schedule:	3-4 years
Budget:	2 FTE/yr (1 material scientist/engineer + 1 NDE engineer)
Ranking:	Medium – vain hope?

C.4 Prioritize Proposed NDE R&D Topics for Piping Fatigue

Following the brainstorming session, the proposed consolidated NDE R&D needs were prioritized and ranked based on an open voting process. The top three proposed R&D needs are as follows:

1. NDE capability to detect and characterize damage/degradation (fatigue and stress corrosion cracking) at an early stage. The efforts should address the physics of measurement–sensitivity to early degradation and extraction of “real” signals from noise (unwanted signals) associated with structural features. New sensor technologies may be needed to measure material property changes of interest (i.e., size and dimension of grain boundaries, commonly measured in tens of microns).

2. Measurement capability for fatigue crack initiation and growth monitoring in welds, base metals, bends and elbows, and along long sections of piping. Sensors and systems are needed to measure below the current conventional NDE detection limits for macrocracks. It is also imperative to ensure that the defined detection limits are adequate for LTO.

3. Measurement capability for in situ material characterization for features of the size usually studied in the laboratory. Of particular interest are sensors that provide material state awareness for selected early degradation modes (e.g., oxide coating assessment).

The table below provides the rankings for all the proposed R&D topics with those considered as overlapping subjects highlighted with the same color.

Table 6.1 Rankings for the proposed R&D topics.

Topic	Proposal Description	Number of Votes	Ranking
	Group 1		
1.	Develop and Evaluate Methods for Early Detection of Damage/Degradation Precursors	12	1
2.	Measurement Technique for Crack Initiation and Growth Monitoring	10	2
3.	Development of Sensors for Harsh Environments	5	6
4.	Development of Measurement Techniques for In-situ Characterization of Materials	9	3
5.	Improved Ultrasonic Phased Array Systems for Inspection of CASS Components	6	5
6.	Global Screening Method for Early Detection of Fatigue Damage/Degradation	2	7
7.	Provide a Statistically Viable Sample Set for Technique Evaluations	1	2’
	Group 2		
1.	NDE Method for Detection of Precursor Damage to Crack Initiation	11	1
2.	Data Fusion and Analysis Algorithms for Determination of Material State	6	5’
3.	Standardized Samples for Material State Assessment	9	2’
4.	First principle Study to Merge Measured NDE Parameters with Materials Science	7	4

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