Study of Updating Initiating Event Frequency using Prognostics

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1. Introduction

Probabilistic Safety Assessment (PSA) has been developed for enhancing design and operational vulnerabilities of Nuclear Power Plants (NPPs). The PSA model enables to find the relative priority of accident scenarios, weak points in achieving accident prevention or mitigation, and insights to improve those vulnerabilities. Thus, PSA consider realistic calculation for precise and confidence results. However, PSA model still 'conservative' aspects in the procedures of developing a PSA model. One of the sources for the conservatism is caused by the assumption of safety analysis and the estimation of failure frequency.

Recently, Surveillance, Diagnosis, and Prognosis (SDP) is a growing trend in applying space and aviation systems in particular. Furthermore, a study dealing with the applicable areas and state-of-the-art status of the SDP in nuclear industry was published [1]. SDP utilizing massive database and information technology among such enabling techniques is worthwhile to be highlighted in terms of the capability of alleviating the conservatism in the conventional PSA.

This paper review the concept of integrating PSA and SDP and suggest the updated methodology of Initiating Event (IE) using prognostics. For more detailed, we focus on IE of the Steam Generator Tube Rupture (SGTR) considering tube degradation. This paper is additional research of previous our suggested the research [2].

2. The concept of integrating PSA and SDP

In the nuclear filed, PSA has been used for evaluation of safety by analytical assessment to estimate accident results. Conventional PSA generally shows static Core Damage Frequency (CDF) or Large Early Release Frequency (LERF). The outcome of Living PSA also shows static outcomes.

In general, NPPs have a design life of more than 40 years. Most of NPPs operating world over belong to first- and second-generation systems and works out to be over 20 years. The evidence of aging may appear in many ways, failure of operating components and safety system, subsequent interruption of plant operation, overall reduction in plant availability and adverse impact on available redundancy or safety margin in safety systems, etc. [3] Thus, we suggest the integrating PSA and SDP.

As mentioned above, we focused on prognostics in SDP for steam generator tube degradation. The prognostics is real-time mathematical methodology and have some advantage. It monitored precursor for Structure, Systems, and Components (SSCs) and consequently estimated Remaining Useful Life (RUL) by extracting regular pattern. Also, it expressed the change of aging with operating condition and environmental stressor. The results of PSA were only probabilistic expression until now. However, the results of the PSA integrated prognostics similarly performed early-warning. According to using prognostics algorithms, it basically has precise distributions due to applying condition indicator form reliability-based distribution.

Fig. 1 shows comparison between reliability-based distribution and condition-based distribution [4]. The prognostics algorithms basically used dynamic Bayesian approach. Thus, in figure 1, the reliability-based distribution corrected condition-based distribution by using condition indicator (environmental stressor, aging signature) after detection.

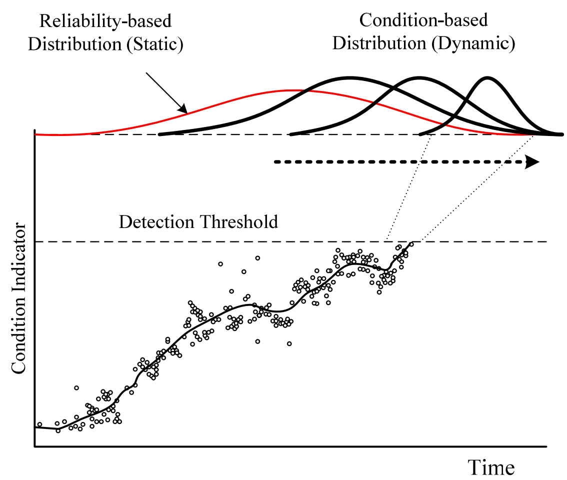

Fig. 1. Comparison between reliability-based distribution and condition-based distribution

For convenience, authors focused on Level 1 PSA. Fig. 2 represents general Level 1 PSA framework. The main outcome in Level 1 PSA is CDF by using event tree analysis and fault tree analysis. The event tree and fault tree basically were made through each accident scenario and correlation of systems. However, the input values is different for quantitative calculation. The event tree was calculated to use initiating event frequency and fault tree was calculated to use basic event (component and human error probabilities) can be obtained through statistical analysis from diverse information related plant and components in Fig. 2 [5].

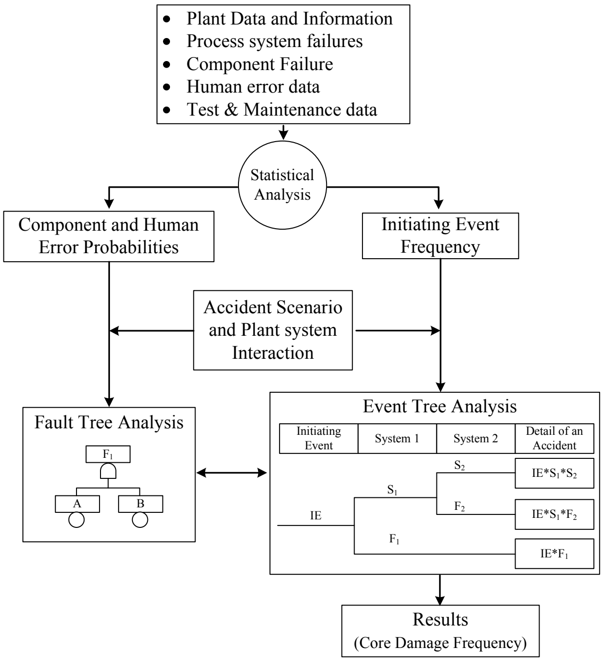

Fig. 2. Level 1 PSA algorithms

The event tree and fault tree basically were made through each accident scenario and correlation of systems. The frequency of an end state of a specific accident scenario is calculated by the combination of an event tree and a fault tree. For instance, if the last end state in Fig. 2 corresponds to core damage state, then it is determined by Equation (1).

$$CDF = IE \times F_1 = IE \times (A \times B) \qquad (1)$$

where IE is the frequency of an initiating event (IE), A and B are the failure probability of basic events (BEs).

In Fig. 2, IE and BEs in conventional Level 1 PSA were calculated by statistical analysis. Present, statistical analysis in conventional Level 1 PSA used reliability-based distribution. At statistical analysis, we applied the condition-based distribution from prognostics then we can expect Fig. 3. Before the observation during inspection, CDF in conventional PSA consisted uniform line due to apply static condition and uncertainty bend also consisted regular interval. However, we can expect that CDF in PSA integrated prognostics was changed between inspections and uncertainty bend was changed due to uncertainty of prognostics algorithms.

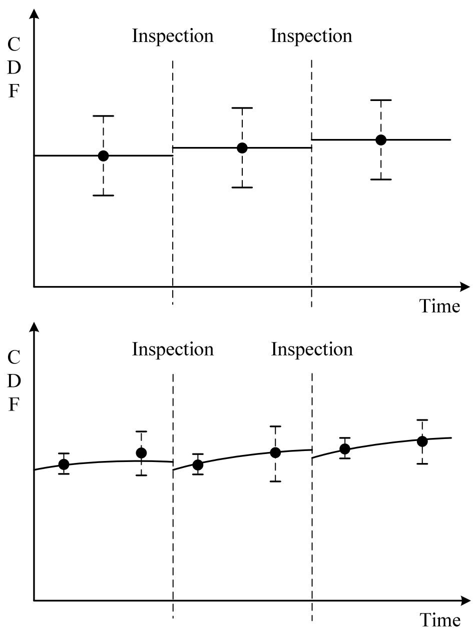

Fig. 3. Comparison of CDF in conventional PSA (upper) and integrating PSA and prognostics (lower)

According to degree of aging and prognostics algorithms, we will have aleatory type uncertainty that is associated with the inherent variability of information. Whereas, we can obtain value more than precise to real CDF and can reduce another type uncertainty (epistemic uncertainty that is associated with the imperfections in our knowledge or ability to make predictions.)

3. Methods and results

In this chapter we described aging of steam generator tube as actual example that monitor degradation of material and prognoses RUL, the method of producing the condition-based distribution, and the comparison of CDF results.

3.1 The Prognosis of Steam Generator Tube

Because of thin tube thickness to increase the heat transfer rate, damage at the steam generator tube occurred higher than other components. From the actual incident, resulting from Stress Corrosion Cracking (SCC) and wear damage was often reported in domestic and foreign plants. In case of occurred incident from this reason, the structural integrity and burst integrity of steam generator tube are required due to leak the radioactive contamination from primary side. The damage of steam generator tube is the initiating event of SGTR that was known for one of significant accident in PSA.

The probabilistic assessments are used in this paper. Probabilistic assessment for the outside axial crack is conducted by Probabilistic Algorithm for Steam generator Tube Assessment (PASTA) program [6].

PASTA is a Windows program based on an optimized probabilistic integrity assessment method to evaluate the integrity of steam generator tube.

The burst pressure for considering the probabilistic axial external and internal crack during the operational test was calculated from equation (2) and (3). These equations were based on the results of the burst test for large-scale rupture of various sizes, derived from engineering analysis such as regression analysis [7]. We employed the Monte Carlo simulation and Lowest 5% method to reduce the uncertainty of non-destructive testing, properties of material and crack propagation. For conservative result, we obtain the lower calculated value from equations (2) and (3).

$$P_B = \frac{t}{R_m} P_N(\sigma_y + \sigma_u) \qquad (2)$$

where P_B: Tube bust pressure
t: Tube thickness
R_m: Tube average radius
P_N: Non-diensionalized bust pressure
σ_y : Yield strength
σ_u : Tensile strength

$$P_B = 0.58(\sigma_y + \sigma_u)\frac{t}{R_i}[1.104 - \frac{L}{L+2t}h] \qquad (3)$$

where R_i: Tube inner radius
h: Crack depth ratio = d/t
d: Crack depth
L: Crack length

The analysis model with the 400 outside axial cracks of a certain NPP was selected. Operation time was set to 0 – 2.5 EFPY (Effective Full Power operation Year; 16 month/EFPY), the number of simulation is 100,000, the outer diameter of SG tubes is 19.05 mm, the thickness is 1.06 mm. Young's modulus is 199.94 GPa and sum of yield strength and tensile strength is 1,035 MPa.

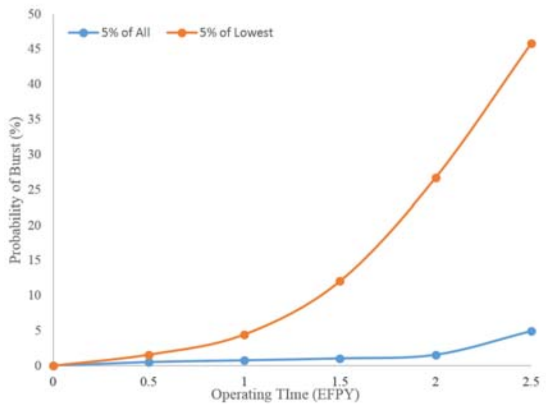

Fig. 4. Probability of burst in axial external crack

3.2 Initiating Event Update Methodology

In this section, updating methodology with steam generator tube aging is discussed. For the understanding, the updating methodology are briefly following described. First, the existing IE frequency are obtained and new frequency are calculated from prognostic data. Finally, existing IE frequency and new frequency are integrated.

As mention above, the conventional PSA are used to analysis SGTR IE frequency from NUREG/CR-5750 [8]. The frequency of SGTR has been estimated by identifying number of observation during interested critical time and update. Three SGTR has been observed in 499 critical years. The IE frequency was calculated using Jeffreys non informative prior in a Bayes updated distribution in equation (4).

$$IE_{SGTR} = \frac{N + 1/2}{T} \qquad (4)$$

where N: the number of observation events,
T: the critical years.

From the NUREG/CR-5750, the SGTR IE frequency was estimated as 7.0E-03 per critical years. SGTR IE was assumed under Poisson distribution. However, SGTR is occurred over once during observation time. In this case, this problem are assumed under exponential distribution. The In the conventional PSA SGTR IE frequency is 7.0E-3.

Table I: Burst Probability of Steam Generator Tube (External)

Operating Time (EFPY)	5% of All	5% of Lowest
0	0	0
0.5	0.52	1.57
1	0.78	4.45
1.5	1.05	12.04
2	1.57	26.7
2.5	4.97	45.81

Table I represent burst probability of steam generator tube (external) from Fig. 4. To obtain new frequency, burst probability are used in Table I. The Poisson distribution is equation (5).

$$P = \frac{(\mu t)^x}{x!} e^{-\mu t} \qquad (5)$$

where μ: mean occurrence rate,
x: the number of occurrences in time,
t: time

In the equation 5, the number of occurrences in time (x) is burst probability in operating time and t is operating time. Mean occurrence rate (ν) are obtained from Maximum Likelihood Estimation (MLE). Finally, the obtained parameter (ν') from MLE and existing parameter (ν) are integrating by using Bayesian approach. MLE and Bayesian approach are showed in equation (6) and equation (7) [9].

$$L(x_1, x_2, \ldots, x_n; \theta_1, \ldots, \theta_m) = \prod_{i=1}^{n} f(x_i; \theta_1, \ldots, \theta_m)$$

$$\frac{\partial \log L(x_1, x_2, \ldots, x_n; \theta_1, \ldots, \theta_m)}{\partial \theta_j} = 0 \qquad (6)$$

$$f''(\theta) = kL(\theta)f'(\theta)$$

$$k = [\int_{-\infty}^{\infty} L(\theta)f'(\theta)d\theta]^{-1} \qquad (7)$$

where L: likelihood function,
θ: parameter.

Fig. 5 shows the result of calculated IE frequency considering tube ageing. As burst probability is increased due to degrade of steam generator tube, SGTR IE are increased, also. Thus, CDF is increased in accordance with equation (3).

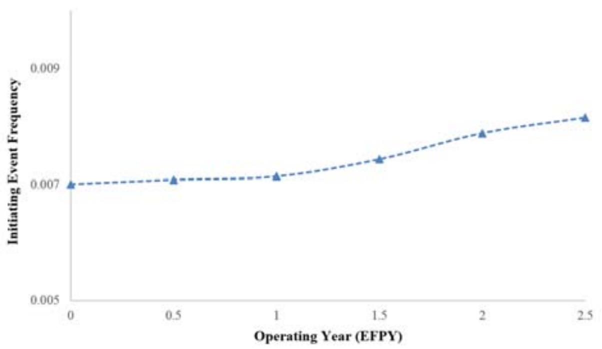

Fig. 5. SGTR IE frequency

In this examples, the IE frequency increase about 0.001 in 2.5 EFPY. Depending on the point of view, this value is a small However, considering possible that create the crack during operation time and the number of NPPs, it is meaningful value.

4. Conclusions

In this paper, the concept of integrating PSA and SDP are suggested. Prognostics algorithms in SDP are applied at IE, Bes in the Level 1 PSA.

As an example, updating SGTR IE and its ageing were considered. Tube ageing were analyzed by using PASTA and Monte Carlo method. After analyzing the tube ageing, conventional SGTR IE were updated by using Bayesian approach.

The studied method can help to cover the static and conservatism in PSA. Even though it is hard to apply at safety assessment directly, it is effectively helpful to Risk-Informed Applications (RIAs) based on PSA. Also, additional study to monitoring thermal-hydraulic systems will be studied. If we integrate the results of additional study and suggested method in this paper, it is more effective to RIAs.

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