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RELIABILITY OF STEAM GENERATOR TUBES WITH AXIAL CRACKS

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ABSTRACT

An approach for estimating the failure probability of tubes containing through-wall axial cracks has already been proposed by the authors. It is based on probabilistic fracture mechanics and accounts for scatter in tube geometry and material properties, scatter in residual and operational stresses responsible for crack propagation and characteristics of nondestructive examination and plugging procedures (e.g., detection probability, sizing accuracy, human errors). Results of preliminary tests demonstrated wide applicability of this approach and triggered some improvements.

The additions to the model are extensively discussed in this paper. Capabilities are demonstrated by results of analysis of steam generator No. 1 in Slovenian nuclear power plant located in Krško after the 1992 inspection and plugging campaign. First, the number of cracked tubes and the crack length distribution were estimated using data obtained by the 100% motorized pancake coil inspection. The inspection and plugging activities were simulated in the second step to estimate the efficiency of maintenance in terms of single and multiple tube rupture probabilities. They were calculated as a function of maximum allowable crack length. The importance of human errors and some limitations of present nondestructive examination techniques were identified.

The traditional wall thickness and crack-length-based plugging criteria are compared. The crack-length-based criterion is shown to be more efficient and more safe, especially because of strong suppression effect on probability of multiple tube rupture. The results are considered to be important for safety and maintenance of existing plants and for further research.

1 INTRODUCTION

The degradation of steam generator tubes made of Inconel 600 is receiving broad attention among the scientific and engineering community. The causes of degradation, predictions of degradation rates and some maintenance countermeasures are described in great detail elsewhere (e.g., Berge, 1990; Hernalsteen, 1991; Clark and Kurtz, 1988; van Vyve, 1991, and references therein).

Only limited attention has been paid to the reliability issues related to the maintenance of degraded steam generator tubing. Pitner et al (1993) concentrate on supporting a particular maintenance strategy by the use of probabilistic fracture mechanics techniques. On the other hand, Mavko and Cizelj (1992) and Cizelj (1993) proposed similar probabilistic fracture mechanics techniques to estimate the reliability of degraded steam generator tubing treated by a set of possible maintenance strategies. In both approaches only the residual stress driven axial stress corrosion cracking in the tube expansion transition zones (also termed PWSCC[1]) is investigated. The maintenance strategies covered are based on defect (crack) length and defect depth plugging criteria (Cizelj, 1993).

The initially proposed probabilistic fracture mechanics model (Mavko and Cizelj, 1992; Cizelj, 1993) has been further refined and expanded. Also, it has been validated by applying it to the state of the steam generator No. 1 in the Slovenian nuclear power plant at Krško after the 1992 inspection and plugging campaign. The probabilistic fracture mechanics model is intrinsically capable of accounting for a substantial set of uncertainties arising from tube geometry and material properties, stable crack growth and maintenance strategy (inspection and plugging), including human errors. A brief description of the current model is given in the next section.

The predictions presented were obtained assuming a "state-of-the-art" nondestructive examination technique as available in the literature (Dobbeni, 1991; Pitner 1993). The main result is tube failure probability as a function of plugging limit *PL*, defining the maximum allowable crack length which remains in steam generator tubing after plugging. In the given example, the crack-length plugging strategy is compared with the crack-depth strategy. The crack length approach is shown to be superior because it leads to lower values of the tube failure (rupture) probability. The identified limitations of the crack length strategy are mainly imposed by the limitations of the nondestructive examination technique. Potential human errors introduced during inspection and plugging are modelled by *residual non-detection probability*.

The final outcome of this analysis are single and multiple tube failure (rupture) probabilities as a function of plugging limit *PL* at different levels of residual non-detection probability.

The numerical example assumed that the most unfavourable conditions occur at a hypothetical feed-line break accident.

2 STEAM GENERATOR TUBE RUPTURE PROBABILITY

The tube failure (rupture[2]) probability P_f is determined from the scatter of the applied loads, crack size and structural resistance properties. The rupture behaviour of the tube is assumed to follow the failure function *g(x)*, which depends on *basic random variables* $x=(x_1, \ldots,$

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[1] Primary Water Stress Corrosion Cracking

[2] Only tube rupture is considered as a failure mode in this paper. The meaning of failure and rupture in this paper are therefore identical.

x_n) denoting applied loads, crack size and structural resistance parameters. $g(x)<0$ implies failure and no failure occurs for $g(x)>0$. The failure probability P_f is then calculated as the probability content of the failure domain $g(x)<0$:

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

where $f_i(x_i)$ represent the probability densities of the respective basic variables x_i. From the computational viewpoint, it is very useful to assume stochastically independent basic variables. On the other hand, this seems to be a sound assumption in the absence of the evidence to the contrary.

Eqn **(1)** is sometimes referred to as *the failure integral*. Numerical solutions of eqn. **(1)** are described in some detail in Brückner (1987). Those applicable to this particular problem have been discussed and their efficiency compared by Cizelj et al (1994), who suggested the use of First- and Second Order Reliability Methods (FORM and SORM). FORM and SORM are therefore used throughout this paper.

2.1 Failure Function

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 *steam generator tube rupture* (SGTR) event. All cracks are assumed to be axially oriented and extend through the entire tube wall. Each tube is assumed to contain exactly one crack. This is consistent with experimental observations in the sense that the longest of multiple axial cracks distributed around the tube circumference tends to fail as a single crack (Cochet and Flesch, 1989). Further, longer cracks tend to leak a detectable quantity of radioactive reactor coolant, which may be a very important precursor of the tube rupture event. Nevertheless, the means available for leak detection were not taken into account in the present analysis, which increases the conservativity of this analysis.

The above assumptions lead to the failure function based on the plastic limit load model:

$$g(a, a_g, R, t, \kappa, \delta, \sigma_Y, \sigma_M) = \sigma_f - m_F \sigma \tag{2}$$

The factor m_F accounts for the crack bulging on account of the internal pressure in the tube (Erdogan, 1976). a and a_g are the random variables representing crack half-lengths after the inspection and plugging procedure and stable crack growth until the next inspection. Both are further discussed in the appropriate subsections below. R and t are random variables representing tube mean radius and tube wall thickness, respectively.

The flow stress σ_f is defined by the means of random variables representing yield strength σ_Y and ultimate tensile strength σ_M. The factor δ is used to adjust the room temperature based values of σ_f and σ_M to the operational temperature (343°C):

$$\sigma_f = \kappa(\sigma_Y + \sigma_M)\delta \tag{3}$$

The factor κ is an empirical measure of strain hardening. Its typical value is about 0.5. The membrane stress perpendicular to the crack direction σ is the pressure difference (p) induced tube hoop stress. Further details on the failure function utilized are given by Mavko and Cizelj (1992).

2.2 Effects of Inspection and Plugging

Given the detection probability P_D and sizing accuracy $p_{M|A}(m|a)$ of the nondestructive examination method, the probability density of crack lengths $p_A(a)$ can be estimated following the procedure of Barnier et al (1992) from the probability density of the measured cracks lengths $p_M(m)$ which is estimated from results of nondestructive examination:

$$p_M(m) = \frac{\int_0^\infty p_{M|A}(m|a)\ p_A(a)\ P_D(a)\ da}{\int_0^\infty p_A(a')\ P_D(a')\ da'} \tag{4}$$

Solution of eqn **(4)** requires a subjective judgment of the appropriate distribution type for $p_A(a)$. Then, its optimal parameters are determined utilizing the minimization of χ^2. Once the type and parameters of $p_A(a)$ are chosen, the probability density of crack lengths left in operation after plugging $p_R(a)$ is defined by:

$$p_R(a) = \frac{p_A(a)\left[1 - P_{pl}(a)\right]}{\int_0^\infty p_A(a')\left[1 - P_{pl}(a')\right] da'} \tag{5}$$

with probability of plugging P_{pl} defined as:

$$P_{pl}(a) = 1/\eta\ P_D(a) \int_{PL}^\infty p_{M|A}(m|a)\ dm\ (1 - \epsilon_{PL}) \tag{6}$$

PL represents the maximum crack length to be left in operation, i.e. the plugging limit. $1/\eta$ defines the fraction of the damaged tube bundle which has been inspected and ϵ_{PL} may be used to model human errors in the plugging procedure.

2.3 Stable Crack Propagation

Stress corrosion cracks in the tube expansion transition zone are driven by the relatively high residual stresses, caused by the tube to tube-sheet expansion process. In this study, through-wall cracks are assumed to initiate at the point with the highest residual hoop stress at the tube inside surface, which is located approximately at the top of tube-sheet. From this point, each crack tip propagates in the tube axial direction under different loading and in different material. The propagation inside the tube sheet is dominated by the residual stresses. The other crack tip propagates out of the residual stress field towards the free span tube. Its propagation is therefore dominated by the operational stresses. An additional restraint is that the velocity of the crack tip located in the non-deformed material (e.g., free span tube) may be significantly lower than in the cold-worked tube (Speidel and Magdowski, 1992). This lead to the asymmetrical crack propagation model based on linear elastic fracture mechanics which is given in some detail in Cizelj (1993) and Cizelj et al (1995).

2.4 Single and Multiple Tube Rupture Probability

On the assumption that each tube contains exactly one crack, the failure probability P_f of a specific tube is defined by eqn (1). Taking advantage of large number of cracked tubes *N*, the probability of having *i* tubes failed follows from Poisson distribution:

$$p(i) = \frac{(N\,P_f)^i}{i!}\, e^{-NP_f} \tag{7}$$

The probability of having at least one out of *N* tubes failed (*steam generator tube rupture*) is then:

$$P(i \geq 1) = 1 - e^{-N\,P_f} \tag{8}$$

Accordingly, two or more tubes (*multiple tube rupture*) will fail with probability of:

$$P(i \geq 2) = 1 - \left(1 + NP_f\right) e^{-N\,P_f} \tag{9}$$

3 NUMERICAL EXAMPLE

3.1 Data on Tube Configuration and Material Properties

A typical Westinghouse D-4 steam generator as installed in the Krško plant is considered in the numerical example. The configuration and material properties are assumed to be normally distributed. The mean values were assumed to coincide with the nominal values, whereas the upper and lower tolerance values were identified with three standard deviations. Yield and ultimate tensile strength values as recorded during the manufacture of the tubes are used for determining the distributions of material properties. The distributions were, however, not

Table 1 Assumed crack length distributions

Distribution type	Parameters		Fraction of detected cracks[*]
	Shape [-]	Scale [mm]	
lognormal $\frac{1}{x\,\sigma\,\sqrt{2\,\pi}}\exp\left[-\frac{1}{2}\left(\frac{\ln(x/\mu)}{\sigma}\right)^2\right]$	μ=0.532	σ=1.627	32.5 %
exponential $\lambda\,\exp(-\lambda x)$	-	λ=1/0.489	47.9 %
Gamma $\frac{1}{\Gamma(\alpha)}\,\beta^{\alpha}\,x^{\alpha-1}\,\exp(-\beta\,x)$	α=0.521	β=1.244	53.9 %
Weibull $\frac{\eta}{\sigma^{n}}\,x^{\eta-1}\,\exp\left[-\left(\frac{x}{\sigma}\right)^2\right]$	η=2.063	σ=1.155	49.0 %

[*] Value estimated from the denominator of eqn (4)

truncated at the specified tolerance limits. This increases the conservativity of this study by accounting for rare events. A detailed data specification is given in Cizelj (1993).

A feed-line break accident is assumed to occur leading to the pressure difference of 196.5 bar. The failure probabilities presented below are therefore conditional, given a pressure difference of 196.5 bar.

3.2 Distribution of Crack Lengths

The distribution of crack lengths was estimated from inspection results (**Fig. 1**) using eqn (**4**). Actually, four different distributions were considered in the subsequent analysis. This was done to estimate the error introduced by the subjective choice of the distribution type. Types of distributions used are listed in Table 1 together with the values of parameters obtained by minimization of χ^2 (eqn (4)).

The crack length distributions used in the analysis are compared in **Fig. 2**. The tail (crack lengths over 10 mm) behaviour is enclosed by the lognormal and Weibull distributions.

Using eqn. (**4**) and the distributions given in Table 1, the frequency histograms of measured crack lengths $p_M(m)$ were estimated for comparison with nondestructive examination data (**Fig. 1**). The Weibull distribution tends to fit the nondestructive examination data the best, while the lognormal distribution predicts larger probabilities of long cracks and is therefore the most conservative.

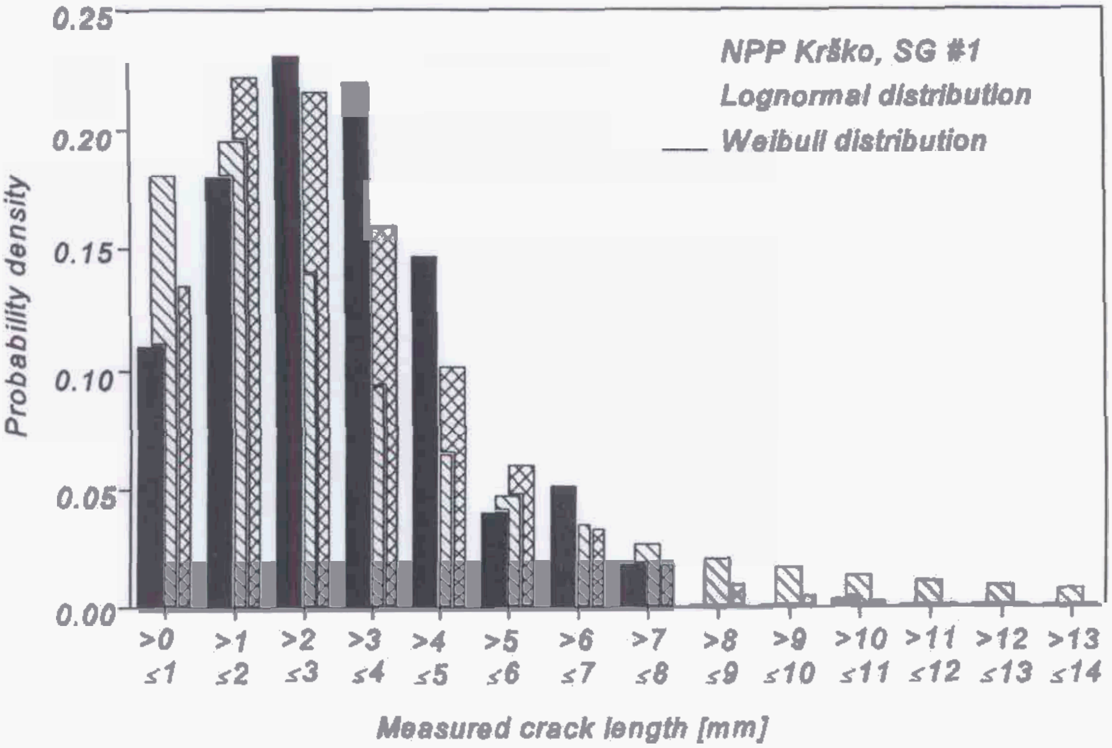

Fig. 1 Comparison of nondestructive examination results and model predictions

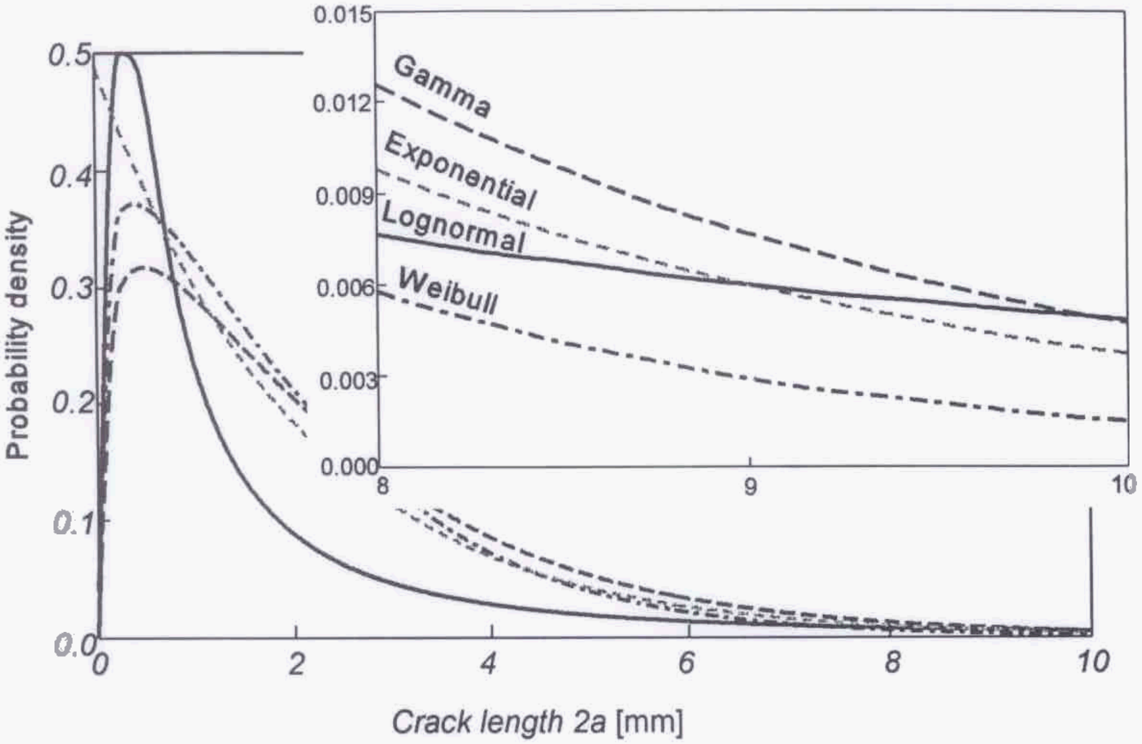

Fig. 2 Assumed crack length distributions

3.3 Parameters of Nondestructive Examination Method

The nondestructive examination method simulated in the analysis was the motorized rotating pancake coil (MRPC) eddy current technique. The following properties were assumed in the calculation:

- sizing error $p_{M|A}(m/a)$ was modelled as a normal distribution with mean a and standard deviation of 0.75 mm. Therefore, only random errors independent of the crack length were considered. The specified MRPC accuracy of ±1.5 mm (Dobbeni, 1991) was assumed to cover 2 standard deviations.

- detection probability was assumed to follow the well known exponential law. Specific for MRPC, the following relation has been proposed (Mavko et al, 1991; consistent also with Pitner et al, 1993):

$$P_D(a) = \left[1 - \exp(-0.45a)\right]\left(1 - \epsilon_D\right) \qquad \textbf{(10)}$$

with a in mm. ϵ_D is residual non-detection probability and may be used to model human errors.

It can be seen from Table 1 that MRPC with the assumed parameters is estimated to detect about 50% or less of all cracks present in the steam generator tubing. In the steam generator analysed, 273 cracks were detected during the 1992 inspection (Dvoršek et al, 1993). Assuming lognormal distribution of crack lengths leads to a total number of 841 tubes with cracks. The fraction of detected cracks (Table 1) is defined by the integral over all possible crack lengths in the denominator of eqn (4) .

3.4 Results and Discussion

The tube failure probability (which corresponds to the fraction of failed tubes P_f, eqn **(1)**) is given as a function of plugging limit in **Fig. 3**. Three distinct regions of *PL* can be observed. At high *PL* values (>20 mm), the plugging limit has virtually no effect on the value of P_f. With the exception of lognormal distribution, the probability of finding crack lengths in this region is virtually zero. This result also means that, for a given population of cracks, plugging at *PL*>20 mm corresponds to *no plugging at all*.

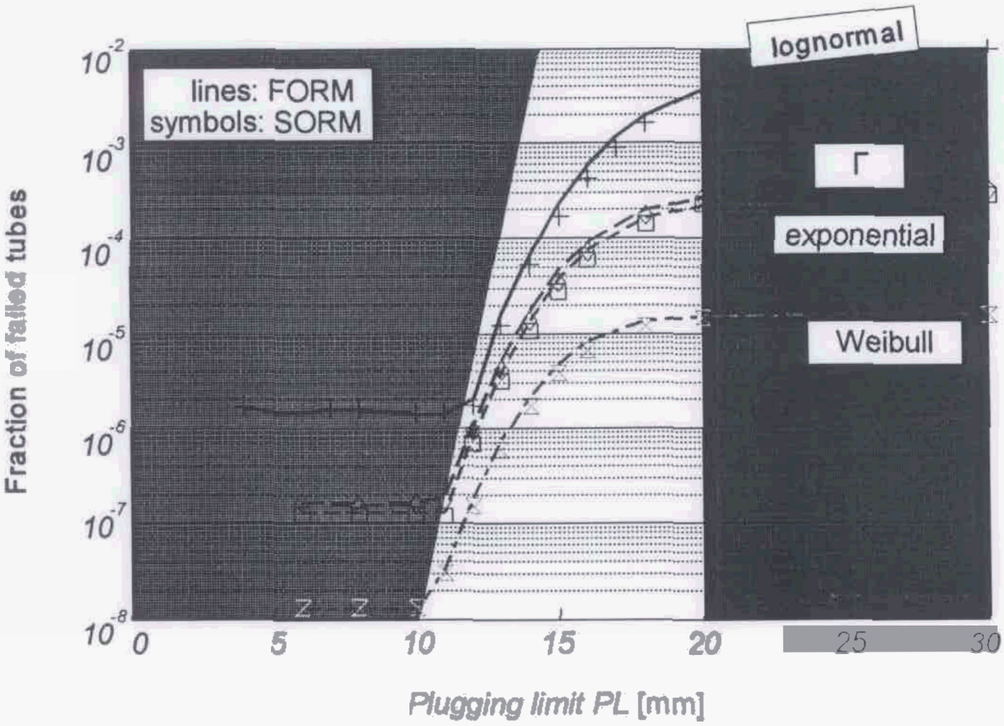

Fig. 3 Fraction of failed tubes

At low *PL* values (<10 mm), a plateau behaviour of P_f is observed again. It is caused by the non-detection probability of the nondestructive examination method simulated. In simple terms, non-detected long cracks become at least as probable as the unfavourable combination of structural resistance properties at cracks with length close to the value of *PL*. The value of *PL* where the plateau and the intermediate region intersect is an obvious candidate for the optimal *PL* value.

The intermediate region defines the efficiency of the nondestructive examination method implemented in terms of tube failure probability. Regardless of the distribution type used, the P_f value can be decreased by four orders of magnitude by implementing lower *PL* values.

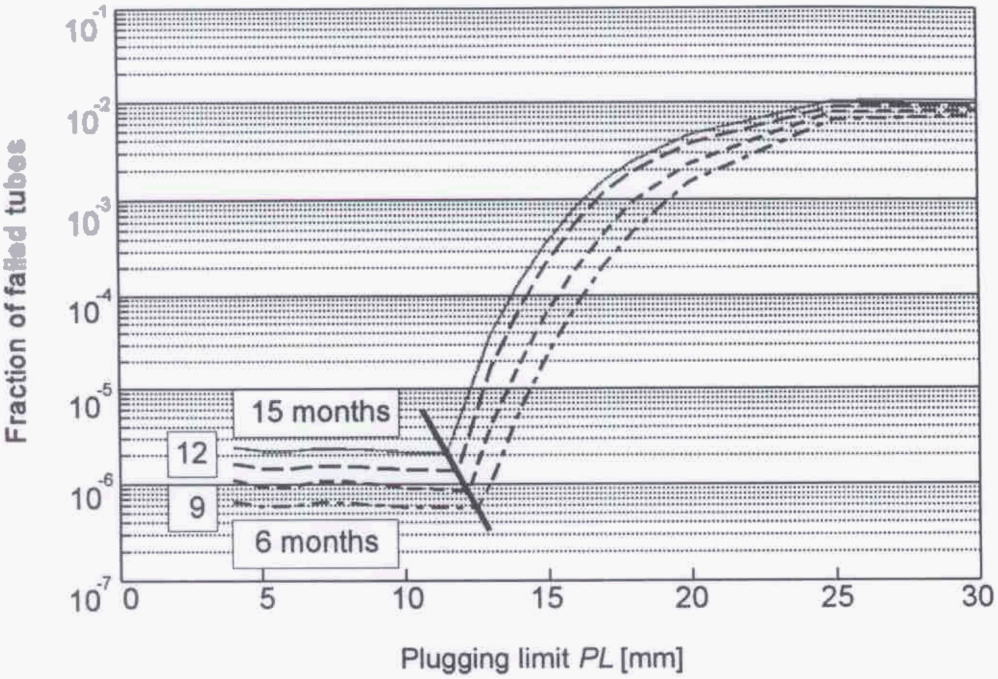

Fig. 4 Effect of increasing time between inspections (lognormal distribution)

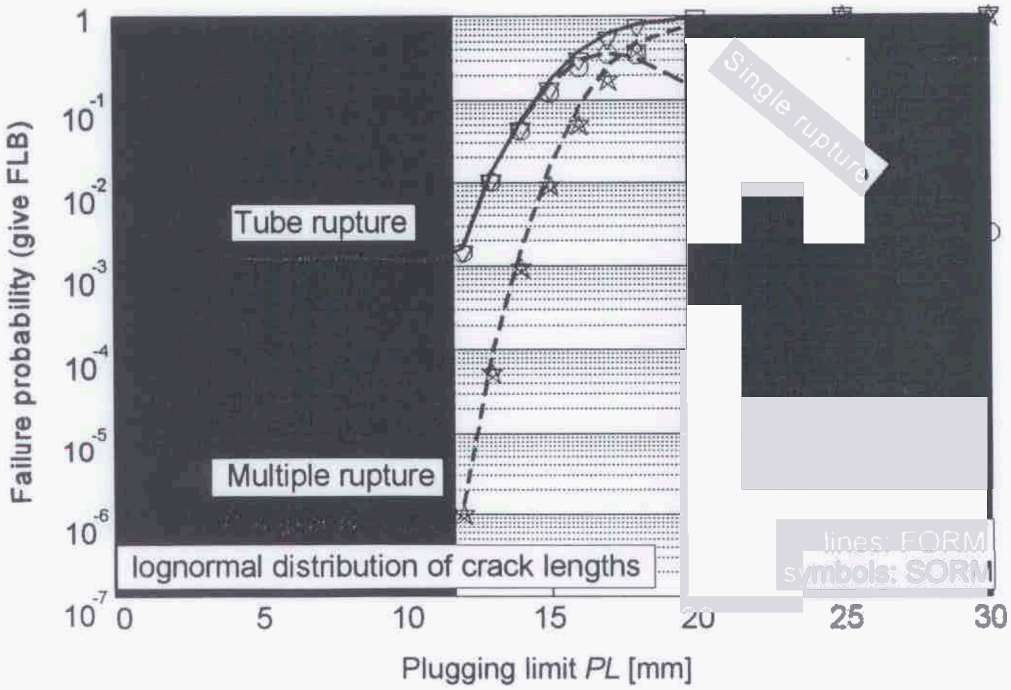

Fig. 5 Single and multiple tube rupture probabilities

The arbitrariness in the choice of distribution can contribute as much as three orders of magnitude (**Fig. 3**). This effect is, however, only meaningful while estimating the absolute value of tube failure probability and does not significantly affect the relative efficiency of the nondestructive examination technique. Consequently, the most conservative lognormal distribution was selected to illustrate both qualitative and quantitative results in further discussions.

Fig. 4 depicts changes in the development of tube failure probability with increasing time between two successive inspections. The optimum *PL* value tends to decrease with increasing inspection interval.

3.4.1 Probability of Single and Multiple Tube Rupture

The event of tube rupture is dominated by the single tube rupture (for probability see eqn. **(8)**) for $PL < 12$ mm (**Fig. 5**). However, the *no plugging at all* ($PL \to \infty$) region is dominated by multiple tube rupture (eqn. **(9)**). A hypothetical feed-line break accident would therefore cause the following:

- at $PL < 12$ mm, a single steam generator tube rupture (SGTR) in approximately 0.1% of cases and multiple SGTR in less than one out of million cases.

- at $PL \to \infty$ a virtually certain multiple SGTR event is to be expected. However, the probability of multiple SGTR might be considerably decreased by implementing a reliable leak detection method. Quantitative assessment could be performed by including the leak detection in the model, which is planned to be done in the near future.

3.4.2 Effects of Human Errors and Sampling Inspection

The prior discussions assumed inspection of all tubes and neglected any possibility of human errors during the inspection or plugging procedures. This may not fully reflect the situation in reality. Consider the following possible situations, which may result in operation with excessively long cracks:

- Only a randomly selected sample of cracked tubes is inspected. In the proposed model, this inspection procedure affects the probability of plugging (eqn. **(6)**) through the term $1/\eta$.
- A cracked tube was inspected but erroneously declared sound after inspection. The probability of such event is given by eqn. **(10)**, which splits the non-detection probability in the two parts. The first one depends on crack length and characterizes the implemented inspection method. The second one does not depend on crack length and is characterized by residual non-detection probability ϵ_D. In this section, only the effects of ϵ_D are studied.
- Finally, an inspected cracked tube is scheduled for plugging, but because of an error it is not plugged. The probability of such event is accounted for by term ϵ_{PL} (eqn. **(6)**).

All of the above events are assumed to be caused by an erroneous decision of the human operator. Only those potential human errors which do not depend on the crack length are covered by the present model. The impact of these potential human errors on the probability of tube rupture is analysed and discussed below.

Recalling eqns **(6)** and **(10)**, the following relation is obtained:

$$\left(1 - \epsilon_D\right)\left(1 - \epsilon_{PL}\right) \approx 1 - \left(\epsilon_D + \epsilon_{PL}\right) \qquad \textbf{(11)}$$

Thus, for small values of ϵ_D and ϵ_{PL}, the results obtained by studying the effects of one of them can be generalized to another one. This result is also true for large fractions of randomly inspected, but cracked tubes ($1/\eta \approx 1$).

Setting the value of $\epsilon_D=10^{-4}$ showed virtually no deviation from above results and therefore, did not significantly affect the overall success of the maintenance strategy. However, larger values of ϵ_D (10^{-3} and 10^{-2}) decrease the maintenance efficiency by one or two orders of magnitude, respectively (see **Fig. 6**). A similar result is obtained also by using random sampling inspection of 99.9 and 99% of cracked tubes.

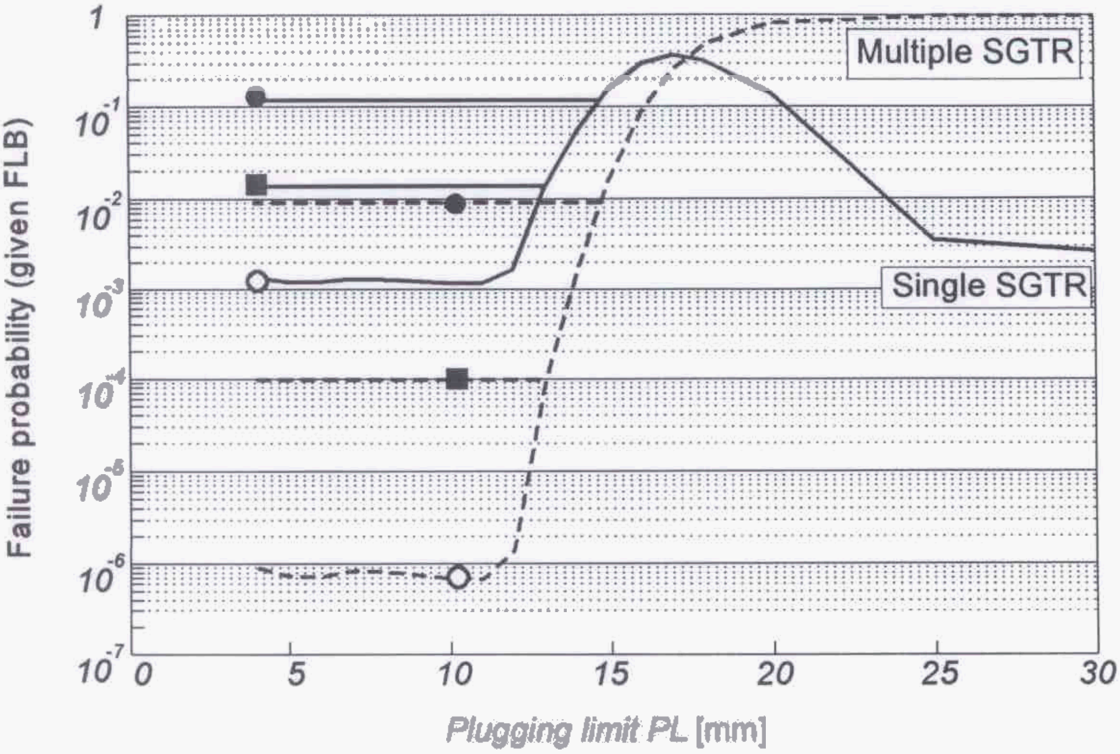

Fig. 6 Single and multiple tube rupture probabilities (lognormal distribution; ○ $\epsilon_D=0$; ■ $\epsilon_D=10^{-3}$; ● $\epsilon_D=10^{-2}$)

The impact of human errors and sampling inspection on single and multiple tube rupture probabilities is depicted in **Fig. 6**. Missing about 1% of cracked tubes tends to increase the probability of multiple tube rupture by about four orders of magnitude. The same conclusion also applies to the identical values of ϵ_{PL} and/or random sampling inspection.

The probability of tube rupture is therefore rather sensitive to human errors. It is also irrelevant if those errors are made during inspection or plugging activities. Two recommendations follow from the results of analysis:

- Inspect 100% of tubes.
- Further investigations in the field of human reliability during inspection and plugging procedures may be worthwhile.

3.5 Crack Length Vs. Depth Plugging Strategy

The 100% MRPC inspection of steam generator No. 1 revealed 273 cracked tubes. However, a 100% inspection of the tube bundle by bobbin coil showed that the depth criterion (loss of 45% wall thickness) was fulfilled only in three cases. Moreover, the observed correlation between the MRPC crack length and bobbin coil crack depth was very poor (Dvoršek et al, 1993). This leads to the following conclusions:

- plugging using the crack depth strategy does not significantly alter the distribution of crack lengths. Hence, the value of P_f is not significantly altered by the plugging procedure and is approximately equal to the value which is obtained for $PL\rightarrow\infty$. In other words, there was no attempt to plug the tubes with the longest cracks.

- plugging using the crack depth strategy eliminates only a small amount of cracked tubes (3 out of 273 detected by MRPC).

This implies that we can accurately describe the crack depth plugging strategy as no plugging at all ($PL\rightarrow\infty$). In this case, a virtually certain multiple SGTR event follows the feed-line break irrespective of the value of ϵ_D. Recalling eqn. **(8)** and **Fig. 5**, this situation leads to a multiple tube rupture given a hypothetical feed-line break accident. As it has been shown in the previous subsection, significantly better results can be obtained using a crack length approach with an appropriate PL value.

4 CONCLUSIONS

The outlined methodology is aiming at estimating the efficiency of steam generator maintenance strategies in terms of tube failure probabilities. It explicitly allows for evaluation of single and multiple tube rupture probabilities, based on scatter in geometry, material properties, stable crack propagation and uncertainties of the maintenance strategy implemented. At this time, the failure models employed allow evaluation of axial stress corrosion cracks in the tube expansion transition zones.

The numerical example is based on the Krško NPP steam generator No.1 after the 1992 maintenance activities. The crack length based maintenance strategy has been studied in detail. The main conclusions that follow from this analysis are:

- The fraction of cracks detected by motorized rotating pancake coil (MRPC) is estimated to be about 50% or lower,

  Selective plugging of the tubes having longer cracks may decrease the tube failure (rupture) probability by a few orders of magnitude despite a relatively low detection probability. This is especially true for multiple tube rupture probabilities;

- Given a tube inspection method, a minimum failure probability exists, that can not be further reduced by implementing a lower plugging limit (allowable crack length).

- Routine 100% inspection of tubes is recommended when implementing crack length based maintenance strategies.

- The overall success of maintenance is sensitive to potential human errors made during inspection or plugging activities. A probability of human errors in the order of about 1% increases the probability of multiple tube rupture event by about four orders of magnitude.

Also, the maintenance strategies based on allowable crack depth and defect length have been compared. The crack length strategy is shown to be superior in terms of steam generator tube rupture probability. In particular, the risk of multiple tube rupture may be significantly reduced by the implementation of crack length based maintenance strategy.

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