IMPROVED ECONOMICS OF NUCLEAR PLANT LIFE MANAGEMENT

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Abstract. The adoption of new on-line monitoring, diagnostic and eventually prognostics technologies has the potential to impact the economics of the existing nuclear power plant fleet, new plants and future advanced designs. 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 the integration of enhanced condition-based maintenance/prognostics philosophies into new plant designs, operation and O&M approaches. The move to digital systems in petrochemical process and fossil fuel power plants is enabling major advances to occur in the instrumentation, controls and monitoring systems and approaches employed. The adoption within the nuclear power community of advanced on-line monitoring and advanced diagnostics has the potential for the reduction in costly periodic surveillance that requires plant shut-down, more accurate cost-benefit analysis, "just-in-time" maintenance, pre-staging of maintenance tasks, movement towards true "operation without failures" and a jump start on advanced technologies for new plant concepts, such as those proposed under the International Gen IV Program. There are significant opportunities to adopt condition-based maintenance when upgrades are implemented at existing facilities. The economic benefit from a predictive maintenance program based on advanced on-line monitoring and advanced diagnostics can be demonstrated from a cost/benefit analysis. An analysis of the 104 U.S. legacy systems has indicated potential savings at over $1B per year when applied to all key equipment; a summary of the supporting analysis is provided in this paper.

1. Introduction

The world is hungry for energy. The global population is growing and many countries are seeking to achieve sustainable development. Production of conventional oil is getting close to its peak and new approaches are being developed to extract and utilize fossil fuels. Expanding use of fossil fuels raises the issues of greenhouse gas emissions and global climate change, with all its potential for adverse economic impacts. Nuclear power is one technology that is able to provide safe, secure and affordable energy, that has limited environmental impact, and which has the potential to meet a significant fraction of global base-load electric and process heat needs.

There are approximately 440 nuclear power reactors in the current global fleet, of which 104 are in the USA. The average age for these facilities is more than 20 years, and the design lives were in the range of 30–40 years. In a number of countries there are programs that are looking to enable operating life extension from 40 to 60 years, and some consideration is being given to "life after 60." The existing nuclear power plants are too valuable to scrap at the end of their current design lives. The cost of building replacement generating capacity, and at the same time providing new plants that meet the growth in demand for electricity, would test both the available technical and economic infrastructures. It is therefore important to see where technology can help to better manage existing power plants, enable life extension for the existing fleet and contribute to both new advanced light water reactors and new designs, with demanding materials and operational requirements. The scope of activities in this area is seen in the proceedings of the first meeting in this series [1], and recent years have seen further developments. IAEA Programs and activities include the Extrabudgetary Programmme on Safety Aspects of Long Term Operation of Water Moderated Reactors (SALTO). This activity started in 2003 to assist Member States considering long-term operation of water-moderated reactors to reconcile related processes and practices, to establish a general long-term operation framework, and to provide a forum for exchange of related information [2].

For nuclear power plants the operations and maintenance (O&M) costs are estimated for various plants and countries at between 40 and 70% of the overall generating cost. In the USA O&M is at the higher end of the range (~60–70%) and fuel costs are at about 15–30%. Of the O&M costs (in USA) about 80% are related to the costs of labor. In both Europe and North America the situation is further complicated by the problem of an aging workforce and a limited supply of replacements [3]. In the rapidly growing Asian economies and developing countries there are also challenges in meeting the skilled workforce needs [4] [5]. There has also 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 the adoption of conservative assumptions with regard to addressing detected indications and intervention. With aging plants there is the risk of "surprises" at outages, which can cause extended down time. A recent study has concluded that current inspection frequencies do not match rates of degradation growth, which adds support to the conclusion that on-line monitoring is needed for both current and new reactors.[1] To address these issues there is already a move to deploy on-line monitoring and condition-based maintenance that has the potential to increase operator situational awareness, enhance safety and provide significant cost savings.

There are already known to be significant opportunities to deploy new technologies when upgrades, including modernization of instrumentation and control systems, are implemented at existing facilities. The economic benefit from a predictive maintenance program can be demonstrated from a cost/benefit analysis. An example is the program for the Palo Verde Nuclear Generating Station [6]. An analysis of the 104 U.S. legacy systems has indicated that the deployment of on-line monitoring and diagnostics has the potential for savings at over $1B per year when applied to all key equipment [7]. On-line monitoring is now being deployed as part of new light water reactor plants; e.g., by AREVA in the new reactor at Olkiluoto in Finland [8]. New designs for advanced nuclear power plants, such as those within the Gen IV program, will require longer intervals (potentially 4 years) between scheduled outages, and also shorter outages. To achieve such performance, enhanced on-line monitoring and diagnostics is essential.

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[1] ANDERSON, M.T., DOCTOR, S.R., KUPPERMAN, D.S. and MUSCARA, J., Assessment of inservice inspection and leak monitoring for detection of materials degradation in light water reactors. PNNL Report and NUREG/CR (20007, In Press).

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 O&M approaches [9]. A recently published report presents a methodology that incorporates predictive models and damage assessment into improvements in the ASME Code Section XI [10]. This material is expected to be included in the next revision of the code to be published in 2008.

1.1. Needs for Advanced Reactor Designs and Past Experience

New advanced gas reactors and 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 to the forefront the potential for many new degradation processes 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 [11]. 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 critical. It is needed to provide operators with better plant situational awareness and reliable predictions of remaining service life of critical systems and components.

In the USA there has been a long history of developing activities that addressed the issues of aging in the current fleet of nuclear power plants. Many of the earlier insights gained have been summarized in a 1992 report [12]. There are also on-going activities and meetings that address water reactor safety/aging issues [13].

The American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code was developed for light water reactors, and addresses 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 nondestructive evaluation (NDE) which 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 and growth of degradation as well as for the key operational parameters that could be the precursors to degradation [9].

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 is 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. These include the potential risk of having surprise failures. These surprises are related to the occurrence of new degradation mechanisms including degradation mechanisms that are accelerated by stressor enhancement due to altered conditions or newly introduced acceleration mechanisms (e.g., corrosion due to accidental chloride introduction). These have a long initiation time and the fact that only the risk-important components are being periodically inspected, which means that fewer components are being 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 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 both new-build water reactors and advanced designs under consideration for Gen 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 [14]. A brief history of the role and future challenges of NDE in civil aviation, which also looked towards future challenges, was provided by Weber [15]. 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 [16]. Similar technology evolutions are in progress in many high-technology/high-risk fields.

2. A DIGITAL REVOLUTION

For new nuclear power plants there are even greater opportunities for improved operation, enhanced capacity factor and reductions in O&M costs through the adoption of true condition-based maintenance philosophies, on-line monitoring and diagnostics. Adopting digital instrumentation and control (I&C) and new system technologies that use on-line monitoring for more assemblies, using wireless sensors and integrating total-cost-of-ownership models can result in fewer surprises at outages, better planning for maintenance and many fewer unplanned outages.

Advances in technologies in other industries can potentially benefit nuclear power plants, particularly when using advanced on-line monitoring and diagnostics for condition-based maintenance and, in the future, prognostics. The move to digital systems in petrochemical, process and fossil fuel power plants is enabling major advances to occur in the instrumentation, controls and monitoring systems and the approaches employed for diagnostics. The adoption within the nuclear power community of advanced on-line monitoring and advanced diagnostics has the potential for the reduction in costly periodic surveillance that requires plant shut-down, more accurate cost-benefit analysis, "just-in-time" maintenance, pre-staging of maintenance tasks, movement towards true "operation without failures" and a jump start on advanced technologies for new plant concepts. The new technologies can also provide enhanced projected data for all aspects of plant status, and these are immediately available to the operator. It can provide improved measurement that enables operation nearer to component limits (power uprates) and give plant-projected performance metrics that can be provided in real time to corporate operations. As diagnostic and predictive tools evolve, component health status is provided to maintenance staff, but with all these advances there is also the potential for increased cyber vulnerability. In the digital instrumentation and controls area there is therefore significant attention being applied to defense in depth, common cause failure and cyber security of computational infrastructures. Planning for and incorporating such technology can improve plant economics, reduce unplanned outages, improve safety and provide better probabilistic risk assessments.

3. DIAGNOSTICS AND 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 an 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.

3.1. Diagnostics

It was recognized in the mid-1970s that nondestructive testing (NDT) needed to become a quantitative science-based technology. Research was initiated and as a result nondestructive evaluation (NDE) has developed [17]. Many of the measurement capabilities for NDT/NDE were identified as set by fundamental physics [18]. Recent years have seen better understanding of the measurement processes and quantification of performance in terms of a probability of detection, rather than an ultimate detection limit number. There has also been development of new approaches to the management of life in mechanical systems [19] and research into characterization of materials in aging systems, particularly looking at phenomena that occur before the defects (cracks in particular) detected by conventional NDT develop [20].

The nuclear community in 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" [21]. 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 [7], [22], [23]. There is a need based on economics and reducing radiation exposure for enhanced system assessment/life-prediction tools. These are to be used for planning, to avoid "surprises" during 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 [6] and this includes data for calculating the avoided cost [24]. An analysis of the 104 U.S. legacy systems has indicated potential savings at over $1B per year when applied to all key equipment [7] and a summary of the supporting analysis is provided in this paper.

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 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 [25]. 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 in advanced light-water reactors and the Gen IV concepts, designers must see their value and start to incorporate them into their designs. Trying to apply them after the designs are completed or later in the plant life cycle will be difficult and in some cases may not be possible. When considering the investment being made in advanced NPPs, it is critical that if nuclear power is going to be cost competitive with other forms of electrical power generation, process heat 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 need to be involved in creating the necessary requirement for these technologies, and the regulators that are going to be overseeing these new technologies and their deployment need to agree to the validity of the changes. There is a tremendous potential to provide significant improvements in safety and economics of advanced NPPs but the reality is that this is going to require many experts working together to make it happen.

3.2. Prognostics

Prognostics (for machinery) is the prediction of a remaining safe or service life, based on an analysis of system or material condition, stressors and degradation phenomena. Moving from diagnostics, based on observed data, to prediction of life and technologies for structural health monitoring/ management, based on predicted behavior, is requiring development of new approaches that are identified in schematic form in Fig 2. A review of machinery diagnostics and prognostics for condition-based maintenance is provided by Jardine et al. [26], but again it does not consider nuclear power systems.

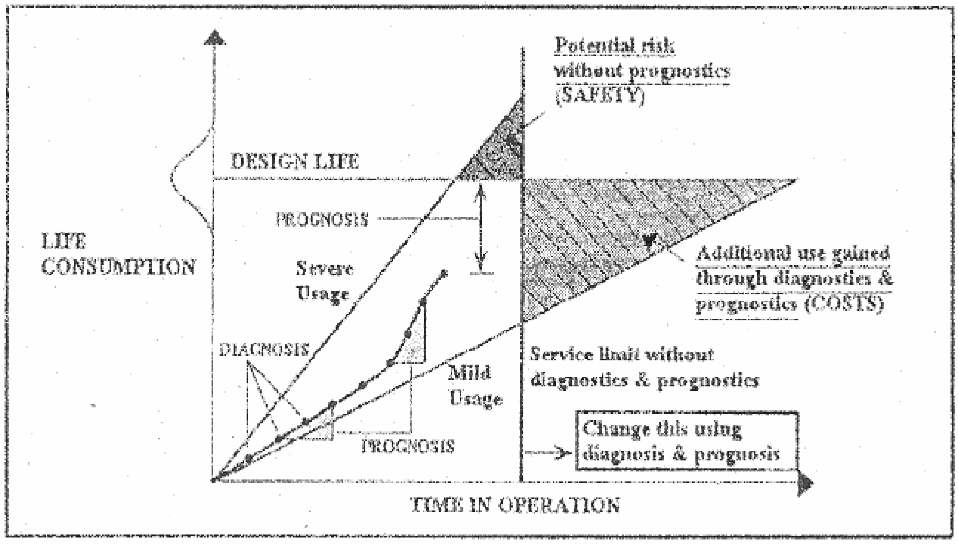

FIG. 1. Overview of structural diagnostics and prognostics showing benefits in operation and support costs and safety [25].

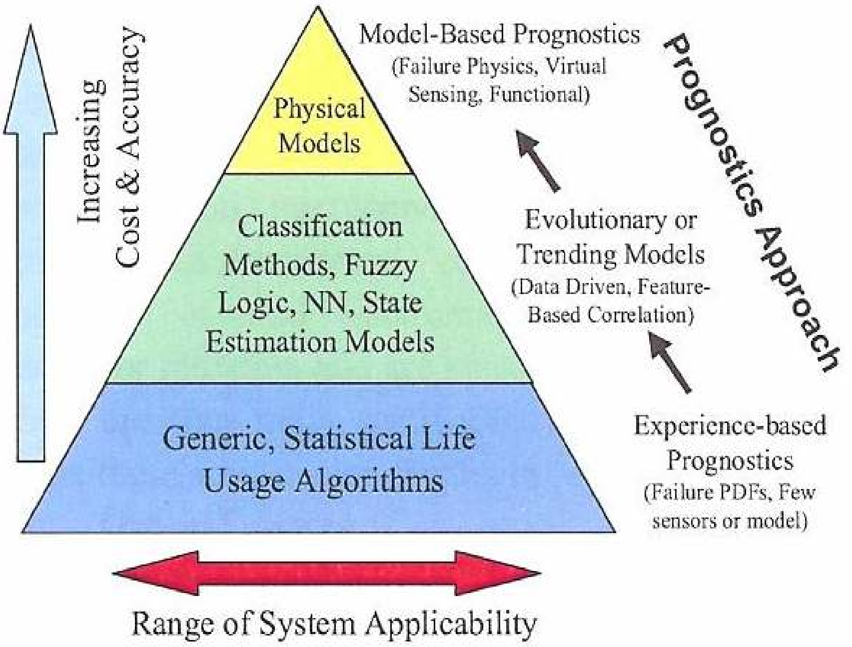

FIG. 2. Range of prognostic approaches.

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. Technologies are being developed for non-nuclear applications, including instrumentation and system health monitoring for electronics, in what is being called “electronics prognostics,” e.g., Urmanov [28]. There are also integrated technologies being developed for advanced fighter aircraft and unmanned aerial vehicle (UAV) system health monitoring, which include both electrical/electronic and mechanical systems. Within the field of advanced diagnostics/prognostics, systems have been deployed for individual elements, but fully integrated systems are still being developed.

Table 1. Assessment of State of Maturity for Diagnostic (D) and Prognostic (P)Technologies [27]

Diagnostic/Prognostic Technology for:	AP[a]	A[b]	I[c]	NO[d]
Basic Machinery (motors, pumps, generators, etc.)	D		P	
Complex Machinery (Helicopter Gearboxes, etc.)		D	P	
Metal Structures	D		P	
Composite Structures			D&P	
Electronic Power Supplies (Low Power)		D	P	
Avionics and Controls Electronics	D		P	
Medium Power Electronics (Radar, etc.)		D		P
High Power Electronics (Electric Propulsion, etc.)				D&P

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

The 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 [29]; 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 [30]; technology to achieve total structural health management [16]; and the NDE community looking at aging due to thermal embrittlement, fatigue and neutron degradation [31].

There is a trend of seeking to move from periodic NDE to on-line condition-based maintenance that started several years ago [32]. A review of the current paradigms and practices in system health monitoring and prognostics has recently been provided by Kothamasu et al. [33]. There remain significant measurement challenges associated with characterization of aging in irradiated reactor components [31], [34]. 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 [35]. This evolved into work to address the demand for describing damage and service-related aging [36]. This work then evolved into a significant European project involving round-robin sample characterization [37] and bringing together condition-dependent NDT and fracture mechanics [31], [38].

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 [39]. 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 are unknown and the regulator has not required the details to be reported. Techniques such as ultrasonic backscatter and acoustic birefringence 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. This figure 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 ensure 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.

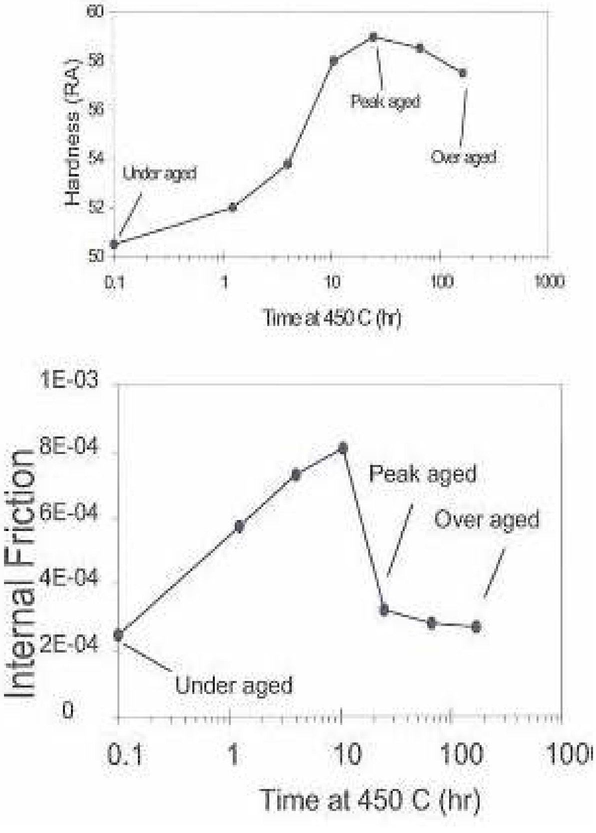

FIG. 3. Example of Monitoring Precipitation-Induced Hardening and Effects on Hardness and Internal Friction [39].

The development of concepts for advanced on-line structural health monitoring for reactor designs such as IRIS has been initiated [40]. Also physics-based approaches to the analysis of aging for prognostics [41], [42], combined with the potential effects on probabilistic risk inspection for designs such as IRIS [43] have been reported.

Key to developing more advanced prognostic schemes (in active systems such as pumps and valves) that 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 [22]. 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.

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.

For the existing nuclear power plants, particularly when life extension is being developed, there are opportunities to deploy on-line monitoring/prognostics, assuming it can be demonstrated that there is still remaining useful life in the plant. This is shown in schematic form as Fig 5.

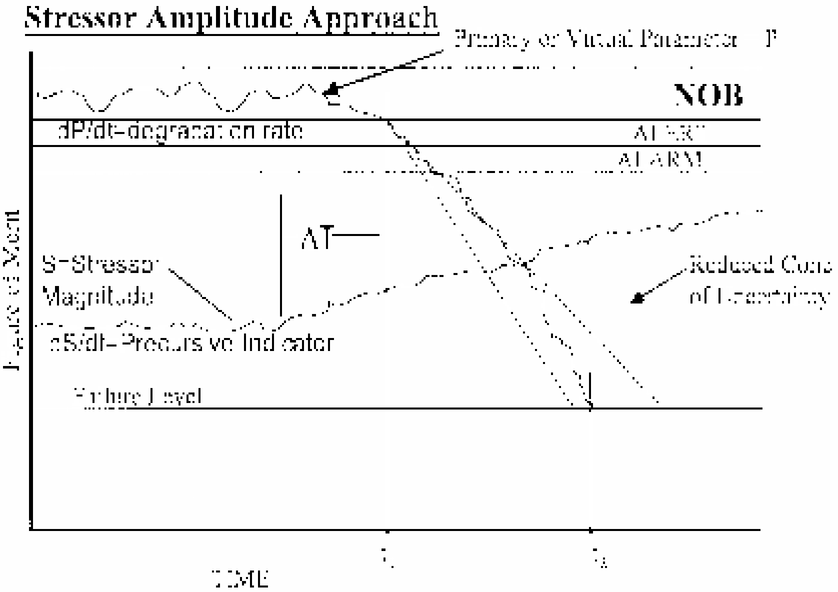

FIG. 4. *Stressor Measurement Giving Time for Intervention Prior to Failure [22].*

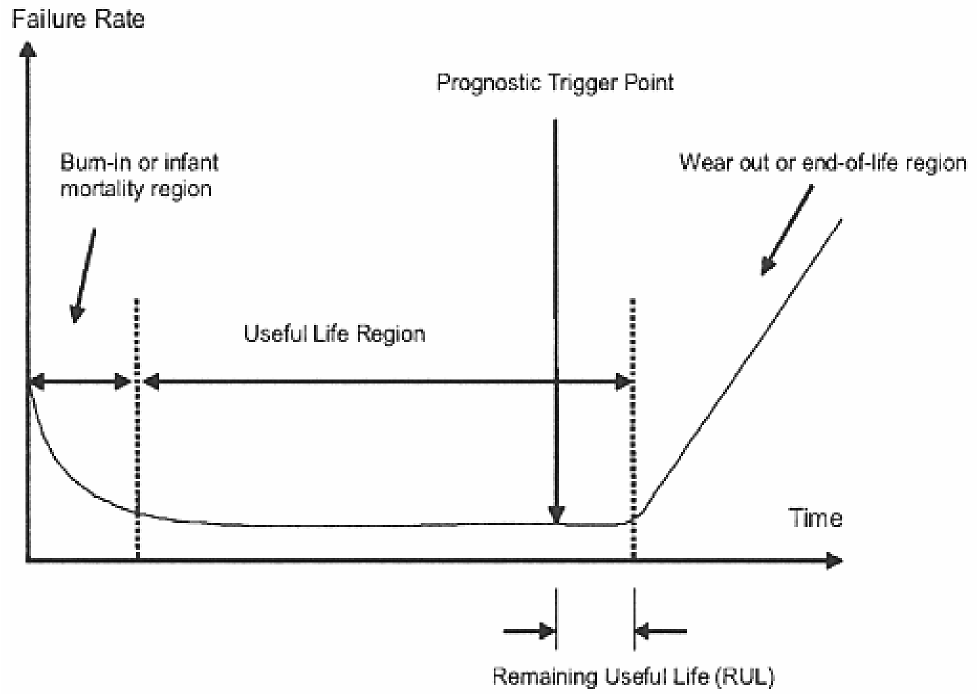

FIG. 5. Typical Life Curve, Showing Prognostics Trigger Point

4. ECONOMIC IMPACT ANALYSIS

4.1. Nuclear Industry

As a task within a DOE project an economic analysis of the potential impact of on-line diagnostiics/prognostics was performed [7]. The data used were those from 2000–2002, when there were 104 commercial nuclear generating units operating in the United States. In 2001, the nuclear industry accounted for 20.3% of the market share of electrical generation in the United States [44].

4.1.1. Present Situation

Over the past decade, the U.S. nuclear industry has made significant performance enhancements. As depicted in Fig. 6 [45], the utilization of the 2001 capacity of 97,860 mega watts improved to an annual net capacity factor of 89.7% [44].

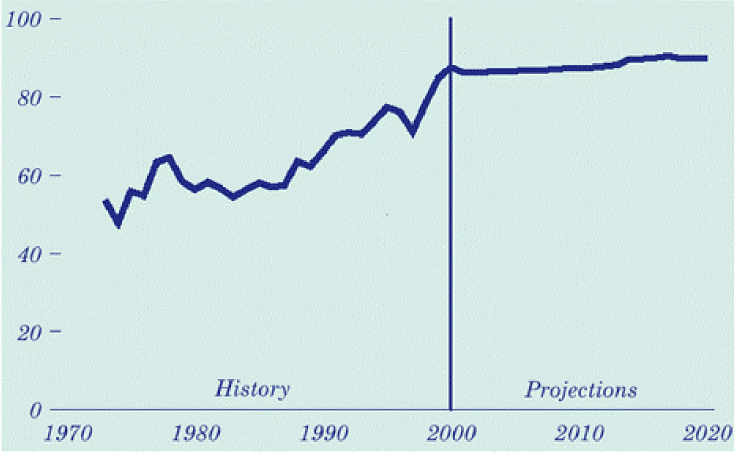

Figure 53. Nuclear power plant capacity factors, 1973-2020 (percent)

History: Energy Information Administration, *Annual Energy Review 2000*, DOE/EIA-0384(2000) (Washington, DC, August 2001). **Projections:** AEO2002 National Energy Modeling System, run AEO2002.D102001B.

FIG. 6. Nuclear Power Plant Capacity Factors [45].

4.1.2. Future Situation

The performance improvements of the nuclear industry are expected to continue into the future. As a result of these improvements, and expected stricter limits on fossil fuel emissions, the nuclear industry is projected to continue to account for a significant portion of the electrical power generation market share in the United States. The Energy Information Administration estimates that even with energy saving measures, the energy demand will increase 1.8% every year through the year 2020. These increases will require building a minimum of 355 gigawatts [45] of new generating capacity to meet growing demand and replace retirement of some existing plants. It is expected that the nuclear industry will help meet some of this electrical demand. Moreover, when this analysis was performed (2002) the NRC had already approved license renewals for 6 nuclear units, 14 were pending review and as many as 24 more intending to apply [45]. It is now expected that life extension will be implemented on the majority of current U.S. plants. The NRC license renewal allows a nuclear unit originally licensed to operate 40 years, an extension to operate up to 20 additional years [46]. This trend is being taken further and consideration is being given to a further extension and “life-after-60.”

Plant improvements are one of the major reasons that the NRC is allowing these extensions. Existing nuclear plants are continuing to improve on safety and reliability, while reducing production costs. However, there are still some opportunities to be more effective, especially in operations and maintenance (O&M).

4.1.3. O&M Practices

Nuclear power plant design is often constrained by the need for frequent access to equipment for inspection and repair. Further, redundancy and diversity of equipment are needed to ensure safety and reliability under a variety of conditions. There are many key drivers for optimizing O&M at nuclear facilities, such as:

- Increase in plant availability
- Reduction in radiation exposure to plant personnel
- Reduction in plant O&M costs
- Increase in plant shutdown safety margins.

Indeed, the nuclear industry is unique in many aspects. However, the nuclear industry follows many of the same O&M practices as other major industries.

4.2. All U.S. Industries: O&M Practices

Traditional maintenance practices that rely on time-consuming procedures are common across many industries and have contributed to high O&M costs. Typically these practices are periodic overhauls or replacement of parts based primarily on historical maintenance records, without regard for the actual "health" of the component or system. In fact, one source suggests that across all industries, "more than $1 trillion is spent each year *(in the USA)* to replace perfectly good equipment because no reliable and cost-effective method is available to predict the equipment's remaining life" [47]. Given adaquate advances in on-line monitoring and predictive tools integrated into condition-based maintenance, opportunities exist for savings due to better planned potential life utilization, and hence delaying replacement costs. Some work has already shown the cost-benefit of adopting condition-based maintenance [6], [24] and opportunities clearly exist to get a significant return on investements from research, development and technology deployment.

4.2.1. Cost-Saving Approach to O&M

A more progressive approach that is starting to be employed in many plants is instrumentation and controls for diagnostics and prognostics (I&C-D/P). The approach requires developing new or upgrading existing systems to *smart* systems that are able to predict system performance and remaining life with high confidence. The smart systems incorporate on-line intelligent monitoring of passive component integrity and the operational status of active system components to determine time to failure. This requires understanding how an entire history of sensor information, given specific environmental and operating conditions, relates to component or system wear and age. Such practices allow overhaul and repair to be performed only when necessary to prevent failure and provide a capability for accessing the risk of delaying selected maintenance tasks. Maintenance methods that predict system performance while utilizing the maximum useful life of subsystems and components represent an innovative and cost-saving approach to O&M activities. The overall reduction of the inventory of required plant safety equipment would likely produce an additional O&M benefit because of reduced surveillance testing requirements in technical specifications [48].

4.3. Economic Analysis: Evaluation Foundation

This economic evaluation is based on a widely accepted product reliability failure rate curve (also known as the bathtub curve), Fig. 7 and associated definitions of the phases of a product life. The curve, which has the outline shape of a bathtub, plots the failure rate (on the vertical axis) of a piece of machinery against time (on the horizontal axis). Typically, the curve depicts three phases:

- An infant mortality or start-up phase, during which faults related to installation and assembly are likely to show up quickly.
- A normal or useful life phase, during which the machine will be reliable as long as it is maintained and used within its design parameters.
- A wear-out phase, during which the machinery reaches the end of its design life, and parts begin to fail more rapidly.
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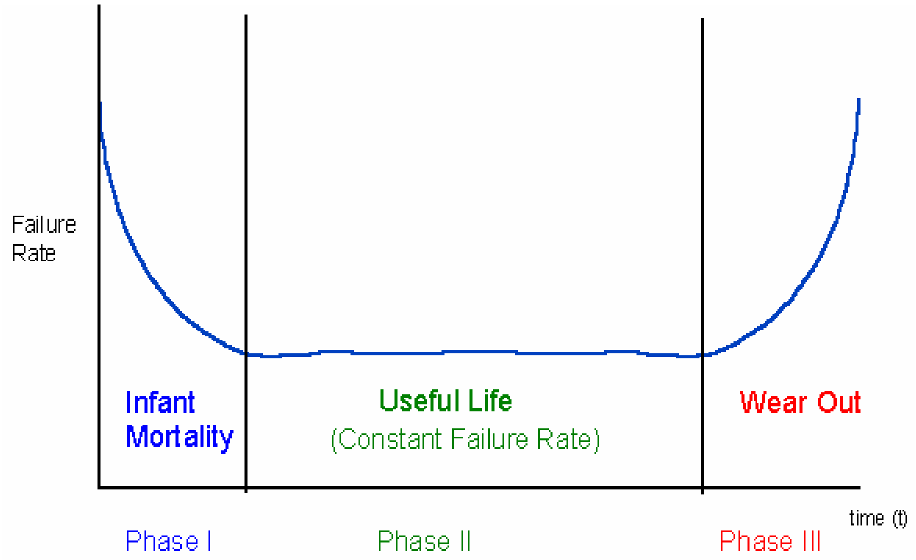

FIG. 7. Product Lifetime Failure Rate Curve

The second phase, in which the constant failure rate is assumed, is the phase that this evaluation is focused on. The economics use an average and constant failure rate that yields a simplified method to calculating maintenance costs. The caveat to using a constant failure rate is that the time when a component actually fails is very important to an economic analysis. An economic function, such as net present value (NPV) calculation, is sensitive to when a failure occurs, such that delayed costs exhibit a bigger advantage that is not fully considered with this approach. Obviously, a more accurate method would be to individually track failure rates for each piece of equipment in a plant from birth to death, which would determine a failure rate while considering factors such as age and application. However, that type of effort is rarely practiced; thus, this approach was used to provide a reasonable estimate of O&M savings opportunities for specified pieces of equipment in the U.S. nuclear and major manufacturing industries.

4.3.1. Equipment Selection

PNNL’s Nuclear Energy Research Initiative (NERI) team selected specific reactor plant mechanical systems and components for investigation based on applicability to current and projected future reactor systems. The information gained through the Nuclear Regulatory Commission’s Nuclear Plant Aging Research program was used for the selection of components and degradation mechanisms used in the study. The recommendation was to investigate pump-motor, heat exchanger and filtration systems operations that result in degraded states. The advantage of knowing the degradation rates and being able to predict time to failure for these pieces of equipment was quantified. The economic analysis which was developed is focused on the nuclear industry but can also be applied to major manufacturing industries [7].

4.3.2. Rotating and Filtration Equipment

Rotating and filtration equipment can be found in large quantities and varieties throughout many industrial facilities. Poor O&M practices reduce equipment reliability and increase the chances of forced outages. If this equipment is located in a critical process flow path without an in-line spare, it can take down the process, cause catastrophic failure and result in high costs to a plant. For example, a 150-hp centrifugal pump on naptha desulphurizer service had a failure that initiated a fire which resulted in excess of $1,000,000 of damage and 18 days of lost production [49]. In addition to forced outages causing major damage expenses, there are many other losses associated with poor O&M practices, such as:

- Loss of revenue
- Severe damage to the equipment or surrounding equipment/personnel/environment
- Reduction of life of the equipment
- High maintenance costs in labor and materials
- Increased costs of spare parts
- Higher electricity costs to operate the equipment
- Potential for liability
- Increases in insurance costs
- Public and political perception of poor safety culture resulting in damage to corporate image.

4.3.3. Evaluation Methodology

Initially, data on motors, pumps and heat exchangers were reviewed to determine a typical failure rate for each piece of equipment. Subsequently, the failure rate (defined as the anticipated number of times that a piece of equipment fails in a specified period of time) is used to determine the associated downtime costs. Two studies, published by the Electric Power Research Institute (EPRI) [50,51] and the Institute of Electrical and Electronics Engineers (IEEE) [52,53], were referenced throughout this evaluation. Both were very thorough in detailing the data compiled, including failure causes, time of failure detection, and associated downtime hours. However, a more recently published list of failure rates reported by the U.S. Army Corps. of Engineers through the Power Reliability Program Enhancement Program (PREP) was also considered in the evaluation.

In addition, because this study supports research and development work focused on pump-motor system failures resulting from misalignment and/or unbalanced conditions, and pump failures resulting from cavitation conditions, an attempt was made to narrow down the published general failure rates to more specific failure rates.

4.3.4. Motor Failure Rate Derivation

The EPRI study was performed in 1982 and the IEEE study in 1983. IEEE also did a 1973 study that indicated similar results to the 1983 study. Both of the more recent studies provided statistics on failure rates and root causes for motor failures. Both studies reviewed a significant population (5000 in EPRI and 1141 in IEEE) of motors, including squirrel cage induction, wound rotor and synchronous motors. The studies were limited to newer motors to review only contemporary designs and eliminate the older motors that were expected to have higher failure rates as a result of age. Any obviously erroneous data or any datum considered a one-time event was eliminated from the study. In addition, the studies examined larger motors (greater than 100 hp for the EPRI study and greater than 200 hp for the IEEE study) that are typically critical to the process. Likewise, the PREP study [54] and [55], also referenced in the NERI work [7], focused on new technology equipment and spent extensive hours collecting and compiling data on reliability and availability.

The EPRI and IEEE studies gave motor failure rate data and determined causes for the failures. The failure rates from these two studies were averaged with the failure rate from the Army study and gave a result of *0.0438* failures per motor per year.

Further, both the EPRI and IEEE studies indicated that the largest single grouping of the motor failures was bearing-related failure. The Army study was not included because it did not give reasons for failure. The percentage of bearing-related failures was averaged at 42.5%. Thus, the average motor failure rate times the percent that are bearing-associated failures, yields a failure rate (FR) of *0.0186* bearing-related failures/motor-year of operating time.

The IEEE study reported that "inadequate maintenance" was the most significant underlying cause of bearing failure at 18% of total bearing failure causes listed. Poor maintenance practices, such as misalignment and/or unbalance, were described in this category; thus, the failure/motor per year (failure rate) was multiplied by 18% to obtain a failure rate of *0.0034* failures/motor per year.

The *0.0034* failures/motor per year, which represents the average failure rate of large motors as a result of bearing problems caused by misalignment, unbalance, and/or other poor maintenance practices, was used below for deriving maintenance cost-saving opportunities.

4.3.5. Pump Failure Rate Derivation

The centrifugal pump is the workhorse of the nuclear industry and many other major industries. Therefore, a failure rate of a centrifugal pump, 0.00422 failures/motor per year from the PREP study [54] and [55], was used as the basis for the economic analysis. In addition, the failure rate chosen is specific to a pump *without a drive* because the study focused on a direct-drive motor-pump system.

Cavitation was also a focus in the NERI project [7]. Cavitation is the hydraulic condition that can exist in any pump and can be caused by excessive suction lift, insufficient net positive suction head (NPSH), throttled pump discharge, or operation at too high a speed. Audible vibration and noise are usually associated with cavitation and if cavitation is left untreated, it can cause excessive wear on the pump components, such as the impellor or bearings.

A review of nuclear industry data from several sources was performed to determine industry-wide operating experience with pumps [56]. The Licensee Event Report (LER) evaluations that are submitted to the NRC by nuclear power plants were reviewed for years 1980–1992 and reported that 56% of failures were due to aging mechanisms because of wear. Further, the data depicted that the pump bearings, impellors, rotors, and wear rings accounted for 71% of the total number of failures. A search on another database from the same study, Nuclear Plant Reliability Data System Evaluation (NPRDS) covered data from the 1973–1992 period and yielded 7538 records. In this study, 76% of the failures were described as due to wear and vibration.

Based on the pump failure data reviewed, an average percentage from the two reports of 66% (56% and 76%) was attributed to wear on pump components. Moreover, the reports discussed in detail some of the primary causes of wear, including hydraulic (i.e., cavitation) and mechanical (i.e., misalignment) stressors. Thus, a conservative estimation of 33% of those wear related failures are considered to be a result of cavitation or misalignment.

The result of these estimations is the basis for a failure rate of:

*0.00422 failures/pump/year*66%*33% = 0.0009 failures/pump/year.*

This rate represents the average failure rate of large pumps as a result of wear caused by misalignment and/or cavitation, and is the basis for deriving maintenance cost-saving opportunities for nuclear and major manufacturing industry.

4.3.6. Heat Exchanger Failure Rate Derivation

The failure rates of the following three types of heat exchanger systems were estimated using data from the Army Corp of Engineers PREP study [54], [55]. The failure rate for the three types of heat exchangers were averaged to obtain a failure rate of 0.01195 failures/heat exchanger per year.

- Boiler system
- Lube oil
- Water and water.
-

Because these systems are found across all industries, the failure rate was considered to be applicable to a nuclear and industrial application.

4.3.7. Costs: Lost Revenue

Increasing plant availability is a major goal across many industries. Many plants operate continuously with only one (for a minimal duration time) planned shutdown a year. A typical refinery will operate at between 90 and 95% availability, and estimated lost production as a result of equipment failures can range from $20,000 to $30,000 per hour. The percentage of failures that caused outages or a reduction in production is given as 17% in the EPRI motor study. The percentage is deemed credible given the fact that the IEEE study showed 56% of bearing failures were found during normal operation instead of a maintenance-scheduled downtime or testing. Therefore a portion of these must have caused an outage, and 17% is a conservative estimate, when considering how many are found while operating.

Pumps are also a major source for process outages. For instance, one reference stated that the leading cause of equipment failures in refineries and ammonia plants are pumps and compressors, and these comprise one-third of all equipment failures [57].

4.3.7.1. Nuclear Industry

The number of motors, pumps and heat exchangers for the nuclear industry was based on the number of the same provided by Columbia Generating Station, operated by Energy Northwest in Richland, Washington, and normalized by generating capacity [7].

A typical calculation for motors, pumps and heat exchangers is as follows (based on motor data):

Loss of revenue based on an outage or reduction of production experienced per year:

*0.0034 failures/motor/year * 2,433 motors * 17% probability of outages = 1.39 outages/year*

*1.39 outages/year * 80 hr/outage * (97.4 * 1000) MW * 38% * $66.90/MWh /10^6 = $275 million/year*

The probability of outages was cited specifically for motors; therefore, because some motor-pump systems have in-line spare pumps, the probability of an outage caused by pumps was reduced by 25% from that for the case of a motor.

Using a similar approach to that used for a pump system, a heat exchanger seemed less likely to take a process down; thus, the probability of an outage was reduced by 25% from that for the case of a motor. However, the logistics of repairing a pump, motor or heat exchanger can be similar; thus, the average hours per failure given by the EPRI study was assumed to be approximately the same.

4.3.7.2. Major Manufacturing Industry

The number of motors and pumps for the major manufacturing industry was based on an Office of Industrial Technology (OIT) study, and the quantity of heat exchangers was estimated from data found on the Department of Commerce and U.S. Census Bureau website [7]. In addition, the revenue lost is based on the U.S. Census Bureau for the same code groups, which were the basis of the OIT study used for the quantity of equipment noted above.

A typical calculation for motors, pumps and heat exchangers is as follows (based on motor data):

Outage or reduction of production experienced per year:

*0.0034 failures/motor/year 346,749 motors * 17% probability of outages = 198 outages/year*

*198 outages/year * 80 hr/outage * 38%*472$M/hr/10^6 = $2.8 Million/year*

4.3.8. Cost of Fuel Replacement: Nuclear Industry

A typical calculation for motors, pumps and heat exchangers is as follows (based on motors):

*1.38 outages/year * 80 hr/outage * (97.6 * 1000) MW * 38% * $30/MWh = $123 Million/year*

The EPRI study determined that auxiliary large drive motor failures cost the average utility over $350,000 per unit per year for alternate energy source during outages, which results in a much larger cost.

4.3.8.1. Major Manufacturing Industry

The basis for replacement costs for major industries can cover a large number of process changes, from simply switching process streams to using an alternate fuel. Consequently, it can also result in a wide range of failure-associated costs. It is likely that a process change will involve a less efficient and more costly alternative. It can also be assumed that the alternative will not cost more than the revenue for the same period of time. Thus, 50% of the net sales per hour (revenue/hour) was used in the NERI study. The estimate is considered to be both reasonable and conservative. Furthermore it is similar to the EPRI findings for the power generation industry also used in the NERI study, and this gives an average revenue of $66/MWh and a replacement cost of $30/MWh.

4.3.9. Cost of Repair (Materials and Labor)

Although repair costs are usually insignificant compared to the lost revenue and replacement costs, they were considered in the NERI study to determine the ranking of economic impacts.

4.3.9.1. Nuclear Industry

The estimate in the EPRI report seemed too low for a nuclear industry facility. Many more crafts are involved, and additional safety tasks need to be addressed, which result in significant cost increases. For example, the cost to remove and install a single pumping unit (circulating water pump) typically equals $65,000 to $75,000, and this includes electrical and mechanical crews and crane rental [58]. The average of these numbers was used as an estimate for the nuclear industry.

4.3.9.2. Major Manufacturing Industry

The average cost to repair a failure as reported by the EPRI study was only $5,484/repair. This was the estimate used by the entire industry for motors, pumps and heat exchangers. An additional 35% was added to estimate the costs for the materials and parts needed for the repair. As noted in the EPRI report, this is a conservative average estimate for only the direct labor involved in a motor-failure repair/replacement task. Typically, indirect costs, such as supervisory and engineering labor, and lighting and electrical resources will be an additional 10% cost.

The full cost of materials and inventory was not considered in the costs, but a benefit would be gained. How the materials are purchased and inventoried will determine their ultimate cost, but as shutdowns are reduced and mean time-to-failures are lengthened, the inventory can be reduced which then results in a reduction of the associated carrying costs.

4.3.10. Cost of Energy

Generally, the energy losses are caused by friction from the bearing motion causing heat generation that must be rejected. Some of the heat is transferred to the motor lubricating oil, shaft, coupling, and pump. The heat generated is based on the loads that the bearing carries and as these loads increase as a result of misalignment or unbalance, the bearing generates more heat, and uses more power. Studies have shown significant energy losses as a result of these conditions. Some of the numbers for these loses have been given as:

A power loss of a motor on a commercial base caused by unbalance resulted in approximately 1% of power loss (unloaded) and 3% of power loss (loaded) as a result of misalignment. A different study stated 2.3% for a loaded machine and 9.1% for an unloaded machine [59].

For example, a typical 100-hp motor operating for 1 year at $0.05/Kw-hr will save $374/year from a 1% efficiency gain (from 93–94%) [60].

Conservative calculations were performed based on a 1000-hp motor and a 125-hp motor, with the energy saved from each averaged and an assumption that 10% of motors would have been misaligned and/or unbalanced. Furthermore the numbers were based on a cost of energy at $0.05/kWh and a 2% efficiency loss.

The energy cost is insignificant when compared to other cost-savings numbers, but when multiplied by many motors, it is still a savings opportunity.

4.3.11. Cost of Life Extension: Nuclear and Major Manufacturing Industries

Motors are designed to last 20 years but typically do not last more than 5 to 10 years; most experience significant failure in 2 to 3 years of life, about 25% less life than designed for a standard motor. The top two reasons cited are bearing failure and motor abuse [61].

Some of the loss of life in a motor is a result of the cycling stress caused by the starting and stopping associated with shutdowns, especially unplanned shutdowns. The life expectancies and the reasons for failure are often different, but it can be stated that pumps and heat exchangers also fail before their time.

Assume that an operator is starting with a new plant and investing in new equipment used for the analysis. Furthermore the assumption is that proper diagnostics can offer a 20% life extension for equipment. This has been demonstrated by numerous cases, including past experience with PNNL's DSOM® (Decision Support for Operations and Maintenance) at the 29 Palms-US Marine Corp Base. This implies that a motor which may get 7-year life, without monitoring, will now last 8.4 years. In addition, using average equipment prices, the expected life of each piece of equipment and a 40-year life of a typical plant, the capital cost savings extended over the life of the plant can be calculated for nuclear and major manufacturing industries using the respective equipment quantities [7].

4.4. Economics Summary

The estimated life cycle costs that can be saved with on-line diagnostics of the type reported in this paper and the NERI study are substantial. The NERI study determined that $48 billion and $208 trillion dollars could be saved by the U.S. nuclear industry and the companies that comprise the major sectors in U.S. manufacturing industries [7] based on a 6% discount rate and a life of 40 years. When the data are applied to the 104 U.S. legacy systems this gives potential savings at over $1B per year when on-line monitoring/diagnostics with some level of prognostics is applied to all key equipment.

5. INTREGRATED APPROACH AND IMPLEMENTATION

For maximum impact it is necessary to adopt an integrated approach to system life. In the prioritization of system elements to which on-line monitoring is applied a probabilistic approach to risk assessment is needed. In addition, where possible, energy management tools, such as PNNL DSOM [51] can give additional economic advantages.

A model was developed for the application of on-line monitoring/prognostics to critical elements in an IRIS reactor [43]. An example of the potential for prognostics to directly impact a reactor's probabilistic risk assessment (PRA) is given in Fig. 8. Fig 8a shows the PRA for a reactor under a specific combination of normal and unplanned events. The coincidence of an unplanned failure and need to replace a service water pump with typical periodic operational activities has the potential to increase risk. The ability to deploy advanced on-line monitoring with remaing life prediction (prognostics) that can reliably predict a potential failure and give the operator the opportunity to move the service water pump replacement has a positive effect on PRA. Such interventions can also have a positive impact on plant O&M costs.

6. TECHNICAL CHALLENGES

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

- Smart components and structures
- Self-diagnostic systems
- Embedded Micro-Electromechanical Systems (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 is the realization of the optimized plant of the Future

7. CONCLUSIONS

The move to digital systems in petrochemical, process and fossil fuel power plants is enabling major advances to occur in the instrumentation, controls and monitoring systems and approaches employed. The adoption within the nuclear power community of advanced on-line monitoring and advanced diagnostics has the potential for the reduction in mandated surveillances, more accurate cost-benefit analysis, “just-in-time” maintenance, pre-staging of maintenance tasks, moving 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. For the USA an analysis of the 104 U.S. legacy systems has indicated that the deployment of on-line monitoring and diagnostics has the potential for savings at over $1B per year when applied to all key equipment.

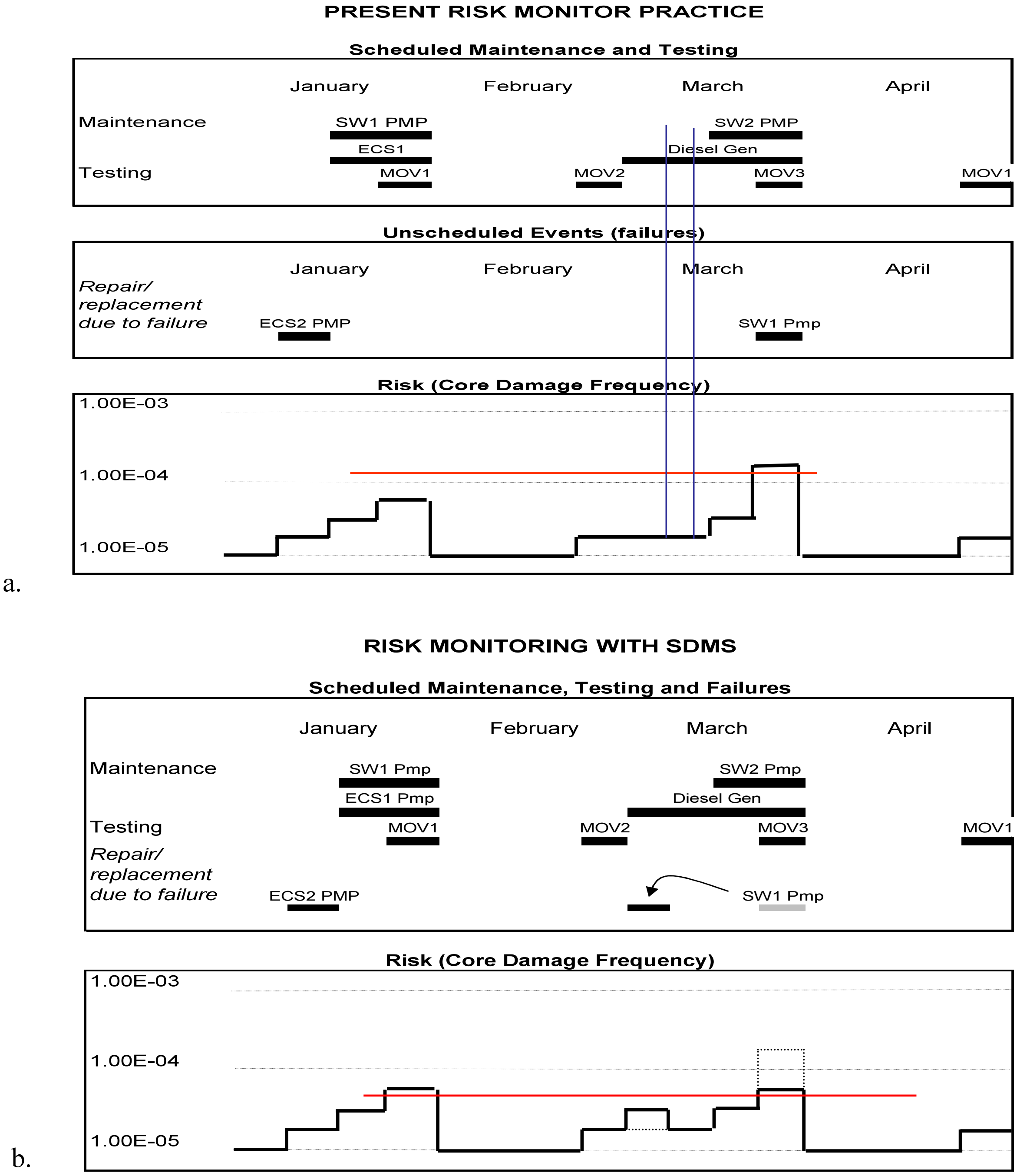

FIG. 8. Example of Effect of First-Principles Prognostics on Reactor Operational Risk – PRA Impact (a) present risk monitoring practice, (b) risk monitoring with SDMS – self-diagnostics monitoring system/prognostics.

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 are to be avoided. Such advances are only possible through the use of new and improved monitoring, and implementation of advanced diagnostics/prognostics. The use of digital I&C provides the opportunity to add enhanced functionality and to move to add prognostics for key system elements.

Opportunities exist to significantly impact operation and maintenance costs for the current legacy fleet; the current generation of light-water reactors, which are being built with digital instrumentation and controls; and most significantly next generation (GEN IV) plants that will require new ranges of operational conditions and enhanced monitoring functionality.

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 on the next generation of new light-water-reactor designs.

For these approaches to be successful it will require the engagement of researchers, advanced reactor (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 new advanced NPPs. The engagement of these many diverse experts must occur NOW in order for these advances to be realized. Otherwise, advanced nuclear power plant performance will simply be an extension of the design, operating and performance standards of the current fleet of light-water reactors.

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