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FAILURE PROBABILITY EVALUATION FOR STEAM GENERATOR TUBES WITH WALL-THINNING

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ABSTRACT

The steam generator (SG) is an important component of a pressurized water reactor. In addition, local wall-thinning has been reported in SG tubes. The burst differential pressure, considering both the internal and external pressures from the primary and secondary coolant systems, should be predicted for the failure probability evaluation or structural integrity assessment of SG tubes. In this study, based on the results of burst tests performed in Japan and the United States, we improved the existing burst pressure estimation method for SG tubes with wall-thinning. In addition, as an example of the utilization of the improved burst pressure estimation method, the conditional failure probabilities for SG tubes with local wall-thinning, which is necessary for probabilistic risk assessment and risk-informed decision making, are calculated considering the dimensions of the wall-thinning.

INTRODUCTION

The steam generator (SG) is an important component of a pressurized water reactor. Flaws such as wall-thinning have been reported in SG tubes (e. g. KEPCO, 2021). The burst differential pressure, considering both the internal and external pressures from the primary and secondary coolant systems, should be predicted to assess the structural integrity of the SG tubes. In addition, to contribute to probabilistic risk assessment and risk-informed decision-making, it is necessary to evaluate the amount of increase in failure probability due to the existence of flaws. To evaluate failure and calculate the failure probabilities of SG tubes, a method for evaluating the burst differential pressure with higher prediction accuracy is required.

Burst pressure estimation methods for cylindrical structures have been proposed in several researches (Faupel (1956), Kiefner (1973) and ASME (2021)). However, most of these methods were developed assuming burst due to internal pressure, and the applicability of these methods to the SG tube has not been confirmed. To develop a burst pressure estimation method for SG tubes subjected to differential pressure, burst tests were performed by various organizations, such as Pacific Northwest National Laboratory (PNL) (Alzheimer, 1979) and Japan Power Plant Institute (JPPI) (JPPI, 1978), for actual aged SG tubes or SG tubes with machined flaws that simulated wall-thinning. On the basis of the test results, several failure estimation methods were proposed by PNL and JPPI. In addition, the authors (Yamaguchi, 2022) proposed burst pressure estimation methods for SG tubes with local wall-thinning by considering the relationship between the flaw size and burst differential pressure based on the investigation of the above burst tests.

In this study, the applicability of existing burst pressure estimation methods developed for cylindrical structures to SG tubes was confirmed, and the existing method was improved to be applicable to SG tubes with local wall-thinning. Then, as an example of the utilization of the improved burst pressure estimation method, the conditional failure probabilities for SG tubes with local wall-thinning were calculated by varying the dimensions of the wall-thinning. From the results, examples of the relationship between the size of the local wall-thinning and failure probability are summarized.

BURST PRESSURE ESTIMATION METHODS

The authors have focused on burst failure due to differential pressure, which is a typical failure mode of SG tubes, and proposed a burst pressure estimation method based on the results of previous burst tests of SG tubes. In this chapter, the applicability of existing burst pressure estimation methods for cylindrical structures, including the method developed by the authors, to SG tubes is confirmed by comparing predicted results with the existing burst test results. Subsequently, the burst pressure estimation method for the SG tubes is selected or modified.

Burst pressure estimation methods for SG tube without wall-thinning

The following methods have been proposed for estimating the burst pressure of the tube without flaws.

- Thin-walled tube method
- Lamé's method
- Faupel's method (Faupel, 1956)

A thin-walled tube method was proposed to evaluate the burst pressure based on the assumption that bursting occurs if the maximum principal stress (i.e., circumferential stress) due to pressure reaches the ultimate tensile strength. The burst pressure of the tube without wall-thinning "p_0" is calculated by the following equation.

$$p_0 = \sigma_u \frac{1}{\left(\frac{R_o}{t}-1\right)}, \tag{1}$$

where σ_u is ultimate tensile strength, R_o is the outer radius of the tube, and t is the thickness of the tube.

Lamé's method was proposed to evaluate the burst pressure based on the assumption that bursting occurs if the maximum principal stress (i.e., circumferential stress at the inner surface) due to the pressure reaches the ultimate tensile strength. p_0 is calculated using the following equation:

$$p_0 = \frac{2X-1}{2X^2-2X+1}\sigma_u \tag{2}$$
$$X = \frac{R_o}{t},$$

Faupel (1956) developed a burst pressure estimation method based on the assumption that bursting occurs when the von Mises stress in the pipe cross-section reaches the value between the yield stress and the ultimate tensile strength. p_0 is calculated using the following equation:

$$p_0 = \frac{2}{\sqrt{3}}\sigma_y(2-\gamma)ln\left(\frac{D_o}{D_i}\right) \tag{3}$$
$$\gamma = \frac{\sigma_y}{\sigma_u},$$

where σ_y is the yield stress. D_o and D_i are outer and inner diameters, respectively.

In previous studies, the burst tests have been conducted for SG tubes without wall-thinning by Alzheimer (1979) and JPPI (1978). Here, to confirm the applicability of the above burst pressure estimation methods to the SG tube, we compared the predicted results of the burst differential pressure using the estimation methods with the burst test results. Figure 1 shows the comparison results, with the abscissa representing the burst differential pressure obtained in the burst tests and the vertical axis representing the burst pressure estimated by each burst pressure estimation method. The residual sum of squares for each estimation method is presented in Table 1. From these comparison results, it can be seen that Faupel's

method has the lowest residual sum of squares among the burst pressure estimation methods compared in this study and can predict burst differential pressure with good accuracy.

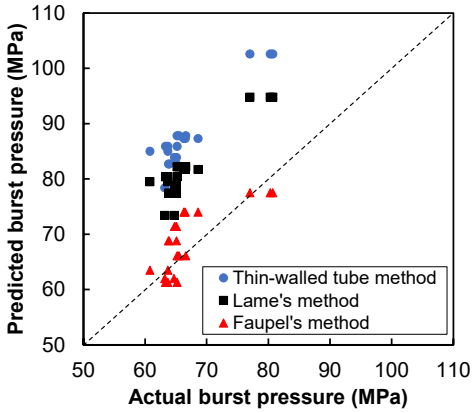


Figure 1: Comparison results of actual and predicted burst differential pressures of SG tubes without wall-thinning.

Table 1: Residual sum of squares for each method for SG tube without wall-thinning.

Burst pressure estimation methods	Residual sum of squares
Thin-walled tube method	9306.7
Lamé's method	4856.6
Faupel's method	395.0

Burst pressure estimation methods for SG tube with local wall-thinning

The following methods have been proposed for estimating the burst pressure of the tube with local wall-thinning.

- The method proposed by PNL (Kurtz, 1990)
- The method proposed by JPPI (1978)
- The method proposed by Kiefner (1973)
- The method described in API 579-1/ASME FFS-1(ASME, 2021)
- The method proposed by authors (Yamaguchi, 2022)

An experimental project named "Steam Generator Tube Integrity Program" was conducted by PNL at the request of the United States Nuclear Regulatory Commission to confirm the margin of failure of aged SG tubes. A burst pressure estimation method for SG tubes with local wall-thinning was proposed by PNL based on the test results, expressed by the following equation:

$$p_{\mathrm{f}} = p_0 \left(1 - \frac{d}{t}\right)^{0.626}, \tag{4}$$

where p_{f} is the burst differential pressure of the tube with wall-thinning, p_0 is the burst differential pressure of the tube without wall-thinning, and d is the depth of wall-thinning.

JPPI (1978) conducted burst tests on SG tubes as part of the Steam Generator Reliability Verification Tests Project, commissioned by the Ministry of International Trade and Industry in Japan. In this project, the following equation was selected as the burst pressure estimation method, which can be applied to an SG tube with local wall-thinning:

$$p_{\mathrm{f}} = p_0 \left[\frac{1-d/t}{1-d/(m\cdot t)}\right] \qquad (5)$$
$$m = (1 + 1.05c^2/Rt)^{1/2},$$

where c is the half length of the axial wall-thinning length and R is the average radius of the SG tube.

Kiefner (1973) proposed a burst pressure estimation method for pipes with a defect based on burst test results for carbon steel pipes with an axial crack. The burst pressure was calculated using the following equation:

$$p_f = \frac{2t}{\sqrt{3}R_i}\sigma_f \left[\frac{1-d/t}{1-d/(m\cdot t)}\right] \qquad (6)$$
$$m = (1 + 1.61L^2/4Rt)^{1/2},$$

where L is the axial wall-thinning length and R_i is the inner radius of the pipe.

API579-1/ASME FFS-1 provided a method for calculating the residual strength factor (RSF) of wall-thinned pipes. RSF is the ratio of the burst pressures of pipes with and without wall-thinning, and is calculated using the following equation:

$$RSF = \frac{p_f}{p_0} = \left(\frac{1-A/A_0}{1-A/A_0 m}\right) \qquad (7)$$
$$m = 1.001 - 0.014195\lambda + 0.2909\lambda^2 - 0.09642\lambda^3 + 0.02089\lambda^4 - 0.003054\lambda^5 + 2.957\times10^{-4}\lambda^6 - 1.8462\times10^{-5}\lambda^7 + 7.1553\times10^{-7}\lambda^8 - 1.5631\times10^{-8}\lambda^9 + 1.4656\times10^{-10}\lambda^{10}$$
$$\lambda = \frac{1.285L}{\sqrt{D_i t}},$$

where A is the cross-sectional area of the wall-thinned region, and A_0 is the initial cross-sectional area of the pipe. From the above equations, p_f can be expressed as follows:

$$p_f = p_0 \left(\frac{1-A/A_0}{1-A/A_0 m}\right), \qquad (8)$$

The authors (Yamaguchi, 2022) proposed a burst pressure estimation method for SG tubes with local wall-thinning based on the relationship between the size of the wall-thinned region and the burst differential pressure obtained from burst tests (Alzheimer (1979) and JPPI (1978)). The burst differential pressure was calculated using the following equation, considering the effects of the axial length and depth of wall-thinning on the burst differential pressure.

$$p_f = p_0 \left(1 - \frac{d}{t}\right)^{1-\exp\left[-\frac{0.058L}{\sqrt{R(t-d)}}\right]}, \qquad (9)$$

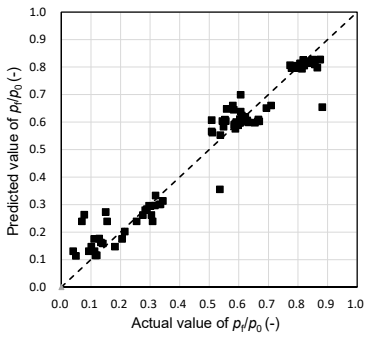
The above burst pressure estimation methods can be broadly separated into two types of methods depending on whether or not the bulging factor *m* (Eqs. (5), (6), (7) and (8)) is used. The bulging factor was optimized based on the burst test results to improve the accuracy of burst differential pressure prediction for the method using the bulging factor. The equation for calculating the bulging factor *m* is expressed as follows, and the coefficient *B* is optimized based on the burst test results.

$$m = (1 + Bc^2/Rt)^{1/2}, \qquad (10)$$

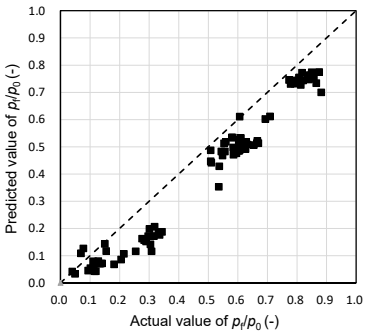
The coefficient B was determined to minimize the residual sum of the squares of the burst differential pressure obtained from the burst tests and the calculated burst differential pressure. The coefficient B was optimized to 0.136. Therefore, a burst pressure estimation method for SG tubes with local wall-thinning is proposed as follows:

$$p_f = p_0 \left[\frac{1-d/t}{1-d/(m\cdot t)}\right] \qquad (11)$$
$$m = (1 + 0.136c^2/Rt)^{1/2} \ ,$$

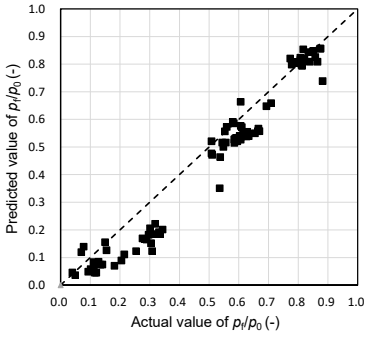
The results of comparing the burst differential pressure obtained from the burst tests with the burst pressure calculated using the above equations are presented in Figs. 2 (a)–(f). The residual sum of squares for each estimation method is presented in Table 2. From these comparison results, the improved method in this study has the lowest residual sum of squares among the burst pressure estimation methods compared in this study and can predict burst differential pressure with good accuracy.



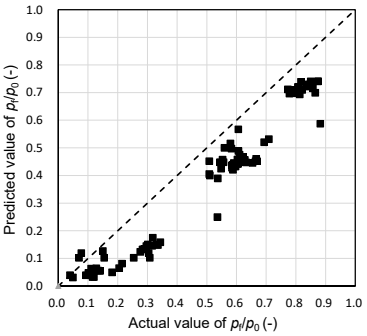
(a) Method proposed by PNL



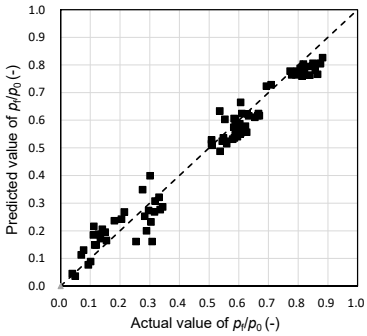
(b) Method proposed by JPPI



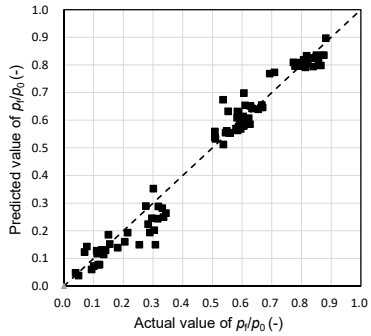
(c) Method proposed by Kiefner



(d) Method described in API 579-1



(e) Method proposed by authors



(f) Improved method in this study

Figure 2: Comparison results of actual and predicted burst differential pressures of SG tubes with local wall-thinning.

Table 2: Residual sum of squares for each method for SG tube with local wall-thinning.

Burst pressure estimation methods	Residual sum of squares
Method proposed by PNL	0.290
Method proposed by JPPI	0.893
Method proposed by Kiefner	1.056
Method described in API 579-1/ASME FFS-1	1.689
Method proposed by authors	0.228
Improved method	0.185

PROBABILISTIC FRACTURE MECHANICS ANALYSIS

If wall-thinning is detected in a SG tube, decision-making shall be done based on the amount of increase in core damage frequency due to the existence of wall-tinning. The core damage frequency is calculated by

probabilistic risk assessment using the amount of increase in failure probability of the SG tube. Therefore, calculating the failure probability of SG tubes according to the wall-thinning dimensions is important for probabilistic risk assessment and risk-informed decision-making. In this chapter, as an example of the utilization of the proposed burst pressure estimation method, the conditional failure probabilities for SG tubes with local wall-thinning were calculated by varying the dimensions of the wall-thinning under conditions with and without earthquake occurrence.

Analysis flow of the failure probability calculation for SG tube

A flowchart of the failure probability calculation procedure for an SG tube with wall-thinning is presented in Fig. 3. The failure probabilities are calculated by considering the failure of the SG tubes by applying differential pressure with/without a seismic load.

First, the dimensions of the SG tube and wall-thinned area, the material properties, the seismic response stress, and the magnitude of the differential pressure are sampled according to the calculation conditions. The yield stress, the tensile strength and the seismic response stress are treated as probabilistic variables based on the approach in seismic PRA.

The failure of the wall-thinned SG tube was estimated by considering several failure modes (such as burst due to differential pressure, plastic collapse due to applied stress including the seismic response stress, and fatigue due to cyclic loading) of the SG tube.

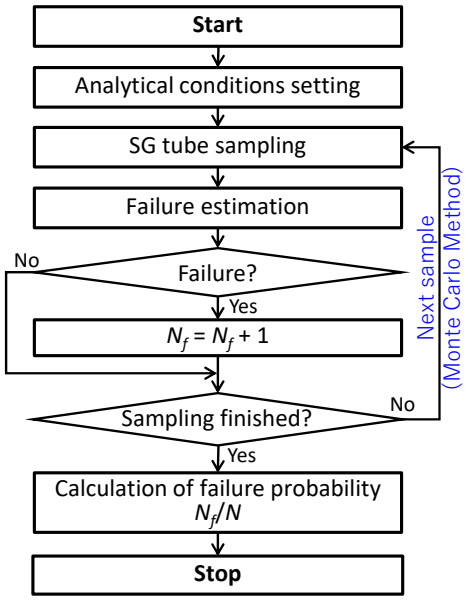
The burst failure is estimated using the burst pressure estimation method described in the previous Chapter. An SG tube is judged to fail owing to plastic collapse if the following condition is satisfied:

For SG tube without wall-thinning:

$$\sigma_b + \sigma_e + \sigma_m \geq \sigma_u, \tag{12}$$

For SG tube with wall-thinning:

$$\sigma_b + \sigma_e + \sigma_m \geq \min\{\sigma_b^c + \sigma_m, \sigma_u\}, \tag{13}$$



N : Number of samples of SG tubes
N_f : Number of failed samples

Figure 3: Probabilistic analysis flow.

where σ_b is the primary bending stress in the tube at the flaw location and σ_e is the secondary stress, including the thermal expansion of the flaw location. σ_m is the general primary membrane stress in the tube at the flaw location. σ_u is the ultimate tensile strength. σ_b^c is the plastic collapse bending stress calculated by the failure estimation method for pipes with local wall-thinning (Li, 2020) and is calculated by considering wall-thinning depth and angle.

The wall-thinned tube is judged to reach failure due to fatigue if the cumulative fatigue damage value U reaches one. U is calculated as follows:

$$U = M/M_f, \tag{14}$$

where M is the number of stress cycles during the evaluation period, corresponding to the number of stress cycles of the seismic response stress. M_f is the allowable number of stress cycles calculated from the stress amplitude and S-N curve determined based on the fatigue data for nickel alloys (JWES, 2017).

Finally, the failure probability of the SG tubes is calculated by dividing the number of samples judged to have failed by the total number of samples.

Analysis conditions

The main analysis conditions are summarized in Table 3. As a typical example, the NCF600TB nickel-alloy tube in JIS G4904 (similar to ASTM SB167) was selected as the material for the SG tube. Five different axial lengths, L/D = 0.2, 0.5, 1.0, 1.5, 2.0, and three different half-angles of the wall-thinned area (θ = 30°, 45°, and 90°) were considered. Different depths of the wall-thinned area were set to obtain the relationship between d/t and the failure probability in the interval d/t from 0.10 to 0.95.

The differential pressures during normal operation and transient events were considered as the differential pressures contributing to the burst failure of the SG tube. The differential pressure during normal operation was set to 9.7 MPa. Based on an existing report (MacDonald, 1996), 12 types of transient events listed in Table 4 were selected, and the maximum differential pressures that could occur for each transient were set. Furthermore, the differential pressures owing to the transients were classified into three categories: 9.7, 12.8, and 17.2 MPa.

Table 3: Main analysis conditions.

Outer diameter of SG tube		22.23 mm
Wall thickness of SG tube		1.27 mm
Material of SG tube		Nickel based alloy (Japanese Industrial Standards JIS G4904 NCF600TB: Similar to ASTM SB167 UNSN06600)
Yield stress of pipe material based on the approach provided in MITI Notification No. 501		Normal distribution Mean value: 210.9 MPa Standard deviation: 10.4 MPa
Ultimate tensile strength of pipe material based on the approach provided in MITI Notification No. 501		Normal distribution Mean value: 566.1 MPa Standard deviation: 28.0 MPa
Geometries of wall-thinning	Axial length, L	4.446 mm, 11.115 mm, 33.345 mm, 44.46 mm (L/D = 0.2, 0.5, 1.0, 1.5, 2.0)
	Half angle, θ	30°, 45°, 90°
	Depth, d	d/t from 0.10 to 0.95
Differential pressure at transients		Table 4
Seismic response stresses	Membrane stress	Log-normal distribution Median value: 93.7 MPa Standard deviation: 0.35
	Bending stress	Log-normal distribution Median value: 41 MPa Standard deviation: 0.35

As the seismic response stress, the membrane and bending stresses were set to 93.7 and 41 MPa, respectively, referring to the seismic response stress due to the reference earthquake motion used in the evaluation of seismic resistance of SG tubes with wall-thinning in the report by KEPCO (2022). The seismic response stress was treated as cyclic stress with constant stress amplitude, in accordance with the Rules on Protection Design against Postulated Pipe Rupture for Nuclear Power Plants (JSME, 2003). The number of equivalent stress cycles was assumed to be 200, based on utility experience. The probabilistic distribution of the seismic response stress was described by a log-normal distribution with a standard deviation of 0.35, based on the report of a seismic probabilistic risk assessment prepared by KEPCO (2018).

Combining the above analysis conditions, seven cases were analyzed, as listed in Table 5.

Table 4: Differential pressure considered in analysis.

Transients	Differential pressure
· Event represents the inadvertent opening of a PORV · Event represents either a medium or large loss of coolant accident · Event represents a feed water system failure · The loss of the plant external power grid	9.7 MPa
· Event represents the inadvertent opening of a steam generator relief valve · Trip of the turbine generator · Event represents a loss of alternating current power to the secondary heat removal system · The loss or reduction of normal feedwater flow for one loop · The loss of reactor coolant system flow in one loop	12.8 MPa
· Event represents the rupture of the main steam line · The rupture of the feedwater line · A transient with subsequent failure to SCRAM the reactor	17.2 MPa

Table 5: Analysis cases.

Case No.	Differential pressure	Consideration of seismic load	Half angle of wall-thinning
Case 1	9.7 MPa	No	30°
Case 2	9.7 MPa	No	90°
Case 3	12.8 MPa	No	30°
Case 4	17.2 MPa	No	30°
Case 5	17.2 MPa	Yes	30°
Case 6	17.2 MPa	Yes	45°
Case 7	17.2 MPa	Yes	90°

Analytical results

Figure 4 shows the relationship between wall-thinning geometry and failure probability for Cases 1 and 2 (i.e., when the differential pressure applied to the SG tubes is 9.7 MPa) without considering seismic load. The horizontal axis represents the wall-thinning depth ratio, and the vertical axis represents the conditional failure probability, assuming the presence of wall-thinning. It can be seen that the failure probability increases with the increasing depth and axial length of the wall-thinning. This trend is consistent with the trend of lower burst differential pressure with deeper depth and longer axial length of wall-thinning in the burst pressure estimation method. On the other hand, no effect of the wall-thinning angle on the failure probability was observed. This is because the effect of the wall-thinning angle on the burst differential pressure was not clearly observed in the range of wall-thinning angles in the burst test data used to propose the burst pressure estimation method in this study, and the effect of the wall-thinning angle was not considered in the burst pressure estimation method. The analytical results for Cases 3 and 4, where the differential pressure differed from that in Case 1, are shown in Figs. 5 and 6, respectively. The deeper and longer the wall-thinning, the higher the failure probability, as in Case 1. However, comparing the analytical results of Cases 1, 3, and 4, it is observed that the higher the differential pressure, the higher the failure probability.

The analytical results for Cases 5–7, where the failure probabilities were calculated considering the occurrence of earthquakes, are shown in Figs. 7–9, respectively. The failure probabilities are apparently larger in the range of small wall-thinning depths compared with the analytical results of Case 4, which does not consider earthquakes. This is because plastic collapse occurs owing to the seismic response stress, even if the wall-thinning region is sufficiently small that burst failure does not occur. In the range of small wall-thinning depths, where plastic collapse due to seismic response stress is dominant, the deeper the wall-thinning depth and the larger the wall-thinning angle, the higher the failure probability. On the other hand, the effect of axial length on wall-thinning was not observed in the range of small wall-thinning depths.

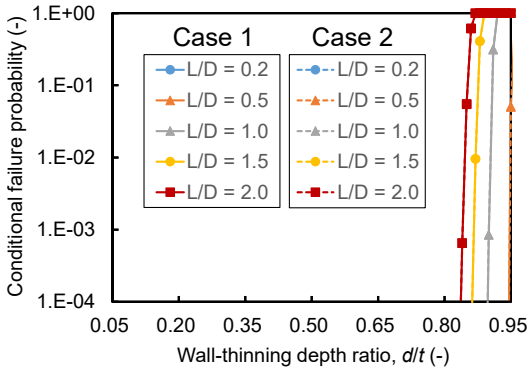


Figure 4: Analytical result of Case 1 and Case 2

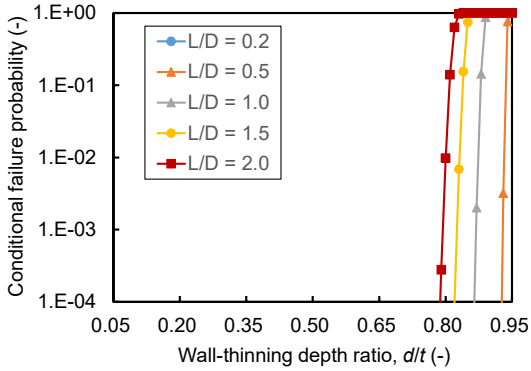


Figure 5: Analytical result of Case 3

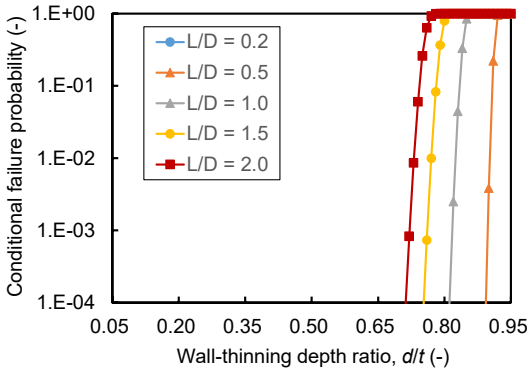


Figure 6: Analytical result of Case 4

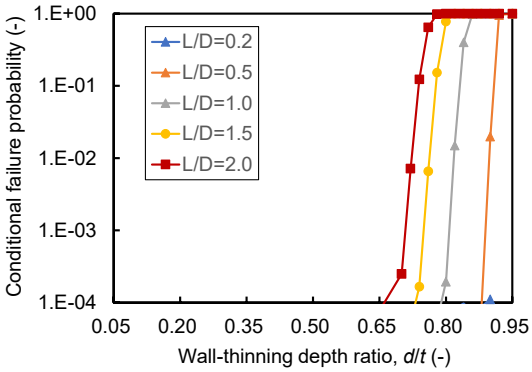


Figure 7: Analytical result of Case 5

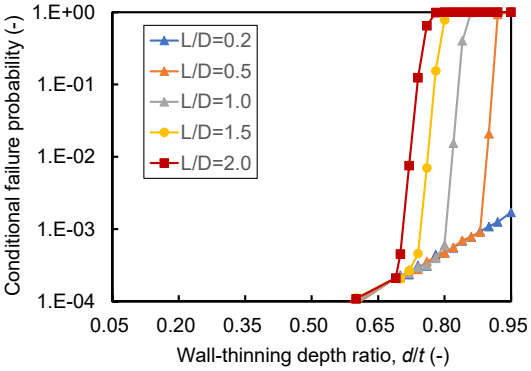


Figure 8: Analytical result of Case 6

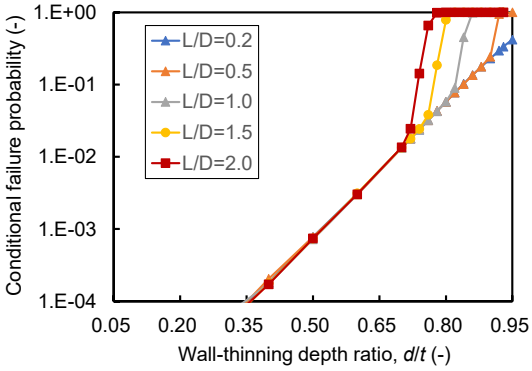


Figure 9: Analytical result of Case 7

SUMMARY

Based on the existing burst test data for SG tubes with and without wall-thinning, a burst pressure estimation method suitable for SG tubes with local wall-thinning was improved by considering the effects of the wall-thinning shape and size on the burst differential pressure. The failure probabilities corresponding to the wall-thinning dimensions were calculated, and examples of the relationship between the wall-thinning dimensions and failure probability were summarized.

ACKNOWLEDGMENT

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REFERENCES

Alzheimer R. M., Clark R. A., Morris C. J. and Vagins M. (1979). *Steam Generator Tube Integrity Program Phase I Report*, NUREG/CR-0718.

API (2021), *Fitness-for-Service*, API 579-1/ASME FFS-1, American Petroleum Institute.

Faupel J. H. (1956), "Yield and bursting characteristics of heavy-wall cylinders," Trans. ASME, 78, 1031-1064.

JPPI (1978). *Investigation Report of Reliability Verification Test for Steam Generator*, Japan Power Plant Institute.

JSME (2003), *The JSME Codes for Nuclear Power Generation Facilities – Rules on Protection Design against Postulated Pipe Rupture for Nuclear Power Plants –,* Japan Society of Mechanical Engineers (in Japanese).

JWES DFC subcommittee (2017), *Organizing Question and Answer of Fatigue Knowledge*.

KEPCO (2018), *Safety improvement assessment report (Takahama Power Station Unit 3)*, Kansai Electric Power Corporation. (in Japanese)

KEPCO (2022), *Flaw of Steam Generator Tube at Takahama Power Station Unit 3*, Kansai Electric Power Corporation. (in Japanese)

Kiefner J. F., Maxey A., Eiber R. J. and Duffy A. R. (1973), "Failure Stress Levels of Flaws in Pressurized Cylinders," *West Conshohocken,PA : PROGRESS IN FLAW GROWTH AND FRACTURE TOUGHNESS TESTING*, ASTM STD 536.

Kurtz R. J., Clark R. A., Bradley E. R., Bowen W. M., Doctor P. G., Ferris R. H. and Simonen F. A. (1990), "Steam Generator Tube Integrity Program/ Steam Generator Group Project Final Project Summary Report," NUREG/CR-5117.

Li Y., Yamaguchi Y. and Katsuyama J. (2020), "Failure estimation method for locally wall-thinned pipes," *2020 International Symposium on Structural Integrity*.

MacDonald P. E., Shah V. N., Ward L. W. and Ellison P. G. (1996), *Steam Generator Tube Failures*, NUREG/CR-6365.

Yamaguchi Y., Mano A., Li Y. (2022). "Failure Estimation Methods for Steam Generator Tubes with Wall-Thinning or Crack", *ASME 2022 Pressure Vessels & Piping Conference*, PVP2022-84697.