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# Moving Beyond Nondestructive Examination to Proactive Management of Materials Degradation

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*There is growing interest in life extensions to enable longer term operation (LTO) for both existing nuclear power plants (NPPs) and proposed new NPPs. In order to justify an initial license extension for the 40–60 yr period, new nondestructive examination (NDE) approaches have been developed and deployed by NPP operators in their aging management programs. However, to achieve the goals of even longer term operation, and specifically for the United States in looking at methodologies to support subsequent license renewal periods (i.e., 60–80 yr and beyond), it is necessary to understand the capabilities of current NDE methods to detect, monitor, and trend degradation and hence enable timely implementation of appropriate mitigation and corrective actions. This paper discusses insights from past experience, the state-of-the-art, and current activities in the move toward providing a capacity for proactive management of materials degradation to support NPP LTO. [DOI: 10.1115/1.4005056]*

## Introduction

There is a growing global interest in the longer term operation (LTO) of the existing fleet of nuclear power plants (NPPs). This requires new and improved approaches to plant-life management as licensees seek to operate beyond the initial license periods of 30 or 40 yr and now move to consider operation beyond 60 yr.

To enable LTO, life management strategies are being developed that become increasingly *proactive* and take a holistic approach toward plant aging. To achieve the goals of safe LTO, it is necessary to understand stressors and degradation mechanisms, as well as the capabilities and limitations of current nondestructive examination (NDE) methods to periodically detect, monitor, and trend degradation and hence enable timely implementation of appropriate corrective actions. The stressors that drive degradation phenomena within the components in a nuclear plant include the pressures, temperatures, radiation flux, coolant chemistry, and local environmental effects. These phenomena all impact the plant materials in various ways and combine to drive aging mechanisms that include embrittlement, creep, corrosion, and fatigue. The consequences of the stressors and the aging mechanisms are then seen in terms of structural damage, which manifests itself through the degradation of mechanical properties, such as fracture toughness, and/or through cracking, deformation, or metal loss. It therefore becomes the characterization and management of the various materials issues that are at the heart of LTO. In looking at NPPs, it is seen that the key parts of the plant where materials issues must be managed are (i) reactor pressure vessel (RPV) and primary piping, (ii) core internals, (iii) secondary systems, (iv) weldments, (v) concrete, (vi) cabling, and (vii) buried piping.

LTO does not fundamentally change operations, but it brings the challenge that the longer life leads to increased exposure to

temperatures (and its cycling), stress (with both high and low frequency phenomena), coolant chemistry with the subsequent chemical material interactions, flow effects, and radiation, in particular neutrons. Extending life has the potential to increase susceptibility to and severity of known forms of degradation. It also provides the opportunity for effects due to new mechanisms, or those that were not significant up to 40 or 60 yr, to become important. Within the materials community, there is the concern that additional years of exposure to neutrons, coolants, and stress may enhance susceptibility to stress corrosion cracking (SCC) and irradiation assisted stress corrosion cracking (IASCC). For the reactor pressure vessel and core internals, the radiation has the potential to cause ductile/brittle transition temperature shifts and late-blooming phases (LBP) with species migration that have been observed in some laboratory studies. For core internals, radiation induced swelling can potentially create tolerance problems. Moving beyond the metals in the primary passive and core internals, there are also phenomena that affect concrete, cables, and underground pipes and vessels which remain topics of ongoing work in the materials community [1].

To support life extension, there is also a need to provide new NDE methodologies and technologies that provide early detection which can then anticipate and hence better manage significant materials degradation, i.e., that which will cause a structure to become unable to meet its design basis, even on the last day of plant operation. To meet the measurement and characterization needs, this includes the migration from traditional NDE, implemented through inservice inspection (ISI) programs, toward structural health monitoring (SHM) that employs online monitoring, with the consequential move from local to global assessment. These SHM strategies are forming the basis for what is being termed proactive management of materials degradation (PMMD) and the predictive methods that provide estimates for remaining life (prognostics).

The changes from NDE to PMMD are fundamentally a move from being reactive, *find and fix defects*, to become more proactive, through including methodologies that manage stressors, understand component or system life utilization, and accurately predict a remaining useful or safe life (prognostics). These methodologies provide increased operator system awareness. They greatly enhanced understanding of the complex interactions between the environmental stressors (e.g., temperatures, pressures, radiation), the materials, and the degradation mechanisms, and, through enhanced monitoring, enable early detection of degradation while there are still opportunities for early corrective action (e.g., water chemistry changes to reduce cracking potential or through changes in operation or output power). The various holistic approaches to plant-life management provide significant opportunities to better understand the complex stressor-material interactions, including the relationships between operating power and power up rates on life utilization and for reduction in plant life cycle costs [2].

In support of NPP license renewal over the past decade, various national and international programs have been initiated [3] and major reports and databases developed: e.g., U.S. Nuclear Regulatory Commission's (NRC) GALL—generic aging lessons learned [4], Proactive Materials Degradation Assessment Expert Panel [5], Electric Power Research Institute (EPRI) issues management tables (IMT) and materials degradation matrix (MDM) [6–8]. The International Atomic Energy Agency (IAEA), Organization for Economic Co-operation and Development (OECD) - Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Infrastructure (CSNI), European groups through the Network of Excellence - Nuclear Plant Life Prediction (NULIFE - EU's) 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 NPP [3]. The move toward consideration of “life-beyond-60” (LB-60), the second period of license extension from 60–80 yr, is serving to focus attention on the science and technology needed. In looking at the issues that surround

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LB-60, the U.S. NRC is seeking to facilitate the establishment of an international forum as part of its activities in PMMD. The various activities are seeking to better facilitate information exchange and enable enhanced coordination in identifying gaps and issues that need to be addressed.

This paper discusses the state-of-the-art in NDE and the current activities in the move toward providing the capacity for PMMD to support NPP LTO.

### Longer Term Operations

Globally, there are about 439 operating plants and up to 222 new plants reported as being planned. In the United States, approximately 20% of its electricity is generated through the operation of 104 nuclear power plants. This capacity accounts for more than 70% of the carbon emissions-free electricity generation, and these assets represent a significant economic and energy resource.

LTO is essentially an economic decision made by operators that may be constrained by technical issues and the investments needed to repair or replace life limiting major components (e.g., head replacement). More than 90% of U.S. plants are currently either considering or implementing license extensions of 20 yr, and similar trends are developing globally, although license periods and regulatory arrangements do vary by country. As plants age and power demand increases, consideration is now being given to the concept of LB-60 with license extension from 60 to 80 yr and potentially longer.

In addition to meeting electricity demand, it is estimated that the first 20-yr life extension for the U.S. nuclear power fleet will eliminate  $\sim 12 \times 10^9$  tons of CO<sub>2</sub> emissions and provide the electricity needed to meet the power needs of  $\sim 70 \times 10^6$  households for 20 yr. A second 20 yr would bring similar benefits. For the non-U.S. global fleet, currently 334 plants, corresponding reductions in emissions are also possible. Directing available funds and engineering resources toward building new plants which increase generating capacity, rather than providing replacement capacity, has the potential to make a substantial contribution as countries seek to provide non-carbon based electricity and the energy resources needed to support sustainable development.

In order to justify an initial license extension for the 40–60 yr period, licensees have developed aging management programs (AMPs) to ensure continued safe operation. To support the inspections required by these AMPs, industry is developing and deploying new NDE approaches.

Developing online monitoring and condition based maintenance (CBM) currently applied to *active components* (e.g., pumps, valves) has the potential to increase operator situational awareness, enhance safety, and provide significant cost savings. Attention is now turning to consider the major *passive components*, including the RPV, RPV internals, concrete, cables, and buried piping (i.e., components not usually considered as replaceable).

As life extension has been investigated for the passive components, there has been a growing recognition that nuclear-plant condition assessment based on nondestructive testing (NDT) at the time of fabrication, followed by intense inspections during outages, requires adoption of conservative assumptions with regard to addressing detected indications and intervention. Also as assessments are based on periodic inspections and management of aging plants is *reactive*, there is the risk of unplanned shut-downs or “surprises” at an outage that can cause extended down time.

As a result of the changing economics of NPP life extension, national and international activities to address plant life management (PLiM) for long-term operation have been developed. Some of these activities include plant modifications for power uprating. The primary drivers have been the changes in the economic/business climate, as well as a need to provide energy to support sustainable development and, in many countries, provide carbon-free electric generation. Various groups have been working to identify and address key issues in three broad areas: technology, regulation, and business.

Degradation is the immediate or gradual deterioration of systems, structures, and components (SSCs) that could impair their ability to acceptably function. Aging is a general process in which characteristics of an SSC gradually deteriorate with time or use. When aging processes are known, they can be monitored through an appropriate AMP and PLiM program and potentially mitigated.

Aging degradation mechanisms 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 metal loss (e.g., corrosion, wear) or by cracking or deformation (e.g., stress corrosion, deformation, cracking). The phenomena of aging degradation in NPPs are complex and require sophisticated, state-of-the-art science and technology procedures to effectively ensure continued safe and reliable operation. In addition, an effective management system is needed to correctly implement mitigation and/or monitoring actions.

### Insights From Past Experience

Reactor performance has, in general, been limited by materials issues. The response of the nuclear industry and regulators to issues of materials degradation in the past generally has been to develop and approve mitigation actions *after* the degradation has occurred. These mitigative actions have involved increases and improvements in ISI; changes in designs, materials, and operating conditions; and repair or replacement of degraded components. This reactive approach has maintained the safety of operating reactors but has proved to be an inefficient and expensive way of managing materials degradation issues for the industry.

In the current U.S. light water reactor (LWR) fleet, new degradation processes have appeared on average at a rate of once every 7 yr [9]. These phenomena started with vibration fatigue in the 1950s and since then have included intergranular stress corrosion cracking (IGSCC), corrosion fatigue, erosion–corrosion, micro-biologically influenced corrosion (MIC), IGSCC for TP 347, and most recently, in about 2000 primary water stress corrosion cracking (PWSCC). The dates for the identification of these phenomena, and its periodicity, are illustrated with Fig. 1. It is probably naïve to assume that the current fleet can expect to operate for another 20–40 yr without new phenomena developing.

Operators need information to better manage power plant life holistically, adjusting operating conditions to reduce the impact of stressors. Because periodic inspections, which typically occur during refueling outages, cannot be assumed adequate to help ensure fitness for service of critical safety systems and components or help ensure optimal plant-life management, developing methodology and designing systems for implementation of SHM and online

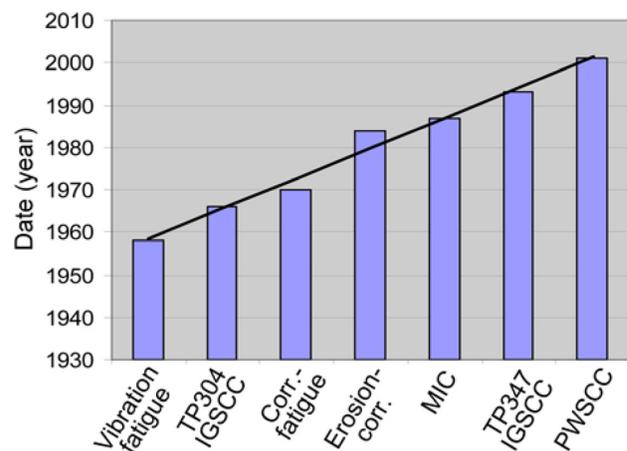


Fig. 1 Data and types of first identification of new degradation processes found in U.S. nuclear power plants [9]

continuous monitoring becomes critical. Data are needed to provide operators with better plant situational awareness and to enable reliable predictions of remaining service life of critical systems and components to be made.

In the United States, many activities have addressed the issues of aging in the current fleet of NPPs. Early insights were summarized in a 1992 report [10] and there are ongoing NRC activities that address LWR safety/aging issues [11].

To address aging issues, the ASME Boiler and Pressure Vessel Code was developed for LWRs, and it addresses fatigue as the dominant failure mechanism. For the current fleet of operating LWRs, the majority of component failures are the failure of active components not operating correctly when called upon to perform a given function such as a valve not opening or closing on demand. The failure of passive components is dominated by failures associated with service degradation, where the four most common degradation mechanisms for pipe failures are reported to be flow assisted corrosion (~32%), stress corrosion cracking (~21%), vibration fatigue (~18%), and various corrosion phenomena (~14%) [12]. Active components are generally managed with a maintenance program that is based on experience. There is a trend toward the adoption of CBM, but in many plants, maintenance is not presently based on the known condition of the component and its need for preventive maintenance. For the passive components, their degradation is managed through periodic inspections as dictated by the ASME Code [13].

Over the past few years, these ISI programs have changed dramatically through the use of risk-based management. Although there is management of risk from a safety standpoint, there are open issues that remain. These ISI and NDE challenges have been discussed by Doctor [14,15], and he reports research that has been performed to develop guidance for risk informing (RI) ISI programs using probabilistic risk assessment (PRA).

The basis for selecting components based on risk importance is addressed by ASME Section XI Code. However, there is also a need to identify other high risk components not already addressed by ASME Section XI Code. In looking at monitoring systems, the NDE method reliability and inspection frequency were intended to maintain a low probability of component failure and the overall objective was to optimize the required ISI programs by RI them.

Unfortunately the way RI-ISI has evolved, the implemented strategy uses risk as the dominant factor and only those components with high contribution to core damage are being included in the ISI program: thus these programs are risk-based and not risk-informed.

U.S. NPP systems and passive components were designed, fabricated, and are to be inspected in a manner that minimizes the impact of core damage due to passive component failures. ISI is an important part of defense-in-depth, and qualification programs such as ASME Section XI Appendix VIII and the European Network for Inspection and Qualification (ENIQ) are the backbone to RI-ISI. Using the risk of core damage to minimize the number of passive piping components to be inspected is inconsistent with the role of ISI in validating original design bases and managing aging effects for long-life passive components. RI-ISI as currently implemented does not fully address the issue of inspection frequency relative to the type of degradation expected.

If known material susceptibilities and operational conditions can predict the occurrence of specific degradation mechanisms, then initiation and growth rate characteristics should be considered. This drives the need to determine how often to inspect components to insure degradation can be reliably detected prior to challenging the structural or leak tight integrity of components. Current RI-ISI applications do not consider this and default to the ASME Code existing 10-yr inspection frequency for safety related piping welds. RI-ISI has evolved by looking backward at all of the operating experience failures, and, as implemented, this approach is not designed to detect the unexpected since it is focused on high risk components.

Nuclear power plants are requesting and receiving up rates to power output and are operating longer. Questions arise regarding the potential for new degradation process to occur and the need to determine if RI-ISI programs are adequate for meeting these challenges of LTO. These include the potential risk of having surprise failures that are related to the occurrence of new degradation mechanisms including those that are accelerated by stressor enhancement due to altered conditions or newly introduced acceleration mechanisms (e.g., corrosion due to accidental resin intrusion). These can have a long initiation time. Only the risk-important components (limited in number) are being periodically inspected, because most of the NPP risk is associated with a small percentage of plant components. Another factor is the movement away from the original strategy of defense-in-depth where ISI was to be used to detect the unexpected that had not been accounted for in design, selection of materials, fabrication processes employed, or operating conditions. It is still unclear how these lessons learned from the existing fleet will be addressed in both new-build U.S. LWRs and advanced designs under consideration for Generation IV NPPs.

Opportunities exist within the nuclear power community to take advantage of the activities and technologies that have emerged in other application areas, such as the aerospace community. There has been a relatively long history of activities applied to jet engines, and this expanded into investigations of issues that surround aging aircraft [16]. A brief history of the role and future challenges of NDE in civil aviation, which also looked toward future challenges, was provided by Weber [17]. This community is currently moving from diagnostics and early applications of prognostics to integrated schemes for vehicle health monitoring and a vision of structural health management [18]. Similar technology evolutions are in progress in several high-technology/high-risk fields.

## NDE to Prognostics

Over recent years, increasingly advanced and more comprehensive philosophies and methodologies, including those called unified life cycle engineering, predictive engineering [19], and material damage prognostics [20] generally now called prognostics, have been proposed for the analysis, monitoring, management, and prediction of the remaining safe, useful, or service life for aging systems. System safe-life determination and sustainment have become crucial to many defense systems and have resulted in major programs; for example, the various aging aircraft and stockpile stewardship programs [21].

The science and technology that is now employed in advanced life management has been developed over a period of nearly 40 yr. In the 1970s, as more advanced methods and systems were designed for use in high-risk technologies such as nuclear power and advanced aerospace, it was recognized that there was a need to better understand the effects of increasingly severe and hostile environments on materials and the significance of defects, in terms of potential for failure. A science base for the theory and measurement of equipment aging, including the use of accelerated aging programs, was established. In addition, it was seen that the capabilities of then available NDT were limited, and there was a lack of an adequate science base for NDT to become a quantitative science. It was necessary to improve the reliability of inspection and relate size and types of defects to their structural significance and the potential effect that they have on performance or potential for loss of structural integrity, and ultimately implement risk-based reliability assessments. Several major research programs were initiated to provide the required science base, including one sponsored by the United States Air Force-Defense Advanced Research Project Agency (USAF-DARPA), which considered the development of quantitative NDE to meet the needs of the aerospace community [21].

The integration of materials, defects, and inspection was achieved through the advent of fracture mechanics, which was greatly enhanced through the ever-improving capabilities of finite element analysis, which was in turn largely facilitated by the

availability of ever-more-powerful computer systems. The philosophies of damage tolerance and retirement-for-cause were developed and applied in the 1970s and early 1980s for application to critical aircraft engine components at all phases of the life cycle design, manufacture, and maintenance [22]. At the same time, other groups of engineers and scientists were considering equally challenging problems of ensuring structural integrity in the nuclear power industry [23] and in the oil and gas industries, in particular, for structures in the North Sea and in Alaska.

During the 1970s and 1980s, great progress was made in both materials science and quantitative NDE in terms of providing a greatly enhanced science base for NDE, new sensors, instrumentation, and data analysis tools for application both at the time of manufacture and during periodic inspection of some types of items in service. The initial focus of much of the research within this emerging community was on metals. This is now expanding to consider advanced composites and ceramics. The initial impetus came in large part from the aerospace and defense communities and soon expanded to include energy, in particular the oil and gas pipelines and facilities and nuclear power. This range of fields of application has now expanded into civil engineering and the application of NDT to civil infrastructure. Novel integrating design approaches such as unified life cycle engineering (ULCE) were proposed and partially applied in various forms of concurrent engineering [24]. The full power and potential of this approach was limited by then available materials science, understanding of materials degradation and response to stressors, and, in particular, the computation power needed to perform many of the design optimizations at a reasonable cost and within a reasonable time.

In the 1980s and early 1990s, it was increasingly recognized that structural assessment, including quantification and evaluation of defect and defect populations, was not all that was required to evaluate the remaining safe-life for complex systems. It was necessary to identify and characterize discrete defects, cracks, and corrosion and determine a rate of growth, investigate the probability of occurrence and probability of detection (POD), and provide measurements of changes in bulk material properties caused by the aging of the materials and the accumulation of damage. The development of the science for damage mechanics and tools to quantify the properties of critical structures became a priority. Studies considered methods for the combination of damage and fracture mechanics, where the effects of damage are seen in microcracks and other physical-chemical changes, short-crack growth phenomena occur, and macrocracks, described with linear elastic fracture mechanics, interact under the influence of a multitude of both physical and chemical environmental factors. The complexity of the phenomena is further increased by inclusion of consideration of "random acts," impacts, explosions, and other short duration transient events, as well as longer term daily and seasonal thermal and chemical loading or operational cycles.

ISI is now evolving into SHM and prognostics and is becoming a family of models, science, and measurement technology tools for use in the integrated methodology, which seeks to provide the framework needed to assess a system, predict a remaining safe-life, and formulate and test strategies for mitigation and minimization of the rate of degradation. The elements which need to be combined into a program for SHM application are still evolving and include the following.

**Evaluation/Analysis.** In the analysis of a system, it is first necessary to understand the combination of physical/chemical mechanisms that cause degradation, damage, or aging. For such an analysis applied to a civil structure, a combination of both field observations/measurements and laboratory studies are needed. For a complete description of the phenomena, it is necessary to understand and quantify both the combination of environmental factors that drive degradation and the science for the degradation/aging mechanisms in the system. Some mechanisms may be the result of normal system operation (i.e., wear in a pump), while others

may be caused by external factors (i.e., salts leaching into a concrete containment). This analysis also serves to identify those key parameters that require monitoring.

**Health Sensors/NDE/Nondestructive Inspection.** These are needed to monitor the key parameters identified in the system analysis. This is to quantify both environmental factors and system operation. This instrumentation can include the use of advanced sensors and measurement systems; embedded optical and acoustic sensors; acoustic emission sensors; arrays of pressure, temperature and other operational variables sensors; and microelectromechanical systems (MEMS) based physical and chemical property sensors, all integrated with distributed processing nodes and employing radio frequency (RF) tag and other technologies for wireless data collection.

**Aging/Damage—Prognostic Models.** These are the predictive tools that can combine data from system health monitoring and use appropriate constitutive formulations to give predictions of rate of degradation and hence estimates for remaining safe-life. The models can also be used to test mitigation strategies and predict and plan requirements for outages for maintenance.

**Probabilistic Analysis.** Age-related degradation, and hence subsequent failures, is to some extent caused by combinations of both random and deterministic events (process stressors). Many environmental and degradation phenomena are natural systems best described using fractals. Other aspects of the aging process are best analyzed using probability functions. This combination of analysis and risk-based (following from PRA) tools provides a statistical framework within which sensor placement, measurement intervals, and reliability for assessments are evaluated.

**Cost-of-Ownership.** This is an economic analysis tool set that can identify high cost drivers, evaluate potential savings and evaluate alternative modes of operation, and enable cost forecasting, budgeting, and modernization/mitigation planning programs to be evaluated.

There is a developing lexicon that is being used to describe the transition from NDE to SHM, PMMD, and prognostics. Models are a key component, particular for NPP implementations where systems are complex and require multiphysics models to understand stressors and the capability to obtain sensor data is limited by limits on access (e.g., high radiation), challenges in deployment (e.g., cabling/wireless systems), and associated costs.

LTO for NPPs will remain demanding. The past, present, and future challenges for NDE applied to NPPs remain topics for discussion [15]. Becoming proactive through online monitoring for CBM and eventually prognostics provides fundamentally different forms of data sets when considered in space-time. In providing coverage, there are practical limits to the numbers of sensors and the frequency of inspections; models are required to enable interpolation between the information provided. This first change between NDE and SHM is illustrated with Fig. 2. NDE provides data at discrete times and is measured over some zone or region; SHM provides data from fixed sensors (discrete locations or zones) as a function of time. Both approaches have limits imposed by numbers of measurements, locations, and time.

The second, and in some ways related, fundamental philosophical change is the move from the use of traditional NDE data, that is reactive (find and fix) to a proactive approach using models to make estimates of future states, including remaining safe life.

The philosophical change from reactive to proactive is illustrated with Fig. 3: Damage develops and is detected either by a "leak" or at an ISI. Proactive approaches seek to detect damage early, before it becomes structurally significant.

To implement SHM for passive components will require advances in sensors; better understanding of what and how to measure within the plant; enhanced data interrogation, communication, and

On-line monitoring sensors provide data as a function of time at discrete locations

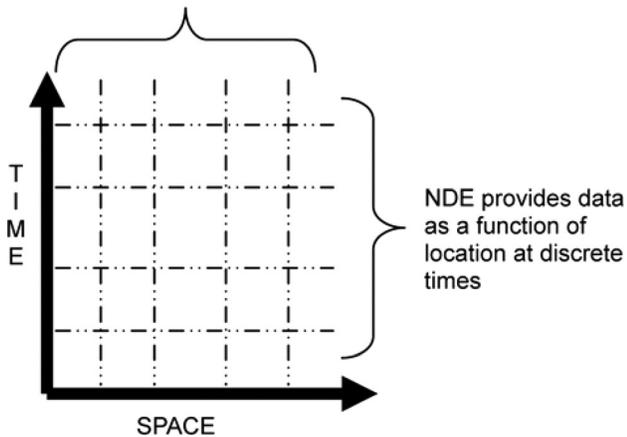


Fig. 2 Illustration of the fundamental differences in data structures between NDE and SHM (after Thompson [25])

integration; new predictive models for materials damage/aging; and effective deployment system integration. Central to all prognostics (remaining life prediction) is quantification of uncertainties in what are inherently ill-posed problems. For implementation, there is the need for integration of enhanced CBM/prognostics philosophies into new plant designs, operation, and operations and maintenance (O&M) approaches [3].

### Prognostics

Prognostics is the prediction of a future condition, the effect of degradation on a system's capability to perform its desired function, and remaining safe or service life, based on an analysis of system or material condition, stressors, and degradation phenomena. Moving from diagnostics, which gives an assessment at a point in time based on observed data (e.g., an NDE or SHM assessment), to prediction of life and technologies for structural health monitoring/management, based on predicted future behavior, requires development of new approaches that are identified in schematic form in Fig. 4. 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.

A review of machinery diagnostics and prognostics for CBM is provided by Jardine et al. [26], but it does not consider nuclear power systems. An assessment of the state of diagnostics and prognostics technology maturity was recently provided by Howard [27]. The current status for various system elements is shown in Table 1.

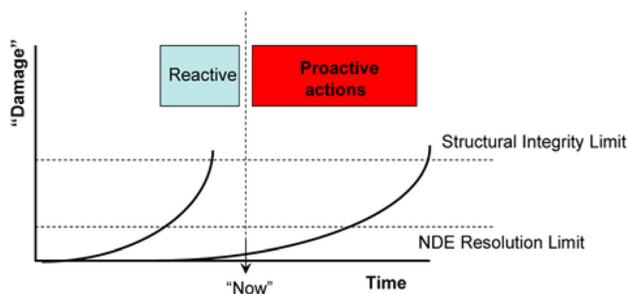


Fig. 3 Schematic diagram illustrating materials or damage development with time, and the differentiation between reactive and proactive actions. Note that the degradation process versus time is rarely linear, as is often assumed.

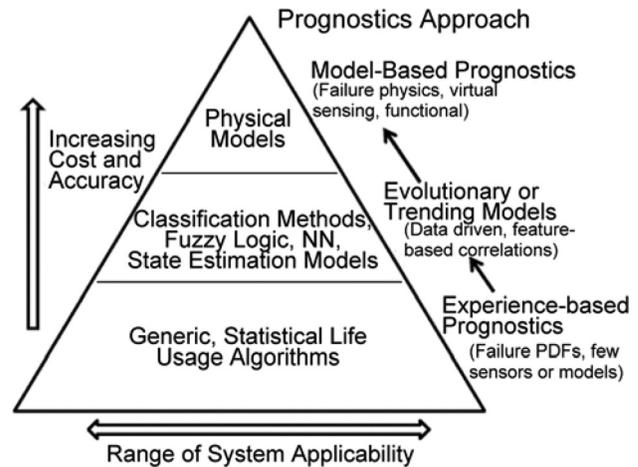


Fig. 4 Range of prognostic approaches

A review of the current paradigms and practices in SHM and prognostics has recently been provided by Kothamasu et al. [28].

Technologies are being developed for non-nuclear applications, including instrumentation and system health monitoring for electronics, in what is being called *electronics prognostics* [29]. There are also integrated technologies being developed for advanced fighter aircraft and unmanned aerial vehicle (UAV) SHM, which include both electrical/electronic and mechanical systems. Within the field of advanced diagnostics/prognostics, systems have been deployed for individual elements, but fully integrated systems are still being developed.

Monitoring technologies developed in other industries can potentially benefit new NPPs, particularly when using advanced online monitoring and diagnostics for CBM and, in the future, prognostics. Digital instrumentation and control (I&C) and advanced diagnostics and prognostics are being developed in the wider high-technology industry communities and are now being considered for NPP deployment.

### Detection of Early Degradation

There is growing interest in sensors and technology, particularly online monitoring for the detection of early damage in structural materials; a comprehensive review paper was provided by Raj et al. [30] and an assessment that relates technology to various phases in degradation development for PMMD was recently prepared by Bond et al. [31]. Figure 5 illustrates the relationships

Table 1 State of maturity for diagnostics (D) and prognostic (P) technologies [25]

Diagnostic/prognostic technology	AP <sup>a</sup>	A <sup>b</sup>	I <sup>c</sup>	NO <sup>d</sup>
Basic machinery (motors, pumps, generators, etc.)	D		P	
Complex machinery (helicopter gearboxes, etc.)		D	P	
Metal structures (passive and active)	D		P	
Composite structures (passive and active)			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

<sup>a</sup>AP = Technology currently available and proven effective.

<sup>b</sup>A = Technology currently available but verification and validation not completed.

<sup>c</sup>I = Technology in process but not completely ready for verification and validation.

<sup>d</sup>NO = No significant technology development in place.

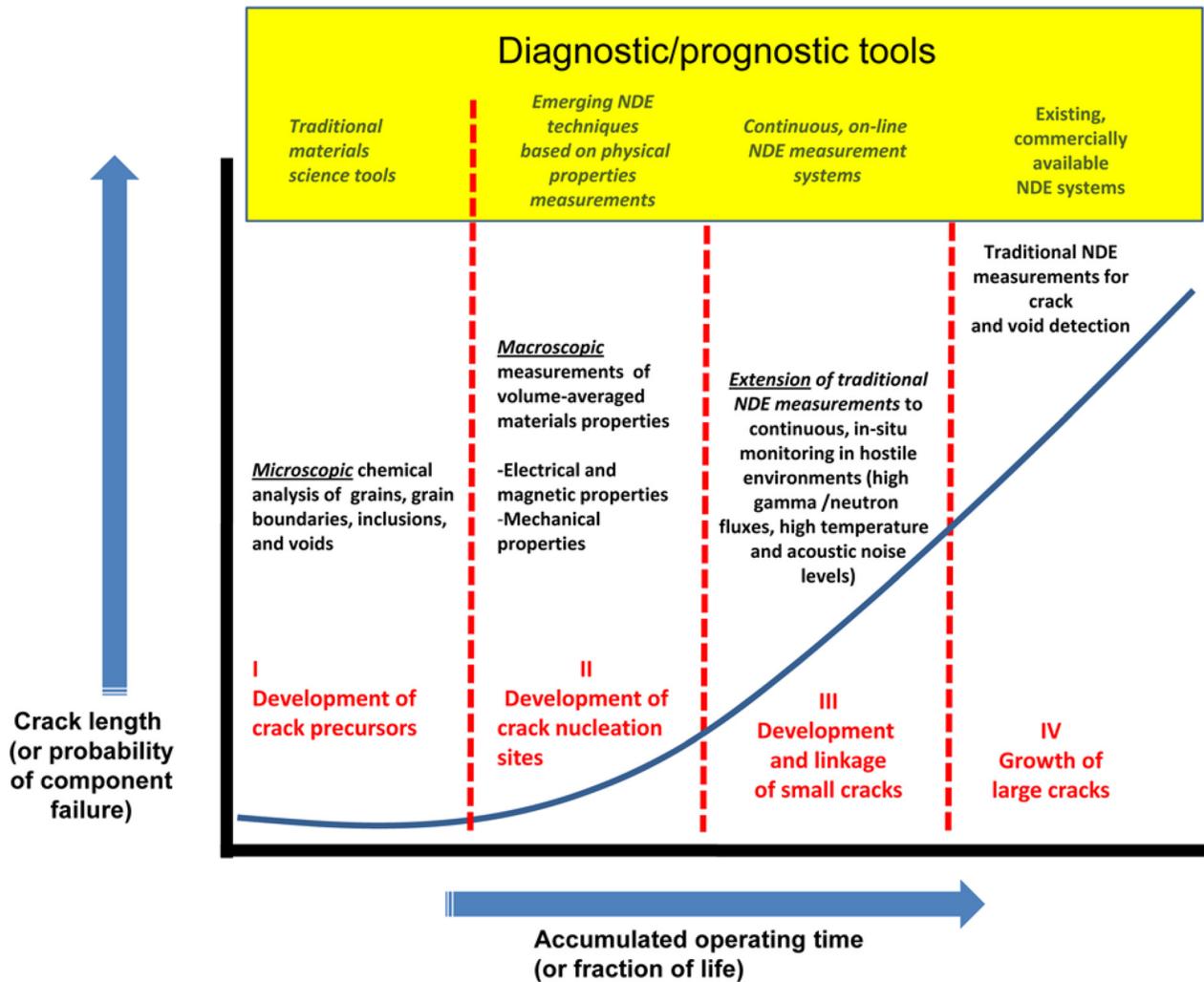


Fig. 5 Strategy for development of a PMMD system

between the degradation regimes, nature of degradation, and some of the methods being used to make measurements. Early detection of degradation is a key element in both system management and prognostics estimates for the remaining life, based on models for degradation development.

Key to developing more advanced prognostic schemes (in both active and passive systems) that give maximum warning of degradation is to focus on monitoring the stressor, rather than just the subsequent effects of aging and degradation. In order for this type of strategy to be successful, good physics-based models relating the stressors to the rate of aging or degradation must be developed in the prognostic scheme. For the existing NPPs, particularly when life extension is being developed, there are opportunities to deploy online monitoring/prognostics, assuming it can be demonstrated that there is still remaining useful life in the plant.

### PMMD and Prognostics

PMMD is the emerging technical and methodological process needed to support enhanced NPP management throughout its life, including life extension for legacy NPPs. These approaches involve “sensing” material property changes and parameter trends that are precursors to traditionally monitored degradation mechanisms and phenomena (e.g., crack initiation and growth). The property changes are detected by conventional NDT technologies such as eddy current or ultrasound. To be effective, PMMD needs to incorporate the phenomena of stressor-material interactions and sense early precursor material property changes. An example of a

possible degradation phenomenon could be radiation-induced void swelling. PMMD also includes the assessment of the impact of material degradation on the SSC or unit life cycle. Prognostics can be defined as being a “forecast of future performance and/or condition.” “Prognostics” (for active and passive components) is the prediction of a remaining safe or service life based on an analysis of the system or materials condition, stressors, degradation phenomena, and operating conditions. In the context of materials degradation assessment, prognostics require the science, enabling technology, and methodologies needed to predict the remaining safe (service or licensable) NPP life and ensure operational reliability for a system or subsystem. Prognostic methods can be implemented in several ways, but in all cases incorporate degradation phenomena, the driving stressors, and (in most cases) models to predict the degradation rate and thereby extrapolate remaining life (or time at which intervention is required). Such methods therefore form a key element within a PMMD program by adding a “predictive” element to the proactive activities through the understanding and quantification of the rate of material degradation and resultant impact on SSC safety/life. Prognostic methods also provide a positive impact on PRA through the ability to manage and schedule outages and maintenance activities [32].

### PMMD—The Future

To support safe sustainability of the nation’s operating commercial LWRs, and in preparation for future decisions regarding new construction of plants, the NRC has initiated a new program

called PMMD. The program will support the collection of knowledge and data to predict aging of materials, components, and systems in operating plants to allow monitoring, maintenance, and repair activities to occur in advance of adverse impacts [3,33].

PMMD leverages a long history of activities focused on understanding materials degradation and will develop new knowledge on materials degradation mechanisms, inspection, and monitoring techniques, and related mitigation and repair. The goal of PMMD is to acquire the technical basis to answer key aging related degradation questions which could have profound impact on the nation's energy strategies for meeting consumption needs. Among these questions are as follows:

- Can licensees safely extend the operating life of existing power plants to 60–80 yr, or longer?
- What are the key technical and regulatory issues that require attention to enable license extension?
- What information is needed to adequately process and respond to applications for a second (or subsequent) license extension?
- What are the remaining open technical and regulatory issues?

To address the issue of PMMD, the NRC has initiated a program to assess the ability to identify early the components that might be susceptible to future degradation, so that mitigation and/or monitoring and repair actions can be proactively developed, assessed, and implemented before the degradation process could adversely impact structural integrity or safety. Two processes are envisioned for PMMD programs. These processes are (a) implementation of actions to mitigate or eliminate the susceptibility of materials to degradation and (b) implementation of effective inspection, monitoring, and timely repair or replacement of degraded SCCs.

Aging degradation mechanisms are usually classified into two main categories—those that (1) affect the internal microstructure or chemical composition of the material and thereby change its intrinsic properties (e.g., thermal aging, creep, irradiation damage) and/or (2) impose physical damage on the component by deformation, metal loss (e.g., corrosion, wear), or cracking (e.g., stress corrosion). The phenomenon of aging degradation in NPPs is complex and requires sophisticated state of science and technology procedures to effectively manage it to ensure continued safe and reliable operation. Not only is technology involved but also an effective management system is needed to correctly implement mitigation and/or monitoring actions.

The pattern of activities that are developing to meet the needs of life extension for the global NPP fleet is complex, and in many cases, there are many interconnections and overlapping relationships. There are various international and multinational activities that overlay national activities. This paper illustrates that the implementation of PMMD programs will require significant basic and applied research. To date, discussion has divided the identified technical gaps into three categories: (1) those need to be addressed by basic science, (2) those addressed by engineering, and (3) those addressed from a regulatory/codes and standards point of view. The full scope of these needs is still being defined.

With appropriate design development, there is the opportunity for future systems to have integration of off-line NDE inspection information with that from intelligent online self-diagnostic capabilities that will alert operators and initiate remediation strategies. Significant progress is being made, but further technological advances are needed in

- smart components and structures
- self-diagnostic systems
- embedded MEMS and other health monitoring sensors
- wireless communication

- distributed data processing and control networks
- prognostics implementation
- advanced NDE technologies
- proactive operations and maintenance program

The result of these advances would be the realization of the optimized plant of the future.

The PMMD program examines LWR materials, and the materials degradation phenomena that affect them, with the goal to effectively predict and prevent development of life-limiting problems. All parts of an NPP are subject to the continuous time-dependent materials degradation due to service conditions, which include normal operation and transient conditions; postulated accident and postaccident conditions are excluded. Some forms of degradation, such as SCC, often exhibit a long initiation time followed by a rapid growth phase, prompting the need for new inspection or monitoring technologies. Examples of advanced technologies that may be needed include NDE techniques to identify SCC precursors and sensitive online monitoring approaches to detect cracks as they initiate and grow. In addition, certain LWR components may not have sufficient NDE programs in place to prevent failures in reactor systems operating well beyond the age range originally intended for the current NDE programs. A review of the reactor components will be needed to determine if altered inspection regimes may be required to deal with new degradation mechanisms, such as some forms of SCC and late blooming phases (LBP) under the influence of radiation which have been seen in the laboratory to cause hardening and embrittlement, that may emerge in operating NPP over time. Also, as reactors lifetimes are expanded, degradation mechanisms previously considered too long-term to be of consequence (such as the LBP and concrete and wiring insulation degradation) may become more important.

## Conclusions

The growing global interest in the longer term operation of the existing fleet of nuclear power plants is being supported by developments in plant-life strategies. Proactive approaches implemented using online monitoring have the ability to both constrain operations and maintenance costs and provide plant operators with greater plant condition awareness. Increased condition awareness will support better economic assessments of life costs and help to ensure continued safe operation as plants operate longer.

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## Nomenclature

- AMP = aging management program
- CBM = condition based maintenance
- CSNI = Committee on the Safety of Nuclear Infrastructure
- ENIQ = European Network for Inspection and Qualification
- EPRI = Electric Power Research Institute
- GALL = generic aging lessons learned (NRC activity and report)
- IAEA = International Atomic Energy Agency
- IASCC = irradiation assisted stress corrosion cracking
- I&C = instrumentation and control
- IGSCC = intergranular stress corrosion cracking
- IMT = issues management tables (EPRI tabulation)
- ISI = Inservice inspection

LB-60 = life-beyond-60  
 LBP = late-blooming phases  
 LTO = longer term operation  
 LWR = light water reactor  
 MDM = materials degradation matrix  
 MEMS = microelectromechanical systems  
 MIC = microbiologically influenced corrosion  
 NDE = nondestructive examination  
 NDT = nondestructive testing  
 NPP = nuclear power plants  
 NRC = U.S. Nuclear Regulatory Commission  
 O&M = operations and maintenance  
 PLiM = plant life management  
 PMMD = proactive management of materials degradation  
 POD = probability of detection  
 PRA = probabilistic risk assessment  
 PWSCC = primary water stress corrosion cracking  
 RF = radio frequency  
 RI = risk informed  
 RPV = reactor pressure vessel  
 SCC = stress corrosion cracking  
 SHM = structural health monitoring  
 SSC = systems, structures, and components  
 UAV = unmanned aerial vehicle  
 ULCE = unified life cycle engineering  
 USAF-DARPA = United States Air Force-Defense Advanced Research Project Agency

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