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Prognostics and Life Beyond 60 Years for Nuclear Power Plants

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***Abstract*—Safe, secure, reliable, and sustainable energy supply is vital for advanced and industrialized life styles. To meet growing energy demand there is interest in longer-term operation for the existing nuclear power plant fleet and enhancing capabilities in new build. There is increasing use of condition-based maintenance for active components and growing interest in deploying on-line monitoring instead of periodic in-service inspection for passive systems. Opportunities exist to move beyond monitoring and diagnosis based on pattern recognition and anomaly detection to prognostics with the ability to provide an estimate of remaining useful life. The adoption of digital I&C systems provides a framework within which added functionality including on-line monitoring can be deployed, and used to maintain and even potentially enhance safety, while at the same time improving planning and reducing both operations and maintenance costs.**

Keywords- materials damage prognostics; material degradation; nuclear power; on-line monitoring

I. Introduction

There are currently about 439 nuclear power plants (NPPs) in the commercial global fleet and by some estimates another 222 projects are in various stages of development. Global demand for electricity continues to surge; the price of oil is increasing. Meeting this growing energy demand converges with the desire, in most countries, to minimize carbon emissions through the use of carbon-free electricity generation. Although recent events in Japan may cause some review and re-assessment of both current and planned nuclear power projects for electricity generation, in the longer term growth continues to be anticipated and nuclear can be expected to remain a significant part of the global energy mix.

Existing plants started operation with 30- or 40-year licenses. In the USA, a total of 60 license extensions, for plants at 34 sites, have been granted to enable operation from 40 to 60 years (December 2010). In addition, another 20 plants at 13 sites are under review. As of September 2010, seven plants in the USA had moved into extended operation (over 40 years). Globally many countries are considering an additional 10 years of operation, and in the USA, a second 20 years of life extension (from 60–80 years) for the current nuclear power plant (NPP) fleet is being considered. For new plants, 60-year design life is now the norm, and even in the planning stage attention is being given to potential for longer term operation (LTO).

Consequently, if countries are to provide safe, secure, and sustainable energy systems, there is a need to better understand and manage the challenges posed by NPP system aging, particularly as plants look at LTO. The deployment of advanced monitoring, and a transition from diagnostics to prognostics for major structures, systems, and components is increasingly considered as important, if not critical, to managing economics, maintaining high-capacity factors, and ensuring plant-safety margins are maintained, and possibly enhanced.

This paper discusses the trends that have occurred in asset management and then considers the status and potential for LTO for nuclear power plants, in particular those in the USA, through the use of advanced diagnostics and prognostics for both active and passive components.

II. Light Water Reactor Sustainability

In 2009, the United States Department of Energy, Office of Nuclear Energy (US DOE-NE) sponsored a Light Water Reactor Sustainability (LWRS) workshop focused on advanced instrumentation, information and control systems, and human-system interface technologies [1]. Three R&D strategic program goals were identified as being central to better understanding the challenges posed by NPP aging, including advanced instrumentation systems. The primary activities identified in this I&C area were:

- Sensors, diagnostics, and prognostics to support characterization and prediction of the effects of aging and degradation phenomena effects 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

Work in this area was supported in part through the Reactor Aging Management (RAM) Focus Area of the PNNL Sustainable Nuclear Power Initiative (SNPI). It has been supported in part by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research under contracts N-6019, N-6029, and N-6957. On-going activities are a part of the DOE-NE Light Water Reactor Sustainability Program.

- New methods for visualization, integration, and information use to enhance state awareness and leverage expertise to achieve safer, more readily available electricity generation.

Material degradation phenomena are in many cases based on longer-term interactions, which 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 [2] that represent a fundamental change from most current inspections that are reactive and based on *find-and-fix*.

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, which continuously monitor and assess the health of NPP SSCs. These technologies can deliver enhanced system condition awareness and improve advance outage and maintenance planning through early warning of conditions and components that require attention, and at the same time minimize exposure to many future and unknown risks. There are many challenges that require this effective on-line monitoring (OLM). Examples are the detection of small component degradation that are located in a "noisy" environment, or degradations that cause similar system behaviors or where some plant systems experience simultaneous multiple or intermittent component failures. When challenges reach this level of complexity, advanced instrumentation using technologies such as stressor-based prognostics, signature analysis, neural networks, pattern recognition, and estimation theory can all be utilized.

III. Trends in Asset Management

Recent decades have seen the evolution of management and maintenance strategies for both active components (e.g., pumps, valves, motors) and passive components (e.g., pressure vessels and piping).

Developments in NDT or NDI started to transition to more quantitative analysis in the 1960s in response to the development of fracture mechanics. Early work in the USA received significant DARPA and USAF funding, and subsequently evolved into programs with wider DOD and FAA support [3, 4]. The past decade has seen a second transition – from NDE to structural health monitoring (SHM) [5]. In the wider high-technology community, most notably in the aero-space and defense communities, there has been a growing recognition that the activity known as prognostics and heath management (PHM) or SHM can bring significant advantages in terms of availability, enhanced safety, and reduced fleet operation costs [6, 7]. The changes in approaches over the past 40 years are illustrated with Fig 1. This evolution has been driven by the desire to increase availability and to adopt approaches that apply preventive, and then predictive and proactive philosophies (see Fig. 2) [8].

There were major programs in the 1980s and into the early 1990s that enabled the U.S. nuclear power industry to demonstrate that there is the technical basis for license

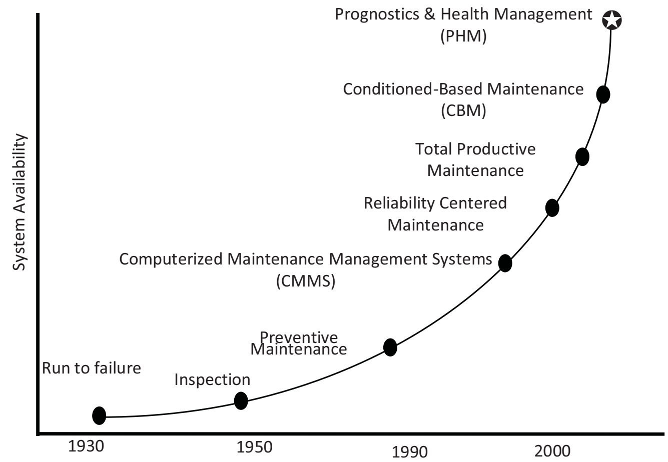

Figure 1. Evolution of maintenance (with the dates being for non-nuclear industry deployment).

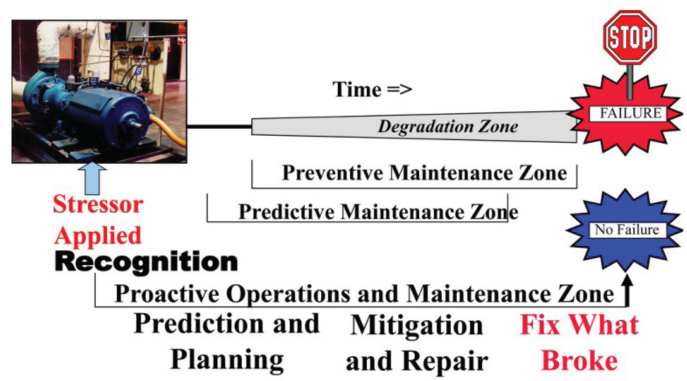

Figure 2. Evolution from preventative to predictive maintenance approaches.

extension, from 40–60 years [e.g., 9, 10]. The move towards consideration of "life-beyond-60" (LB-60), the second period of license extension from 60–80 years, is serving to further focus attention on the science and technology needed. In the nuclear industry, in support of NPP license renewal and looking forward to further license extensions over the past decade, various national and international programs have been initiated [11]. In looking at the issues that surround LB-60, the U.S. Nuclear Regulatory Commission (NRC) is seeking to facilitate the establishment of an International Forum for Reactor Aging Management (IFRAM). Major reports and databases have been developed (e.g., GALL – Generic Aging Lessons Learned [12-14], Proactive Materials Degradation Assessment Expert Panel [15], EPRI Issues Management Tables (IMT) and Materials Degradation Matrix (MDM) [16-18]). The IAEA, OECD-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 a number of other countries are all recognizing the challenges faced in LTO for NPPs and are establishing programs to address aspects of the technical issues [11].

To enable LTO, it is necessary to understand stressors and degradation mechanisms, the capabilities and limitations of current non-destructive examination (NDE) methods to periodically detect, monitor, and trend degradation and hence enable timely implementation of appropriate corrective actions. There are fundamental changes occurring that move "monitoring" from reactive, *find-and-fix degradation or defects (NDT or condition-based maintenance [CBM])*, to become more proactive, through including methodologies that manage stressors, understand component or system life utilization, and can accurately predict a remaining safe life (prognostics) [8].

Current needs in terms of LTO for existing and new plants, including small modular reactors (SMR), are causing the community to look beyond locally monitored CBM, towards fleet-wide monitoring, increased functionality, and the potential for prognostics. SMR are expected to operate with fewer scheduled outages and have more limited access to key equipment, some of which will be located inside containment, which will increase remote operation and there will be more limited on-site staff.

The community (in the USA) is looking towards the lessons learned from major design and construction upgrades, including extensive balance-of-plant (BOP) work, from Browns Ferry, Watts Bar, and Bellefonte restarts. From an economics perspective, it is looking increasingly as if it could be installation issues for new technology that may be the final determinate regarding the feasibility for LTO (the second license extension – for 60–80 year operation) for a given plant.

Currently, active components (i.e., pumps, valves, etc.) in NPPs are routinely diagnosed and managed under a maintenance rule. Passive components (i.e., pressure vessel, piping, etc.) are managed using aging management plans (AMPs) and periodic in-service inspection (ISI) programs. One element in current activities is looking beyond CBM to prognostics, for both active and passive components. The move from periodic, manual assessments and surveillance of physical systems to on-line condition monitoring represents an opportunity for an important transformational step in the management of physical assets. In this process, technologies give the potential to provide real-time monitoring and assessment of physical systems and hence enable better management of components based on their actual performance. Such technologies provide the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions regarding asset and safety management.

IV. Current On-line Monitoring Practice

When the past experience of the nuclear industry is considered, with regard to on-line monitoring, it has tended to focus on issues of sensor calibration [19].

In most current NPPs, instrumentation is deployed to monitor reactor noise, acoustic signals and vibration in various forms, and to enable some form of leak monitoring. There is currently a transition in progress from manual periodic inspections of active systems, such as pumps, motors, and valves, to establish capabilities to enable more automated CBM, including use of wireless networks [20].

Based on both nuclear and wider industry experience, many, if not all, active components can potentially be well managed, routinely diagnosed, analyzed, and upgraded as needed using a combination of periodic and online condition-based monitoring/condition-based maintenance (CBM^2). Adding a prognostic component has the potential to avoid unscheduled outages, and reduce operation and maintenance costs.

Some methods of on-line monitoring have been deployed for passive components, probably best known of which is acoustic emission. Both active interrogation and passive (listening) NDE methods are being investigated – several of which use ultrasound, guided waves, diffuse fields, and acoustic emission. Methods for the analysis of such technologies are being investigated [21].

The ability to successfully manage passive systems and structures is seen as the key to LTO, including looking beyond 60 years of operation. Passive structures are currently managed through ISI performed at intervals as set out in the plant AMP. Changes in regulatory guidance will be needed to enable a combination of NDE and on-line monitoring in the emerging management strategies.

V. On-line Monitoring: Active Components

There have been various studies that have demonstrated OLM for nuclear systems, including using wireless-based data transmission and the data analysis, with system monitoring/diagnostic capabilities. One such activity was performed as a DOE-NE NERI project [22]. The activities developed and tested the components in a pilot-scale service water system. A motorized valve with sensors and wireless tag using with a hand-held reader is shown in Fig 3. An example of a rig-monitoring screen is shown in Fig 4. This system has now been developed into a test bed that has been used in several studies [23, 24].

A growing body of work, mostly outside the nuclear industry, is reporting "prognostics" for many classes of active components [e.g., 7]. A number of reviews now discuss both condition-based maintenance for machinery [25, 26] and the various classes of prognostics algorithms used [27].

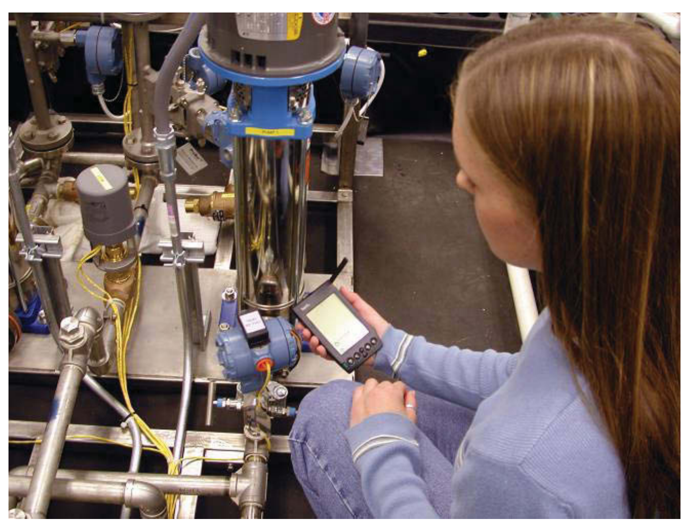

Figure 3. A motorized valve with sensors and wireless tag is shown, with a hand-held reader.

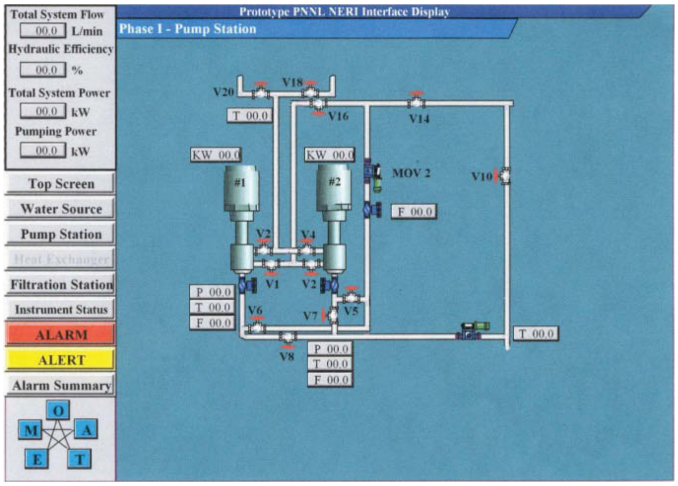

Figure 4. Example of a rig-monitoring screen for part of a pilot-scale service water system.

The data recorded for monitoring and prognostics can be as simple as an assessment of vibration in a rotating machinery unit using a hand-held vibration meter. The data can be reviewed by an experienced technician or higher levels of automation and analysis deployed. Diagnosis can provide identification, and prognosis enables a prediction of remaining useful life to be provided. This hierarchy of responses, culminating in mitigation actions, is illustrated with Fig. 5. [28].

When the data-to-action processes is implemented using digital systems, there is the ability to provide enhanced functionality (as illustrated in Fig. 6), and these data can be utilized locally or potentially in various forms of centralized monitoring systems.

The adoption of what is termed stressor-based prognostics [22] has the potential to increase warning time, and increase sensitivity. For example, monitoring of phenomena such as cavitation in a pump gives the identification of a mechanism for potential future damage, whereas a measurement of metal loss, after cavitational erosion, only tells the inspector how much damage there is. Through monitoring stressors, new classes of mitigation process, rather than reactive responses, can be implemented. The additional time available (T) through stress monitoring is shown in schematic form as Fig 7. The estimation of remaining useful life, for data such as that shown in Fig 7, can be made using a simple extrapolation or more robust Bayesian methods can be employed [29].

VI. On-line Monitoring: Passive Components

For passive NPP components (i.e., structures), there is activity in the wider technical community that is reported for structural health monitoring, and that which has been referred to as damage prognostics or materials damage prognostics [30, 31]. There is also an extensive literature that reports the issues relating to understanding and mitigating aging in NPPs [32].

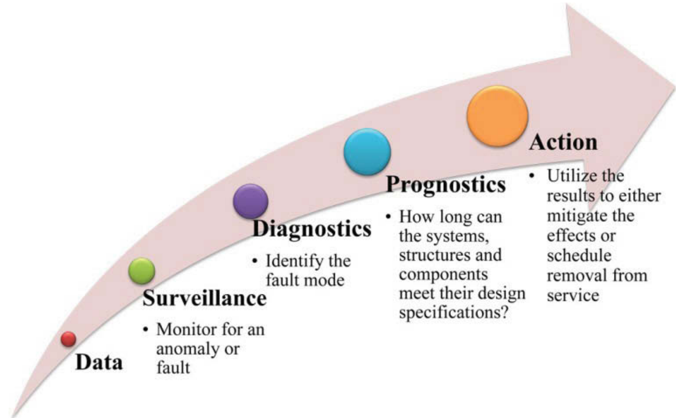

Figure 5. A hierarchy of data analysis and responses.

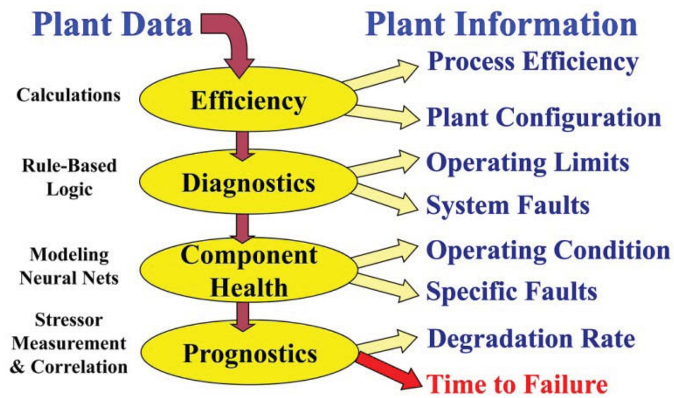

Figure 6. Relationship between plant data and performance, including classes of algorithm.

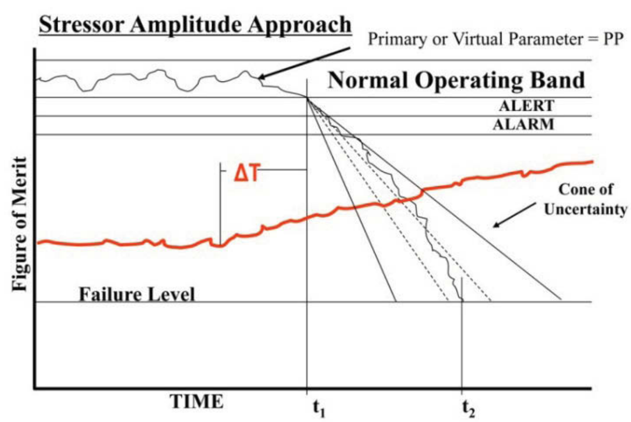

Figure 7. Schedule showing features in terms of early warning (response time from stressor-based prognostics)

For structures that contain cracks of significant size (mm or larger dimensions), conventional NDE, combined with probabilistic fracture mechanics, provides a robust framework that supports the current AMPs and ISI performed at outages [33, 34].

In looking to longer-term operation the interest is now focusing on early (or earlier) detection and quantification of degradation, combined with a prognostic capability that can give a remaining useful life. This approach then has the potential, when combined with on-line monitoring, to avoid surprises that can be costly when issues are detected at an outage. There are however significant challenges in provided monitoring methods, as well as the related data processing. The philosophy of moving beyond NDE to what is being called proactive management of materials degradation (PMMD) was reviewed in a paper by Bond [8].

Early degradation in NPP systems and structures is being investigated by a significant number of researchers worldwide in PMMD-related research programs [11]. Major activities include work by Dobmann et al. [35] and extensive reviews by Raj et al. [36] and Bond et al. [37]. A first demonstration of a fatigue prognostic, based on early degradation detection and laboratory measurements, has recently been reported [38].

An example of a fatigue prognostic, from measurements of nonlinear acoustic responses [39] to progressive fatigue damage accumulation in a carbon steel specimen is shown as Fig 8. Measurements in the degradation precursor stage were used, along 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 form of information can be used, along with information on failure probabilities, to estimate remaining useful life of passive structural components based on early degradation detection [40]. It is likely that similar approaches to prognostics for passive components will be necessary to enable LTO. Clearly, 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 [40].

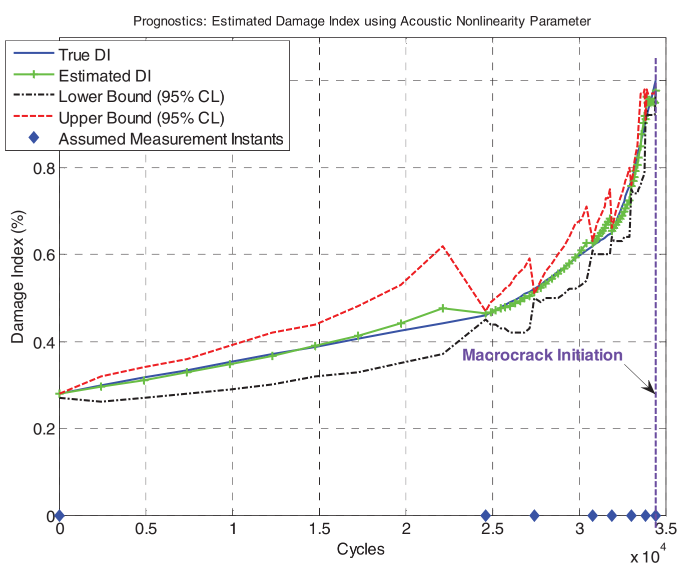

Figure 8. Prediction of DI from acoustic nonlinearity measurements, to demonstrate the feasibility of the prototype Bayesian algorithm.

VII. Integrated Prognostics

As indicated earlier, integrated prognostics methods have been demonstrated for active components. The challenges are with passive components. The application of prognostics to NPP SSCs will require adoption of a philosophical and cultural change in the nuclear community. A schematic showing the integration of some of the elements in the on-line monitoring/NDE elements of the LWRS program are shown as Fig 9.

In successfully delivering prognostics within the NPP community (as well as many other industries), it is necessary to first *understand* degradation processes in extreme environments, including the quantification of relationships between stressors, degradation precursors, and integration of insights into a physical model of degradation growth. Given these insights, it is necessary to then *relate* degradation to measurable physical quantities. This includes the adaption or design of sensors for in-situ degradation monitoring and assessment of the current SSC state.

When the appropriate sensors are deployed (and there needs to be significant thought given to the number of locations, measured parameters, and system parameters such as sampling rate and use of centralized or distributed computing), an algorithm can then be used to *estimate* RUL or a damage or condition metric using model-based prognostics. Following the RUL or metric estimation, these data can be used as input into probabilistic risk assessment (PRA) models and to then inform the proactive scheduling of mitigation activities. In looking towards deployment, an integrated framework that combines the understanding of phenomena, the relationships between stressors and systems (or components), and provides a RUL and actionable guidance to operators is necessary.

While the use of prognostics in NPPs clearly has potential, several challenges exist in this regard:

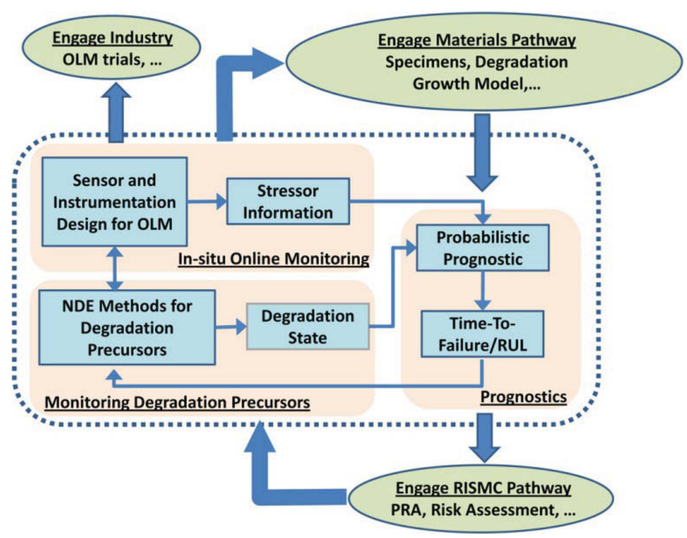

Figure 9. Element in the on-line monitoring tasks under the LWRS Program—DOE-NE

A. Models of Degradation Accumulation

Model-based approaches to prognostics typically are the most accurate, providing the best estimates of the rate of degradation growth. Developing and validating such models presents significant challenges, both experimentally and mathematically. In particular, the physics of failure (from damage initiation to failure of the component) is still poorly understood, especially for structural materials [41]. For instance, while the factors that impact the growth of a crack in materials are reasonably well-understood, the dynamics of incipient crack growth are less well-known. The impact of one or more stressors on the rate of growth of degradation is also needed. Numerical studies, backed by careful experiments, are being conducted at several institutions worldwide to obtain a better understanding of damage phenomena, especially in structural materials used in NPP.

B. Diagnostics and Damage State Awareness

A related issue is the availability of diagnostic methods that are sensitive to early stages of degradation. At issue are both the sensitivity and specificity of the diagnostic method to the degradation mechanism of interest. Further, the issue of determining the current damage state (or level) from the diagnostic measurements is also challenging. It is likely that advances in diagnostics technology from other industries can be adapted to the unique needs of the nuclear power area. It is also likely that no single diagnostic method can provide adequate information about the damaged state of a material, component, or system. Instead, multiple orthogonal diagnostic tools will be necessary, as will novel data fusion methods, to uniquely determine the damaged state of the component.

C. Prognostics from Precursors

To be useful, estimates of RUL are necessary from early stages of degradation (precursors). Challenges in this area include appropriate definitions of degradation precursors (i.e., what is a degradation precursor), availability of measurement tools sensitive to precursors, and an understanding of degradation development from precursor states to component failure.

D. Uncertainty Quantification

Given the various uncertainties associated with measuring the current state of components and those associated with stressors and degradation evolution, the RUL estimate is likely to be somewhat uncertain as well. Methods for quantifying the uncertainty associated with the RUL are available and constraining (bounding) estimates will need to be validated for NPP implementation.

VIII. Conclusions

The science base for advanced diagnostics and prognostics needed to support its use in NPPs for active components (pumps, valves, etc.) has been demonstrated in other industries—the challenge is in adaption for NPP deployment and the validation of the methods. Applications for passive structures are being researched and early laboratory work is demonstrating the potential for these methods. The transition from condition-based methods for active components and current ISI to on-line monitoring and prognostics for passive components will be helped if regulatory relief from some ISI inspections is granted when an on-line monitoring approach is deployed. The adoption of digital I&C systems provides a framework within which the added functionality provided with on-line monitoring can be deployed, and used to reduce operations and maintenance costs.

Acknowledgment

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