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INTEGRATED EVALUATION OF MAINTENANCE OPTIMIZATION FOR PIPES IN NUCLEAR POWER PLANTS BASED ON PROBABILISTIC FRACTURE MECHANICS

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ABSTRACT

As an application of probabilistic fracture mechanics (PFM) and a financial method, risk-benefit analyses were performed for the purpose of optimizing maintenance activities of steam generator (SG) tubes used in pressurized water reactors (PWRs). Parameters such as inspection accuracy, inspection interval, sampling inspection, replacement of SGs and maintenance criteria (operation with verified cracks) were selected for sensitivity analyses. In the analysis of the operation introducing maintenance criteria, the effect of quantitative accuracy of the inspection (sizing performance) was also taken into account. Although the analyses were mainly conducted for SG tubes made of Inconel 600 mill anneal (MA) materials, the analyses were also performed for Inconel 690 thermal treatment (TT) materials with making assumptions on their crack initiation probabilities and crack propagation laws. To justify whether or not it is worth while implementing the selected maintenance strategies in terms of an economic point of view, net present value (NPV) was calculated as an index which is one of the most fundamental financial indices for decision-making based on the discounted cash flow (DCF) method. For the purpose of optimizing the plant operation including the influence of the level of public acceptance, change of the leakage cost by frequency of accidents is modeled.

Keywords: PFM, Nuclear, Maintenance, Optimization, Economy.

1. INTRODUCTION

Stress corrosion cracking (SCC) is a main degradation mode for steam generator (SG) tubes made of Inconel 600, which has been affecting availability of pressurized water reactors (PWRs) and frequently led to replacement of the SG tubes by higher corrosion resistant Inconel 690 tubes. Thus, it is preferable to establish a reliable evaluation method to optimize maintenance strategies for SG tubes in order to keep safe operation of PWR plants as well as to avoid unnecessary maintenance activities.

The objective of this study is to establish an economic evaluation model of maintenance strategies for steam generator tubes using probabilistic fracture mechanics and a financial method. Although some researches have been performed to optimize SG tube maintenances based on probabilistic methodologies focusing on the risks [1-5], there seems to be no research focusing on both risks and costs, and even profitability for SG tube maintenance.

2. METHODS AND INPUT DATA

Table 1 Summary of variables for risk evaluation

Parameters	Value
Plant Type	4-loop SG, including 3382 × 4 tubes
Material	Inconel 600
Wall thickness	1.27 mm (0.05 inch)
Inside radius	22.22 mm (0.875 inch)
Plant lifetime	60 years
Steady-state temp.	323 °C
Normal operating pressure	95.5 atm
Flow stress	Normally distributed Average 43 kg/mm^2 Std. Dev. 4.3 kg/mm^2
Residual stress	Normally distributed Average 20 kg/mm^2 (in base case) Std. Dev. 1 kg/mm^2
Threshold for detectable leak rates	Every leakage is detectable and repaired when it is found
Crack initiation	Log-normally distributed Average 14.6years, Std. Dev. 9.6 (See Fig. 3)
Crack shape at a initiation	Depth : 0.0254mm (0.001inch) (deterministic) Length : Log-Normally distributed Median 3.18mm (1/8inch) Shape parameter : 0.85
Crack propagation law	(See Fig. 1)
Inspection accuracy	(See Fig. 2)

2.1 Risk analysis

The probabilities of SG tube leakage and rupture are defined as risks in the present study. 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 operations due to SCC located in roll expansion zones of the tubes at the top of the tubesheet

The model assumes generation of initial semi-elliptical circumferential surface cracks with a fixed crack depth and log-normally distributed crack lengths at the inner surface of SG tubes defined in Table 1. Crack initiation occurs at log-normally distributed crack incubation period t defined as follows.

$$f(t)=\frac{1}{\sqrt{2\pi}\times 0.6t}\exp\left\{-\frac{(\log t-2.5)^2}{0.72}\right\} \qquad (1)$$

Regarding SCC crack propagation laws of Inconel 600 in primary water under PWR operating conditions, the experimental data were reported by Scott et. al [6] as shown in Fig.1. In this study, the crack propagation laws were assumed to be linear for the simplicity in accordance with *a* selected crack propagation law given in Eq.2,

$$\log \dot{a} = -12 + CK \qquad (2)$$

C = 0.100 (base case in Fig. 1)
where K is the stress intensity factor.

The rupture was assumed to take place in accordance with net-section failure criteria given as follows,

$$\sigma_L A_p \geq \sigma_{flow}\left(A_p - A_{crack}\right) \qquad (3)$$

In this expression A_p is the cross-sectional area of the tube, A_{crack} is the area of the crack, σ_L is the load-controlled component of the axial stress, and σ_{flow} is the flow stress of the material.

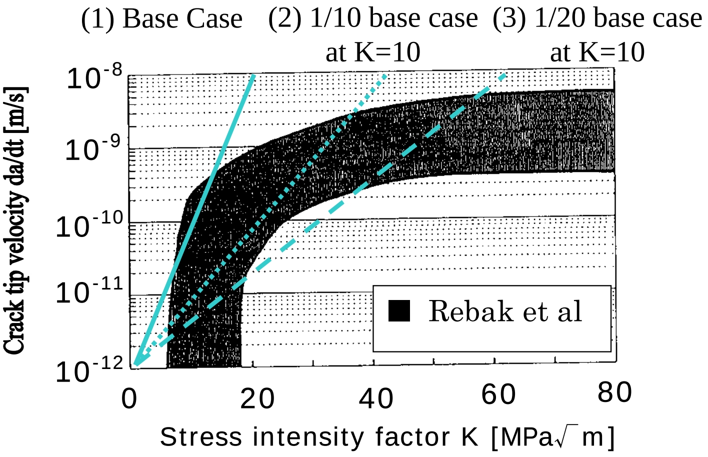


Fig.1 Crack propagation laws for assumed materials analysis

Input data applied in the analysis are summarized in Table 1. The data are based on the normal operation conditions and literatures.

Because the original pc-PRAISE code enables to calculate the probabilities of leakage and rupture for a single pipe, the following calculation process was used in order to apply it to whole SG tubes in a 4-loop unit.

Supposing that the probability of leakage, p, 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:

$$p_i = {}_nC_i\, p^i (1-p)^{n-i} \tag{4}$$

Thus, the probability of leaking at least one SG tube in the unit, p_f, is described as follows:

$$p_f = 1 - {}_nC_0\, p^0 (1-p)^{n-0} \tag{5}$$

Because it is assumed that p_i follows Poisson distribution in this study, the p_f can be given as Eq.(6).

$$p_f = 1 - e^{-np} \tag{6}$$

The same calculation process was also conducted to obtain the probability of at least one SG tube rupture in a 4-loop unit.

2.2 Maintenance strategies

2.2.1 Inspection accuracy

Three detection probability curves were selected in this study, expressed as,

$$P_D = 1 - \left\{ (1-\varepsilon)\left(1 - \frac{2}{\sqrt{\pi}} \int_0^{\gamma \log A/A^*} e^{-t^2} dt \right) + \varepsilon \right\} \tag{7}$$

where,

$$A^* = \frac{\pi}{4} a^* \times 9.8 \tag{8}$$

where P_D is the probability of detecting a crack of area A(mm^2). The parameters, γ, ε, and a^* are defined for each detection curve as follows.

a.) 40% through wall (TW) defects are detectable with probability of 0.5 (case D_{40} in Fig.2)
$\varepsilon = 0.005$, $a^* = 0.017$, $\gamma = 3.6$

b.) 20% TW defects are detectable with probability of 0.5 (case D_{20} in Fig.2)
$\varepsilon = 0.005$, $a^* = 0.010$, $\gamma = 4.0$

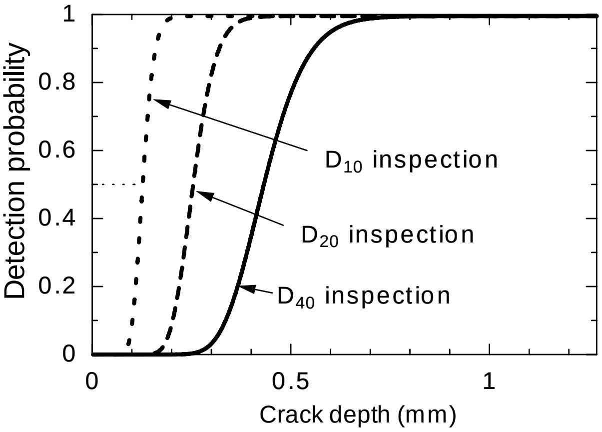


Fig.2 Detection probabilities for ISI

c.) 10% TW defects are detectable with probability of 0.5 (case D_{10} in Fig.2)
$\varepsilon = 0.005$, $a^* = 0.005$, $\gamma = 4.0$

The case D_{40} almost simulates a conventional eddy current testing (ECT) probe using bobbin type coils. The inspection accuracy of the case D_{20} and that of case D_{10} would be expected through development of the SG tube inspection probes. It should be noted here that cracks are repaired whenever they are detected by inspection during outage, except SCC allowance operation case which will be described later.

2.2.2 In-service inspection interval

Considering the situation when long-term cycle operation is adopted, calculations were performed for the inspection intervals of 12, 18 and 24 months.

2.2.3 Sampling inspection

Considering the adoption of sampling inspection of SG tubes from the viewpoint of maintenance efficiency, sensitivity analysis was conducted for sampling inspections. Two types of sampling inspection were evaluated as follows.

a.） Dividing all SG tubes into two parts and inspecting each part every two years alternatingly (1/2 sampling inspection)

b.) Dividing all SG tubes into three parts and inspecting each part every three years (1/3 sampling inspection)

In addition to the analysis of sampling inspection, a 100 percent inspection was analyzed to be compared by the sampling inspection cases.

In the analysis of the 1/3 sampling inspection, the probability of at least one tube leakage in a 4-loop unit, $P_{1/3s}$, was calculated as the following process.

The three regions for the 1/3 sampling inspection are named A_1, A_2 and A_3 and each region will be inspected every three years, namely, the region A_1 will be inspected in the first year, A_2 in the second year, and A_3 in the third year. Assuming that the tube leakage probabilities for a single SG tube located in the three regions are P_{A1}, P_{A2} and P_{A3} , the probability of no SG tube leakage in a 4-loop unit, P_0, is expressed by the following equation,

$$P_0 = (1-P_{A1})^{n/3}(1-P_{A2})^{n/3}(1-P_{A3})^{n/3} \qquad (9)$$

where n is the total number of SG tubes in the unit. Thus, the probability of at least one SG tube leakage in the unit through 1/3 sampling inspection, $P_{1/3s}$, can be obtained by Eq.(10).

$$P_{1/3S} = 1-\left\{(1-P_{A1})^{n/3}(1-P_{A2})^{n/3}(1-P_{A3})^{n/3}\right\} \qquad (10)$$

It should be noted that the probabilities of the leakage of the tubes are assumed to be independent on the location of the tubes in this study.

2.2.4 Application to Inconel 690 TT SG tubes

As mentioned in the introductory part, some old steam generators using Inconel 600 MA SG tubes have been replaced by new steam generators using Inconel 690 TT SG tubes of excellent corrosion resistance. Although no SCC has ever been detected in the new SG tubes in the field as well as laboratory tests simulating PWR water chemistry, similar risk-benefit analysis was applied to Inconel 690 TT SG tubes assuming its crack initiation probability and crack propagation law as illustrated in Figs. 3 and 1. In Fig.3, the accumulated crack initiation probability of Inconel 690 TT SG tube is normalized by that of Inconel 600 MA SG tube at the operation time of 60 years. In Fig.1, the slope of crack propagation law of Inconel 690 TT SG tube is normalized by the slope of Inconel 600 MA SG tube (base case).

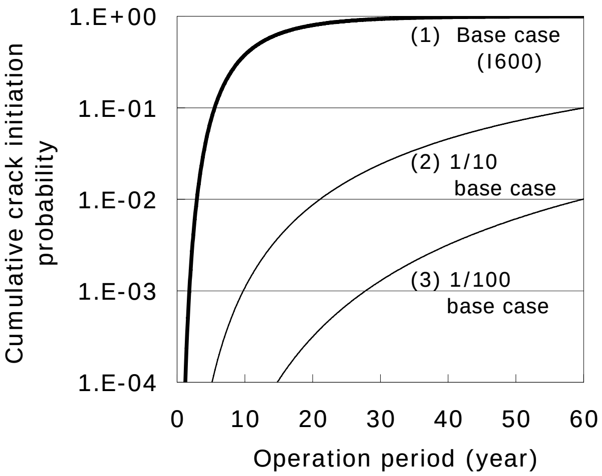


Fig.2 Detection probabilities for ISI

2.2.5 Effect of introducing maintenance criteria

The analysis was also applied to investigate of the effect of introducing maintenance criteria (SCC allowance operation) on the profitability for detected cracks in the SG tubes during outage. Examples are shown for cases when using the case D_{20} inspection.

In the analyses of introducing maintenance criteria, it should be noted that the accuracy of sizing capability of the inspection is very influential to the results. Therefore, as shown in Fig. 4, the sizing errors of the depth of detected crack were assumed to have two normal distribution curve with standard deviations of 10 and 20 % of the SG tube thickness.

2.2.6 SG replacement

The effect of SG replacement was also evaluated in this study.

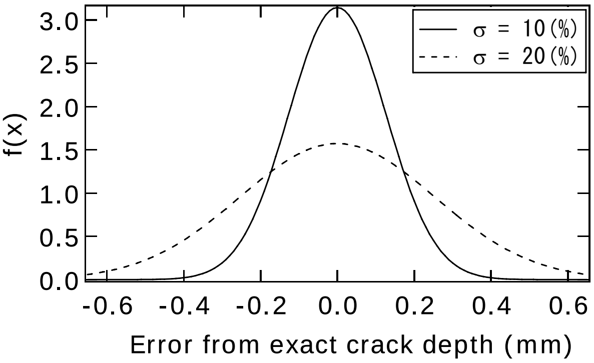


Fig.3 Crack initiation probability for assumed materials analysis.

Table 2 Variables and their meanings for cost evaluation

	Items	Value in this analysis	Comments
$NPV(T)$	Net present value at the time of T (million yen)	---------------	------------
T	Operation time (year)		------------
N_{tube}	Total SG tubes in a 4-loop unit	3,382×4SG	------------
$S(t)$	Sales from power generation (million yen)	80,000	No leak and No rupture
$C_{\mathrm{others}}(t)$	Cost for power generation (except SG maintenance cost) (million yen)	70,000 (ISI interval : 12month) 60,000 (ISI interval: 18month) 55,000 (ISI interval : 24month)	No leak and No rupture
$C_{\mathrm{R\&D}}(t)$	Cost for improvement of inspection accuracy of SG tubes (million yen, per one reactor)	0 (D_{40}) 400 (D_{20}) 1,000 (D_{10})	Depreciation for five years
$C_{\mathrm{inspect}}(t)$	Cost for inspection of SG during outage (million yen)	400 (Base) 200 (1/2 Sampling) 133 (1/3 Sampling)	------------
C_{repair}	Cost for repairing one SG tube (million yen)	5 (/1tube)	------------
C_{leak}	Expected loss from leakage (million yen)	10,000	------------
C_{rupture}	Expected loss from rupture (million yen)	100,000	------------
$C_{SGR4}(\mathrm{t})$	Cost for replacement of 4 SG units	20,000	------------
r_{b}	Discount rate (%)	1	------------
r_{tax}	Effective tax rate (%)	50	------------

2.3 Risk-benefit analysis

As risk-benefit analysis, the expected costs for 60-year operations were calculated first and then the expected profitability was also assessed considering both costs and re

venues for 60-year operation.

2.3.1 Cost analysis

The quantification of the risks for the leakage and rupture enables to evaluate maintenance strategies from the viewpoint of cost. The expected costs of tube leakage and rupture in the t th year per one plant were calculated as follows,

$$(\text{Expected cost of leakage}) = C_{\mathrm{leak}} \times p_{\mathrm{leak}}(t) \qquad (11)$$

$$(\text{Expected cost of rupture}) = C_{\mathrm{rupture}} \times p_{\mathrm{rupture}}(t) \qquad (12)$$

where C_{leak} and C_{rupture} denote the expected losses from the leakage and rupture, and $p_{\mathrm{leak}}(t)$, $p_{\mathrm{rupture}}(t)$ represent the probabilities of leakage and rupture at least one SG tube for the t th year per one plant, respectively.

In the same way, the cost of repairing SG tubes in the t th year per one plant was also defined as follows,

$$(\text{Cost of repairing SG tubes in a 4} - \text{loop unit}) = N_{tubes} \times C_{repair} \times p_{repair}(t) \qquad (13)$$

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

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

2.3.2 Profitability analysis

On decision-making for long-term investment, it is required to consider the time value of money [7]. In such a case, discounted cash flow (DCF) method is often used to evaluate the long-term investment. Here, net present value (NPV) was calculated as an index of the investment. The NPV is one of the most fundamental financial indices for decision-making based on DCF. At the time of T, if $NPV(T)>0$, it is justified to be worth while investing by the time of T, namely, keeping operation of the plant with a specific maintenance strategy in the case of this study. The $NPV(T)$ here was defined as:

$$NPV(T)=\sum_{t=1}^{T}\left\{S(t)-C_{all}(t)\right\}\Big/(1-r_b)^t \tag{14}$$

$$C_{all}(t)=C_{leak}(t)-C_{rupture}(t)-C_{repair}(t)-C_{ISI}(t)-C_{R\&D}(t)-C_{SGR4}(t)-C_{others}(t)$$

The meanings of the symbols indicated in eq.(14) are summarized in Table 2.

2.4 Effect of the level of Public Acceptance

For the purpose of optimizing the plant operation including the influence of the level of public acceptance, change of the leakage cost by frequency of accidents is modeled. In this model, if leakage occurs twice within three years, the cost for leakage increases ten-times more than that of original in the latter accidents.

3. RESULTS AND DISCUSSION

3.1 Inspection accuracy

Figure 5 illustrates the items of annual costs when investment to improve inspection accuracy is carried out. It is suggested that the improvement of the inspection accuracy reduces the cost of leakage after about 10-year operations due to detecting and repairing cracks at the early stage. Therefore, the investment to improve the inspection accuracy seems to be essential for minimizing the maintenance cost.

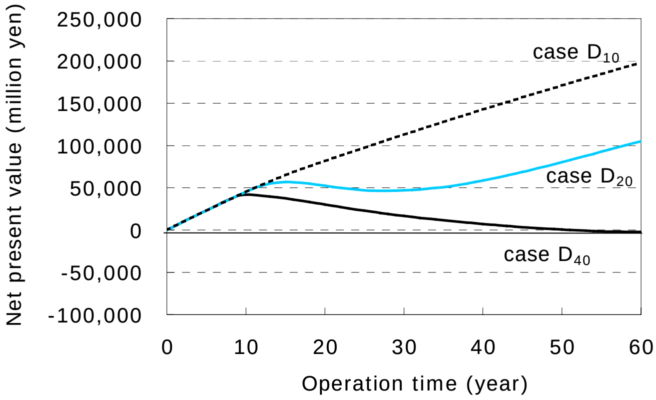
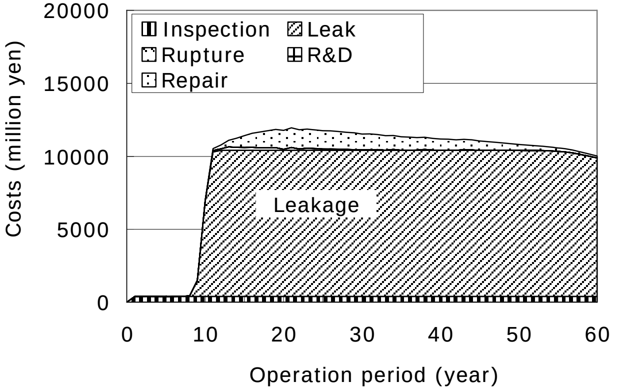
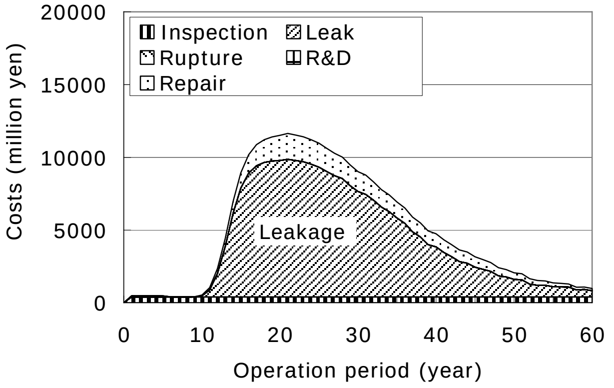


Fig.6 Net Present Value for various inspection accuracies (I600 case).

(a) case D_{40} (Base case)



(b) case D_{20}



(c) case D_{10}

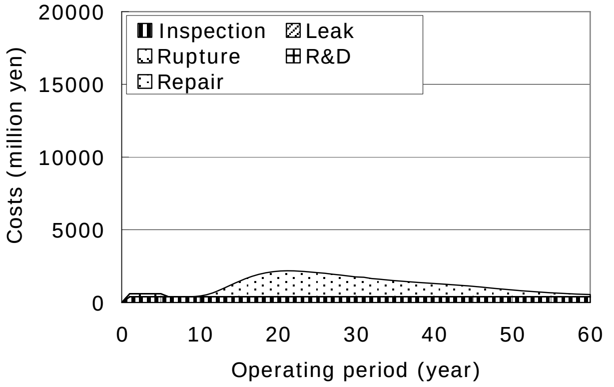
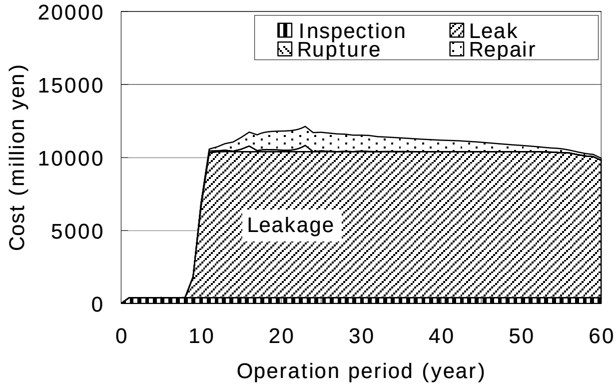
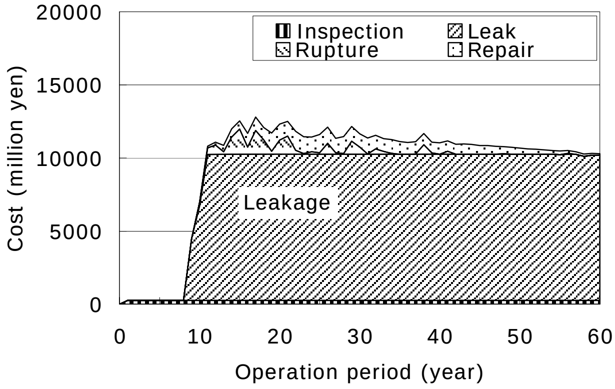


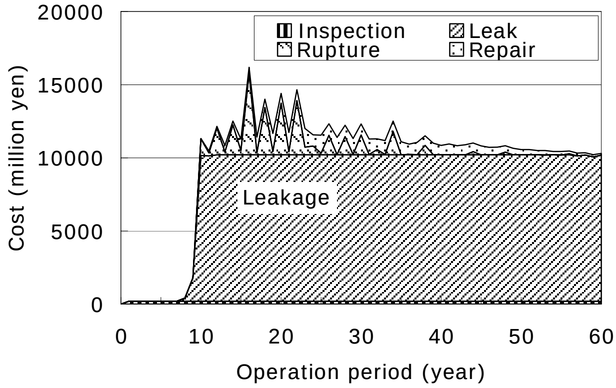
Fig.5 Evaluated costs for various inspection accuracies. (a) case D_{40}, (b) case D_{20}, (c) case D_{10}



(a) 12 months

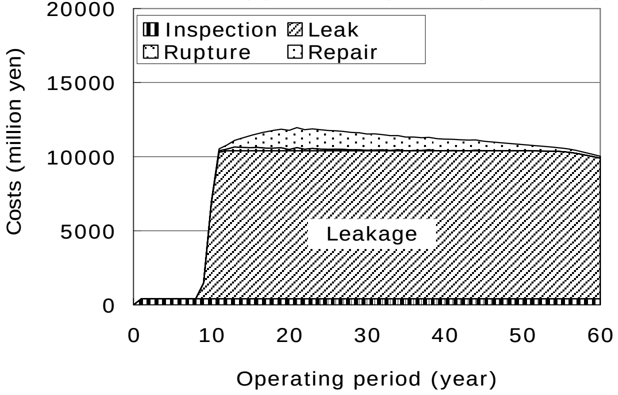


(b) 18 months

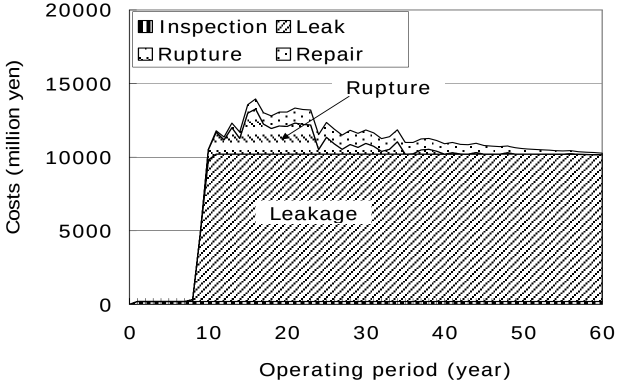


(c) 24 months

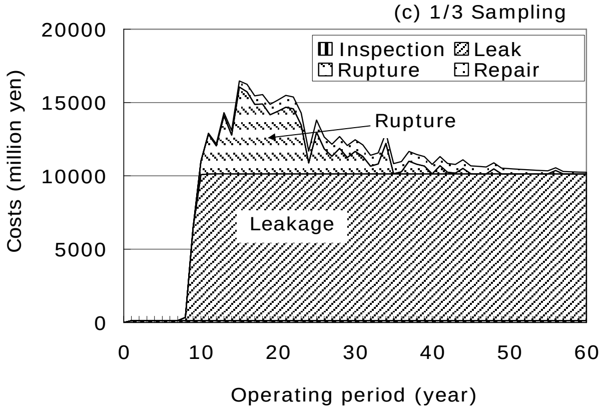
Fig.7 Evaluated costs for various inspection intervals.



(a) 100% inspection (Base case)



(b) 1/2 Sampling



(c) 1/3 Sampling

Fig.9 Evaluated costs with various sampling inspections.

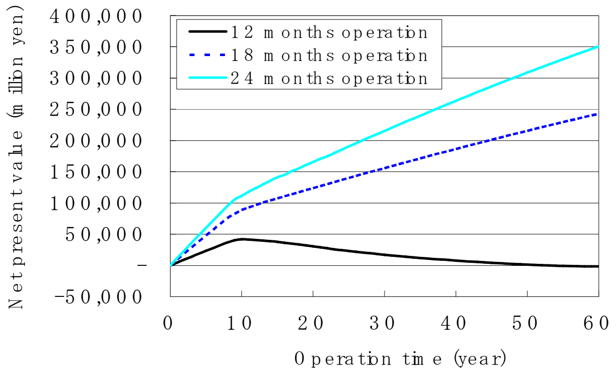


Fig.8 Net Present Value for various inspection intervals (I600 case).

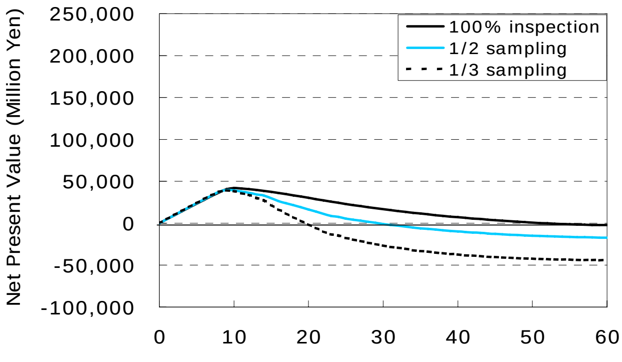


Fig.10 Net Present Value for various sampling inspections (I600 case).

Figure 6 shows the effect of inspection accuracy on NPV, suggesting that there is almost no difference in NPV among the three inspection accuracy until 10 years. However, with "case D_{40}" inspection, it is no longer profitable to keep the operation after 10 years.

3.2 Inspection interval

Figure 7 illustrates the items of annual costs for various inspection intervals. Figure 8 shows the effect of inspection interval on NPV. From Figure 7, it is seen that the cost owing to the tube rupture increases when the inspection interval becomes longer. However, because of the reduction of other cost due to the long-cycle operation (Table 2), NPV becomes higher even though the higher cost due to the longer inspection interval takes place.

3.3 Sampling inspection

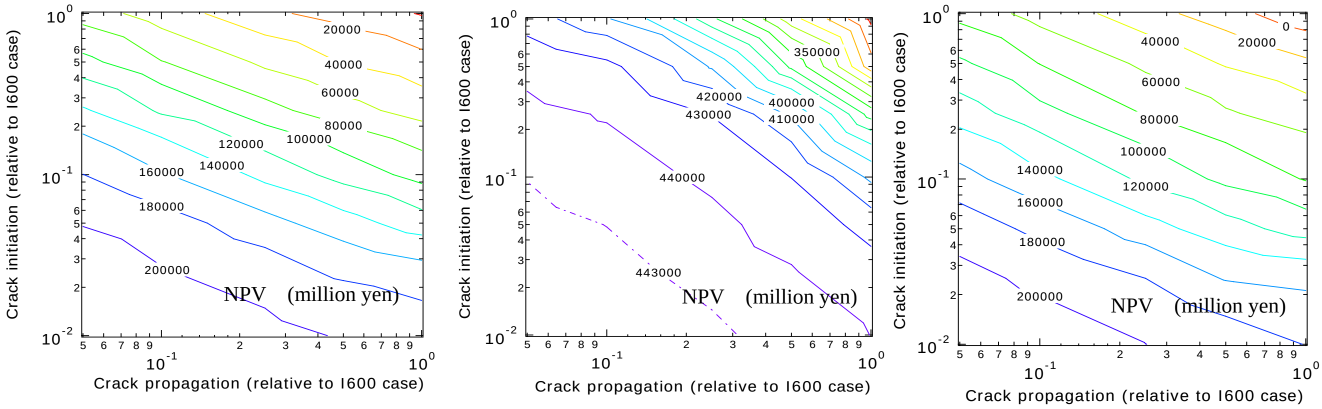
Figure 9 shows the items of annual costs when the two types of sampling inspection are conducted. Because SG tubes made of Inconel 600 suffer from corrosion damage severely, the annual costs for the sampling inspection cases increase compared to 100% inspection case after approximately 10-year operations.

Figure 10 shows the NPV with the sampling inspections. Both of the NPV values calculated for the sampling inspections are less than that calculated for 100% inspection. This result indicates that it is not worth while to perform sampling inspection for plants using Inconel 600 MA SG tubes which exhibit poor resistance to SCC from a viewpoint of long-term profitability.

3.4 Application to Inconel 690 TT SG Tubes

Figure 11 shows NPVs of 60-years operation for various assumed SCC resistant materials under selected maintenance strategies. In the figure, x and y-axes show normalized crack initiation probability and crack propagation velocity by those of Inconel 600 MA SG tube, respectively. Comparing the upper two graphs, it is seen that with a better D_{20} inspection, NPV is higher especially in the region where SCC resistance is low (close

(a) D_{40} whole inspection (c) D_{20} 18months inspection interval (e) D_{40} 1/2 sampling inspection



(b) D_{20} whole inspection (d) D_{20} 24months inspection interval (f) D_{20} 1/2 sampling inspection

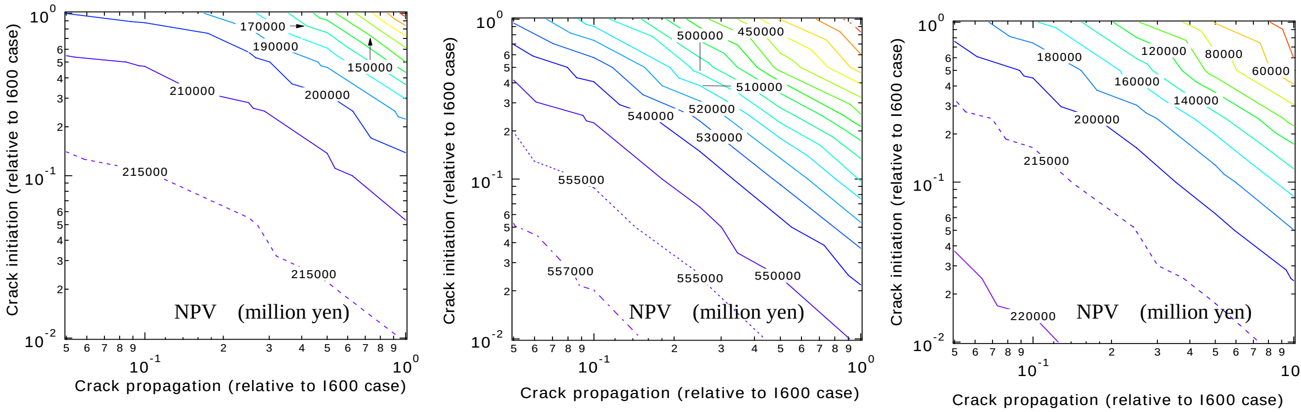


Fig.11 NPV of 60-years operation for various assumed SCC resistant materials.

to Inconel 600). From the middle two graphs, a longer 24 months inspection interval shows higher NPVs in the whole area. This should be due to the higher availability of the plant and the subsequent reduction of maintenance cost including inspection cost. The lower two graphs indicate that the sampling inspection with a better D_{20} inspection, a drastic increase in NPV is seen where the SCC resistance is low (close to Inconel 600).

Although no SCC has ever been experienced in Inconel 690 TT SG tubes in the field, one can understand and compare NPVs, or profitabilities under selected maintenance strategies, when assuming characteristics of Inconel 690 TT over SCC in the x-y plane in Fig. 11. Besides, using Fig. 11, one can know various useful information such as how much investment could be possible to study SCC characteristics of Inconel 690 TT SG tubes and to develop another new SG tube material, if necessary.

3.5 Effect of introducing maintenance criteria

Figures 12-14 are typical examples of applying risk-benefit analyses to the introduction of the maintenance criteria. Figure 12 shows the results obtained on the assumption that the crack initiation and propagation are the base cases, namely, the cases of Inconel 600 MA SG tube in this study as appeared in Figs. 3 and 1 and on the assumption that the inspection accuracy is the case D_{20} as appeared in Fig. 2. Because the SCC resistance of Inconel 600 is not so good, NPV reduces markedly when the criteria of crack depth become larger.

Figure 13 shows the results obtained on the assumption that the crack initiation is the 1/10 base case, that propagation velocity is the 1/10 base case and that the inspection accuracy is the case D_{20}. Since this result shows an excellent SCC resistant case, crack initiation and propagation are limited, resulting in no big difference in NPV among the maintenance criteria.

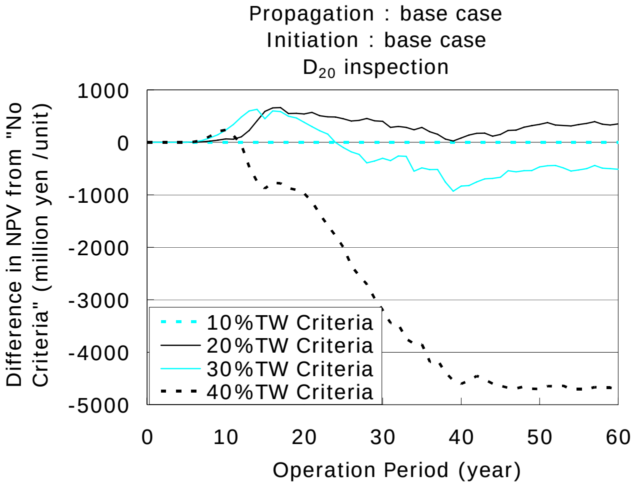


Fig.12 Difference in NPV from "No Criteria" for various SCC allowed operation (I600 case).

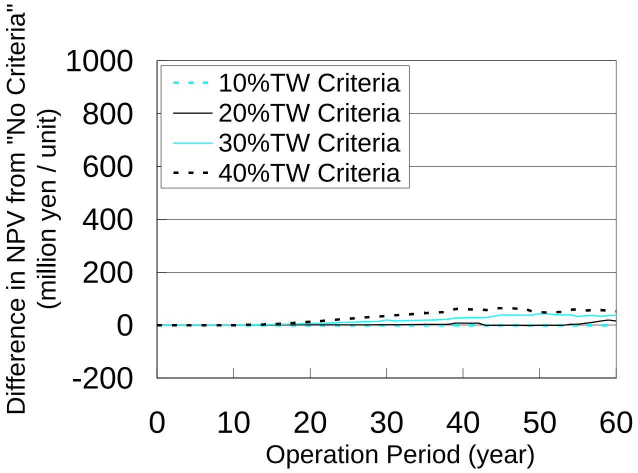


Fig.13 Difference in NPV from "No Criteria" on SCC allowed operation

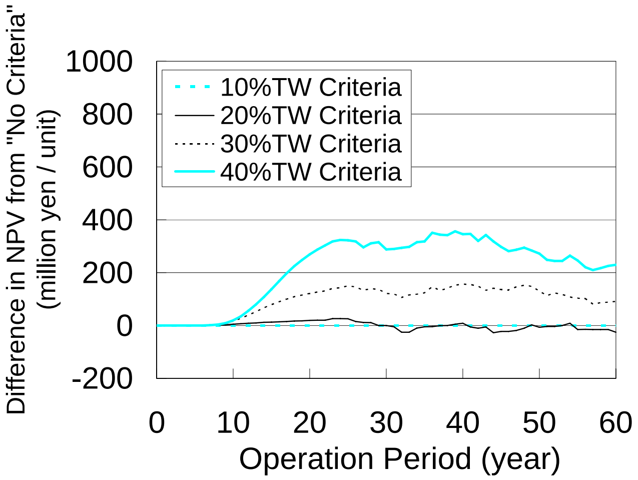


Fig.14 Difference in NPV from "No Criteria" on SCC allowed operation.

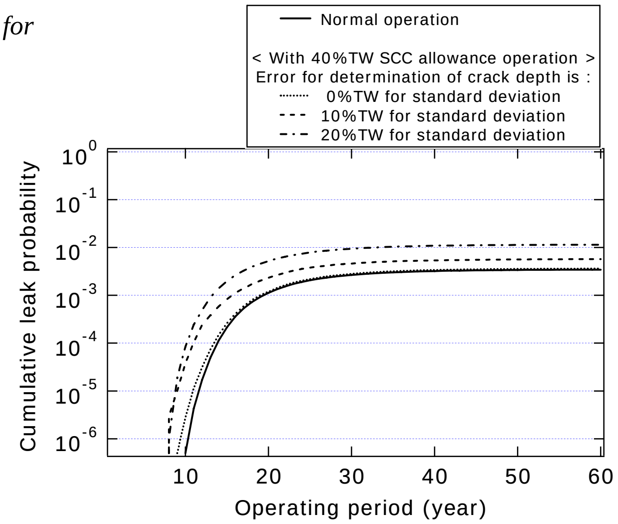


Fig.15 Cumulative leak probability conducting 40%TW SCC allowance operation with sizing errors.

Figure 14 shows the results obtained on the assumption that the crack initiation is the 1/2 base case and that the other conditions are the same as those shown in Figure 13. This result indicates the SCC resistance with which some differences in NPV are observed.

Differences in NPV from “no criteria” shown in Figs. 12-14 suggest that depending on the SCC resistance, appropriate maintenance criteria can be determined in terms of profitability using the model developed in this study.

Figure 15 shows the effect of quantitative accuracy of the inspection on the leakage probability under 40%TW SCC allowance operation with D_{20} inspection. Depending on the quantitative accuracy (0-20%TW), the leak probability shows about an order of difference.

Figure 16 shows the total cost during 60 years lifetime under 40% TW SCC allowance operation with D_{20} inspection as a function of quantitative accuracy of inspection for the detected crack depth. It is clear that the quantitative accuracy affects the cost strongly, when the SCC allowance level is higher.

3.6 SG replacement

As shown in Fig. 17, NPV was evaluated for SGR after 12 years operation. The evaluated SGR options were SGR by the same Inconel 600 SG tubes and SGR by a better SCC resistant material and the results were compared by no SGR case. Although SGR needs a certain level of cost at the time of SGR, NPV becomes much higher after the SGR with a better SCC resistant material.

3.7 Effect of the level of Public Acceptance

Figure 18 shows the estimated leakage costs applying the effect of the level of public acceptance in Inconel 600 MA case. In this analysis, the inspection accuracy is the case D_{40} as appeared in Fig. 2. Because the SCC resistance of Inconel 600 is not so good, the cost of leakage increases markedly from 13th year.

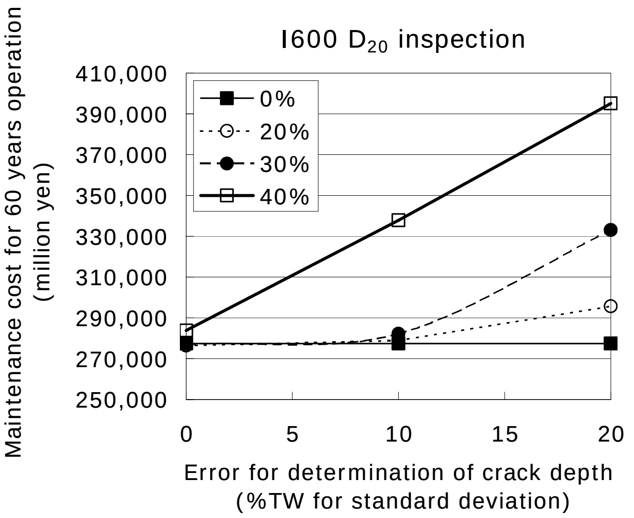


Fig.16 Maintenance cost for 60 years operation vs. Error for the determination of crack depth (I600).

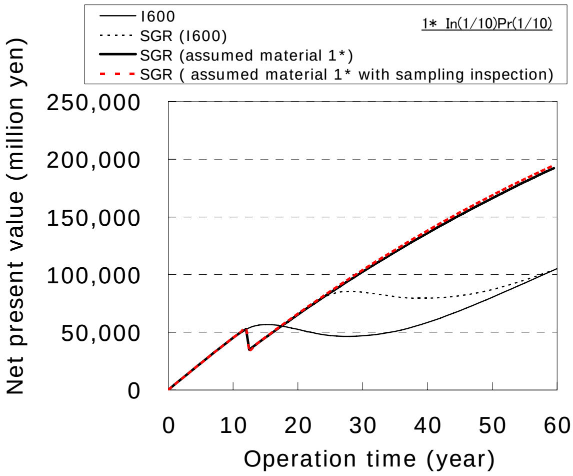


Fig.17 Net Present Value for SG replacement.

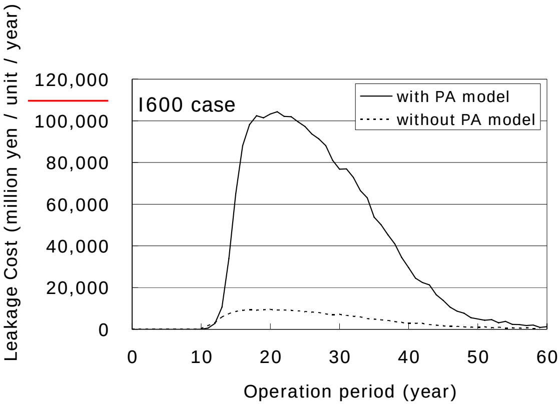


Fig.18 Estimated cost for Leakage applying the effect of the level of public acceptance

4. CONCLUSIONS

An attempt was made to develop an economic evaluation model for the purpose of optimizing the maintenance activities of SG tubes in PWRs based on PFM approach. In the model, probabilities of SG tube leakage and rupture were defined as risks, and the probabilities of these risks were evaluated first and then the risk-benefit analysis was carried out to evaluate costs and profits as well during 60 years lifetime under various maintenance strategies.

The application of the risk-benefit analysis in this study to various SG tube maintenance strategies including replacing Inconel 600 MA SG tube by Inconel 690 TT SG tube and introducing maintenance criteria for detected cracks during an outage period would be useful for decision making from the viewpoints of both safety and profitability. The model would be applied to not only SG tubes but also to tubes which are critical in terms of safety, availability and economy.

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