Probabilistic Fracture Mechanics Analyses of Steam Generator Tube: A Sensitivity Study

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ABSTRACT
The risk-based and cost-based analyses were performed for the purpose of optimizing maintenance strategies of steam generator (SG) tubes made of Inconel 600 based on probabilistic fracture mechanics (PFM). In the risk-based analysis, the SG tube leakage and rupture were defined as risks, and the influence parameters accounted for were crack propagation law, inspection interval, accuracy of inspection and sampling inspection. In the cost-based analysis, based on the risk-based analysis, evaluation was carried out to quantify the effect of investment to improve inspection accuracy and sampling inspection as maintenance strategies on the total cost during 60-year operation.

1. INTRODUCTION

Some degradations, especially stress corrosion cracking, in steam generator (SG) tubes made of Inconel 600 have been affecting the availability of pressurized water reactors (PWRs). Actually, some old steam generators have been replaced because of severe damage of SG tubes and resulting in high maintenance cost. It is therefore preferable to establish a reliable evaluation method to forecast the integrity of SG tubes in order to keep the safe operation of nuclear power plants as well as to avoid unnecessary maintenance.

In Japan, as maintenance activities of steam generators, utilities inspect all of SG tubes using eddy current testing at every outage and repair any SG tubes which cause abnormal signal without confirming existence of defects. Furthermore, most of the steam generators with Inconel 600 SG tubes have been replaced by new steam generators with Inconel 690 SG tubes of higher corrosion resistance. Although various researches have been performed outside Japan to optimize SG tube maintenance based on probabilistic methodologies [1-5], there seems to be no probabilistic maintenance approach in Japan.

This paper describes sensitivity analyses of several significant parameters that influence SG tube leakage and rupture using probabilistic fracture mechanics (PFM). In addition, an attempt was made to establish risk-based and cost-based maintenance strategies for SG tubes based on PFM.
2. METHODS AND INPUT DATA

2.1. Risk-based Analysis

2.1.1 Input data

In the risk-based analysis, the SG tube leakage and rupture were defined as risks. A model was made modifying pc-PRAISE (Piping Reliability Analysis Including Seismic Events) to evaluate primary-secondary leakage and SG tube rupture during 60-year operation due to stress corrosion cracking located in roll expansion zones at the top of the tubesheet. Here parameters such as inspection accuracy, inspection interval, sampling inspection and crack propagation law were taken into account as significant parameters to influence the probabilities of the leakage and rupture.

The model assumed generation of initial semi-elliptical circumferential surface cracks with a fixed crack depth and lognormally distributed crack lengths at the inner surface of SG tubes after crack initiation periods defined in Table 1, and then it assumed propagation of the cracks in accordance with selected crack propagation laws defined in Fig.1.

The rupture was assumed to take place in accordance with net-section failure criteria. Input data applied in this analysis are summarized in Table 1.

The original pc-PRAISE code enables to calculate the probabilities of leakage and rupture for one tube. Accordingly, in order to apply it to whole SG tubes in a 4-loop unit, the following equation was used.

Supposing that the probability of leakage, \( p_i \), can be applied to all of the SG tubes in spite of the location of each SG tube, the probability of leakage of \( i \) tubes out of \( n \) tubes is expressed as follows.

\[
p_i = C_i P_i(1 - p)^{n - i}
\]  

(1)

Thus, the probability of leaking at least one SG tube, \( p_o \), is described as follows.

\[
p_o = 1 - n C_0 P_0^0 (1 - p)^{n - 0}
\]  

(2)

Because it is assumed that \( p_i \) follows Poisson distribution in this study, the \( p_i \) can be given as Eq.(3).

\[
p_i = 1 - e^{-\lambda}
\]  

(3)
Similar calculations were also conducted to obtain the probability of SG tube rupture.

2.1.2 Analyzed parameters

(1) Crack propagation law

Regarding crack propagation laws of Inconel 600 in PWR operating conditions, the experimental data were reported by Scott et. al. [6] as shown in Fig. 1. Sensitivity analysis was performed for three crack propagation laws as shown in Fig. 1. The laws were numbered as "case 1", "case 2" and "case 3".

(2) In-service inspection interval

Supposing that long-time cycle operation would be adopted in the future, calculations were performed for the inspection intervals of 12, 18 and 24 months.

(3) Inspection accuracy

Three non-detection probability curves were considered. The following is the definition of each curve.

- 40% through wall (TW) defects are detected with the probability of 0.5 ("Normal" in Fig. 2)
- 20% TW defects are detected with the probability of 0.5 ("Better" in Fig. 2)
- 10% TW defects are detected with the probability of 0.5 ("Best" in Fig. 2)

The "Normal" simulates a conventional eddy current testing (ECT) using bobbin coils.

The inspection accuracy of "Better" and "Best" cases would be expected through future development in the SG tube inspection.

(4) Sampling inspection

Because sampling inspection of SG tubes will be adopted from a viewpoint of maintenance efficiency, sensitivity analysis was also conducted for sampling inspections. Two types of sampling inspection were evaluated as follows.

- Dividing all SG tubes into two parts and inspecting each part every other year (1/2 sampling inspection)
- Dividing all SG tubes into three parts and inspecting each part every three year (1/3 sampling inspection)

The 100 percent inspection was also analyzed to compare the sampling inspection cases.

![Fig. 1 Crack propagation laws for analysis](image1)

![Fig. 2 Non-defective probability curves for this analysis](image2)

2.2. Cost-based Analysis

2.2.1 Cost evaluation

The quantification of the risks for leak and rupture enables to evaluate maintenance strategies from a viewpoint of cost. In this analysis, the evaluation was performed in terms of two maintenance strategies, that is:

- Investment to improve inspection accuracy
- Sampling inspection

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The costs of leak and rupture in \( t \) th year per unit were calculated as follows,

\[
\begin{align*}
\text{(Cost of leakage)} &= C_{\text{leak}} \times P_{\text{leak}}(t) \\
\text{(Cost of rupture)} &= C_{\text{rupture}} \times P_{\text{rupture}}(t)
\end{align*}
\]  

(4) (5)

where \( C_{\text{leak}} \) and \( C_{\text{rupture}} \) denote the anticipating costs of leak/rupture, and \( P_{\text{leak}}(t), P_{\text{rupture}}(t) \) represent the probabilities of leak/rupture for \( t \) th year per unit.

In the same way, the cost of repairing SG tubes in the \( t \) th year per unit was also defined as follows,

\[
\text{(Cost of repairing SG tubes in a 4-loop unit)} = N_{\text{tube}} \times C_{\text{repair}} \times P_{\text{repair}}(t)
\]

(6)

where \( N_{\text{tube}} \), \( C_{\text{repair}} \), and \( P_{\text{repair}}(t) \) denote the number of SG tubes in a 4-loop unit, the cost of repair and the probability of repairing one SG tube in \( t \) th year, respectively.

The other cost items considered in this analysis are summarized in Table 2. It should be noted that the numbers in Table 2 are tentative numbers for the present study.

2.2.2 Discounted cash flow method

On decision-making for long-range investment, it is required to consider the time value of money [7]. In such a case, discounted cash flow method (DCF) is often used to evaluate the long-range investment. Here, net present value (NPV) was calculated as an index of the investment. The NPV is one of the most fundamental financial indexes for decision-making based on DCF. At the time of \( T \), if \( \text{NPV}(T) > 0 \), it is justified to be worth while investing, namely, keeping operation of the unit in the case of this study.

The \( \text{NPV}(T) \) here was defined as:

\[
\text{NPV}(T) = \sum_{t=0}^{T} \frac{S(t) - C_{\text{setup}}(t) - C_{\text{R&D}}(t) - C_{\text{Ins}}(t) - N_{\text{tube}}C_{\text{repair}}P_{\text{repair}}(t) - C_{\text{leak}}P_{\text{leak}}(t) - C_{\text{rupture}}P_{\text{rupture}}(t)}{(1 + r_{\text{cap}})^t}
\]  

(7)

The meanings of the symbols in eq.(7) are summarized in Table 2.
3. RESULTS & DISCUSSION

3.1. Risk-based Analysis

(1) Crack propagation velocity

Figure 3 shows the sensitivity of the crack propagation laws to the cumulative leak probability for one SG tube. In this result, the probability of the leakage based on "case 3" crack propagation law was at least two orders of magnitude higher than that based on "case 1". Especially, the difference of the probabilities was significant during 10 years after operation. It was therefore found that the leak probability has a strong correlation with the crack propagation. Although very limited numbers of crack propagation law are available in literature, it is suggested from above result that obtaining an accurate propagation law especially at the early stage of crack propagation is quite essential to perform evaluation.

In the following evaluations, the "case 3" propagation law was adopted as the base case.

(2) In-service inspection interval

The effect of the in-service inspection on the probability is illustrated in Figure 4. There was little difference among the intervals. Accordingly, the inspection intervals between 12 and 24 months had little sensitivity to the probability of leakage.

(3) Inspection accuracy

Figure 5 indicates the result of the sensitivity analysis for inspection accuracy. The
probability of leak in the case of "Better" inspection was two orders of magnitude lower than that in the case of "Normal". The "Best" inspection significantly reduced the probability of leak to five orders of magnitude over 60-year operation period compared with the "Normal" inspection.

Accordingly, inspection accuracy has high sensitivity to the probability of leak, suggesting that improvement of inspection accuracy of SG tubes can dramatically increase the integrity of SG operation.

(4) Sampling inspection

Figure 6 indicates the probabilities of leak and rupture of a 4-loop unit per reactor-year with two types of sampling inspections. With respect to the leak, the probability is roughly to unity after 12 years. It should be noted that this result was obtained for the material of Inconel 600 and that in the case of Inconel 690TT which has high corrosion resistance, the lower probabilities are expected.

Fig. 7 Evaluated costs for inspection accuracy.
(a) Normal, (b) Better, (c) Best

Fig. 8 Evaluated costs with sampling inspections
(a) 100%, (b) 1/2 sampling, (c) 1/3 sampling
3.2. Cost-based Analysis

3.2.1 Cost analysis

Figure 7 and 8 illustrate the items of annual costs when investment to improve inspection accuracy and sampling inspection are carried out, respectively.

The improvement of the inspection accuracy reduced the cost of leakage as well as total annual cost dramatically (Fig.7) due to detecting and repairing cracks at the early stage. Therefore, the investment to improve the inspection accuracy is efficient with assumptions in Table 2. It should be noted here that cracks are repaired whenever they are detected by inspection in pc-PRAISE.

The sampling inspections increased the cost of rupture compared to 100% inspection as shown in Fig.8. Because SG tubes made of Inconel 600 suffer corrosion damage severely, the total annual cost for sampling inspection increased compared to 100% inspection after approximately 10-year operation.

3.2.2 Cost - benefit analysis

(1) Inspection accuracy

Figure 9 shows the effect of inspection accuracy on NPV, suggesting that there was almost no difference in NPV among the three inspections until 10 years. However, with "Normal" and "Better" inspections, it was no longer profitable to keep the operation after 10 and 30 years, respectively.

(2) Sampling inspection

Figure 10 shows the NPV value when sampling inspections were performed. Both NPV values calculated for the two types of sampling inspection were less than that calculated for 100% inspection. This result indicates that it is not worth while to operate plant with sampling inspection from a viewpoint of long-range investment, although the result was calculated for Inconel 600.

![Fig.9 Net present values for various inspection accuracy.](image1)

![Fig.10 Net present value with sampling inspections](image2)

4. CONCLUSION

An attempt was made to perform risk-based and cost-based analyses for the maintenance of steam generator (SG) tubes made of Inconel 600 based on PFM.

In the risk-based analysis, SG tube leakage and rupture were defined as risks, and the probabilities of these risks were found to be influenced significantly by crack propagation law, accuracy of inspection and sampling inspection.

In the cost-based analysis, it was suggested that investment to improve inspection accuracy would reduce the total cost during 60-year operation.

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REFERENCES


