Investigation on Leak Rate of Steam Generator Tubes with Multiple Cracks

Jae-Uk Jeong,a Seung-Cheon Yu,a Yoon-Suk Chang,a Young-Jin Kim,a Seong-Sik Hwang,b and Hong-Pyo Kim,b
a School of Mechanical Engineering, Sungkyunkwan Univ., 300 Chunchun-dong, Jangan-gu, Suwon, Kyonggi-do 440-746, Korea, yjkim50@skku.edu
b Korea Atomic Energy Research Institute, 150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea

1. Introduction

Steam generator (SG) tubes in pressurized water reactors have experienced diverse types of degradation [1]. To prevent rupture of the tube caused by unanticipated degradation, lots of structural integrity assessment and leak rate estimation models have been developed [2, 3]. However, normal operating leak rates from corrosion induced through-wall cracks are highly variable due to the presence of ligaments separating total through-wall crack length and uncertainties related to pressure drop and crack morphology parameters. In this research, preliminary leak rate measurement tests are performed by using laboratory induced stress corrosion cracked tube specimens. Then, a series of sensitivity analyses are carried out to examine the simplified leak rate estimation model as well as a crack opening displacement estimation model.

2. Leak Rate and Crack Opening Displacement Estimation Models

The leak rate in cracked tubes can be determined from either single phase flow models or two phase flow models. As representative leak rate estimation programs, PICEP [4], SQUIRT [5] and pc-leak codes were developed and widely used for leak-before-break application. Most of them employ Henry's two phase flow model and consider coefficient of friction, momentum of fracture section and fluid condition and so on. Although the two phase flow model is promising, there are also limitations to use, i.e., many specific variables have to be specified and uncertainties are included.

In the present study, accounting for above limitations, the following single phase flow model [6] based on well-known Bernoulli equation was used to determine the leak rate (Q):

$$Q = K \times COA\sqrt{\frac{2\Delta p}{\rho}} \qquad (1)$$

where, K is the experimental flow coefficient, p is the applied pressure on SG tube and ρ is the fluid density.

On the other hand, Usually, a crack opening area (COA) as a function of crack opening displacement (COD) is predicted by engineering equations presented in facture mechanics handbook [7] or detailed finite element analyses. In this research, the leak rate as well as COA was calculated using the COD (δ) estimation equation [3] by assuming elliptical crack shape. The following Eqs. (2) and (3) are applicable for axial through-wall crack and circumferential through-wall crack, respectively.

$$\delta / \delta_e = \left[\frac{0.3 + 0.7\exp(-0.8L_r^{3.5})}{(1+0.5L_r^2)^{1/2}}\right]^{-2} \qquad (2)$$

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where, δ is the total COD and δ_e is the elastic component of δ and L_r is the ratio of applied pressure and reference pressure (p_{oR}). The reference pressure is determined from mean radius (R) and thickness (t) of the tube as well as half crack length (c).

$$p_{oR} = \gamma \cdot p_L \qquad (4)$$
$$\gamma = -0.0007\rho^2 + 0.0202\rho + 0.9595$$
$$\rho = \sqrt{\frac{c}{Rt}}$$

3. Leak Rate Test

Four laboratory induced stress corrosion cracked tube specimens were prepared by sensitizing technique in a vacuum furnace and the crack geometry was identified by eddy current method. The leak rate tests were carried out by KAERI, and the results such as direction of crack, pressure difference and measured leak rate are summarized in Table 1.

Table 1 Preliminary leak rate test results of cracked SG tubes

Specimen ID	Direction	Pressure difference Δp (MPa)	Measured leak rate Q (l/min)	Measured COA (mm^2)
A	Axial	20.0	4.950	2.17
B	Axial	19.3	0.458	0.93
C	Circum.	20.0	0.080	0.33
D	Circum.	17.2	0.116	0.21

Based on the preliminary leak rate test data, the flow coefficient K was determined as 0.2. Fig. 1 shows a good correlation between the measured leak rates and estimated leak rates of cracked SG tubes. However, it was pointed out that the crack is open when the tube is pressurized but closed in amount of δ_e after the test (refer to Fig. 2).

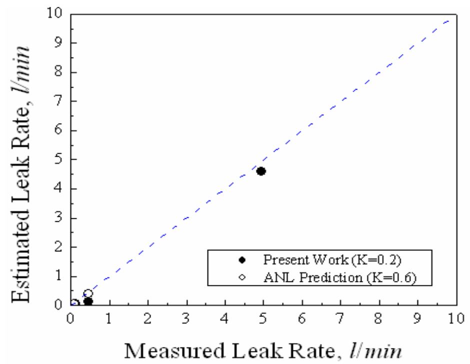
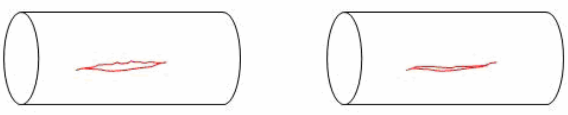


Fig. 1 Comparison of measured and estimated leak rates of cracked SG tubes



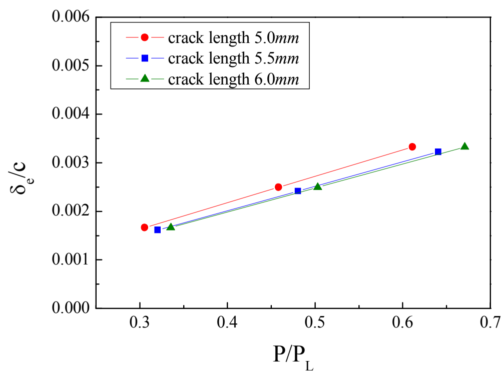
(a) During the test (b) After the test

Fig. 2 Schematic illustration of COA variation

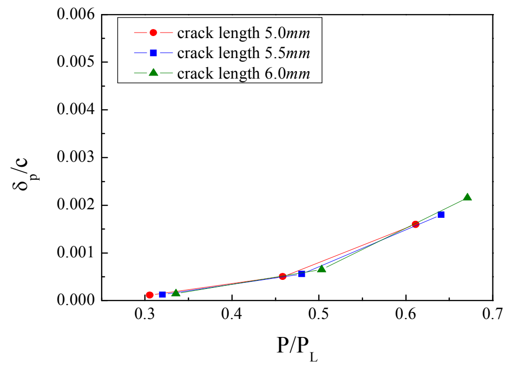
4. Sensitivity Analysis

In order to examine the amount of elastic component of COD, a series of sensitivity analyses were carried out for SG tubes made of Alloy 600. The outer diameter and thickness of the tube are 19.05 mm and 1.07 mm, respectively. Yield strength of the tube material is 241 MPa and Young's modulus is 207 GPa. The crack length is set to 5, 5.5 and 6 mm, and the applied pressure is varied from 6.89 to 13.79 MPa in increment of 3.45 MPa (from 1000 to 2000 psi in increment of 500 psi).

Fig. 3 compares calculated COD values under varying applied pressures and crack lengths, in which the applied pressure is normalized by limit pressure (p_L). Fig. 4 depicts the resulting COA values in accordance with increasing pressures. As shown in the figures, elastic components of COD were larger than plastic components of COD while the plastic components were increased as the increase of crack length and applied pressure; Mean of 93% under 1000 psi, 81% under 1500 psi and 64% under 2000 psi. This unanticipated phenomenon was caused by multiple small cracks.



(a) Elastic components



(b) Plastic components

Fig. 3 Calculated COD with different crack lengths

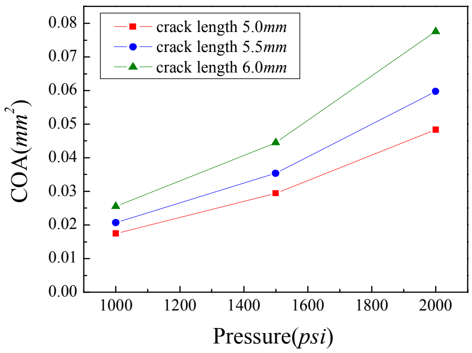


Fig. 4 Calculated COA under varying applied pressures

5. Concluding Remarks

In the present research, preliminary leak rate measurement tests were performed by using stress corrosion cracked tube specimens. Then, a series of sensitivity analyses were carried out to examine the simplified leak rate estimation model as well as a crack opening displacement estimation model. The key findings of this work will be used to determine a realistic experimental flow coefficient incorporating ongoing leak rate measurement tests of multiple cracked steam generator tubes.

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