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On the risk-based steam generator lifetime optimisation

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Abstract

A probabilistic fracture mechanics model is employed to estimate the failure probability of axially cracked steam generator tubes. The model estimates the failure probability from the random changes of the influencing parameters such as tube and crack geometry, material properties and non-destructive examination results, reliability and sizing accuracy and stable crack propagation. The performance of the model is illustrated by a numerical example. A steam generator tubing severely affected by the stress corrosion cracking is studied during most unfavourable accidental conditions. Two different plugging approaches are analyzed and the quality is compared, showing the superior performance of crack length oriented approach over tube wall thickness reduction both in terms of SG failure probability and extent of plugging. Thus, apart from setting the acceptable SG failure probability, all elements for the risk-based SG lifetime optimisation are provided on the example of stress corrosion cracking in the tube expansion transition zone.

1. Introduction

Steam generator (SG) tubes made of Inconel 600 are experiencing severe degradation processes. In particular, stress corrosion cracking (SCC) in the tube expansion transition zone seems presently to be the leading degradation cause [1]. It results in deep, often through the tube wall, mostly axially oriented cracks [2]. Steam generator tubes represent a substantial part of the second fission product barrier in a PWR nuclear power plant. Decrease of structural reliability of affected tubes therefore implies reduced plant availability and safety.

A variety of maintenance activities have been developed and employed to control the steam generator and plant safety [3]. In most cases, tubes are examined by non-destructive examination (NDE) methods. The tubes with NDE indications exceeding a certain allowable extent are then plugged (or sleeved in some cases). The allowable extent of the NDE indication of degradation is usually called plugging criterion. Generally, two approaches to define the plugging criteria have been accepted. Traditionally, the approach developed in the United States (US) is employed. Thus, the acceptable defect magnitude equals 40% of the tube wall thickness reduction [4]. The defect sizing relies on bobbin coil (BC) eddy current technique (ECT) regardless of the defect type or morphology characteristics. Examination of a random sample of tubes may satisfy the regulatory requirements completely [5].

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Recently, some European countries developed defect specific plugging criteria for stress corrosion cracks in the tube expansion transition region. In particular, a Belgian approach [6] is considered in this paper. Following the Belgian approach, axial cracks up to a certain length may remain in operation. More effective motorized pancake coil (MRPC) ECT is applied in this case to enable sufficiently accurate crack length determination [7]. A routine inspection of 100% of SG tubes is performed. We should note here that tubes which are declared operable using the Belgian approach may be plugged when using the US 40% criterion. This may lead to excessive tube plugging and early SG retirement.

The purpose of the present paper is to investigate the influence of the maintenance strategy on the SG failure probability. A two step analysis has been performed in this context. In the first step, the failure probability of axially cracked steam generator tubes has been estimated. A suitable probabilistic fracture mechanics model has already been proposed [8] following the plugging approach in [6]. In the second step, the performance of the traditional (40% tube wall thickness reduction) plugging strategy together with the bobbin coil ECT is assessed on the same defect distribution [9]. In this way, reasonable comparison of both technologies has been performed by the means of a numerical example. A Slovenian Krško nuclear power plant steam generator is considered during the most unfavourable conditions (hypothetical feed-line break accident). Recent NDE results from Krško NPP have been used in the analysis.

By defining an *acceptable* SG failure probability, such maintenance strategy can be chosen, which minimizes the extent of plugging. However, our intention is to develop suitable failure probability estimation models rather than setting *acceptable* values.

2. Steam generator failure probability

Steam generator failure is defined as the onset of unstable crack propagation in at least one of the cracked tubes. This is in fact a tube rupture accident. All cracks are assumed to be through wall, which is a conservative assumption [10]. Further, no credit has been given to the means available for leak detection.

2.1. Failure probability considerations

Probabilistic fracture mechanics deals with the determination of failure probabilities P_f of crack containing structural components from the scatter of the applied loads and structural resistance properties. The failure behaviour of the structure is described by a failure function $g(x)$, depending on basic random variables $x = (x_1, \ldots, x_n)$ which denote applied loads and structural resistance parameters such as dimensions and material properties. By definition, $g(x) < 0$ implies failure, whereas no failure occurs for $g(x) > 0$. The failure probability P_f can be calculated as the probability content of the failure domain $g(x) < 0$:

$$P_f = \int_{g(x_1, \ldots, x_n) < 0} f_1(x_1) \ldots f_n(x_n)\, dx_1 \ldots dx_n, \tag{1}$$

where $f_i(x_i)$ represent the probability densities of respective basic variables x_i, which are for the sake of simplicity assumed to be stochastically independent. Eq. (1) is sometimes referred to as failure integral, which can be solved for example by direct Monte Carlo simulation [11].

2.2. Failure function

Extensive research work has been performed to determine the conditions governing the tube failure (see for example [12] and [10]). The plastic limit load model has been chosen to adequately describe the failure [13]. Thus, the failure function may be written as:

$$g(a_1, R, t, K, \delta, \sigma_Y + \sigma_M) = \sigma_f - m\sigma. \tag{2}$$

The factor m accounts for the crack bulging due to the internal pressure in the tube [14]:

$$m = 0.614 + 0.386 e^{\left(-2.25 \frac{a_1}{2} / \sqrt{Rt}\right)} + 0.866 \left(\frac{a_1}{2} / \sqrt{Rt} \right), \tag{3}$$

a_1, R and t being crack length at the end of inspection cycle, tube mean radius and tube wall thickness, respectively. Flow stress σ_f is defined by the means of yield stress σ_Y and ultimate tensile strength σ_M and adjusted for the operating temperature conditions by factor δ where appropriate:

$$\sigma_f = K(\sigma_Y + \sigma_M)\delta. \tag{4}$$

The membrane stress perpendicular to the crack direction σ is pressure difference (p) induced tube hoop stress:

$$\sigma = p\left(\frac{R}{t} - \frac{1}{2}\right). \tag{5}$$

2.3. *Crack length distribution*

In the operating steam generator, the vast majority of the influencing parameters and their respective probability distributions are already known prior to the operation. We will assume here that the only change affecting the structural reliability is the development of axial cracks. Therefore, the state of the steam generator tubing under investigation is defined by the number of cracks and the distribution of crack lengths. Furthermore, all maintenance activities will affect only the number and distribution of the cracks and their respective lengths. This is in perfect agreement with maintenance strategies in field use (see for example [6]).

The non-destructive in-service inspection is performed to detect and size the cracks in steam generator tubing. The number and length distribution of cracks is estimated based on the in-service inspection results. The tubes containing cracks exceeding specified allowable length called plugging limit (PL) are then removed from service (e.g., plugged). However, a certain amount of cracks exceeding PL may be missed during the inspection process. This fraction is governed by the detection reliability function ($P_d(a_m)$), which is generally a function of crack length. We may summarize this behaviour:

$$a_0 = \begin{cases} a_m + a_e, & a_m + a_e < \mathrm{PL}, \\ a_m + a_e, & a_m + a_e \geq \mathrm{PL} \text{ and } \zeta \leq P_d(a_m), \\ 0 \text{ otherwise.} & \end{cases} \tag{6}$$

a_0 is a random variable representing the crack length obtained after the end of the maintenance process, while a_m and a_e represent the as measured crack length and the measurement error, respectively. ζ is a uniformly distributed random variable.

2.3.1. *Detection reliability*

Unfortunately, the information about the detection reliability available in the literature is limited to sentences like "All cracks in excess of 3 mm were detected" [7]. To allow for the probabilistic assessment of this important parameter, the following assumption has been applied [15]:

$$P_d(a) = 1 - \exp(-0.45a). \tag{7}$$

2.4. *Stable crack propagation*

A fraction of cracks is propagating in a stable manner during the period between two consecutive inspections. A simple stochastic combination of the stochastic propagation law proposed in [2] and the measured crack length is applied at the moment to yield the end of the inspection cycle crack length a_1:

$$a_1 = a_0 + a_g. \tag{8}$$

2.5. *Tube failure probability*

By solving Eq. (1), the failed fraction of the given population of tubes is estimated. In order to predict the probability of having n out of N cracked tubes ruptured, the binomial distribution can be applied:

$$P_n = \frac{N!}{n!(N-n)!} P_f^n (1 - P_f)^{(N-n)}. \tag{9}$$

Asymptotically, the probability of having one or more tubes failed within the population of N cracked tubes follows Poisson distribution [11]:

$$P = 1 - e^{(-NP_f)}. \tag{10}$$

3. Bobbin coil inspection efficiency

The uncertainties of the BC inspection procedures have been well defined and extensively discussed by Bowen et al. [16]. However, the sampling plans analyzed did not include the US NRC Reg. Guide 1.83 [5] sampling inspection scheme. This has however been investigated by Cizelj and Mavko [9]. The main assumption in this investigation has been that there is no information about the past defect distributions in the steam generator under investigation. This conservatively allowed for a random choice of tubes to be inspected. A short review of the concept and results is given below.

3.1. US NRC regulatory guide 1.83 inspection scheme

The tubes with BC indications are described as either degraded (with damage below the plugging limit PL) or defective, where the tube is affected beyond the PL. We shall assume that the fractions of defective and degraded tubes in the steam generator are p_1 and p_2, respectively. The probability of finding k_1 defective and k_2 degraded tubes in n random single tube inspections is then given by:

$$P_{k_1,k_2,n} = \frac{n!}{k_1!k_2!(n-k_1-k_2)!} \times p_1^{k_1} p_2^{k_2} (1-p_1-p_2)^{n-k_1-k_2}. \tag{11}$$

To calculate the probability that the steam generator is declared operable (accepted) in the first inspection step we only have to sum the probabilities of all possible states which are acceptable according to the procedure defined in [5]. Allowing for D_1 defective and d_1 degraded tubes in a random sample of n_1 tubes (see Table 1) will yield the total probability of accepting the steam generator in the first inspection step:

$$P_1 = \sum_{i=0}^{D_1} \sum_{j=0}^{d_1} p_{i,j,n_1}. \tag{12}$$

If the first inspection step indicates rejection, additional sample of $n_2 - n_1$ should be inspected. The acceptance probability is therefore conditional, because only certain outcomes of the first step ($P(1_i \to 2)$) will trigger and at the same time enable the acceptable outcome of the second step ($P(2|1_i \to 2)$):

Table 1
Sampling inspection data

Step i	Cumulative sample size n_i	Acceptable number of defective tubes (≥ PL) [a] D_i	Acceptable number of degraded tubes (< PL) d_i	Ref. [5]
1	138	0	13	C.5.b
2	276	1	27	C.5.c
3	552	3	55	C.7.d
All tubes	4578	N/A	N/A	N/A

[a] Defective tubes found during the inspection should be plugged afterwards.

$$P_2 = \sum_i P(1_i \to 2) P(2|1_i \to 2). \tag{13}$$

When analysing the third inspection step an analogous approach should be used. Additionally, the possibility of bypassing the second step should be taken into account. This may happen if the allowable values for the second step are exceeded during the first step, but the outcome still enables the acceptance of the third step. Summing over all appropriate outcomes again gives:

$$P_3 = \sum_i P(1_i \to 2) \sum_j P(2_j|1_i \to 2) P(3|2_j \to 3) + \sum_k P(1_k \to 3) P(3|1_k \to 3). \tag{14}$$

Some further useful expressions may be derived from the above equations. For example, the probability of plugging no more than D_1 tubes is clearly given by P_1.

In Eqs. (11) to (14) a perfect detection technique has been assumed. A closed form solution for the real (BC) performance can hardly be expected. Therefore, a Monte Carlo simulation of the inspection process has been accomplished [9].

3.2. Monte Carlo simulation

A Monte Carlo simulation of steam generator in-service inspection was established (Fig. 1) according to the procedure outlined in [5]. The same conservative assumptions were retained: no

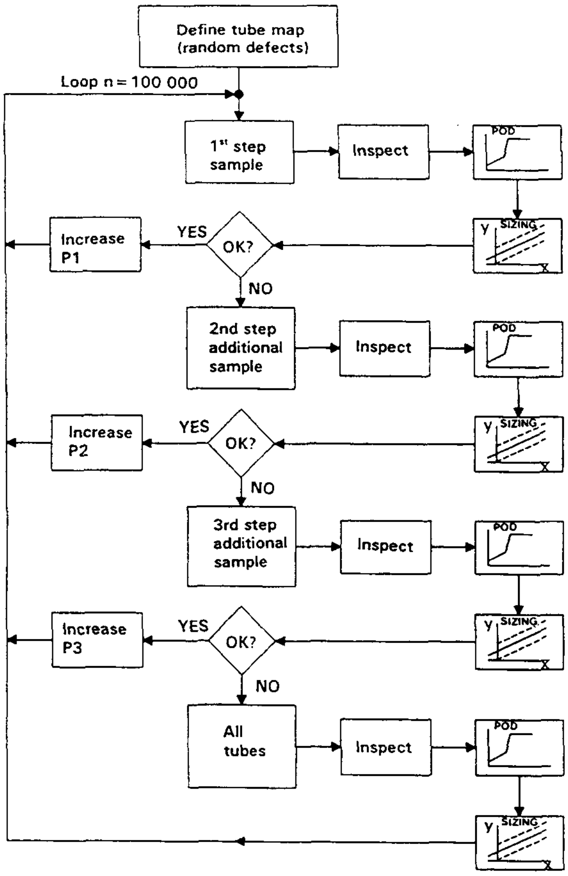

Fig. 1. Monte Carlo simulation setup.

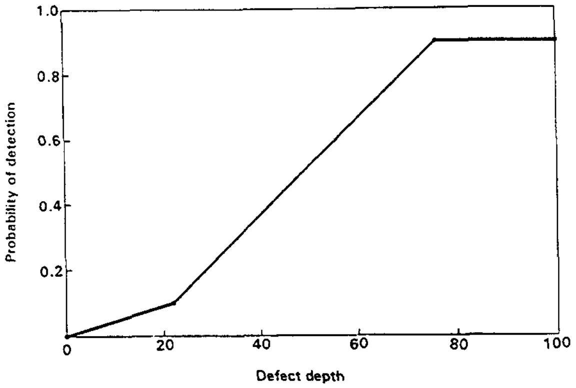

Fig. 2. Defect detection probability.

credit is given for any information regarding the history of observed or any other steam generators. Additionally, no false calls are considered.

First, a predefined number of defective and degraded tubes (Fig. 3) is distributed on a random basis over the tube map. The defect distribution in Fig. 3 corresponds to the recent 100% BC inspection in the Krško NPP. Second, an inspection procedure simulation is repeatedly performed over the same distribution of defects to evaluate the probability of accepting the steam generator (summing Eqs. (12), (13) and (14)). Basically, if the defect is found within a sample, the decision regarding further processing is made on the basis of detection probability (POD in Fig. 1) as defined in Fig. 2. If this decision requires further processing, the defect size is calculated according to Eq. (15). After the inspection of the initial sample is completed, the findings are evaluated in order to stop the inspection or to continue with the next inspection step (Fig. 1). A typical Westinghouse D-4 steam generator as installed in Krško NPP is considered. The sampling inspection parameters are listed in Table 1. Plugging limit is set to PL = 50%.

3.2.1. Detection probability

In general, the detection probability is a function of parameters which influence the inspection process. A suitable model, proposed in [16], is based on an extensive comparison of ECT signals and destructive metallographic analyses. This model given in Fig. 2 does not consider the false call probability.

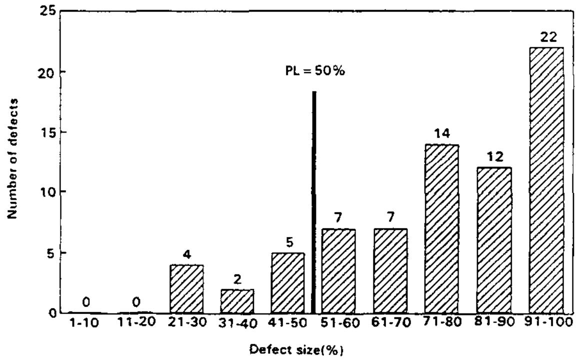

Fig. 3. Defect size distribution.

Table 2
Steam generator data summary

Variable	Distribution		Unit	Comment
	Type	Parameters		
R	normal	$\mu = 9.525$, $\sigma = 0.0254$	mm	mean radius
t	normal	$\mu = 1.055$, $\sigma = 0.0464$	mm	–
a_m	gamma	$\alpha = 3.21$, $\beta = 0.83$	mm	assumed
a_g	gamma	$\alpha = 0.92$, $\beta = 0.69$	mm	–
a_e	normal	$\mu = 0.0$, $\sigma = 1.5$	mm	–
K	normal	$\mu = 0.545$, $\sigma = 0.03$	–	–
δ	normal	$\mu = 0.928$, $\sigma = 0.003$	–	–
$(\sigma_Y + \sigma_M)$	normal	$\mu = 1080.0$, $\sigma = 54.3$	MPa	–

Distributions are not truncated.

3.3. *ECT sizing errors*

An ECT sizing error model is proposed in [16], considering the systematic influence of real defect size X and random influence of other parameters (e.g., personnel proficiency) e on the ECT reading Y:

$$Y \mid X = 17.459 + 0.437X + e, \tag{15}$$

where e represents a zero mean random error with variance of 261.14.

4. Numerical example

The following situation has been assumed for the purpose of this analysis. The same population of tubes with cracks in the tube expansion transition zone has been subjected to both BC and MRPC examinations. The MRPC results have been used to define the extent of plugging when using the Belgian crack length plugging criterion. Also, the SG failure probability has been estimated from the MRPC data.

The BC examination results have been used primarily to assess the extent of plugging. The assumption of poor correlation between BC wall thickness reduction data and MRPC crack length reading enabled straightforward assessment of the remaining SG failure probability.

4.1. *Data summary*

A typical steam generator as installed in Slovenian Krško nuclear power plant subjected to hypothetical accidental operating conditions is taken as a numerical example. The accidental condition considered is feed-line break with differential pressure of 196 bar. The summary of geometrical and material data is outlined in Table 2, together with assumed "as measured" crack length distribution.

The assumed distribution of the wall thickness reductions is given on Figure 3. This is the find-

Table 3
Sampling inspection scheme results

Step i	Probability of acceptance p_i [%]	Perfect detection Monte Carlo			Real detection Monte Carlo		
		Probability of acceptance [%]	Average number of plugged tubes	Average number of degraded tubes	Probability of acceptance [%]	Average number of plugged tubes	Average number of degraded tubes
1	15.23	14.88	0.00	0.34	36.71	0.00	0.99
2	4.39	4.19	1.00	0.68	13.25	1.00	1.93
3	1.37	1.49	2.85	1.32	10.53	2.75	3.95
all tubes	N/A	79.44 [a]	62.00	11.00	39.53 [a]	33.01	32.40
average [b]	N/A	N/A	49.34	8.83	N/A	13.47	13.07

[a] Probability of rejecting the steam generator after three inspection steps.
[b] Expectation in repeating the examination of the fixed defect pattern.

ing of BC inspection of Krško SG-1, which is also characterized by the crack length distribution as listed in Table 2.

5. Results

The failure probabilities presented in this section are based on the hypothetical feed line break differential pressure. Thus, assuming the feed line break probability to be in the order of magnitude of 10^{-2}, the absolute SG failure probabilities printed below decrease for two orders of magnitude.

5.1. Bobbin coil inspection

Probabilities of accepting the steam generator are listed in Table 3. Additionally, average numbers of tubes found to be degraded and defective during the inspection simulation are listed, indicating another measure of inspection quality. The probability of accepting steam generator in the first three steps when using a perfect detection technique (see Table 3) exceeds 20%. Employing a real inspection technique as described above increases this probability to over 60%. In other words, we can conclude that a steam generator with 62 defective tubes (see Fig. 3) will be declared operable in more than half of the inspections without significant plugging.

Further, it is clear (Table 3) that defective tubes are governing the acceptance/rejection decision process. While the perfect inspection technique will pick up all the tubes with any kind of degradation if 100% inspection was performed, we can only hope that half of the defective tubes will be plugged using the real inspection technique. This fact may have considerable consequences in studying the steam generator tube rupture probability.

5.2. MRPC inspection

A parametric study has been performed showing the influence of the applied plugging limit on the SG failure probability. The decrease of failure probability with decreasing plugging limit is clearly shown in Fig. 4 (points denoted as MRPC), especially for values below 16 mm. Additionally, the number of plugged tubes is shown as a function of applied plugging limit in Fig. 5. For plugging limits in excess of 12 mm, no significant plugging is necessary. However, it becomes progressive when decreasing PL below 10 mm as shown in Fig. 5 and Table 3. Recalling Table 3, the probability of having this case is 13.25%. If the 100% inspection by BC has been performed, 32 tubes have been plugged. It is obvious, that on the given defect distribution, the Belgian plugging strategy performs better. Even at the technically minimal plugging limit of 4 mm (MRPC reliable detection threshold is about 3 mm), it will not exceed the number of tubes plugged following the traditional US approach.

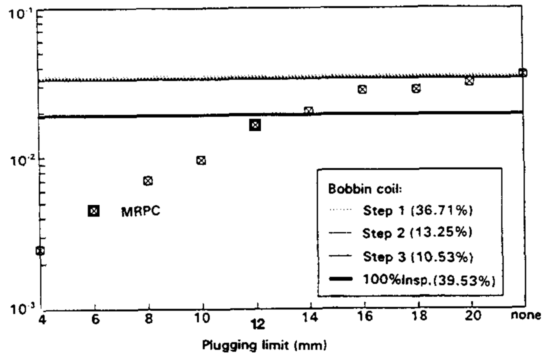

Fig. 4. Failure probability at different plugging limits.

The situation is very similar when considering SG failure probabilities. When the SG is declared

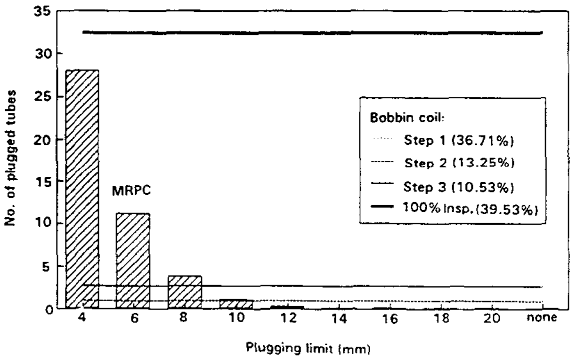

Fig. 5. Number of plugged tubes at different plugging limits.

operable after the Step 1, which has the probability of 36.71%, all cracked tubes will remain in operation (Fig. 4 and Table 3). This situation is effectively the same as *no plugging at all* in terms of the Belgian approach. Even for the 100% inspection, the traditional plugging cannot perform better than the Belgian with the plugging limit set to 14 mm (Fig. 4).

Comparing Fig. 5 and Fig. 4, the space constrained by plugging limits of 8 and 14 mm seems to be optimal from the viewpoint of the number of plugged tubes, when using the Belgian plugging approach. The SG failure probability can be adjusted by a factor of 2 in this range. However, if a lower SG failure probability is required, it can be achieved on the expense of reduced SG performance.

6. Conclusions

A complete methodology for assessing the steam generator plugging strategy has been proposed for the case of axial stress corrosion cracking in the tube expansion transition zone. It consists of a probabilistic fracture mechanics model and a Monte Carlo simulation setup designed to assess the bobbin coil inspection uncertainties. Also, the random sampling inspection scheme contribution to the overall inspection uncertainty has been considered.

This methodology enables the comparison of different plugging strategies such as the US NRC wall thickness reduction and the Belgian crack length plugging criterion together with appropriate in-service inspection concepts. Steam generator failure probability and number of plugged tubes are proposed as a measure of efficiency.

A numerical example considering the Krško NPP steam generator has been presented. The failure probability of steam generator tubing, severely affected by stress corrosion cracking, has been calculated. Further, by comparing the efficiency of both plugging approaches studied, the Belgian approach is recognized to be superior both in extent of plugging and steam generator failure probability.

For a given numerical example, the optimal plugging limit in terms of allowable crack length is derived. It minimizes the extent of plugging at a given steam generator failure probability, and thus extends the steam generator lifetime. However, no attempts have been made to define the acceptable steam generator failure probability.

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