Online condition monitoring to enable extended operation of nuclear power plants

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Abstract: Safe, secure, and economic operation of nuclear power plants will remain of strategic significance. New and improved monitoring will likely have increased significance in the post-Fukushima world. Prior to Fukushima, many activities were already underway globally to facilitate operation of nuclear power plants beyond their initial licensing periods. Decisions to shut down a nuclear power plant are mostly driven by economic considerations. Online condition monitoring is a means to improve both the safety and economics of extending the operating lifetimes of nuclear power plants, enabling adoption of proactive aging management. With regard to active components (*e.g.*, pumps, valves, motors, etc.), significant experience in other industries has been leveraged to build the science base to support adoption of online condition-based maintenance and proactive aging management in the nuclear industry. Many of the research needs are associated with enabling proactive management of aging in passive components (*e.g.*, pipes, vessels, cables, containment structures, etc.). This paper provides an overview of online condition monitoring for the nuclear power industry with an emphasis on passive components. Following the overview, several technology/knowledge gaps are identified, which require addressing to facilitate widespread online condition monitoring of passive components.

Keyword: online monitoring; condition monitoring; diagnostics; prognostics; nondestructive evaluation

1 Introduction

In a post-Fukushima world, there is a heightened awareness of the importance of the roles of safety and security in the affordable operation of nuclear power plants (NPP). Plant life management (PLiM) has become a critical topic as life extension is considered for the existing fleet, as new monitoring technologies are considered for use in new-build large reactors, and as attention turns to opportunities to meet sustainable energy needs using both light water and, in the longer term, advanced small modular reactor designs [5].

The current global fleet was developed with plant design lives that were typically either 30 or 40 years. In the USA, which has many of the older plants, a process has been developed to enable operators to seek a 20-year license extension, providing operation from 40–60 years. Of the 104 U.S. plants, to date 71 plants have been granted the license extension, the majority of the remaining plants are expected to seek an extension, and 9 plants are now in longer-term operation (LTO). In looking to meet future energy demand, two delayed plants are being completed by the Tennessee Valley Authority (TVA); construction has been approved for two Westinghouse AP-1000 plants at the Vogtle, Georgia site; and approval is expected soon for two further plants at the V.C. Summer site, where site preparation is in progress. Attention is now turning to consider the feasibility of extended LTO for the legacy fleet (beyond 60 years) and any additional refurbishments or modifications that will be needed to ensure safe operation through the end of a second license extension, and also to manage new plant builds with a 60-year design life.

It is the management of materials issues that will ultimately determine the safe operating life limits for a nuclear power plant. Since the start of plant operation for the current light-water reactor (LWR) fleet, new degradation processes have appeared on average at a rate of once every seven years [6]. To address these issues in support of NPP license renewal over the past decade, various national and international programs have been initiated [7] and major reports and databases developed by both regulators, with the U.S. Nuclear Regulatory Commission's (NRC's) GALL – Generic Aging

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Lessons Learned [8], and Proactive Materials Degradation Assessment Expert Panel [9], and industry, with the Electric Power Research Institute (EPRI) Issues Management Tables (IMT), and Materials Degradation Matrix (MDM) [10-12]. The international community has also focused on the issues with the IAEA's PLiM [13], OECE-NEA's Committee on the Safety of Nuclear Infrastructure (CSNI), European Groups through the NULIFE Program, the Materials Aging Institute in France, PMMD Programs in Japan and Korea, and related work in a number of other countries that are all recognizing the challenges faced in extended LTO for NPP [7].

The components, systems, and structures in NPPs are in general categorized in two classes: active or passive. Active components are managed under a maintenance rule, and this covers items such as pumps, motors, valves, and compressors. Passive components, which include the reactor pressure vessel, piping, core internal components, the containment structure, and cables, are managed using in-service inspections (ISI) performed in the context of an aging management plan (AMP). Degradation found under an ISI program is managed through mitigative actions, changes in designs, and repair or replacement of degraded components. This reactive, *find and fix*, approach has maintained the safety of operating reactors but it is becoming increasingly expensive as plants age. Attention is now moving to consider the potential for more proactive management of both active and passive components [7,14,15].

At a recent meeting, the authors presented an overview of some of the challenges facing extended operation of LWRs as well as the operation of advanced reactors, which are expected to consist of new materials, operate at higher stressor levels, and for which relatively little operating experience has been accumulated. Online monitoring of active and passive NPP components was offered as a means to address these challenges [16]. This paper provides an overview on the status of online condition monitoring for the nuclear power industry with an emphasis on passive components. Section 2 describes how aging issues and economic aspects of plant operation are important considerations for the development of plant life management strategies. Section 3 highlights and summarizes the status of "life beyond 60" (LB60) and issues or needs in support of improved management of materials degradation for extended operation of nuclear power plants. Section 4 provides a snapshot of the state of online measurements for the nuclear power industry, placing an emphasis on the status of tools for online measurements of passive components. In Section 5, a brief overview of prognostics and its implementation in nuclear power plants is discussed. This concerns the processing and interpretation of data collected from online measurements to determine current and predict future component condition. In Section 6, several overarching technology/information gaps are identified for which devoted research efforts would greatly facilitate online condition monitoring of passive components. Some brief conclusions are provided in Section 7.

2 Plant life management

Aging and degradation mechanisms in materials are usually classified into two main categories: (1) those that affect the internal microstructure or chemical composition of the material and thereby change its intrinsic properties (*e.g.*, thermal aging, creep, irradiation damage), and (2) those that impose physical damage on the component either by material loss (*e.g.*, corrosion, wear) or by cracking or deformation (*e.g.*, stress-corrosion, cracking). The phenomena of degradation due to aging in NPPs is complex and requires sophisticated, state-of-the-art science and technology procedures to detect, monitor, quantify, and track processes to ensure continued safe and reliable operation. An effective aging management program and supporting measurement systems, along with data analysis, are needed to determine what mitigating action is needed.

The material degradation phenomena are in many cases based on longer-term interactions that may not necessarily represent an immediate challenge to safety. However, impact on system efficiency (capacity factor), costly unplanned outages, and reduction of safety margins should not be ignored. As plants continue to age, more proactive approaches are being proposed [17], representing a fundamental change from most current inspections that are reactive and based on *find and fix*.

For nuclear power plants, the operations and maintenance (O&M) costs are estimated for various plants and countries at between 40 and 70% of the overall generating cost. In the USA, O&M is at the higher end of the range (~60–70%) and fuel costs are at about 15–30%. Of the O&M costs (in the USA) about 80% are related to the costs of labor. In both Europe and North America the situation is further complicated by the problem of an aging workforce and a limited supply of new workers [18]. In the rapidly growing Asian economies and developing countries, there are also challenges in meeting the skilled workforce needs [19].

Active components are now routinely managed and replaced through plant maintenance programs. The state-of-the-art has advanced significantly in recent years, and condition-based maintenance and increasingly online monitoring is being employed [20]. There are already known to be significant additional opportunities to deploy new technologies when power uprates and upgrades, including modernization of instrumentation and control systems, are implemented at existing facilities. The economic benefit from a predictive maintenance program can be demonstrated from a cost/benefit analysis. An example is the program for the Palo Verde Nuclear Generating Station [21]. An analysis of the 104 U.S. legacy systems has indicated that the deployment of online monitoring and diagnostics has the potential for savings at over $1B per year when applied to all key equipment [22].

For passive components, these are currently managed through in-service inspection. The potential and use of online monitoring is still at the R&D stage. There has been a growing recognition that nuclear plant condition assessment based on nondestructive testing (NDT) for metal components at the time of fabrication followed by intense inspections during outages requires the adoption of conservative assumptions with regard to addressing detected indications and intervention. With aging plants there is the risk of "surprises" at outages, which can cause extended down time. There is a concern that current inspection frequencies may not match rates of degradation growth, which adds support to the conclusion that online monitoring is needed for both current and new reactors.

Reviews of requirements looking towards more holistic and proactive plant management approaches provide opportunities to define, develop, and deploy advanced online surveillance, diagnostic, and prognostic techniques that continuously monitor and assess the health of NPP structures, systems, and components (SSC). These technologies can potentially deliver enhanced condition awareness and improve advanced outage and maintenance planning through early warning of conditions and components that require attention while at the same time minimizing exposure to many future and unknown risks.

3 Life-beyond 60 years

The move in the USA towards consideration of extended longer-term operation or LB-60, the second period of license extension from 60–80 years, is serving to focus attention on the science and technology needed. In 2009 the U.S. DOE-NE sponsored a Light Water Reactor Sustainability (LWRS) workshop focused on advanced instrumentation, information, and control (II&C) systems, and human-system interface technologies [17]. Three R&D strategic program goals were identified as being central to better understanding the challenges posed by nuclear power plant aging, including advanced instrumentation systems. The primary activities identified in this II&C area were:

- Sensors, diagnostics, and prognostics to support characterization and prediction of the effects of aging and degradation phenomena on critical systems, structures, and components (SSCs)
- Online monitoring of SSCs and active components, generation of information, and methods to analyze and employ online monitoring information
- New methods for visualization, integration, and information use to enhance state awareness and leverage expertise to achieve safer, more readily available electricity generation.

The LWRS strategy has been recently further refined and updated [23], but these needs remain. Initial progress in several areas been described in multiple reports [24,25].

Another LWRS workshop was held in 2010 focusing on online monitoring (OLM) technologies. The workshop was organized to bring industry and researchers together to identify the technology and research gaps associated with the nuclear industry's OLM needs. The intent of the workshop was also to foster collaboration between industry and research organizations in addressing the gaps [26].

From 2007–2011, the International Atomic Energy Agency (IAEA) facilitated a cooperative research program (CRP) to establish the state-of-the-art in online monitoring, surveillance, diagnostics, and prognostics technologies for the equipment and structural health monitoring (SHM) in the nuclear industry and to identify the technology gaps and research needs of the nuclear industry with respect to surveillance, diagnostics, and prognostics [27].

EPRI has been engaged in LTO research activities and has collaborated with the U.S. DOE-NE through the LWRS program. In 2011, EPRI hosted a Nuclear Online Monitoring workshop consisting primarily of participants from U.S. utilities and vendors of advanced pattern recognition (APR) software. Utility members shared experiences with regard to the implementation of APR software and building effective business cases to encourage investments in online monitoring technologies for offsetting maintenance costs. EPRI also updated members on the development of a fault signature database for diagnostic assessments and, eventually, remaining useful life (RUL) estimations [28].

Among the various activities looking at the issues that surround LB-60, the NRC is seeking to facilitate the establishment of an International Forum for Reactor Aging Management (IFRAM) as a part of its activities in a program called proactive management of materials degradation (PMMD). The IFRAM activities are seeking to better facilitate information exchange and enable enhanced coordination in identifying gaps and issues that need to be addressed [29].

4 Online measurements in NPPs

Within a nuclear power plant, the reactor's instrumentation and control system provides online monitoring of various process and environmental parameters, including temperatures, pressures, flows, and neutron flux, in a range of locations [30]. These data are not, in general, directly related to the effects of environmental conditions on life utilization for plant systems and components. The current state-of-the-art for online monitoring of component condition, as opposed to process parameters, in NPPs includes systems that measure reactor noise, acoustic signals and vibration in various forms (*e.g.*, loose parts monitoring and leak monitoring) [31-34]. In addition there are aspects of process sensor recalibration that are addressed, in some plants, employing online monitoring [27,35]. Mostly, however, online monitoring for degradation of system elements within the nuclear power industry has been as part of condition-based maintenance programs, and it has been limited to active components.

4.1 Active components

When the state of the art is reviewed [15,36], it appears that many, if not all, active components, which are the pumps, valves, motors, and other moving parts, in an NPP can potentially be well-managed and routinely diagnosed, analyzed, and upgraded as needed using a combination of periodic and online condition-based maintenance (CBM). These approaches are being implemented by the industry.

The basis for the application of advanced diagnostics and prognostics to active components outside the nuclear industry has a longer history. It emerged, in large part, from the use of vibration signatures and is routinely employed for pumps, valves, motors, and other rotating machinery [37,38]. The potential for application in the nuclear industry has been considered in several studies, including work on elements in a pilot-scale service water system [39] and wireless sensors on rotating equipment at a research reactor [40]. Distributed sensors and computing can be used on "smart" components, which provide a condition or degradation metric. An example of this is a type of hand-held unit for monitoring on a valve in the service water system is shown in Fig. 1.

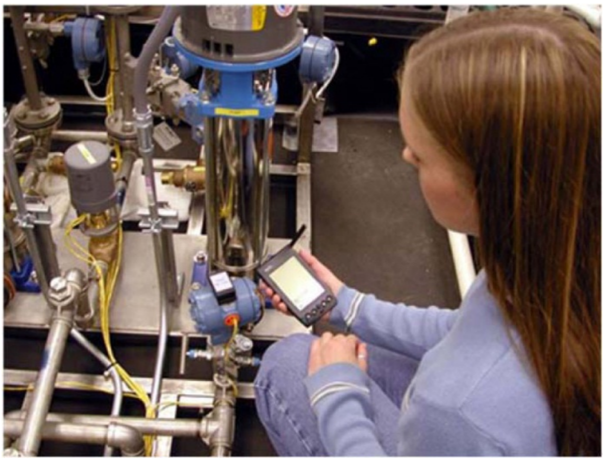

Fig. 1 Motorized valve with sensors and wireless tag is shown with a hand-held reader [16]. Reproduced with permission from ICI/Korea Nuclear Society.

There is currently an EPRI program looking at online monitoring for active components focused on legacy plants, and there are a number of utilities who are deploying both wireless networks and monitoring for active components. Data analysis is based on pattern recognition for anomaly detection. These techniques are basically automating current manual CBM tests and signature collection. The success with this technology is causing the community to look beyond diagnostics to prognostics and beyond locally monitored CBM to site and then centralized fleet-based CBM [41].

Online monitoring is now being deployed as part of new LWR plants; for example, by AREVA, where 256 online measurement channels are included in the new reactor at Olkiluoto in Finland [42]. New designs for small modular reactors and advanced nuclear power plants, which will require longer intervals between scheduled outages and also shorter outages, are seeing enhanced online monitoring and advanced diagnostics as essential.

4.2 Passive components

It is increasingly expected that the management of the passive components in legacy systems, including the feasibility and the economics of deploying enhanced monitoring, will determine the acceptability of extended longer-term operation. The passive systems of particular interest include the pressure vessel, Class 1 piping, concrete structures in the form of those which support and surround the nuclear island and the containment, buried piping, core-internals and cables. Passive components can also include some of the structural components that are related to active components—such as large pump or valve cases.

In looking beyond current capabilities that are effective in detecting and characterizing large cracks and other degradation/corrosion/erosion, there is interest in those methods capable of detecting and monitoring early degradation. Several researchers worldwide are engaged in PMMD-related research programs, which include detection and monitoring of early degradation [29]. Significant activities in this area include work by Dobmann et al. [43] and Ramuhalli et al. [44,45]. There are extensive reviews of this area in papers by Raj et al. [46] and Bond et al. [47].

4.2.1 Monitoring large defects in metal components

Rules for the ISI of SSCs in commercial LWRs are provided by Division 1 of Section XI of the ASME Boiler and Pressure Vessel Code. The rules and regulations outlined by the Code are mandatory and are enforceable in the USA through Title 10 of the Federal Code of Regulations, Part 50 (10 CFR 50). The requirements of the Code are often generic and more specific guidelines are often issued by industry or owner's groups (*e.g.*, Nuclear Energy Institute [NEI] and EPRI through the Boiling Water Reactor Vessels and Internals Project [BWRVIP] and Materials Reliability Program [MRP]).

Inspection and examination methods are classified in Article IWA-2000 as visual, surface, or volumetric examination methods. Specific nondestructive technologies are called out for the surface and volumetric examinations in Article IWA-2000. These are shown in Table 1. However, provisions exist within the Code to accommodate the use of alternative examination methods assuming they are demonstrated to be superior or equivalent to the specified methods.

Table 1 Summary of NDE techniques included in Section XI of the ASME Boiler and Pressure Vessel Code.

Surface Examination	Volumetric Examination
Magnetic Particle	Radiographic
Liquid Penetrant	Ultrasonic
Eddy Current	Eddy Current
Ultrasonic	Acoustic Emission
Visual	

Rules for inspection schedules are provided in Article IWB-2000. Generally, a "phased" schedule is applied to examinations, with the specification that all required examinations for a given category be distributed over three inspection periods within a 10-year inspection interval. The Code establishes a hierarchal and layered sampling strategy for the inspection of components based on their perceived importance to safety. Systems in direct contact with reactor coolant (Class 1) receive the most stringent and populated inspections because it is important to maintain the coolant inventory and contain radioactivity. Secondary systems (Class 2), such as those that remove primary heat or are necessary to actuate in case of emergency, also must be examined, but smaller populations of components are generally inspected than on Class 1 systems. Class 3 systems, such as the component cooling water supply, service water, and steam conversion systems, which provide support functions, are inspected in lesser numbers and less rigorously. Balance-of-plant components are not under the purview of ASME Code rules.

Many operating licensees have adopted risk-informed inservice inspection (RI-ISI) programs to define the locations and sample size for ISI of safety-related (Class 1, 2, and 3) piping welds at their plants. The concept behind RI-ISI is to use insights from a plant risk analysis to develop a ranked order of components and apply ISI resources to those contributing the higher risk. Therefore, RI-ISI could provide a more meaningful basis for selecting the specific components to be inspected than was originally developed by the Code [24].

Currently, acoustic emission (AE) is the only tool sanctioned by the ASME Code for performing online monitoring of passive SSCs. There is a significant history relating to AE in the nuclear industry, but it has seen only limited use in the USA. Field studies have been conducted that demonstrated the feasibility of using AE for crack monitoring in actual NPP environments. In one study, AE was used to continuously monitor the growth of a known flaw in a reactor pressure vessel (RPV) nozzle to safe-end weld at the Limerick Generating Station Unit 1 [2]. Similarly, AE technology was field tested on a known flaw in a nozzle at the Watts Bar Unit 1 reactor [48]. A waveguide was used to couple the AE transducers to the pipe being monitored, which reduced the temperature seen by the piezoelectric elements. A diagram illustrating the location of AE monitoring is shown in Fig. 2 and a photograph of the Limerick Unit 1 setup is provided in Fig. 3. The study demonstrated AE technology for NPP monitoring, culminating with continuous online monitoring field trials of nuclear reactor components. These NRC/Pacific Northwest National Laboratory (PNNL) research efforts were then used as a basis for developing an ASME Code Case for the use of AE to monitor nuclear reactor components. This Code Case was followed by the development of AE methodology that was included in the ASME Code, Section V, Articles 12, 13, and 29. The criteria for interpreting AE data were included in ASME Code, Section XI, IWA-2234. This work also provided invaluable insights into the issues that will be encountered, and will need to be overcome, in deployment of online monitoring/prognostics in a field-deployable system. For example, more robust transducers and electronics are required than were used at the Limerick site. Difficulties associated with routing large numbers of cables and transferring large volumes of sensitive data in and out of containment during reactor operation were also highlighted. In addition to continuous monitoring of crack growth, AE has been used for continuous monitoring of leaks in pipes [31] and valves [32]. Other applications of AE in NPPs include preservice and periodic inservice hydrotesting of pressure vessels [33] and loose parts monitoring [34]. The work that has been conducted has shown the feasibility of deploying AE and other online monitoring systems in an NPP.

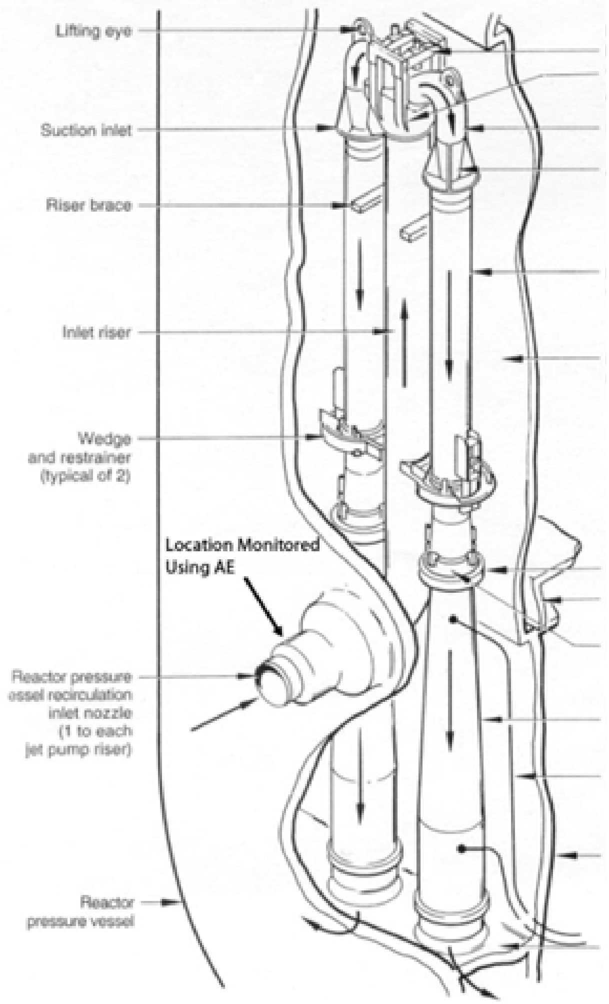

Fig. 2 System geometry for tests at Limerick NPP (NUREG/CR-5963) [2].

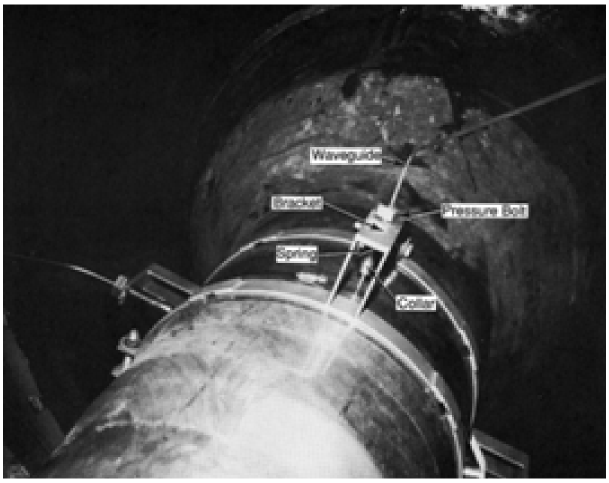

Fig. 3 AE sensor in place at Limerick NPP (NUREG/CR-5963) [2].

Research is continuing to investigate the use of modern AE systems with digital signal processing and more robust transducers, as well as guided-wave technology. A recent study [49] has shown that instrumentation developments now enable both advanced AE and guided-wave techniques to be used for the detection and monitoring of larger size defects in passive structures relevant to NPPs. These tools were validated by monitoring fatigue damage induced in an SA 312 TP304 stainless steel pipe specimen (see Fig. 4). Acoustic emission detected signals caused by a crack initiation prior to visual confirmation of crack formation. Guided ultrasonic wave was employed to monitor the growing cracks and the response was related to the crack size. AE has been recently applied to monitor the simulated failure of the main cooling pipe of an NPP. The amplitude and energy of AE events were considered for indications of failure, and the amplitude distribution and event rate were correlated to damage stage [50].

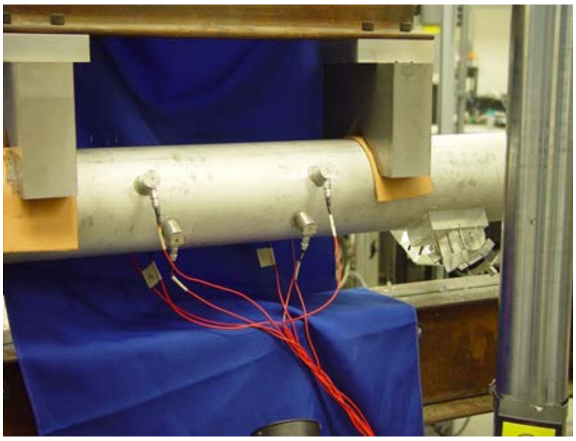

Fig. 4 Four-point bend test conducted on a TP304 stainless steel pipe specimen (schedule 80).

Guided ultrasonic wave (GUW) technology is also receiving serious consideration as a crack detection and degradation monitoring tool for piping inspection in the nuclear industry. GUW can minimize the need to remove insulation, and inspections are performed by injecting relatively low frequency (wavelength ~ component dimension) waves into a target component. In this regime, ultrasonic energy interacts significantly with the boundaries of the components and is thus sensitive to discontinuities introduced by damage. Currently, a Section V working group is developing ASME code methodology requirements for GUW inspections. GUW has been investigated as a means to detect defects in steam generator tubing

[51,52], as well as coolant piping [53], containment liner plates [54], buried piping [55], and fuel cladding [56]. In addition to straight line components, researchers have explored the impact introduced by such complexities as water loading [57], weld seams and joints [58]. The rapidly maturing state of GUW technology, combined with increasing recognition by the nuclear community, enables an imminent field demonstration [59]. Typical LWR operating temperatures can pose a challenge to performing GUW inspections online with transducers incorporating lead zirconate titinate (PZT) piezoelectric elements. As a consequence, alternate piezoelectric materials and also a laser fiber-optic system has been investigated as means to excite and detect guided waves in a pipe. A system for detecting flaws in PWR cooling pipe has been demonstrated up to temperatures of 300°C [60].

A further monitoring technology that has potential for field deployment is based on low-frequency ultrasonic phased arrays (PAUT) [61]. The reliability of this technique has been studied for several difficult examination scenarios [62-66]. Applications considered include examination of degradation in coarse grain materials (such as cast austenitic stainless steels [65]), examination of dissimilar welds [62], examination of PWR surge line piping welds [63], far-side examinations of austenitic stainless steel piping welds [64], and examinations of interference fits of control rod drive mechanism (CRDM) penetrations [66]. In such measurements, various forms of signal processing including synthetic aperture focusing (SAFT) are utilized [67]. Recent trends utilizing electronic beam steering improve the characterization of flaw indications and expand the immediately inspectable volume of the probe from a stationary placement compared to single element UT systems. A factor limiting the use of current PAUT technology for online monitoring is temperature during reactor operation. A high temperature PAUT probe is under development for applications in liquid sodium cooled fast reactors (SFRs). The probe is targeted for under sodium viewing (USV) to perform inspections during outages when the temperature of the liquid sodium is in the range of 200°C–250°C [68]. Such efforts can potentially be leveraged to benefit development of PAUT technology for online deployment in LWRs.

4.2.2 Monitoring early degradation in metals

Degradation in metal components in its early stage is characterized by development of crack nucleation sites and then small cracks, which are below the size for which current NDT is sensitive. Laboratory techniques, including optical methods and those using potential drop, can be used to study crack initiation. In deployed systems, inspection sensitivity to degradation in its early stages could lead to improved state awareness by increasing the probability that degradation phenomena are identified with sufficient time for planning and implementing corrective action. Earlier knowledge of degradation also has the potential to provide plant staff with greater flexibility in responding to degradation indications, and the opportunity to avoid a failure or leak rather than merely delaying or mitigating its negative effects.

The four stages in the evolution of aging degradation in passive components are discussed by Bond et al. [47] and these are illustrated in Fig. 5, together with an assessment of the maturity of technologies suitable for their detection. Traditional NDE technologies are only sensitive to the most severe stages (stage IV) of degradation while the early degradation (stage I) is typically observable only using traditional tools of material science. The need is to investigate phenomena between these two extremes and provide field deployable technologies that are sensitive to “early” degradation (stages II-III).

The development of methods sensitive to the phenomena of degradation at early stages first requires the identification of suitable observables that correlate with changes in material condition. Such changes could be local changes in electrical, mechanical, or thermal properties that “localize” before initiation of a macro-defect, which could become metal loss or a crack. For example, gradual loss of fracture toughness may result from generation of dislocations and voids preceding failure due to mechanical-, thermal-, or irradiation-induced phenomena. To be useful from a plant aging management perspective, precursors should be detectable and quantifiable using non-invasive measurements. This may be achieved by

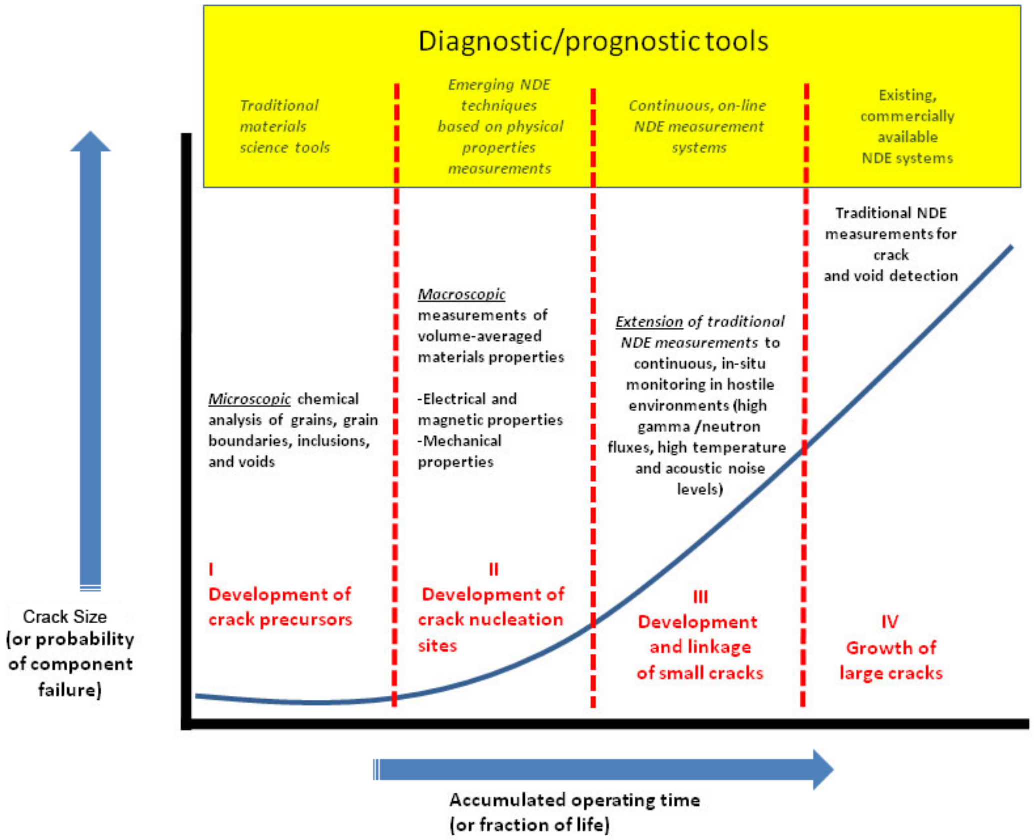

Fig. 5 Evolution of material degradation and correlation with damage measurement technologies [3].
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understanding and linking the underlying microstructure property changes to measurable bulk material properties (elastic, magnetic, and electrical). Material aging can be manifest at the microstructural level in several ways. Examples include changes in dislocation density, grain size/orientation/shape, precipitation of second phases, and others. The influence of such microstructural phenomena on measurable bulk magnetic and elastic properties is described in the extensive review by Raj et al. [46].

One of the challenges then becomes detecting and characterizing small local changes from among natural variability in a nominally homogeneous material using a modest number of sensors to interrogate critical regions. This challenge can be thought of in terms of determining what to measure, how to measure it, where to measure it, and how many measurements to make, all using sensors and instrumentation that will not be significantly impacted or degraded by the operating environment (temperatures, radiation, and chemistry) during extended periods.

Several NDE technologies are emerging as potential candidates to meet early degradation (stages I–III in Fig. 5) measurement needs. These include micromagnetic techniques in the form of magnetic Barkhausen noise (MBN) and B-H curve analysis. MBN is particularly sensitive to imperfections such as the presence of precipitates and inclusions which resist the motion of magnetic domain walls. Substantial efforts to relate thermal, mechanical, and radiation embrittlement degradation to micro-magnetic responses are described by Raj et al. [46] and Dobmann et al. [43]. Nonlinear acoustic/ultrasonic techniques are also promising with research indicating that nonlinear techniques are more sensitive to micro-damage than conventional linear ultrasonic techniques [69]. Four kinds of material nonlinear responses, which correlate with micro-damage, have been identified, and these are described by Jhang [69]. These include the generation of higher-harmonics, generation of sub-harmonics, nonlinear resonance, and signal modulation (referred to as mixed frequency response).

4.2.3 Primary containment structures

Typical safety-related concrete structures contained in LWR plants may be grouped into four general categories: primary containments, containment internal structures, secondary containments/reactor buildings, and other structures. Primary containment structures, in particular, have significant safety responsibilities including serving as a final barrier to the release of radionuclides, providing protection from severe external anomalies such as missile attacks or natural disasters, and also providing shielding for the external environment from radiation. As a consequence, primary containment structures must satisfy functional requirements for structural integrity and leak tightness. They have been the subject of recent studies and reviews to understand the relevant aging mechanisms, their impact on the lifetime of the NPPs, and the adequacy of aging management plans for discovering and mitigating the effects of primary containment degradation [70,71].

In the United States, approximately 80% of PWRs and 30% of BWRs licensed for commercial operation use either reinforced or prestressed concrete primary containments. Usually a very recognizable feature of an NPP site, these structures consist of a foundational basemat, cylindrical walls, and a dome-shaped cap. Concrete containments can be up to 50 m in diameter, and up to 70 m tall, with wall and dome thicknesses approaching 1.4 m. Basemats can be up to 4.1 m thick. Leak tightness is achieved with the use of a metal liner on the inside surface of the containment. The liner is typically composed of carbon steel plates. Leak tightness at joints and penetrations is achieved through welding or the use of polymeric seals and gaskets. Because of its foundational structure, the basemat is heavily reinforced with steel. The walls and dome of the structure also contain reinforcing steel while prestressed containments also use tendons, which are tensioned to hold the walls and dome in compression [70].

A variety of phenomena can compromise the functional integrity of concrete structures, including aging degradation, collapse of soils under the raft of the nuclear island which impacts load distribution, seismic activity, and long-term or transient fluctuations in pressures and temperatures during an incident. Leak tightness can be compromised by degradation of welds and seals at joints or through-thickness corrosion of liner plates. Structural integrity is impacted by many forms of degradation associated with both the cement-aggregate mixture and supplemental metallic hardware. The porosity and permeability of the concrete significantly influences susceptibility to degradation through impact on transport of moisture and chemical species through the interior of the member. Degradation of the cement-aggregate mixture can occur by chemical or physical attack, which is ultimately manifest as cracking and loss of strength. Some forms of chemical attack include alkali-silica reactions, carbonation, and sulfate attack. Examples of physical attack include freeze/thaw cycles, shrinkage, creep, and drying. Corrosion of metallic hardware embedded in the concrete can lead to cracking in the concrete. Loss of tension in the tendon system is a concern associated with prestressed containments and can occur by shrinkage or creep of the concrete, tendon relaxation, or corrosion of tendon cables and anchorage hardware [70-72].

Inspection requirements of concrete sections of the containment, metallic reinforcement systems, and post-tensioned tendon systems are covered by Article IWL-2000 of Section XI of the ASME Boiler and Pressure Vessel Code. IWL-2000 specifies two types of visual inspections for these components referred to as a general visual inspection and a detailed visual inspection. The purpose of detailed visual inspections is to assess the severity of degradation identified during the general visual inspection. Components that are not accessible for visual inspections are subject to an environmental assessment to determine the likelihood for degradation. Single wires or strands from sample tendons are removed to undergo detailed visual examination and a series of mechanical tests. Article IWL-2000 specifies that components must be inspected at 1, 3, and 5 years following containment construction and every 5 years thereafter. Rules for the inspection of metallic liners are outlined in Subsection IWE of the ASME Code, Section XI. The Code specifies general visual inspections for all surfaces accessible to inspection. Paragraph IWE-1241 specifies criteria for which surface regions require additional augmented inspections by either more detailed visual or ultrasonic means. In addition to the ASME Code requirements, additional regulations are contained in the Code of Federal Regulations, specifically, Appendix J of 10 CFR Part 50. These rules specify the requirements for verifying the leak tightness of the containment boundary and specify the frequency of periodic leak testing [72].

Structural assessments of concrete containments are normally performed through NDE and destructive mechanical and chemical analysis of core samples. The heterogeneous nature of concrete containments and variety of degradation mechanisms requires the application of diverse techniques to obtain a holistic assessment of structural integrity. Some issues associated with concrete inspections are associated with access. Examples include sections that are below grade or thick concrete members such as the basemat, which is also heavily reinforced. Some difficulty has also been experienced in accessing portions of metal liners embedded in concrete [72,73]. A comprehensive overview of inspection techniques for concrete structures at NPPs is included in a review by Naus [73]. Motivated by large costs associated with manual containment inspections in addition to risks to personnel safety, EPRI supported a project to instrument the containment structure at the Ginna nuclear generating station with optical strain gauges for monitoring the stress of a sample of prestressed tendons. The real-time information provided by the instrumentation gives operators a significantly greater state awareness of tendon conditions [74]. For new plants, there is increased interest in the use of embedded optical fibers to continuously monitor the condition of concrete structures [75,76]. Guided ultrasonic waves have been the focus of efforts to inspect embedded portions of concrete containment liners [54], and researchers are increasingly investigating GUW techniques and AE as a means to monitor strain in prestressed tendons [77-81], as well as reinforcing steel for signs of corrosion and delamination [82-86]. Diffuse ultrasonic fields are under investigation for detection of damage in the heterogeneous cement – aggregate mixture [87-89].

4.2.4 Cable condition monitoring

Cables are a part of power, instrumentation, control, and communication circuits in NPPs and are essential to both normal and post-accident plant operations. Thousands of kilometers of cables, of a variety of classes, are routed throughout NPPs [90]. Most cables were selected and tested to have a nominal 40-year life. Licensee data shows that the number of cable failures is already increasing even within the 40-year nominal lifespan [91]. However, LTO is now seeking operation to 60 and even 80 years. In many cases, cables are difficult and expensive to replace. It has even been suggested that it is the economics of cable replacement that could be the determining factor in the economic assessment for the feasibility of plant LTO [92].

The main components of an I&C or low-voltage power cable include the conductor(s), electrical insulation, shielding, and outer jacket [93]. Typical cable architecture consists of one or several conductors individually wrapped with electrical insulation and bundled inside of a protective jacket (see Fig. 6). Single conductor cables will consist of the components listed above while multiple conductor cables will also include extra filler material between individual conductors to constrain the movement of individual conductors within the jacket. The cable insulation and jacket components are normally composed of polymeric materials. Common insulating materials include cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), ethylene propylene dimonomer (EPDM), and polyvinyl chloride (PVC). Common jacket materials include neoprene, hypalon (CSPE), and PVC [94]. The polymeric materials will often contain protective additives (i.e., anti-oxidants, thermal stabilizers, fire retardants) [93].

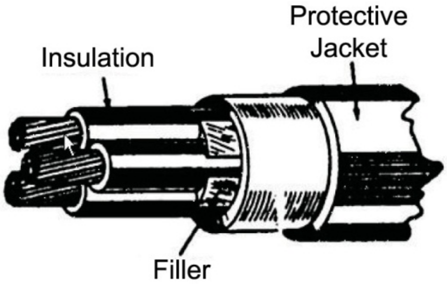

Fig. 6 Depiction of a typical cable architecture.

The aging degradation of a cable will be governed by the polymeric system, environmental conditions, and the time scale for which age-inducing stressors are applied [93]. Exposure to high temperatures, moisture, and radiation are key aging stressors for cables [95]. Polymeric insulation and jacket materials can become embrittled with sufficient exposure to high temperature and radiation while moisture intrusion can reduce the dielectric integrity of the cable [93]. Exposure of cables to boric acid and mechanical vibration are also potential aging factors. In addition to the main cable body, splices and connectors can also be potential locations for degradation and failure [96].

Cable aging management in the U.S. nuclear power industry is not subject to formal requirements. The NRC has performed an evaluation of cable aging degradation and cable condition monitoring techniques to form the technical basis to support the development of regulatory guidance [91]. Recently, guidance documents have been published by EPRI for the aging management of both low-voltage [97] and medium-voltage [98] cables in NPPs. The EPRI guidance documents define the scoping criteria for including cables in an aging management plan. Factors that determine if a condition assessment is required include the 1) relevance of the cable to safety and 2) severity of the cable environment. These documents also provide guidance for cable testing, acceptance criteria, and actions to address degraded cables.

Localized degradation ("hot spots") can disrupt the function of the entire cable. Thus, consideration of cable architecture, connectors, potential environmental stressors, hot spot phenomena, and the desire to perform measurements in situ impose a complex set of requirements on cable condition monitoring systems. The current cable condition monitoring techniques have been reviewed by Hashemian et al. [96]. Condition assessment techniques are generally visual, mechanical, chemical, or electrical in nature and these approaches are summarized in Table 2. Visual, mechanical, and chemical techniques can provide detailed characterizations of damage but are often localized or destructive in nature. Further, in situ evaluations in extreme environments, such as within containment, are unlikely if sampling requires direct human interaction. Electrical techniques can sample larger sections of cable, they are nondestructive, and some techniques can be performed online. However, electrical techniques are most sensitive to damage in the conductor and are limited in their ability to characterize damage prior to a failure that impacts electrical function. The application of several condition monitoring techniques is often necessary to form a comprehensive assessment of cable condition [99,100]. Thus, efforts continue in the development of in situ online cable monitoring tools that are able to provide a more holistic assessment of cable condition [96].

Table 2 Summary of cable condition monitoring techniques [96]

Property	Technique
Mechanical	Elongation at break (EAB)
	Indenter Modulus
Chemical	Oxidation induction time (OIT)/temperature
	Fourier transform infrared (FTIR) spectroscopy
	Nuclear magnetic resonance imaging (NMRI)
	Gel content or gel fraction test
Electrical	Insulation resistance
	High voltage testing
	Impedance testing
	Time domain reflectometry (TDR)
	Frequency domain reflectometry (FDR)

5 Prognostics for the nuclear power industry

Prognostics are methods for predicting the future condition and remaining safe or service life, based on understanding the effect of stressors which cause degradation phenomena that impact a system's capability to perform its desired function. Depending on data available, this prediction can be made using various classes of algorithms which vary in terms of the ability to make a prediction for a specific unit or an average performance for a class of components.

Current practice with condition-based monitoring can be used to identify an off-normal condition for a specific unit, such as a pump or motor, and to initiate maintenance or replacement in order to avoid a failure. Current practice is moving from diagnostics, which gives an assessment at a point in time based on observed data (*e.g.*, CBM assessment, an NDE, or structural health monitoring (SHM) assessment), to prediction of remaining useful life. This predictive element can be achieved using the range of approaches, based on different classes of data sets and algorithms, which are identified in schematic form in Fig. 7. These range from the general statistical data-based assessments based on populations, such as the performance of all pumps of a particular type or class, to those based on physical degradation models with specific data taken on a particular part or component. Those methods shown at the top of the pyramid increase accuracy, but they also come at a higher cost, require greater understanding of the system under study, and often require more data for analysis.

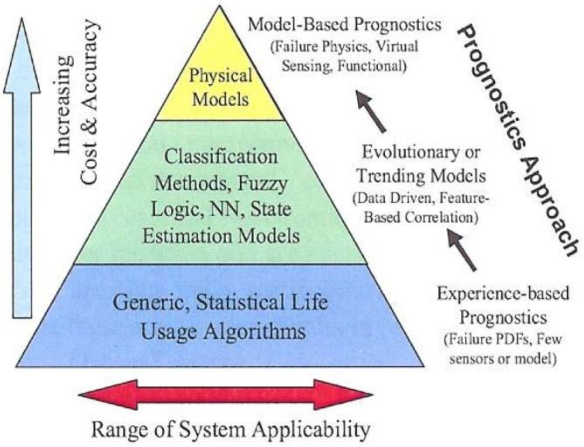

Fig. 7 Range of prognostic approaches [3]. Copyright 2011 by the American Nuclear Society, La Grange Park, Illinois.

There is an extensive history of prognostics technologies for non-nuclear applications, including instrumentation and system health monitoring for electronics, in what is being called "electronics prognostics" [101-103]. There are also integrated technologies being developed for advanced fighter aircraft and unmanned aerial vehicle (UAV) system health monitoring, which include both electrical/electronic and mechanical systems. A review of machinery diagnostics and prognostics for CBM is provided by Jardine et al. [104], but again it does not consider nuclear power systems. There is also a review by Kothamasu et al. [105] that considered both the current health monitoring paradigms and the tools and standards.

As suggested by the "No Free Lunch" Theorem, no one prognostic algorithm is ideal for every situation [106,107]. A variety of models have been developed for application to specific situations or specific classes of systems. The efficacy of these algorithms for a new process or system depends on the type and quality of data available, the assumptions inherent in the algorithm, and the assumptions that can validly be made about the system. As such, these prognostic algorithms can be categorized according to many criteria. One proposed categorization focuses on the type of information used to make prognostic estimates [108]. In practice, there is no need to limit oneself to a particular prognostic algorithm for any given component. Different algorithms may be more suitable over certain stages of a component's lifetime depending on the information that is available.

The state-of-the-art in prognostics technology for condition-based monitoring has been reviewed by Lybeck et al. [25], Coble et al. [109], and Hines et al. [110,111]. An assessment of the state of the art in diagnostics and prognostics in terms of technology maturity for different classes of systems was provided by Howard [4], and this has been recently updated and expanded to specifically include aspects of nuclear systems [1]. The status for these various elements is shown in Table 3.

Lybeck et al. [25] assessed the state-of-the-art of prognostics technologies for nuclear power implementation. The assessment covered component selection methodologies, prognostic algorithms, and prognostic architectures. The assessment considered several commercial software packages originally intended for other industries in an effort to leverage those resources for deployment of prognostics in the nuclear power industry.

Table 3 State of Maturity for Diagnostics (D) and Prognostic (P) Technologies [1] and adapted from Howard Keynote Address [4], by permission of the MFPT.

Diagnostic/Prognostic Technology for:	AP(a)	A(b)	I(c)	NO(d)
Basic Machinery (motors, pumps, generators, etc.)	D&P			
Complex Machinery (helicopter gearboxes, etc.)	D&P			
Metal Structures	D	P		
Composite Structures		D	P	
Electronic Power Supplies (low power)	D	P		
Avionics and Controls Electronics	D	P		
Medium Power Electronics (radar, etc.)	D	P		
High Power Electronics (electric propulsion, etc.)	D	P		
Instrument re-calibration – monitoring (NPP)	D			P
Active components – nuclear power plants	D		P	
Passive components – nuclear power plants			D	P

(a) AP = Technology currently available and proven effective.
(b) A = Technology currently available, but verification and validation (V&V) not completed.
(c) I = Technology in process, but not completely ready for V&V.
(d) NO = No significant technology development in place.

The importance of component selection, when implementing advanced pattern recognition (APR) software tools in the nuclear power industry, was emphasized at an EPRI Nuclear Online Monitoring workshop in 2011. Industry experience with APR shows that integration of such tools in the field is certainly feasible [41]. However, success is correlated with the amount of fore-thought and planning associated with an implementation strategy [112]. Thus, a key aspect to enabling widespread application of prognostic tools in the nuclear industry is for utilities to have well developed strategies for implementing these products. Likewise, a poorly conceived implementation strategy can have negative consequences that significantly impact the likelihood that prognostic tools can be transferred to industry in a timely fashion. Beyond these discussions of industry experience, industry is also developing a fault signature database for diagnostic assessments with the goal of eventually deploying the ability to make remaining useful life (RUL) estimations [28]. The success of these efforts relies on industry participation for database population.

5.1 Integrated prognostic

As indicated, prognostics methods have been successfully applied to active components and the challenges remain with passive components. The application of prognostics to NPP SSCs will require adoption of a philosophical and cultural change in the nuclear community.

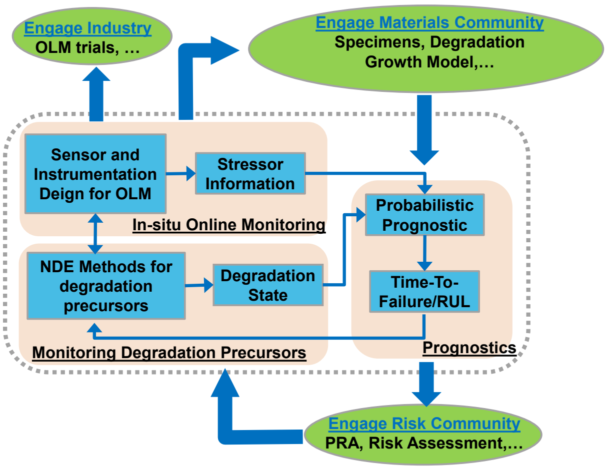

Fig. 8 Elements in the LWRS on line monitoring activities to provide prognostics [16]. Reproduced with permission from ICI/Korea Nuclear Society.

A schematic showing the integration of some of the elements in the online monitoring/NDE elements of the LWRS program is shown as Fig. 8.

An example of the ability to predict damage accumulation is provided with the data in Fig. 9 [16]. This is a fatigue prognostic for a passive component based on measurements of the nonlinear acoustic responses in data from Kulkarni et al. [113]. Measurements in the degradation precursor stage were used, with a semi-empirical model of damage accumulation and assumed stressor profiles, to predict the level of damage at future times using a Bayesian algorithm. This information can be used, together with failure probabilities, to estimate RUL of passive structural components, extrapolating from early degradation detection [67]. The use of online NDE monitoring techniques can enable frequent updates to the condition of the structure and subsequently to the RUL estimate. Further, data from multiple measurement modes can potentially help improve the accuracy and reduce the uncertainty associated with the prediction [114].

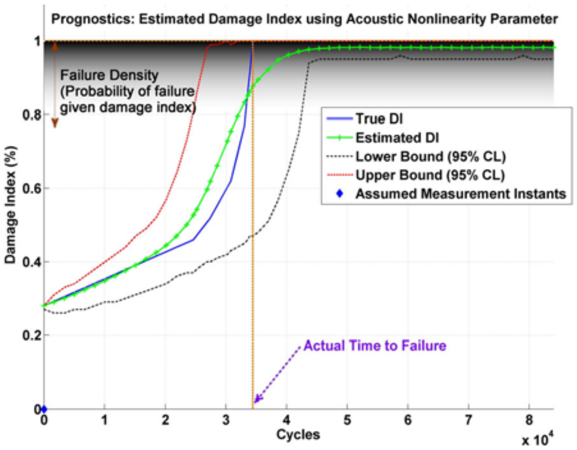

Fig. 9 Prediction of DI from acoustic nonlinearity measurements, to demonstrate the feasibility of the prototype Bayesian algorithm.

6 Technology/Knowledge gaps

For passive component assessment, researchers have investigated NDE technologies that are sensitive to degradation precursors due to mechanical fatigue, thermal aging, and radiation effects. Most research to date has resulted in empirical relationships between precursor phenomena and NDE measurement parameters. More work is needed to fully understand the separate effects of multiple microstructural phenomena on NDE signals and to develop physical models correlating microstructural changes, induced by aging, to macroscopic NDE measurements.

Quantification of uncertainty through the measurement and prediction process is essential to bounding the confidence of diagnostic assessments and RUL predictions. Uncertainties are associated with the NDE measurements, interpretations of the degree of damage, stressor history, future stressors, and the models used to integrate factors and extrapolate and bound predictions moving forward in time.

The development of ruggedized sensors for NPP environments is key to the successful deployment of online surveillance technologies. Not only must sensors survive, but they must exhibit robust behavior while exposed to stressors for periods of several years or decades. Excellent tolerance to thermal stress is required for sensors assigned to monitor pressure boundary components while sensors for internal component monitoring require an even higher tolerance to temperatures and radiation effects.

The what and how to measure questions remain only partially answered, as does the issue of the number and location of the sparse network of sensors to be used for monitoring degradation in passive components. Strategies are still needed to optimize placement of sensors. Such placement could be informed by expert opinion and/or the results of a risk-based analysis. As the number of sensors grows larger, data management and wireless implementation becomes important, particularly with regard to power needed for sensor operation and data transmission to a monitoring and analysis location.

Data fusion is also needed to form more holistic condition metrics at the system level from data obtained by multiple measurements. Components with complex architectures, such as cables, are most illustrative of this need. It is also likely that combined measurements can enable more complete condition indications for concrete and metal components as well. Methods to meaningfully combine stressor information with damage characterization are also needed to facilitate stressor-based prognostics.

7 Conclusions

Safe, secure, and economic operation of nuclear power plants will remain of strategic significance. New and improved monitoring will have increased significance in the post-Fukushima world.

The science base for advanced surveillance of active components has benefited from work primarily conducted in the aerospace and defense industries. Although some open issues remain, active components are being well managed, maintained, and replaced as needed using condition-based maintenance approaches. There is increasing adoption of online monitoring and centralized monitoring, with consideration being given to the adoption of prognostics for active components.

For legacy plants, the challenges relate to monitoring passive components when looking at extended LTO (60 years+ of operation), particularly in providing the science base for early detection of changes using advanced surveillance. As interest in this field grows, it is likely that several more promising measurement techniques will be identified. It is also likely that prognostics techniques for passive components will become a necessary part of extended operation for NPPs. The application of prognostics to NPP passive components still presents technical challenges and will require adoption of a philosophical and cultural change in the nuclear community if it is to be successful.

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References

[1] BOND, L. J., COBLE, J., BOND, J. W. D.: Economics of On-line Monitoring and Nuclear Power Plant Life Extension, Richland, Washington: Pacific Northwest National Laboratory, 2012 (draft).

[2] HUTTON, P. H., FRIESEL, M. A., DAWSON, J. F.: Continuous AE Crack Monitoring of a Dissimilar Metal Weldment at Limerick Unit 1, NUREG/CR-5963, PNL-8844, Washington, DC: U.S. Nuclear Regulatory Commission, 1993.

[3] BOND, L. J., DOCTOR, S. R., GRIFFIN, J. W., HULL, A. B., MALIK, S. N.: Damage Assessment Technologies for Prognostics and Proactive Management of Materials Degradation, Nucl. Tech., 2011, 173(1):46-55.

[4] HOWARD, P.: Prognostic Technology – New Challenges. In Proceedings of the 59th Meeting of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, Virginia, Society for Machinery Failure Prevention Technology (MFPT), Haymarket, Virginia, 2005.

[5] INGERSOLL, D. T.: Deliberately Small Reactors and the Second Nuclear Era, Progr. Nucl. Energ., 2009, 51:589-603.

[6] WILKOWSKI, G., TREGONING, R., SCOTT, P., RUDLAND, D.: Status of Efforts to Evaluate LOCA Frequency Estimates Using Combined PRA and PFM Approaches. In 28th MPA-Seminar, Universitaet Stuttgart, Germany, Materials Testing Institute, 2002.

[7] BOND, L. J., DOCTOR, S. R., TAYLOR, T. T.: Proactive Management of Materials Degradation - A Review of Principles and Programs, PNNL-17779, Richland, Washington: Pacific Northwest National Laboratory, 2008.

[8] NRC: Generic Aging Lessons Learned (GALL) Report - Final Report, NUREG-1801, Rev. 2, Washington, D.C.: Office of Nuclear Reactor Regulations, U.S. Nuclear Regulatory Commission, 2010.

[9] ANDRESEN, P. L., FORD, F. P., GOTT, K., JONES, R. L., SCOTT, P. M., SHOJI, T., STAEHLE, R. W., TAPPING, R. L.: Expert Panel Report on Proactive Materials Degradation Assessment, NUREG/CR-6923, BNL-NUREG-77111-2006, Washington, D.C.: U.S. Nuclear Regulatory Commission, 2007.

[10] LAIN, T.: Materials Reliability Program: Pressurized Water Reactor Issue Management Tables, MRP-205. Rev. 1, Palo Alto, California: Electric Power Research Institute, 2008.

[11] PATHANIA, R.: EPRI Materials Degradation Matrix, Rev. 1, Palo Alto, California: Electric Power Research Institute, 2008.

[12] STARK, R.: BWR Vessel and Internals Project: Boiling Water Reactor Issue Management Tables, BWRVIP-167NP, Rev. 1, Palo Alto, California: Electric Power Research Institute, 2008.

[13] IAEA: Nuclear Power Plant Life Management for Longer Term Operation, Vienna: International Atomic Energy Agency, 2010.

[14] BOND, L. J.: Moving Beyond Nondestructive Examination to Proactive Management of Materials Degradation, J. Pres. Vessel Technol., 2012, 134(1):014501-014508.

[15] BOND, L. J.: Moving Beyond NDE to Proactive Management of Materials Degradation. In Proceedings of the ASME 2010 Pressure Vessels & Piping Division / K-PVP Conference (PVP2010), Bellevue, Washington, American Society of Mechanical Engineers, New York, 2010.

[16] BOND, L. J., MEYER, R. M.: Online Monitoring to Enable Improved Diagnostics, Prognostics and Maintenance. In International Symposium on Future I&C for Nuclear Power Plants, Cognitive Systems Engineering in Process Control, International Symposium on Symbiotic Nuclear Power Systems (ICI 2011), Daejeon, Korea, 2011.

[17] HALLBERT, B.: Report from the Light Water Reactor Sustainability Workshop on Advanced Instrumentation, Information, and Control Systems and Human-System

Interface Technologies, INL/EXT-09-16631, Idaho Falls, Idaho: Idaho National Laboratory, 2009.

[18] WOGMAN, N. A., BOND, L. J., WALTAR, A. E., LEBER, R. E.: The Nuclear Education and Staffing Challenge: Rebuilding Critical Skills in Nuclear Science and Technology, J. Radioanal. Nucl. Chem., 2005, 263(1):137-143.

[19] AMIN, F. M.: Passing the Tourch: The Asian Network for Education in Nuclear Technology, IAEA Bulletin, 2004, 46(1):15-17.

[20] HASHEMIAN, H. M.: On-line Monitoring Applications in Nuclear Power Plants, Progr. Nucl. Energ., 2011, 53(2):167-181.

[21] JOHNSON, B., MAXWELL, H.: Predictive Maintenance – The Effect on a Company's Bottom Line, Part 1 - The Global View. In Proceedings of the 56th Meeting of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, Virginia, MFPT Society, Haymarket, Virginia, 2002.

[22] BOND, L. J., DOCTOR, S. R., JARRELL, D. B., BOND, J. W. D.: Improved Economics of Nuclear Plant Life Management. In Second International Symposium on Nuclear Power Plant Life Management, Shanghai, China, International Atomic Energy Agency, 2008.

[23] DOE: Light Water Reactor Sustainability Program: Integrated Program Plan, INL/EXT-11-23452, Rev. 0, Washington, D.C.: U.S. Department of Energy, Office of Nuclear Energy, 2012.

[24] MEYER, R. M., COBLE, J. B., RAMUHALLI, P., BOND, L. J.: Advanced Instrumentation, Information, and Control System Technologies: Nondestructive Examination Technologies - FY11 Report, PNNL-20671, Richland, Washington: Pacific Northwest National Laboratory, 2011.

[25] LYBECK, N., PHAM, B., TAWFIK, M., COBLE, J. B., MEYER, R. M., RAMUHALLI, P., BOND, L. J.: Lifecycle Prognostics Architecture for Selected High-Cost Active Components, INL/EXT-11-22915, Rev. 0, Idaho Falls, Idaho: Idaho National Laboratory, 2011.

[26] BALDWIN, T., TAWFIK, M., BOND, L. J.: Report from the Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies, INL/EXT-10-19500, Idaho Falls, Idaho: Idaho National Laboratory, 2010.

[27] IAEA: Advanced Surveillance Diagnostics, and Prognostics Techniques Used for Health Monitoring of Systems, Structures, and Components in Nuclear Power Plants: CRP Report Volume I, IAEA-NE-D-NP-T-3.14, Vienna, Austria: International Atomic Energy Agency (IAEA), 2012 (in press).

[28] BICKFORD, R.: Presentations from EPRI COLM Workshop, January 28, 2011. Source information not publicly available.

[29] IFRAM: International Forum for Reactor Aging Management, 2011. http://ifram.pnnl.gov/default.asp.

[30] IAEA: Core Knowledge on Instrumentation and Control Systems in Nuclear Power Plants, IAEA Nuclear Energy Series No. NP-T-3.12, Vienna: International Atomic Energy Agency, 2011.

[31] KUPPERMAN, D. S., SHEEN, S. H., SHACK, W. J., DIERCKS, D. R., KRISHNASWAMY, P., RUDLAND, D., WILKOWSKI, G. M.: Barrier Integrity Research Program: Final Report, NUREG/CR-6861, Washington, D.C.: U.S. Nuclear Regulatory, 2004.

[32] HUTTON, P. H.: An Overview of Development and Application of Acoustic Emission Methods in the United States, Nucl. Eng. Des., 1989, 113(1):59-69.

[33] BENTLEY, P. G.: A Review of Acoustic Emission for Pressurised Water Reactor Applications, NDT International, 1981, 14(6):329-335.

[34] MACLEOD, I. D., ROWLEY, R., BEESLEY, M. J., OLLEY, P.: Acoustic Monitoring Techniques for Structural Integrity, Nucl. Eng. Des., 1991, 129:191-200.

[35] HINES, J. W., SEIBERT, R.: Technical Review of On-line Monitoring Techniques for Performance Assessment, Volume 1: State-of-the-Art, NUREG/CR-6895, Vol. 1, Washington, D.C.: U.S. Nuclear Regulatory Commission, 2006.

[36] ASME: Long-Term Operations: The Feasibility of Extending the Life of U.S. Nuclear Facilities to 60 Years and Beyond, Final Report to A. P. Sloan Foundation, Grant #B2009-23, Washington, D.C.: American Society of Mechanical Engineers (ASME), 2010.

[37] VACHTSEVANOS, G., LEWIS, F. L., ROEMER, M., HESS, A., WU, B.: Intelligent Fault Diagnosis and Prognosis for Engineering Systems, John Wiley & Sons, Inc.: Hoboken, New Jersey, 2006.

[38] WADE, R. BARNARD, H.: Enabling Sustainable Systems, Proceedings 2011 Society for Machinery Failure Prevention Technology Meeting (MFPT 2011). Virginia Beach, Virginia, May 10-12, 2011, 2011, Society for Machinery Failure Prevention Technology.

[39] JARRELL, D. B., SISK, D. R., BOND, L. J.: Prognostics and Conditioned-Based Maintenance: A New Approach to Precursive Metrics, Nucl. Tech., 2004, 145(3):275-286.

[40] HASHEMIAN, H.: Wireless Sensors for Predictive Maintenance of Rotating Equipment in Research Reactors, Ann. Nucl. Energ., 2011, 38:665-680.

[41] YOUSUF, M.: Presentations from EPRI COLM Workshop, January 28, 2011. Source information not publicly available.

[42] AREVA: OneproD MVX and MVP On-Line Systems, Product Literature, Oilkiluoto 3, Finland: AREVA, 2007.

[43] DOBMANN, G.: NDE for Material Characterization of Aging Due to Thermal Embrittlement, Fatigue and Neutron Degradation, Int. J. Mater. Prod. Tech., 2006, 26:122-139.

[44] RAMUHALLI, P., GRIFFIN, J. W., FRICKE, J., HENAGER C.H, J., DIXIT, M., BOND, L. J.: Diagnostics and Prognostics Tools for Assessing Remaining Useful Life of Nuclear Power Plant Materials. In Enabling Sustainable Systems, Proceedings 2011 Society for Machinery Failure Prevention Technology Meeting (MFPT 2011), Virginia Beach, Virginia, Society for Machinery Failure Prevention Technology, 2011.

[45] RAMUHALLI, P., BOND, L. J., GRIFFIN, J. W., DIXIT, M., HENAGER JR., C. H.: A Bayesian Prognostic Algorithm for Assessing Remaining Useful Life of Nuclear Power Components. In 7th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC&HMIT 2010), Las Vegas, Nevada, American Nuclear Society, La Grange Park, Illinois, 2010.

[46] RAJ, B., MOORTHY, V., JAYAKUMAR, T., RAO, K. B. S.: Assessment of Microstructures and Mechanical Behaviour of Metallic Materials through Non-destructive Characterisation, Int. Mater. Rev., 2003, 48(5):273-325.

[47] BOND, L. J., DOCTOR, S. R., GRIFFIN, J. W., HULL, A. B., MALIK, S. N.: Damage Assessment Technologies for Prognostics and Proactive Management of Materials Degradation (PMMD), Nucl. Tech., 2011, 173:46-55.

[48] HUTTON, P. H., DAWSON, J. F., FRIESEL, M. A., HARRIS, J. C., PAPPAS, R. A.: Acoustic Emission Monitoring of Hot Functional Testing: Watts Bar Unit 1 Nuclear Reactor, NUREG/CR-3693, Washington, D.C.: U.S. Nuclear Regulatory Commission, 1984.

[49] MEYER, R. M., CUMBLIDGE, S. E., RAMUHALLI, P., WATSON, B. E., DOCTOR, S. R., BOND, L. J.: Acoustic Emission and Guided Wave Monitoring of Fatigue Crack Growth on a Full Scale Pipe Specimen. In Proceedings of SPIE, Volume 7984 - Health Monitoring of Structural and Biological Systems 2011; SPIE Smart Structures/NDE, San Diego, California, Society of Photo-Optical Instrumentation Engineers, Bellingham, Washington, 2011.

[50] AI, Q., LIU, C.-X., CHEN, X.-R., HE, P., WANG, Y.: Acoustic Emission of Fatigue Crack in Pressure Pipe Under Cyclic Pressure, Nucl. Eng. Des., 2010, 240(10):3616-3620.

[51] ROSE, J. L., DITRI, J. J., PILARSKI, A., RAJANA, K., CARR, F.: A Guided Wave Inspection Technique for Nuclear Steam Generator Tubing, NDT & E International, 1994, 27(6):307-310.

[52] SILK, M., BAINTON, K.: The Propagation in Metal Tubing of Ultrasonic Wave Modes Equivalent to Lamb Waves, Ultrasonics, 1979, 17:11-19.

[53] CHEONG, Y.-M., LEE, D.-H., JUNG, H.-K.: Ultrasonic Guided Wave Parameters for Detection of Axial Cracks in Feeder Pipes of PHWR Nuclear Power Plants, Ultrasonics, 2004, 42(1–9):883-888.

[54] KWUN, H.: Feasibility of Magnetostrictive Sensor Inspection of Containments, NUREG/CR-5724, ORNL/SUB/98-SZ272V, Washington, D.C.: U.S. Nuclear Regulatory Commission, 1999.

[55] EPRI: Recommendations for an Effective Program to Control the Degradation of Buried Pipe, Report No. 1016456, Palo Alto, California: Electric Power Research Institute (EPRI), 2008.

[56] KWUN, H., MADER, E., KRZYWOSZ, K.: Guided Wave Inspection of Nuclear Fuel Rods. In Proceedings of the 7th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, Yokohama, Japan, European Commission Joint Research Centre, Luxembourg, 2009.

[57] CHO, Y., ROSE, J. L.: Guided Waves in a Water Loaded Hollow Cylinder, Nondestructive Testing And Evaluation, 1996, 12(5):323-339.

[58] NISHINO, H.: A Feasibility Study on Pipe Inspection Using Ultrasonic GuidedWaves forMaintenance of Nuclear Power Plants. In International Symposium on the Ageing Management & Maintenance of Nuclear Power Plants (ISaG2010), Toyko, 2010.

[59] ODAKURA, M., KOMETANI, Y., KOIKE, M., TOOMA, M., NAGASHIMA, Y.: Advanced Inspection Technologies for Nuclear Power Plants, Hitachi Review, 2009, 58(2):82-87.

[60] YANG, J., LEE, H., SOHN, H.: An Optical-fiber Guided Ultrasonic Excitation and Sensing System for Online Monitoring of Nuclear Power Plants under High-temperature Considering an Insulator. In 38th Annual Review of Progress in Quantitative NDE, Burlington, Vermont, 2011.

[61] SCHUSTER, G. J., DOCTOR, S. R., BOND, L. J.: A System for High-Resolution, Nondestructive, Ultrasonic Imaging of Weld Grains, IEEE Trans. Instrum. Meas., 2004, 53(6):1526-1532.

[62] DIAZ, A. A., CINSON, A. D., CRAWFORD, S. L., ANDERSON, M. T.: Technical Letter Report: An Evaluation of Ultrasonic Phased Array Testing for Reactor Piping System Components Containing Dissimilar Metal Welds, JCN N6398, Task 2A, PNNL-19018, Richland, Washington: Pacific Northwest National Laboratory, 2009.

[63] DIAZ, A. A., CINSON, A. D., CRAWFORD, S. L., MATHEWS, R., MORAN, T. L., PROWANT, M. S., ANDERSON, M. T.: An Evaluation of Ultrasonic Phased Array Testing for Cast Austenitic Stainless Steel Pressurizer Surge Line Piping Welds, NUREG/CR-7122, PNNL-19497, Washington, D.C.: U.S. Nuclear Regulatory Commission, 2011.

[64] DIAZ, A. A., CINSON, A. D., CRAWFORD, S. L., CUMBLIDGE, S. E., DOCTOR, S. R., DENSLOW, K. M., AHMED, S., ANDERSON, M. T.: An Assessment of Ultrasonic Techniques for Far-Side Examinations of Austenitic Stainless Steel Piping Welds, NUREG/CR-7113, PNNL-19353, Washington, D.C.: U.S. Nuclear Regulatory Commission, 2011.

[65] ANDERSON, M. T., CRAWFORD, S. L., DIAZ, A. A., MORAN, T. L.: Improvements in Low-Frequency, Ultrasonic Phased-Array Evaluation for Thick Section Cast Austenitic Stainless Steel Piping Components. In Proceedings of the Eighth International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, Berlin, Germany, European Communities, Luxembourg, Netherlands, 2010.

[66] CINSON, A. D., CRAWFORD, S. L., MACFARLAN, P. J., MATHEWS, R., HANSON, B. D., DIAZ, A. A.: Ultrasonic Phased Array Evaluation of Control Rod Drive Mechanism (CRDM) Nozzle Interference Fit and Weld Region. In ASME 2011 Pressure Vessels and Piping Conference, Baltimore, Maryland, 2011.

[67] RAMUHALLI, P., CRAWFORD, S. L., CINSON, A. D., DIAZ, A. A., ANDERSON, M. T.: Evaluation of Signal Processing Tools for Improved Phased-Array Ultrasonic Weld Inspection. In Proceedings of SPIE, Volume 7982 - Smart Sensor Phenomena, Technology, Networks, and Systems 2011; SPIE Smart Structures/NDE, San Diego, California, Society of Photo-Optical Instrumentation Engineers, Bellingham, Washington, 2011.

[68] GRIFFIN, J. W., POSAKONY, G. J., HARRIS JR., R. V., BALDWIN, D. L., JONES, A. M., BOND, L. J.: High Temperature Ultrasonic Transducers for In-Service Inspection of Liquid Metal Fast Reactors. In IEEE International Ultrasonics Symposium 2011, Orlando, Florida, IEEE, Piscataway, New Jersey, In press.

[69] JHANG, K.-Y.: Nonlinear Ultrasonic Techniques for Non-destructive Assessment of Micro Damage in Material: A Review, Int. J. Precis. Eng. Manuf., 2009, 10(1):123-135.

[70] NAUS, D. J.: The Management of Aging in Nuclear Power Plant Concrete Structures, JOM, 2009, 61(7):35-41.

[71] SHAH, V. N., HOOKHAM, C. J.: Long-term Aging of Light Water Reactor Concrete Containments, Nucl. Eng. Des., 1998, 185:51-81.

[72] NORRIS, W. E., NAUS, D. J., GRAVES III, H. L.: Inspection of Nuclear Power Plant Containment Structures, Nucl. Eng. Des., 1999, 192:303-329.

[73] NAUS, D. J.: Inspection of Nuclear Power Plant Structures - Overview of Methods and Related Applications, ORNL/TM-2007/191, Oak Ridge, Tennessee: Oak Ridge National Laboratory, 2009.

[74] LINDBERG, J.: Monitoring and NDE to Support Long Term Operation of the Nuclear Fleet - Augmented Containment Inspection. In 38th Annual Review of Progress in QNDE, Burlington, Vermont, 2011.

[75] HENAULT, J. M., SALIN, J., MOREAU, G., DELEPINE-LESOILLE, S., BERTAND, J., TAILLADE, F., QUIERTANT, M., BENZARTI, K.: Qualification of a Truly Distributed Fiber Optic Technique for Strain and Temperature Measurements in Concrete Structures, EPJ Web of Conferences, 2011, 12:03004 (8 pp.).

[76] ROCTEST GROUP: Nuclear Power Plant Structural Health Monitoring, 2012. http://www.roctest-group.com/applications/nuclear.

[77] BEARD, M. D., LOWE, M. J. S., CAWLEY, P.: Ultrasonic Guided Waves for Inspection of Grouted Tendons and Bolts, J. Mater. Civ. Eng., 2003, 15(3):212-218.

[78] CHAKI, S., BOURSE, G.: Guided Ultrasonic Waves for Non-destructive Monitoring of the Stress Levels in Prestressed Steel Strands, Ultasonics, 2009, 49(2):162-171.

[79] YUYAMA, S., YOKOYAMA, K., NIITANI, K., OHTSU, M., UOMOTO, T.: Detection and Evaluation of Failures in High-Strength Tendon of Prestressed Concrete Bridges by Acoustic Emission, Construct. Build. Mater., 2007, 21(3):491-500.

[80] CULLINGTON, D. W., MACNEIL, D., PAULSON, P., ELLIOTT, J.: Continuous Acoustic Monitoring of Grouted Post-Tensioned Concrete Bridges, NDT & E International, 2001, 34:95-105.

[81] VOGEL, T., SCHECHINGER, B., FRICKER, S.: Acoustic Emission Analysis as a Monitoring Method for Prestressed Concrete Structures. In 9th European Conference on NDT (ECNDT 2006), Berlin, 2006.

[82] MILLER, T. H.: Nondestructive Inspection of Corrosion and Delamination at the Concrete-Steel Reinforcement Interface, Tucson: The University of Arizona, 2010.

[83] SHARMA, S., MUKHERJEE, A.: Longitudinal Guided Waves for Monitoring Chloride Corrosion in Reinforcing Bars in Concrete, Structural Health Monitoring, 2010, 9(6):555-567.

[84] REIS, H., ERVIN, B. L., KUCHMA, D. A., BERNHARD, J. T.: Estimation of Corrosion Damage in Steel Reinforced Mortar Using Guided Waves, J. Pres. Vessel Technol., 2005, 127(3):255-261.

[85] IDRISSI, H., LIMAM, A.: Study and Characterization by Acoustic Emission and Electrochemical Measurements of Concrete Deterioration Caused by Reinforcement Steel Corrosion, NDT & E International, 2003, 36:563-569.

[86] ZDUNEK, A. D., PRINE, D., LI, Z., LANDIS, E., SHAH, S.: Early Detection of Steel Rebar Corrosion by Acoustic Emission Monitoring. In CORROSION95, the NACE International Annual Conference and Corrosion Show, Orlando, Florida, NACE International, 1995.

[87] SCHURR, D. P., KIM, J.-Y., SABRA, K., JACOBS, L. J.: Monitoring Damage in Concrete Using Diffuse Ultrasonic CODA Wave Interferometry. In Annual Review of Progress in Quantitative Nondestructive Evaluation, San Diego, California, 2010.

[88] DEROO, F., KIM, J.-Y., QU, J., SABRA, K., JACOBS, L. J.: Detection of Damage in Concrete Using Diffuse Ultrasound, J. Acoust. Soc. Am., 2010, 127(6):3315-3318.

[89] LU, Y.: Analysis and Modeling of Diffuse Ultrasonic Signals for Structural Health Monitoring, Atlanta: Georgia Institute of Technology, 2007.

[90] GAZDZINSKI, R. F., DENNY, W. M., TOMAN, G. J., BUTWIN, R. T.: Aging Management Guideline for Commercial Nuclear Power Plants - Electrical Cable and Terminations, SAND 96-0344, Albuquerque, New Mexico: Sandia National Laboratories, 1996.

[91] VILLARAN, M., LOFARO, R.: Essential Elements of an Electric Cable Condition Monitoring Program, NUREG/CR-7000; BNL-NUREG-90318-2009, Washington, D.C.: U.S. Nuclear Regulatory Commission, 2010.

[92] IAEA: Management of Life Cycle and Ageing at Nuclear Plants: Improved I&C Maintenance, IAEA-TECDOC-1402, Vienna, Austria: International Atomic Energy Agency, 2004.

[93] IAEA: Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: In-containment Instrumentation and Control Cables. Volume I, IAEA-TECDOC-1188, Vienna, Austria: International Atomic Energy Agency, 2000.

[94] KIM, J.-S.: Evaluation of Cable Aging Degradation Based on Plant Operating Condition, J. Nucl. Sci. Tech., 2005, 42(8):745-753.

[95] FANTONI, P. F.: Presented at INL On-Line Monitoring Workshop, Seattle, Washington, June 10-12, 2010.

[96] HASHEMIAN, H. M., BEAN, W. C.: Advanced Cable-Testing Techniques for Nuclear Power Plants, Nucl. Tech., 2011, 176(3):414-429.

[97] EPRI: Plant Support Engineering: Aging Management Program Development Guidance for AC and DC Low-Voltage Power Cable Systems for Nuclear Power Plants, Report No. 1020804, Palo Alto, California: Electric Power Research Institute (EPRI), 2010.

[98] EPRI: Plant Support Engineering: Aging Management Program Guidance for Medium-Voltage Cable Systems for Nuclear Power Plants, Report No. 1020805, Palo Alto, California: Electric Power Research Institute (EPRI), 2010.

[99] NRC: Condition Monitoring Program for Electric Cables Used in Nuclear Power Plants, Draft Regulatory Guide DG-1240, Washington, D.C.: U.S. Nuclear Regulatory Commission, 2010.

[100] AHMED, S., CARFAGNO, S. P., TOMAN, G. J.: Inspection, Surveillance, and Monitoring of Electrical Equipment Inside Containment of Nuclear Power Plants, with Applications to Electrical Cables, NUREG/CR-4257, Washington, D.C.: U.S. Nuclear Regulatory Commission, 1985.

[101] URMANOV, A.: Electronic Prognostics for Computer Servers. In Proceedings, Reliability and Maintainability Symposium, 2007 (RAMS07 2007), IEEE, 2007.

[102] VICHARE, N. M., PECHT, M. G.: Prognostics and Health Management of Electronics, IEEE Trans. Compon. Packag. Tech., 2006, 29(1):222-229.

[103] KALGREN, P. W., BAYBUTT, M., GINART, A., MINNELLA, C., ROEMER, M. J., DABNEY, T.: Application of Prognostic Health Management in Digital Electronic Systems. In Aerospace Conference, 2007 IEEE, Big Sky, Montana, 2007.

[104] JARDINE, A. K. S., LIN, D., BANJEVIC, D.: A Review on Machinery Diagnostic and Prognostics Implementing Condition Based Maintenance, Mechanical Systems and Signal Processing, 2006, 20:1483-1510.

[105] KOTHAMASU, R., HUANG, S. H., VERDUIN, W. H.: System Health Monitoring and Prognostics – A Review of Current Paradigms and Practices, International Journal of Advanced Manufacturing Technology, 2006, 28:1012-1024.

[106] HO, Y.-C., PEPYNE, D. L.: Simple Explanation of the No Free Lunch Theorem of Optimization, Cybern. Syst. Anal., 2002, 38(2):292-298.

[107] KOPPEN, M.: No-Free-Lunch Theorems and the Diversity of Algorithms. In Congress on Evolutionary Computation (CEC2004), Portland, Oregon, 2004.

[108] HINES, J. W., USYNIN, A.: Current Computational Trends in Equipment Prognostics, Int. J. Comput. Intell., 2008, 1(1):95-109.

[109] COBLE, J. B., HINES, J. W.: Prognostic Algorithm Categorization with PHM Challenge Application. In 2008 International Conference on Prognostics and Health Management (PHM 2008), Denver, Colorado, IEEE, Piscataway, New Jersey, 2008.

[110] HINES, J. W., BAILEY, K., COBLE, J., HUMBERSTONE, M., SHARP, M.: Recent Advances in Empirical Methods for Equipment Condition Monitoring and Prognostics. In 2010 Maintenance and Reliability Conference, Knoxville, Tennessee, The University of Tennessee, Reliability and Maintainability Center, 2010.

[111] HINES, J. W., GARVEY, J., PRESTON, J., USYNIN, A.: Empirical Methods for Process and Equipment Prognostics. In 53rd Annual Reliability and Maintainability Symposium (RAMS), 2008 Proceedings, Las Vegas, Nevada, 2008.

[112] PARKINSON, B. A.: Presentations from EPRI COLM Workshop, January 28, 2011. Source information not publicly available.

[113] KULKARNI, S. S., ACHENBACH, J. D.: Structural Health Monitoring and Damage Prognosis in Fatigue, Structural Health Monitoring, 2008, 7(1):37-49.

[114] KHAN, T., RAMUHALLI, P., DASS, S.: Sequential Monte Carlo Methods for Multisensor Data Fusion in Inverse Problems, IEEE Trans. Instrum. Meas., 2011 (in press).