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Original Article

RELIABILITY DATA UPDATE USING CONDITION MONITORING AND PROGNOSTICS IN PROBABILISTIC SAFETY ASSESSMENT

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ABSTRACT

Probabilistic safety assessment (PSA) has had a significant role in quantitative decision-making by finding design and operational vulnerabilities and evaluating cost-benefit in improving such weak points. In particular, it has been widely used as the core methodology for risk-informed applications (RIAs). Even though the nature of PSA seeks realistic results, there are still "conservative" aspects. One of the sources for the conservatism is the assumptions of safety analysis and the estimation of failure frequency. Surveillance, diagnosis, and prognosis (SDP), utilizing massive databases and information technology, is worth highlighting in terms of its capability for alleviating the conservatism in conventional PSA. This article provides enabling techniques to solidify a method to provide time- and condition-dependent risks by integrating a conventional PSA model with condition monitoring and prognostics techniques. We will discuss how to integrate the results with frequency of initiating events (IEs) and probability of basic events (BEs). Two illustrative examples will be introduced: (1) how the failure probability of a passive system can be evaluated under different plant conditions and (2) how the IE frequency for a steam generator tube rupture (SGTR) can be updated in terms of operating time. We expect that the proposed model can take a role of annunciator to show the variation of core damage frequency (CDF) depending on operational conditions.

1. Introduction

Probabilistic safety assessment (PSA) has evolved as a decision-making tool for enhancing the design and operational vulnerabilities of nuclear power plants (NPPs) since the 1970s. Risk-informed applications (RIAs) supported by PSA are particularly useful for allocating limited resources while maintaining safety. The nature of PSA seeks realistic calculations so the PSA model enables engineers to find the relative priority of accident scenarios, weak points in achieving

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accident prevention or mitigation, and insights to improve those vulnerabilities. However, there are still "conservative" aspects in the procedures for developing a PSA model. One of the sources for the conservatism is the assumptions of safety analysis and the estimation of failure frequency. However, the scope of RIAs are getting wider by virtue of state-of-the-art enabling techniques in recent years [1].

Surveillance, diagnosis, and prognosis (SDP) utilizing massive databases and information technology is one such enabling technique. It is worth highlighting SDP in terms of its capability of alleviating the conservatism in conventional PSA. SDP is common in massive manufacturing lines and safety critical industries, whereas its pros and cons have not been explicitly verified in the nuclear field due to the principle of "proven technology". Because there are many methods for SDP, it is difficult to explain the pros and cons for all individual SDP methods. Therefore, the common characteristics of SDP methods are explained in this article. The SDP methods can be roughly categorized as physical methods and empirical methods.

If the underlying physical mechanisms of a system are well understood, then an analytical model based on first principles can be developed to describe the expected behavior depending on operating conditions. However, these methods can be costly and time-consuming to develop for large, complex systems, and the developed models often have limited applicability. Additionally, simplifying assumptions are often necessary for phenomena that are not fully understood or to improve runtime performance. Meanwhile, empirical models are built on the historical operation data without an explicitly defined understanding of the underlying physical mechanisms of the system. However, it is difficult to collect enough data to develop a model and update it when a new observation occurs [2,3].

Nevertheless, it does not seem that the nuclear industry can avoid the approaching technical tide. Recently, a study dealing with the applicable areas and state-of-the-art status of SDP in the nuclear industry was published [2]. A detailed technical description can also be found in the literature [4–7]. Various approaches merged with SDP and other enabling techniques such as living PSA [8], dynamic PSA [9], and aging PSA [10] have been proposed to increase the value of PSA.

Recently, the concept of "state-dependent PSA" was suggested and a case study about the degradation of steam generator tubes was analyzed using mechanistic aging models and surveillance techniques [11]. Additionally, in order to overcome the weakness of event tree and fault tree analysis, which is to say their static nature, the calculation of real-time risk using "Go-Flow" was suggested [12].

This article shares the same motivation with the previous works and introduces a recent achievement regarding a method of improving the applicability of PSA using condition monitoring for the performance of passive safety systems and condition prognostics for material degradation. The concept of online PSA which is a common designation of time- and condition-dependent PSA is discussed in more detail in the next section. Then two enabling techniques and preliminary results to support an on-line PSA model are reviewed. The authors illustrate (1) how to develop a condition-dependent PSA that will be demonstrated by a passive residual heat removal system (PRHRS) and (2) how to use prognostics to update the initiating event (IE) frequency under material degradation and how this contributes to a time-dependent PSA which will be illustrated by an accident scenario, steam generator tube rupture (SGTR).

2. Background

This study originated from the question: Why can't PSA be used as a real-time risk annunciator? The authors took note of the availability of the SDP techniques. There are a lot of factors for PSA modelling and those factors seemed to be able to have a real-time nature when they are integrated with the SDP techniques. The main benefit of SDP is to reduce uncertainty (which means fewer systematic and random errors) and to forecast future risk because SDP can update statistical information in a timely manner.

The conventional PSA generally results in static estimation for core damage frequency (CDF) or large early release frequency. Variations of the conventional PSA models attempted to provide dynamic information but they belong to essentially "offline" analysis. Aside from the practical availability of the SDP techniques in the field, they can supply online information, if successful, so it is expected that a PSA model will also be able to have an online nature; for example, real-time CDF depending on the occurrence of an external event or in terms of operating time.

There are a lot of issues that should be considered to achieve the online method. The authors are conducting two themes: (1) condition monitoring for performance of passive safety systems and (2) condition prognostics for material aging or degradation. We named the former as condition-dependent PSA and the latter as time-dependent PSA to clarify the purpose of the SDP techniques. The result of the conventional PSA was the probabilistic expression for risk from the current viewpoint, whereas the result of the online PSA integrated with the SDP techniques can perform the similar function of early warning.

Fig. 1 shows a comparison between a reliability-based distribution coming from the conventional PSA and a condition-based distribution. The reliability-based distribution can be obtained from traditional time-to-failure analysis. The transition from a reliability-based distribution to a condition-based distribution can be done by dynamic Bayesian approaches with the observation of condition indicators. The condition-based distribution characterizes the lifetime of a specific system or components operating in components operating in that system specific environment. In Fig. 1, the monitoring of condition indicators updates the condition-dependent model and the condition prognostics support the time-dependent model [13].

For convenience, the authors focused on Level 1 PSA to illustrate our ideas. Fig. 2 represents the general outcomes for Level 1 PSA. The main outcome in Level 1 PSA is a CDF using event-tree analysis and fault-tree analysis. The event tree and fault tree were basically made to include each accident scenario and correlation of systems. The frequency of an