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Prognostic Health Monitoring System: Component Selection Based on Risk Criteria and Economic Benefit Assessment

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Abstract. Prognostic health monitoring (PHM) is a proactive approach to monitor the ability of structures, systems, and components (SSCs) to withstand structural, thermal, and chemical loadings over the SSCs planned service lifespan. The current efforts to extend the operational license lifetime of the aging fleet of U.S. nuclear power plants from 40 to 60 years and beyond can benefit from a systematic application of PHM technology. Implementing a PHM system would strengthen the safety of nuclear power plants, reduce plant outage time, and reduce operation and maintenance costs. However, a nuclear power plant has thousands of SSCs, so implementing a PHM system that covers all SSCs requires careful planning and prioritization. This paper therefore focuses on a component selection that is based on the analysis of a component's failure probability, risk, and cost. Ultimately, the decision on component selection depends on the overall economical benefits arising from safety and operational considerations associated with implementing the PHM system.

1. Introduction

Long-term safe and economic operation, i.e., beyond 60 years, of the current fleet of nuclear power plants (NPPs) is an important element in the overall energy stability of the United States in coming decades. One of the main challenges in keeping these plants operational is ensuring the integrity and performance of systems, structures, and components (SSCs). The current approach to manage degradation and aging includes periodic maintenance and in-service inspection of SSCs [1,2]. Periodic maintenance involves the examination of SSCs at regular time intervals. For this scheme to succeed, the maintenance interval should be short with respect to the actual time it takes for the degradation to progress from inception to failure. A limitation of this method is that emerging degradation cannot be detected until the next scheduled maintenance period.

To ensure long-term safe and economic operation of NPPs, the U.S. Department of Energy (DOE) sponsored the Light Water Reactor Sustainability (LWRS) Research and Development (R&D) Program. One of the LWRS Program's R&D pathways is *Advanced Instrumentation, Information, and Control System Technologies* [3]. The goal of this pathway is to establish advanced condition monitoring and prognostic technologies for use in understanding the aging of SSCs in NPPs.

A proactive approach to monitoring the health of SSCs, such as Prognostic Health Monitoring (PHM), can be used to better manage aging and degradation mechanisms, including emerging mechanisms. The argument for implementing PHM in the nuclear industry has been carefully analyzed in several previous studies [4,5]. Notably, the implementation of a PHM system would strengthen plant safety, reduce plant outage time duration, and reduce the operation and maintenance costs compared to routine maintenance activities. However, implementing a PHM system in NPPs presents an economic challenge besides challenges associated with feasibility, verification, and validation.

Selecting the components to be monitored is a crucial step for successful PHM implementation in NPPs because covering a large number of SSCs requires careful planning and prioritization. SSCs in a NPP are divided into safety-related SSCs and nonsafety-related SSCs. Implementation of the PHM system on safety-related SSCs is understandably more expensive and time consuming because of the probable need for regulatory approval. These additional expenses (time and labor) should be factored into the component selection process. In this paper, components that can cause plant outage because of relatively higher component failure probability and risk are selected to evaluate the benefit of the PHM system. The benefit is analyzed by considering component reliability, maintenance costs, and PHM implementation costs.

The rest of the paper is organized as follows: Section 2 presents a brief introduction to the PHM system; Section 3 discusses component selection criteria; Section 4 presents an assessment of the benefits of the PHM system; Section 5 provides examples and gives the reason for component selection; and Section 6 presents the conclusion and recommendations.

2. Prognostic health monitoring system

Implementing a PHM system requires three critical steps:

a. Selecting the SSCs for monitoring
b. Developing a diagnostic model enabling early detection of degradation in selected SSCs
c. Developing a prognostic model to estimate expected remaining useful life (RUL).

Selecting the SSCs for Monitoring: Selecting the SSCs is a crucial step in implementing the PHM system because the SSCs in NPPs are diverse and require different types of monitoring sensors to measure the parameters of interest. The various factors considered when selecting these SSCs are discussed in Section 3.

Diagnostic Model: Diagnostic models are used to identify and classify the faults or degradation occurring in a selected SSC. Diagnostic models are based on pattern recognition techniques. Different types of measured physical parameters such as temperature, vibration, pressure, etc., are input to diagnostic models. The output of the diagnostic model is analyzed to understand degradation and its associated symptoms.

Prognostic Model: Prognostic models, also known as RUL models, are used to estimate the expected RUL and the associated uncertainties for selected SSCs based on current operating conditions and diagnostic information. RUL can be defined as the time period after which the performance of the component is not expected to meet minimal operational requirements. Many prognostic models exist and are broadly classified into Type 1, Type II, and Type III prognostic models. Details on the different types of prognostic models are beyond the scope of this paper, and can be found in [6].

For a complex system in NPPs, one should keep in mind that the PHM predictions, such as failure mode from diagnostic model or RUL from prognostic model, have inherent uncertainties. These uncertainties result from the lack of knowledge about underlying physics and instrumentation errors and thus need to be creditably quantified. The prediction uncertainty should be taken into consideration for final actionable decisions.

3. Component selection for PHM system

Selecting the components to be monitored is one of the crucial steps for successful PHM implementation in NPPs. As in any decision-making process, the selection should be based on the rigorous consideration of numerous significant influencing factors, including the feasibility of a specific monitoring procedure, component failure probability, and risks (or consequences) associated with component failure.

The selection criteria are based on:

- Feasibility considerations
- Component failure probability
- Consequences associated with component failure
- Economical effectiveness of the selected component PHM system.

As mentioned earlier, SSCs in NPPs are categorized as safety-related SSCs and nonsafety-related SSCs [1]. The safety-related SSCs are relied upon to remain functional during and following design basis events. This ensures the integrity of the reactor coolant pressure boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, and the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposure. These SSCs require special treatment by the Nuclear Regulatory Commission (NRC). The nonsafety-related SSCs do not require special treatment by the NRC, but their failure could prevent safety-related SSCs from fulfilling their safety-related function or could cause a reactor scram or actuation of a safety-related system.

For some safety-related components, it is not possible to implement any additional instrumentation or even change the maintenance practice without prior approval from NRC. Therefore, PHM implementation for such components bears heavy burdens of justification for approval on top of other expenses associated with the PHM system. Alternatively, the unavailability of nonsafety-related SSCs may cause plant outages, even if the associated core damage risk is not significant. This fact, coupled with the additional regulations associated with monitoring safety-related SSCs, makes nonsafety-related components ideal candidates for coverage under a PHM system. For these reasons, this paper emphasizes nonsafety-related SSCs that are risk significant for coverage by the PHM system.

3.1. Feasibility

In assessing the feasibility of deploying monitoring for a SSC, there are a series of individual topics that require consideration:

- **Timeline**. The PHM system implementation should meet the timeline requirements of the aging fleet of existing NPPs by providing monitoring capabilities before a major failure occurs.
- **Operational compatibility with other components and sensor reliability**. The PHM system should not pose an unacceptable increase in risk, in terms of its impact on other components (instrumentation constraints). Typically, the number of installed sensors available is small in NPPs. The sensors are still considered to be a weak link because they are sometimes less reliable than the systems they monitor. Advanced sensor validation and qualification is required to overcome sensor reliability issues. More challenges come from the harsh environments that can be encountered in some parts of the NPP system.
- **Availability of operational data, including failure data**. Empirical (data-driven) techniques constructed from operational data (including historical failure data) use signal processing and transformation techniques to extract information-rich features for the data. Neural networks, nonlinear regression algorithms, and Markov Chains are some of the examples of empirical techniques. These methods require access to large quantities of data from failures observed in the field.
- **Availability of physics-based failure models**. Physics-of-failure (model-based) approaches use mathematical models of the degradation mechanisms. These methods also consider environmental stresses on the component such as temperature, load, vibration, etc. These models can be used to analyze the degradation and life of the component under actual operating conditions. They also serve as an important tool for validating data driven models and understanding degradation mechanisms.
- **Verification and validation (V&V).** Adequate V&V of prediction models or procedures, including uncertainty quantification, is necessary to mitigate false alarms, missed alarms, and inaccurate RUL

predictions. Novel ways to provide automated V&V are needed and have been deployed in the defense and aerospace industries. Where components (e.g., pumps and motors) are also deployed in other industries, common approaches can be used; however, there are some unique operating conditions (for example, radiation effect) faced by the aging NPPs that may require nuclear-specific approaches.

- **Mitigation actions**. Predictions should provide actionable information, and the PHM methodologies must give the user a high degree of confidence. This is particularly important when decisions can impact safety, the confidence of the component condition assessment, the availability of resources to mitigate the problem, the cost to the operator, and the ability to reschedule the planned maintenance.

3.2. Component failure probability

Calculating failure probability requires understanding the physics of failure, state awareness, and fault and failure progression rates; performance properties as components age; and the effects of degradation across the system. Failure probabilities of components are included in the probabilistic risk assessment (PRA), which is also being expanded to include the effects of aging [7]. The Electric Power Research Institute (EPRI) has a preventive maintenance application center that gathers data on components.

3.3. Consequences associated with component failure

Many consequence scenarios and the occurrence probability associated with component failure are quantified in PRA analysis. Such analysis is commonly extended to formally include plant downtime, equipment repair, replacement cost, and possible exposure to personnel and the environment. PRA is frequently used to support the business case for preventative maintenance and condition-based monitoring [8,9].

4. Assessment of PHM system benefit

The overall benefit of a PHM system implementation serves as a decisive factor in the component selection process. The deployment of PHM systems provides significant benefits, including:

- *Safety benefits:* Reducing risk, minimizing safety impact, and increasing reliability.
- *Operational benefits*: Minimizing unplanned plant shutdown, decreasing focus on reliable systems or components, and increasing flexibility in the scheduling of maintenance are some of the operational benefits. This leads to improved planning of inspection and repair activities, higher quality maintenance, shorter and less complex outages, fewer surprises during outages, the elimination of unnecessary tests, and reduced radiation exposure.

The economics of nuclear plant life management are discussed in greater details in [10]. The financial benefits include both safety and operational benefits, due to (i) increased plant availability and capacity factor by avoiding unplanned plant shutdown; and (ii) practicing optimal maintenance schedules. Thus, the overall economical savings, S , (in terms of dollars) resulting from the implementation of the PHM system is expressed as

$$S = S_{\pi} + S_{m} \tag{1}$$

where S_{π} is the savings due to reduction of component failure probability and S_{m} is the savings due to improvements in plant maintenance activities. The PHM system is financially beneficial for the seleted component when the overall economic benefit is greater than the implementation cost of the PHM system, denoted by C in Eq. (2)

$$S_\pi + S_m > C \tag{2}$$

The benefit is analyzed by taking three factors into consideration: (i) increase in reliability resulting from implementation of the PHM system; (ii) reduction of component maintenance costs (plant specific) due to because of fewer inspections, tests, and repairs; and (iii) cost of the PHM system implementation. The selected components should have high savings (S_π, S_m, or both) and low cost (C).

4.1. Economical benefit of PHM system due to reduced component failure probability

Fig. 1 depicts the economical aspects of implementing the PHM system at the component level [11]. The economical benefits arise from the fact that the PHM system reduces the probability of unexpected component failure by prompting timely component inspection, repair, and/or replacement. Without a PHM system to monitor operating conditions, a component may unknowingly be exposed to operating conditions beyond acceptable tolerances, increasing the probability of failure. A PHM system can be used to identify any undesirable conditions, allowing operators to make adjustments that will reduce the probability of failure. The PHM system can also alert personnel to any emerging component degradation, allowing timely replacement and reducing the likelihood of unexpected failure. Let p_c denote the component failure probability without a PHM system, and p_m denote the component failure probability with a PHM system such that $p_m << p_c$. Subsequently, the probability of plant failure (e.g., core damage frequency) conditional on the subject component failure is also reduced. Let π be the conditional probability of a plant specific failure mode, for example core damage, given that a component failure occurs with probability p_c. Let π_m be the conditional probability of core damage after PHM implementation given that a component failure occurs with reduced probability p_m; therefore $\pi_m << \pi$ (Fig. 1.). The value of π can be estimated from the risk importance measures.

The conditional loss associated with component failure, denoted by *y,* includes not only the cost of component replacement but also includes all expenses and losses incurred because of plant downtime, evacuation, emergency systems activation, and mitigation of radioactive releases. The economic benefit (or savings) of the proposed PHM system is the difference in expenses with and without the PHM system, and can be estimated by the expression

$$S_\pi = (\pi - \pi_m) \cdot y \tag{3}$$

The economical benefit of the PHM system (Eq. (3)) depends on the reduction of conditional plant failure probability because of the reduction of subject component failure probability with the PHM system. The SSCs with high failure frequency and high risk significance leading to higher original (without PHM) conditional plant failure probability pose a higher financial risk to the plant ($\pi \cdot y$). Therefore they are excellent candidates for consideration for coverage by a new PHM system because of the high potential economical savings. The economic benefit of the PHM system increases further as a component ages because the increasing original plant failure probability is a function of increasing component failure probability.

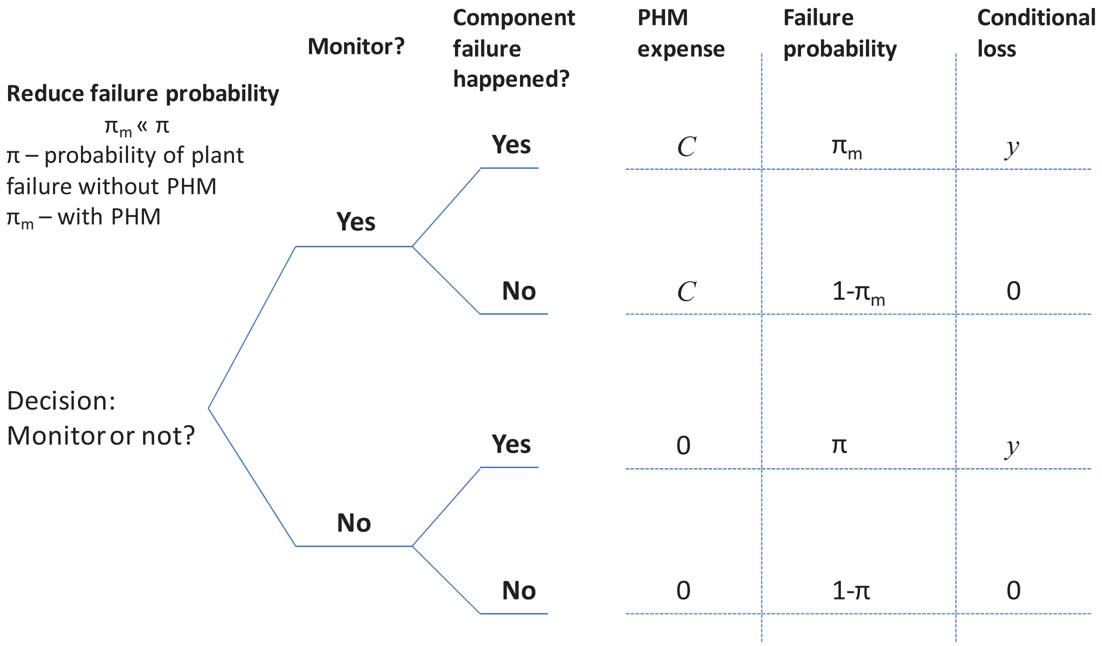

Fig. 1. Economical aspects of implementation of PHM system based on reduce component failure probability

4.2. Economical benefit of PHM system due to improved maintenance activities

Besides reducing component failure probability, a successful implementation of the PHM system for SSCs in a NPP also leads to fewer inspections, tests, and repairs of SSCs by using performance-based maintenance planning instead of traditional periodic maintenance. The economical benefit (S_m) arising from the reduction of plant maintenance costs is plant-specific. The estimation of costs associated with the avoidance of a component failure is complicated because of multiple factors beyond the scope of this paper.

4.3. Cost of PHM system implementation

The cost term C in Eq. (2) represents the cost of implemeting a PHM system. It includes the cost of labor and equipment required to install additional data acquisition and processing capabilities, purchase and set up monitoring software and hardware, train personnel, and provide justification for approval (especially for safety related components). The justification cost for safety-related components could be higher compared to the cost associated with nonsafety-related components, as the former requires regulatory approval. For some safety-related components, it is not possible to implement any additional instrumentation or even change the maintenance practice without prior approval from the NRC. Therefore, implementing PHM for such components requires substantial effort to demonstate not only the reliability improvement of the monitored component, but also that the added system does not adversely impact overall plant risk.

5. Examples

As a part of a LWRS pilot project to implement online monitoring for active components, the following components have been identified for implementation of the PHM system.

- **General step up (GSU) transformer (nonsafety-related component):** GSU transformers represent one of the most important and expensive components in NPPs. Because of their nonsafety-related status and low perceived failure probability, maintenance programs for GSU transformers consist of periodic external inspections and off-line electrical tests. Occasionally, detailed oil testing is performed [12]. Unexpected failure of transformers can occur as a result of common failure modes such as a reduction in dielectric and thermal strength of paper insulation because of partial discharge and aging, or a reduction in electrical insulation caused by oil contamination or electrical leakage inside the transformer. Unexpected failures lead to long outages, partly because of the long lead time to order a replacement. If a PHM system can accurately estimate the RUL of a GSU transmformer based on current operating conditions, it allows utilities to order the replacement in advance. Therefore, GSU transformers are good candidates for coverage by a PHM system. The authors are making plans to work with a utility to collect GSU data and implement relevant diagnostic and prognostic models.

- **Emergency diesel generator (high risk significant, safety-related components):** A diesel generator is an example of safety-related component that can be covered by the PHM system implementation, although the cost term C is higher compared to transformers for the reasons mentioned earlier. A diesel generator is required to provide power to essential safety systems in the case of loss of offsite power. Even though a diesel generator does not directly affect the plant safety under normal operation, it is safety critical and the consequences of failure in emergency situations makes it a risk significant component. Some of the common failure modes in diesel generator are cylinder pressure and vibration, fuel oil pump vibration and pressure, lubricating oil temperature, etc. The implementation of a PHM system will therefore improve diesel generator reliability and operation by diagnosing problems sooner, thus avoiding large periods of downtime. Currently, the authors are making plans to work with a utility to collect diesel generator data and implement relevant diagnostic and prognostic models.

6. Conclusions and recommendations

This paper considers a PHM system in the context of aging management for NPPs, thus strengthening the technical basis for long-term safe and economic operation of the current fleet of light water reactor plants. The present effort is motivated by the idea of developing a quantitative framework that aids systematic identification of plant components that are selected for cost-effective PHM. It is proposed that such a framework be based on the assessment of overall financial benefits, including both plant safety and operational benefits brought by information obtained with a PHM system. The scoping study indicates substantial challenges in quantifying the cost benefits from implementation of a PHM system.

It is recommended that case studies on determining cost benefits of PHM for future research be performed for a safety-related emergency diesel generator and nonsafety-related system (GSU transformers).

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