From NDE to prognostics: a revolution in asset management for Generation IV Nuclear Power Plants

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ABSTRACT

For Generation IV nuclear power plants (NPP) to achieve operational goals it is necessary to adopt new on-line monitoring and prognostic methodologies, giving operators better plant situational awareness and reliable predictions of remaining service life. Such techniques can improve plant economics, reduce unplanned outages, improve safety and provide probabilistic risk assessments. This paper reviews the state of the art and the potential impact from monitoring, diagnostics and prognostics on advanced NPP, with a focus on the needs of Generation IV systems.

INTRODUCTION

Generation IV nuclear power plants (NPP) are expected to operate with high capacity factor (90%+), for longer fueling cycles (4-6 years) and have necessary inspections and maintenance performed during shorter outages. One challenge is limited knowledge of material performance for next-generation designs, including balance of plant and secondary units for process heat or hydrogen production. Gen IV NPP will operate at higher temperatures (potentially 510°C to 1000°C). Operation in this temperature range brings the potential for many new degradation processes to the forefront that have not been experienced in current reactors and thus are not well understood or accounted for in the design. In the current light-water reactor fleet, new degradation processes have appeared on average at a rate of one every seven years [1]. Operators need information to better manage power-plant life holistically, adjusting operating conditions to reduce the impact of stressors. Since periodic inspections, which typically occur during refueling outages, cannot be assumed to be adequate to help ensure fitness for service for critical safety systems and components or help ensure optimal plant life management, developing methodology and designing systems for on-line continuous monitoring becomes a critical component in providing operators better plant situational awareness and reliable predictions of remaining service life of critical systems and components.

The American Society for Mechanical Engineers Boiler and Pressure Vessel Code was developed for light water reactors and address fatigue as the dominant failure mechanism. Thus, this Code is not adequate as written for Generation IV NPPs. The new materials, new degradation mechanisms and the new operating environments mean that flaw acceptance standards are unknown at this time both for fabrication flaws and for service induced flaws. Clearly the ASME Code needs to be evolved to lead Gen IV design, construction and operation. Some of the Generation IV NPPs are being designed to maintain the reactor core at operating temperatures even when shut-down for maintenance and this will mean that the periodic NDE that is conducted will need to be performed at these high operating temperatures placing further challenges on the NDE. Since refueling cycles are of extended duration for Gen IV NPPs, periodic inservice inspections may simply be unable to manage degradation because of this long interval between inspections. In some Gen IV designs, refueling will occur on line and shut-downs will be driven by maintenance schedules for active components. One alternative would be to develop fully automated robotic NDE inspection tools that could be deployed during operation so that inspections could be conducted based on degradation initiation times, degradation growth rates and the effectiveness of the NDE being deployed. Advanced nondestructive measurements might be developed to provide a means to monitor material properties so that as these changes occur during operation they could be detected, quantified and trended. Alternatively, sensors could be deployed at all key locations to monitor for the initiation of degradation and growth as well as for the key operational parameters that could be the precursors to degradation.

For the current fleet of operating light water reactors, 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 are dominated by failures associated with service degradation. The active components are managed with a maintenance program that is based on experience and not 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. Over the past few years these inservice inspection programs have changed dramatically using risk based management. Although there is management of risk from a safety standpoint, there are open issues that remain with regard to always having surprise failures. ,These surprises are related to new degradation mechanisms occurring that have a long initiation time, the fact that only the risk-important components are being periodically inspected, which means that fewer components are being inspected, since 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 inservice inspection was to be used to detect the unexpected that had not been accounted for in design, selection of materials, fabrication processes employed or the operating conditions. How will these lessons learned be addressed in Gen IV NPPs?

The move to digital systems in petrochemical plants, process plants and fossil fuel power plants is enabling major advances to occur in the instrumentation, controls and monitoring systems and in the approaches employed. The adoption within the nuclear power community of advanced on-line monitoring and advanced diagnostics has the potential for a reduction in mandated surveillances, more accurate cost-benefit analysis, "Just-in-time" maintenance, pre-staging of maintenance tasks, a move towards true "operation without failures" and a jump start on advanced technologies for new plant concepts, such as those under the International Gen IV Program [2]. Planning for and incorporating such technology can improve plant economics, reduce unplanned outages, improve safety and provide probabilistic risk assessments.

PROGNOSTICS –STATE OF THE ART AND POTENTIAL

There has been a growing recognition that nuclear-plant condition assessment based on NDT 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 unplanned shut-downs or "surprises" at outage that can cause extended down time. Developing on-line monitoring and condition-based maintenance has the potential to increase operator situational awareness, enhance safety and provide significant cost savings.

The nuclear community within the USA is performing instrumentation upgrades to operating NPPs. It is recognized that "digital technology provides significant benefits. Modern systems provide functional upgrades and solve reliability and maintenance problems"[3]. However, in the short term, to ensure licensability in the USA for nuclear power plant technologies for deployment in the next generation of systems (i.e. those for deployment in association with the DOE-NP2010 Program) advanced on-line diagnostics and prognostics functionalities are being limited to those with proven regulatory acceptability.

Looking to the longer term, new integrated approaches to system life cycle management are being investigated to support Gen IV system needs [4, 5, 6]. There is a need based on economics and reducing radiation exposure for enhanced system assessment/life prediction tools for planning, to avoid "surprises" at the start of an outage and to ensure that at the end of an outage there is confidence that the NPP components and systems are in a condition to operate efficiently without failure until the next planned outage.

There are significant opportunities to adopt condition-based maintenance when upgrades are implemented at existing facilities. The economic benefit from a predictive maintenance program can be demonstrated from a cost/benefit analysis. An example is an analysis for the Palo Verde Nuclear Generating Station [7]. An analysis of the 104 US legacy systems has indicated potential savings at over $1B per year when applied to all key equipment [4].

For new plants there are even greater opportunities for improved operation, enhanced capacity factor and reductions in operating and maintenance costs through the adoption of true condition-based maintenance philosophies, on-line monitoring and diagnostics. Adopting digital instrumentation and control (I&C) and new advanced system technologies that employ on-line monitoring for more components, systems and structures, utilizing wireless sensors and integrating total-cost-of-ownership models (from design stage through plant decommissioning) can result in fewer surprises at outages, better planning for maintenance and many fewer unplanned outages. The progress and challenges in system health monitoring (SHM), for non-nuclear power system applications, was reviewed in a paper by Adams and Nataraju [8]. This paper includes the diagram given as Fig. 1, which provides a good visualization of the relationships between life, operation and economics. Some of these tools are available today or can be developed as needed but in order for them to be utilized, the Gen IV designers must see their value and start to incorporate them into their designs. Without this crucial step taking place it will be much less impactful to try to apply them after the designs are completed or later in the Gen IV cycle. When considering the investment being made into Gen IV NPPs, it is critical that if nuclear power is going to be cost competitive with other forms of electricity power generation or hydrogen production, then designers must take an aggressive lead in adopting technology solutions to achieving this goal. The designers need to be included in the team of researchers developing the technologies, the codes and standards personnel involve in creating he necessary requirement for these technologies along with the regulators that are going to be overseeing these new technologies and their deployment. There is a tremendous potential to provide significant improvements in safety and economics of Gen IV NPPs but the reality is that this is going to require many experts working together to make it happen.

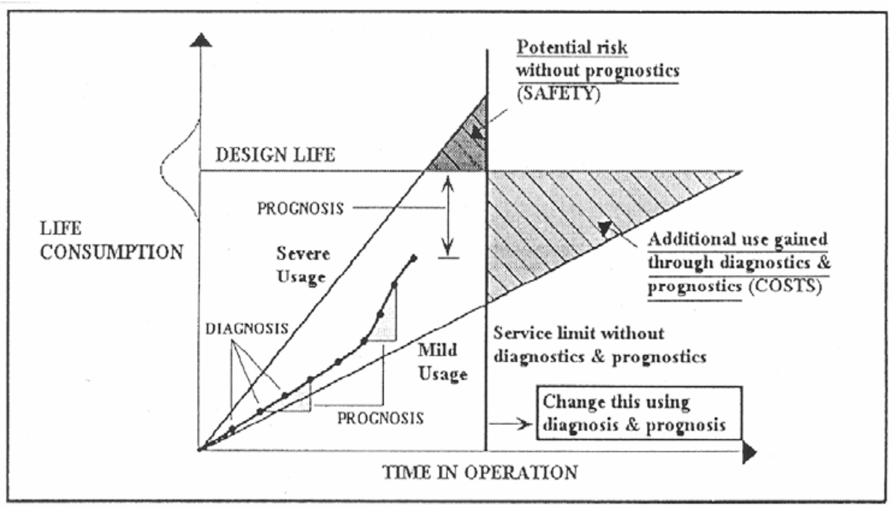

Fig. 1 Overview of structural diagnostics and prognostics showing benefits in operation and support costs and safety [8].

A review of machinery diagnostics and prognostics for condition-based maintenance is provided by Jardine et al. [9], but again it does not consider nuclear power systems. An assessment of the state of diagnostics and prognostics technology maturity was recently provided by Howard [10]. The current status for various system elements is shown in Fig. 2. Technologies are being developed for non-nuclear applications, including for instrumentation and system health monitoring electronics, in what is being called "electronics prognostics," e.g. Urmanov [11]. There are also integrated technologies being developed for advanced fighter aircraft and unmanned aerial vehicle (UAV) system health monitoring, which includes 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.

Diagnostic/Prognostic Technology For:	AP	A	I	NO
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

AP – technology currently available and proven effective
A - technology currently available, but V&V not completed
I – technology in process, but not completely ready for V&V
NO – No significant technology development in place

Fig. 2 Assessment of state of maturity for diagnostic and prognostic technologies [10].

The advances in monitoring technologies developed in other industries can potentially benefit new nuclear power plants, particularly when using advanced on-line monitoring and diagnostics for condition-based maintenance and, in the future, prognostics. Digital 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. There is a convergence between material damage prognostics [12]; the civil engineering damage and damage evolution models under multiple stressors; the traditional "vibration" monitoring community looking towards new challenges in systems used by the defense community [13];

technology to achieve total structural health management [14]; and the NDE community looking at aging due to thermal embrittlement, fatigue and neutron degradation [15].

There is a trend of seeking to move from periodic NDE to on-line condition-based maintenance which started several years ago [16]. A review of the current paradigms and practices in system health monitoring and prognostics has recently been provided by Kothamasu et al [17]. There remain significant measurement challenges associated with characterization of aging in irradiated reactor components [18, 19]. An example of one major series of activities in moving from NDE to characterization of aging and degradation is found in the work of Dobmann and colleagues. In their early papers they reported using ultrasonic and micromagnetic techniques to measure strength and toughness and detecting early damage [20]. This evolved into work to address the demand for describing damage and service-related aging [21]. This work then evolved into a significant European project involving round-robin sample characterization [19] and bringing together condition-dependent NDT and fracture mechanics [15, 23].

Work is in progress within various groups to develop both ultrasonic and electromagnetic techniques for the characterization of embrittlement due to void swelling and precipitate evolution in reactor core materials [24]. All U. S. pressurized water reactors that have been granted an operating license extension beyond the original 40 years, have stated to the regulator that they have a program working to develop the tools to manage these degradation processes. However, the details of these programs is unknown and the regulator has not required the details to be reported. Techniques such as ultrasonic back scatter and acoustic bi-refringence are being investigated as possible tools for in-service monitoring. Examples of data for monitoring the effects of radiation on hardness and internal friction are shown as Fig 3. Figure 3 clearly shows that the timing for making material property measurements is critical to being able to quantify the changes and to trend them to determine where they become important to challenging the structural integrity of a component. One of the ways to address this timing issue is to employ continuous on line monitoring to insure that the property is being measured at the critical times. Continuous monitoring of properties is essential to identify trends and peaks in data, which could potentially be missed if only periodic measurements are performed.

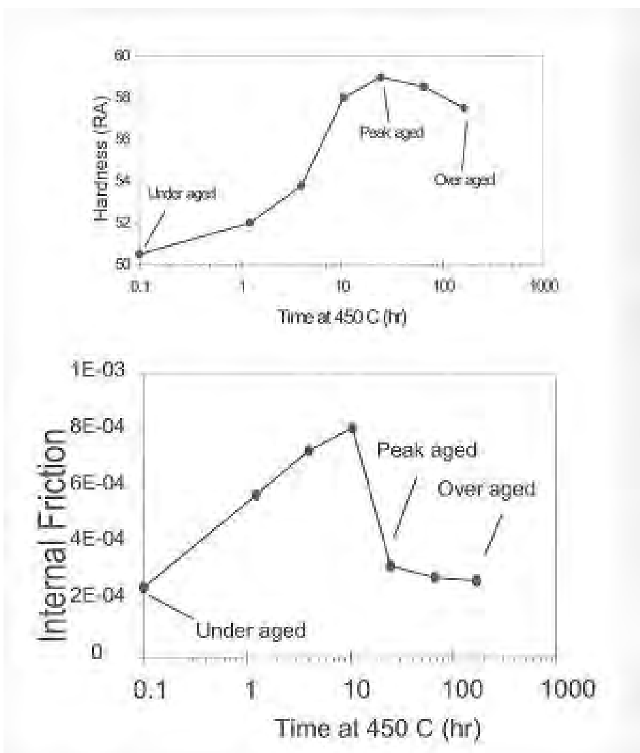

Fig. 3 Example of monitoring precipitation induced hardening and effects on hardness and internal friction [24]

The development of concepts for advanced on-line structural health monitoring for reactor designs such as IRIS has been initiated [25]. Also physics-based approaches to the analysis of aging for prognostics [26,27], combined with the potential effects on probabilistic risk inspection for designs, such as IRIS [28] have been reported.

Key to developing more advanced prognostic schemes (in active systems such as pumps and valves) which give maximum warning of degradation is to focus on monitoring the stressor, rather than just the subsequent effects of aging and degradation. A schematic showing system operational performance and stressor magnitude is given as Fig 4 [5]. The monitoring of the stressor (e.g. a temperature, cavitation, vibration or a pressure) combined with active system control parameter management across several processors, enables use of the "warning time" (ΔT in Fig 4), to adjust operational parameters and limit or at least control rates of degradation for a path to failure. 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.

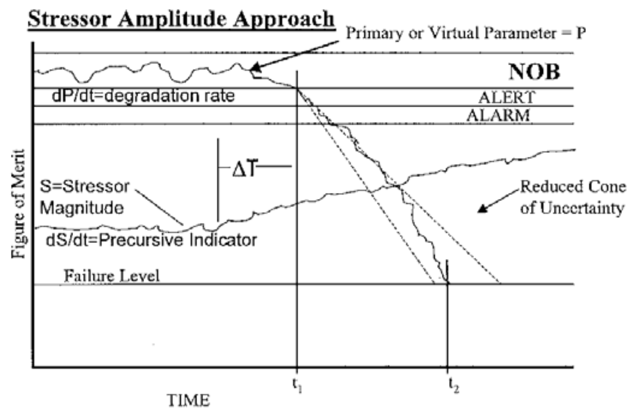

Fig. 4 Stressor measurement giving time for intervention prior to failure [5].

To move from periodic inspection to on-line monitoring for condition-based maintenance and eventually prognostics will require advances in sensors; better understanding of what and how to measure within the plant; enhanced data interrogation, communication and integration; new predictive models for damage/aging evolution; system integration for real world deployments; quantification of uncertainties in what are inherently ill-posed problems; and integration of enhanced condition-based maintenance/prognostics philosophies into new plant designs, operation and operating and maintenance approaches.

Conclusions

Recent experience has shown the potential economic impact of adopting condition-based maintenance (CBM) in nuclear power plants. There is a need to move beyond current approaches to CBM and into the realm of on-line diagnostics and prognostics. Operators need enhanced situational awareness if unwanted outages need to be avoided. Such advances are only possible through the use of new and improved monitoring, implementation of advanced diagnostic. The use of digital I&C provides the opportunity to add enhanced functionality and to move to add prognostics for key system elements.

The adoption of advanced diagnostic and prognostic technologies for Generation IV nuclear power plants can significantly impact plant economics. However, before the deployment of such systems is possible it is necessary to demonstrate methodologies, understand stressors, sensors, communication, analysis and quantify uncertainty in remaining life prediction as well as to demonstrate long term monitoring system reliability. But in order for these approaches to be successful it will require the engagement of researchers, Gen IV designers, component manufacturers, codes and standards personnel, material suppliers, and regulators working as a team to develop, demonstrate and validate these new and advanced measurement and monitoring technologies for Gen IV NPPs. The engagement of these many diverse experts must occur NOW in order for these advances to be realized. Otherwise, Gen IV plants will simply be extensions of the design, operating and performance standards of the current fleet of light water reactors.

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