# Assessment of NDE technologies for detection and characterization of stress corrosion cracking in LWRs

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**Abstract**. Stress corrosion cracking (SCC) in light water reactors (LWRs) has been a persistent form of degradation in the nuclear industry. Examples of SCC can be found for a range of materials in boiling and pressurized water reactor environments, including carbon steels, stainless steels, and nickel-base alloys. The evolution of SCC is often characterized by a long initiation stage followed by a phase of more rapid crack growth to failure. This provides a relatively short window of opportunity to detect the start of observable SCC, and it is conceivable that SCC could progress from initiation to failure between subsequent examinations when managed by applying periodic in-service inspection techniques. Implementation of advanced aging management paradigms in the current fleet of LWRs will require adaptation of existing measurement technologies and development of new technologies to perform on-line measurements during reactor operation to ensure timely detection of material degradation and to support the implementation of advanced diagnostics and prognostics. This paper considers several non-destructive examination (NDE) technologies with known sensitivity to detection of indicators for SCC initiation and/or propagation, and assesses these technologies with respect to their ability to detect and accurately characterize the significance of an SCC flaw. Potential strategies to improve SCC inspection or monitoring performance are offered to benefit management of SCC degradation in LWRs.

## 1. Introduction

The degradation of passive components in the current fleet of U.S. light water reactors (LWRs) is managed through periodic in-service inspection of components and plant aging management plans. This approach is challenged by certain degradation mechanisms that grow quickly and may conceivably grow to failure while eluding detection. In addition, extended operation of these plants beyond 60 years will pose additional challenges as new and unexpected forms of degradation occur. This potential has motivated efforts to create extensive tabulations of materials and their susceptibility to known or anticipated forms of degradation [1]. These tabulations help prioritize efforts to systematically treat anticipated issues before they occur rather than reacting to serious manifestations of these problems in the field. This proactive philosophy can also be extended to address the way degradation occurrences are managed. It is within this context that proactive aging management employing elements of advanced diagnostics, online condition monitoring (OLM), and prognostics have been proposed [2].

This paper focuses on an assessment of several NDE technologies for the detection and characterization of SCC as an initial step in developing proactive methods to manage SCC occurrences in LWRs. The significance of SCC degradation in LWRs is well documented [3, 4] and its continued relevance to the safe operation of LWRs is validated by expert panel summaries of LWR degradation issues [1, 5].

The U.S. Nuclear Regulatory Commission has recently established the Program to Assess the Reliability of Emerging Nondestructive Techniques (PARENT) [6]. This is a follow-on to an earlier international cooperative Program for the Inspection of Nickel Alloy Components (PINC) [7]. The goal of PINC was to evaluate the capabilities of various NDE techniques to detect and characterize surface-breaking primary water stress corrosion cracks (PWSCCs) in dissimilar-metal welds (DMW) in bottom-mounted instrumentation (BMI) penetrations and small-bore piping components. NDE methods assessed by this program included conventional ultrasonic testing (UT), phased array UT, eddy current testing (ET), and potential drop methods.

## 2. Stress corrosion cracking (SCC)

SCC can occur when three necessary preconditions are simultaneously present. These three necessary preconditions include: 1) the presence of a susceptible material, 2) the presence of tensile stress, and 3) the presence of a corrosive environment. Generally, SCC can propagate in intergranular (following grain boundaries – known as IGSCC) or transgranular (through grains – known as TGSCC) modes. Propagation can occur through a combination of both modes or may involve switching between modes as the crack progresses. In addition to the three preconditions mentioned above, SCC initiation is highly dependent on surface conditions. Areas of unusual stress concentration on a material surface due to surface imperfections caused by cold work or localized corrosion can trigger the initiation of SCC. Two major factors contributing to SCC susceptibility of austenitic stainless steels in boiling water reactors (BWRs) include thermal sensitization and cold work. Factors that most strongly influence PWSCC susceptibility in nickel-based alloys include carbide morphology and cold work [8].

The slip oxidation model of SCC relates crack advance to the rupture of stable oxide film at the crack tip and subsequent re-oxidation of exposed bare metal surface. Under this model, crack extension in the underlying metal is discontinuous and is facilitated by exposure to high-temperature water upon repeated cracking and regrowth of the oxide film on the surface at the crack tip. The periodicity of the oxide film rupture is determined by the strain rate and oxidation kinetics at the crack tip. The strain rate is determined by the external loading conditions and oxide growth while oxidation kinetics are determined by environmental and material chemistries [9]. SCC growth rate is often related to the strain rate at the crack tip. A linear relationship between SCC growth rate and strain rate at the crack tip has been proposed by [10]. Crack growth rate saturates for very high strain rates as the metal at the crack tip is continuously exposed. In the other extreme, crack growth can become disrupted.

The Swedish Nuclear Power Inspectorate (SKI) has performed a systematic evaluation of service-induced crack characteristics. This evaluation was initially performed using information from failure analysis reports from the nuclear and non-nuclear industries through 1994 [11, 12]. Cracks are assessed according to crack type and material with several different crack types considered in the analysis. The mean COD for SCC cracks analyzed ranged from 16–30 µm. In many instances, the crack tip radius could not be measured, however, given the data available; the mean crack tip radius appears to be ~ 1 µm or less for SCC cracks.

A process for growing SCC cracks in qualification specimens has been developed, referred to as the MISTIQ process [13]. It is reported that through the MISTIQ process, SCC flaws with characteristics similar to those observed in the field and compiled by Wale [12], can be manufactured. This technique is used to qualify several types of inspection including ultrasonic, visual, eddy current, and radiography.

There has been a recent push to obtain a more fundamental understanding of SCC through atomistic modeling. This effort has been called the “Quantitative Micro-Nano (QMN)” approach to predicting stress corrosion cracking. Meetings on QMN have been held in 2010 and 2011 and another meeting is planned for 2012 [14].

## 3. Monitoring technologies

### *3.1. Bulk ultrasonics*

An overview of UT reliability is provided in a recent report [15]. UT inspection reliability has improved over the years and has been the detection method most often used for inservice inspections at nuclear power plants (NPPs) [16]. The variability in UT reliability in NDE is affected by several different factors. Several papers and reports are cited in Moran et al. [15], which show that the performance of UT inspections are affected by different flaw sizes and shapes, grain structure of materials, frequency and beam angles, interference by detected and refracted signals, couplant variations, human factors in acquiring and analyzing data, curvature of the component and surface interferences, weldment design and orientation and location of the flaw relative to the angle of the signal beam. An in-depth review of the influence of essential flaw parameters on UT examinations is provided by Kemppainen and

Virkkunen [17]. This review is performed considering the compilations of crack characteristics by SKI [11, 12] and from the perspective of validating or confirming the representativeness of flaw specimens for NDE qualification.

A discussion of performance demonstration (PD) testing in Japan for depth sizing of IGSCC cracks using phased-array and conventional UT testing is provided in Sasahara and Hide [18]. Japanese PD testing is based on ASME Section XI, Appendix VIII with some modifications. Improvements in the reliability are observed as a result of implementation of PD. The best sizing accuracy is observed using both conventional and phased-array techniques. Errors of 0.17 mm for depth sizing and a standard deviation of 2 mm are observed. As part of the NRC's PINC program, blind testing was performed on test blocks with a variety of SCC and fabricated flaws in DMW and BMI components. The results of this study indicated that similar performance was achieved by using either conventional UT or phased-array UT methods individually, and that significantly greater performance could be achieved by using a combination of the two methods. Applied individually, the POD achieved using conventional and phased-array UT methods on flaws with 10-mm depth is approximately 50% [6, 7].

The use of synthetic aperture focusing techniques (SAFT) and phased array with SAFT to characterize SCC flaws in nuclear reactor components is under investigation by the BAM Federal Institute for Materials Research and Testing with beams from multiple angles to help reconstruct flaw images [19].

### *3.2. Visual testing*

A comprehensive overview of visual testing can be found in the ASNT Nondestructive Testing Handbook, Volume 9 [20]. Visual examinations are frequently performed on nuclear reactors to determine the condition of critical inner surfaces. Critical surfaces include high stress points at the junctions of nozzles and the vessel or nozzles and the cladding. Visual examinations are also performed to determine the condition of various parts such as studs, bolts, and nuts as well as vessel bushings and closure washers.

In coordination with the U.S. Nuclear Regulatory Commission and Electric Power Research Institute, PNNL has been assessing the capability of remote visual inspection techniques as a proposed means for replacing the use of volumetric techniques for the inspection of NPP components [21, 22]. A parametric study was conducted which examined the impact of six parameters on crack detectability using visual techniques. These six parameters included crack size, lighting conditions, scanning speed, camera resolution, surface specularity, and surface conditions. In addition, NUREG/CR-6943 [21] reviews the prior relevant work relating probability of detection with crack opening displacement (COD) including studies by Efsing et al. [23], Enkvist [24], and Virkkunen et al. [25]. The COD of service-induced cracks in nuclear components is determined to be one of the most important parameters affecting the reliability of visual inspections. The factors influencing the COD of SCCs are complex due to the interactions of the environment, material susceptibility, and stress. Generally, more susceptible materials, higher stresses, and more aggressive chemical environments will exhibit SCCs with greater COD. It is noted that that measurements of COD are not correlated with flaw depth.

Some important conclusions of NUREG/CR-6943 [21] are that remote visual inspections can effectively detect cracks with CODs greater than 100 µm provided conditions are not overly unfavorable. Conversely, cracks with CODs smaller than 20 µm cannot be effectively detected. The reliability of detecting cracks with CODs between 20 and 100 µm is strongly dependent on several factors including camera magnification, lighting, and human factors. The impact of oxide scales or layers on crack detection is not yet well understood.

### *3.3. Acoustic emission*

Several source mechanisms are possible for the generation of acoustic emission (AE) during SCC degradation, the origins of which are related to mechanical fracture or corrosion processes [26]. Sources associated with mechanical fracture include brittle crack jumps, plastic deformation, decohesion of inclusions or precipitates, martensitic transformation, twinning, microcracking, and slip deformation. Corrosion-related sources include dissolution of metal, evolution of hydrogen gas bubbles, and cracking or breakdown of oxide films. The emissivity of these sources depends significantly on the material and exact crack advance or corrosion process taking place. Brittle fracture generates discontinuous AE that is directly linked to crack growth processes and the corresponding AE signals have relatively large amplitudes [27]. Yuyama [26] provide an overview of the early work that characterized the excellent emissivity of high strength materials and materials suffering from hydrogen embrittlement.

The anodic dissolution process has been described as disappointing from the perspective of AE monitoring because it is more of a chemical process versus a mechanical one and does not result in straining the lattice of the underlying material [27]. Gerberich et al. [28] and Jones et al. [29] postulated the rupture of ligaments behind the advancing crack front as a source of AE during fracture assisted by anodic dissolution. Recently, Alvarez et al. [30] have investigated SCC processes in several materials and have concluded that ligament rupture is a consistent source of AE during fracture assisted by anodic dissolution.

Several investigations have noted that electrochemical corrosion processes are clearly emissive. Many studies point to evolution of hydrogen as a significant source of AE during pitting, crevice, and uniform corrosion [31-33]. Jones and Friesel [34] and Cakir et al. [35] have attributed AE during pitting corrosion to the rupture of salt caps or oxide films covering gas filled pits. Others have also attributed observed AE activity to metal deformation [36], rupture of passive films [31, 36], or instantaneous stress changes on the surface [37].

Oxide films can produced detectable AE when they crack or spall as a result of significant stress accumulation due to growth or thermal cycling. Detectability of film cracking depends on the thickness of the oxide film. Cracking of oxide films several microns thick is detectable; whereas, passive films on the nm order thickness are not detectable through cracking activity [26].

Reactor coolant noise may be severe enough at low frequencies (≤ 0.2 MHz) to prevent effective SCC monitoring with AE. Defect detection is facilitated at higher frequencies for which noise is significantly reduced [38, 39]. However, attenuation of AE signals is usually severe at higher frequencies and only localized AE monitoring of damage is feasible.

### *3.4. Potential Drop (PD) techniques*

Direct current potential drop (DCPD) voltage measurement is now routinely used to measure crack length in compact tension (CT) specimens during laboratory-based LWR SCC testing and corrosion fatigue testing [40-42]. Its applicability is strongly dependent on the environment, material resistivity, specimen geometry, and required data acquisition rate. Highly optimized systems can track 1 µm crack length increases. Important aspects include: (1) Maintain tight control over specimen temperature because resistivity fluctuates with temperature. (2) The medium inside the crack should be low conductivity relative to the material being cracked to ensure maximum resistance increase as the crack extends. LWR water has very low conductivity compared to typical metals of interest. (3) Statistical noise can be minimized by averaging together a large number of voltage samples to generate a single DCPD measurement. If a crack is moving slowly, then this allows for a larger number of measurements that can provide greater sensitivity. (4) The CT specimen geometry promotes a straight crack that spans the thickness of the specimen. A straight crack front that runs the entire thickness of the specimen provides the greatest sensitivity in crack length measurement. (5) Another important aspect of the DCPD measurement is that the phenomenon causing cracking should not significantly alter the resistivity of the material. For example, the plastic deformation that typically takes place in a J-integral fracture toughness test leads to an increase in resistivity of the material that causes a false crack length increase. Another example would be that testing of some metals at elevated temperature causes microstructural evolution that changes the material resistivity and results in false crack length changes. Methods for compensation are sometimes possible. With the advent of high-power desktop computers and inexpensive finite element modeling packages, the viability of DCPD crack length measurement to a particular system can now be easily assessed, and factors that are going to be most responsible for crack length resolution can be determined.

Although not normally used for field measurements on reactor components, potential drop techniques were evaluated as part of the NRC's PINC program. Several potential drop techniques were considered in the program including DCPD, alternating current PD (ACPD), induced-current PD (ICPD), and closely coupled probe potential drop (CCPD) [6, 7].

### *3.5. Eddy current techniques*

PWSCC has historically been a major cause of steam generator tube failure, particularly in Alloy 600 tubes, and often occurring at u-bend regions, expansion regions, and in dented tube regions [43]. Outside diameter stress corrosion cracking (ODSCC) is another form of SCC degradation that can occur in the crevice region of the tube-to-tube sheet transition, sludge pile, tube support plates, or free span regions [44]. Eddy current technology has largely been applied to inspect for SCC degradation in steam generator tubing with the development of several types of probes including bobbin coils, magnetic rotating pancake coils (MRPC), and array probes [44, 45]. A round-robin exercise has been performed to assess steam generator inspection reliability using bobbin coil and MRPC technologies. This exercise employed a steam generator mock–up at Argonne National Laboratory with several types of simulated degradation. Eleven teams participated in the round-robin and their detection results were used to develop POD curves as a function of flaw significance. Variables that are considered to have an impact on performance include inspection equipment and procedure, location of the flaw, and noise level [46].

An assessment of eddy current testing for the detection of cracks in cast stainless steel (CSS) reactor piping components was performed by Diaz et al. [47]. Eddy current testing is specifically sensitive to a variety of factors (apart from flaws) that affect the response of the eddy current probe. These factors include the electrical conductivity and magnetic permeability of the material, frequency of the probe, geometric features of the component and the probe *lift-off*. Electrical conductivity can be affected by several factors including the material composition, presence of conductive coatings, ambient temperature, residual stress, work hardening, and heat treatment. The magnetic permeability can have significant spatial variation in a material as a result of several factors including macrostructure (grain type and orientation), residual stress distribution, and thermal aging affects. Eddy current response is impacted by geometric effects such as material thickness and proximity to boundaries. Surface irregularities and curvature can impact the consistency of probe lift-off and subsequently have a negative impact on inspections. In the studies performed by Diaz et al. [44], it was found that eddy current techniques were adequate for detecting and sizing surface-breaking defects in CSS material, but the technique was not effective for measuring the depth of such defects. CSS material exhibits a greater level of noise than isotropic, homogenous, or fine-grained materials.

Of the techniques considered as part of the NRC's PINC program, eddy current testing exhibited the highest level of performance for detecting surface breaking SCC and fabricated flaws in DMW and BMI components [6, 7].

### *3.6. Emerging methods/other methods*

Other techniques to consider for SCC inspections and monitoring include electrochemical techniques, radiographic techniques, and guided ultrasonic waves (GUW). A variety of electrochemical techniques exist to measure corrosion processes [48]. Digital radiographic techniques may be used for piping inspection and monitoring though it is mainly used for the inspection of fabrication flaws and is very sensitive to the orientation between beam angle and direction of flaw penetration [15]. GUW techniques are quickly evolving and are increasingly being considered for inspection and monitoring applications by nuclear utilities [49]. In looking beyond current capabilities that are effective in detecting and characterizing large cracks and corrosion, there is interest in those methods capable of detecting and monitoring degradation at earlier stages. Several NDE technologies are emerging as potential candidates to meet early degradation measurement needs. These include micromagnetic techniques such as magnetic Barkhausen noise (MBN) and B-H curve analysis. MBN is sensitive to imperfections which resist the motion of magnetic domain walls [50, 51]. Nonlinear acoustic/ultrasonic techniques are also promising with research indicating that nonlinear techniques are more sensitive to micro-damage than conventional linear ultrasonic techniques [52]. Extensive reviews of this area are provided in the papers by Raj et al. [50] and Bond et al. [53]. A paper by Ramuhalli et al. [54] presents recent MBN and nonlinear acoustics measurements obtained from mechanically loaded specimens. The NRC's PARENT program includes an open round-robin testing phase designed to assess emerging/novel NDE methods. Some of the emergent methods to be considered include non-linear acoustic/ultrasonic, laser ultrasonic, and microwave microscopy [6].

## 4. Conclusions

Several strategies can be pursued to improve the management of SCC in LWR components. These strategies include: 1) Increase SCC degradation sampling and minimize influence of human factors through automation and on-line monitoring; 2) Improve SCC detection and monitoring reliability through use of diverse, multiple, and complementary methods or techniques; 3) Improve SCC detection and monitoring effectiveness by employing technologies that are sensitive to earlier stages of SCC degradation. Significant implementation challenges will require innovative strategies that anticipate where SCC degradation is likely to occur to guide and optimize sensor placement and the development of ruggedized sensors to withstand the harsh operating environments for on-line monitoring. A paper by Montgomery et al. [55] describes efforts at PNNL to foster the science and technology needed to address these goals for managing general forms of degradation in materials related to nuclear power generation.

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