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Failure Analysis Module for the Probablistic Fracture Mechanics Code for PWR Steam Generator Tube Maintenance

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1 INTRODUCTION

Due to the fast degradations they sometimes experience, steam generator tubes receive special care on the part of French power utility EDF, which currently operates over 170 steam generators. Of course, while such degradations can affect unit capability factor and lead to expensive maintenance operations (inspections, repair and even early replacement of equipment), they may also decrease installation safety level. These tubes are part of the second containment barrier, the integrity of which can be affected. Numerous studies on this topic have been carried out for many years in various fields, all aimed at improving safety and availability at the lowest possible cost: prevention (chemistry control, improvement of materials and their installation during the building phase), in-service surveillance (ongoing surveillance of operational leakages, non-destructive tests or examination of pulled out tubes), corrective actions (preventive repair or intervention on operational equipment), operator's taking into account of risks of tube break (faulted operating procedures), along with theoretical studies whose purpose is two-fold: to explain why such degradations occur, and to evaluate safety-related consequences (risks of break for a given fault, likelihood of this fault to lead to leakage while in service, enabling additional operational surveillance).

So far, theoretical studies have been marked by a strong deterministic approach [1]; with only proven models, both in terms of mechanical and thermohydraulic behavior, the temptation was strong to apply a probabilistic approach to these studies to allow a more quantified view of operational equipment safety, enable comparison among different equipment items and evaluate the effect of maintenance operations on the safety level. These global probabilistic studies are supported by a software tool, designated the COMPROMIS code (see description of general architecture in [2]). The module related to failure analysis is described hereafter. The first development phase focused on the most common sort of degradation, i.e., primary water stress corrosion cracking (PWSCC) in the roll transition zone. The examples below concern this type of degradation.

2 DETERMINISTIC FAILURE CRITERIA

Numerous tests, which were interpreted using numerical models, have made it possible to define a break criterion for a longitudinal crack in the roll transition zone (1). This criterion is expressed by the following formula:

$$M^* \times \sigma_\theta^* = \sigma_f \qquad (1)$$

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where: M^* is the bulging factor of the specific cracked tube in the transition zone. It has the following form: $M = f(a_i, a_e, \delta, \phi, t)$; parameters necessary to calculate M are given in Figure 1.

σ_θ^* is the nominal hoop stress, which only takes into account the pressure loadings applied to the tube (internal, external and crack lips).

$$\sigma_\theta = f(P_p, P_s, P_f, \phi, t) \qquad \text{(See Figure 1)}$$

σ_f is the flow stress, which in fact characterizes the break of a sound tube: $\sigma_f = f(Sy + Su, k)$, where Sy and Su are elastic and break limits, respectively; k is a coefficient characterizing tube heat.

It is clear that criterion (1) can be described using ten parameters, five of which are related to the cracked tube geometry, three to loading and two to its mechanical characteristics.

3 APPLYING A PROBABILISTIC APPROACH TO THE CRITERION IN THE FAILURE ANALYSIS MODULE

Among parameters listed above, the two related to internal and external pressure loading can be considered as deterministic, since they are characteristic of the operating situation under study (normal or faulted).

Since the very purpose of this module is a probabilistic study of the critical sizes of analyzed tubes, the probabilistic approach need only be applied to uncertainties concerning five parameters:

- parameters related to tube geometry in the transition zone: ϕ, t, δ,
- parameters related to tube mechanical characteristics: Sy + Su, k, and the additional parameter P_f, whose value is uncertain from P_p to P_s.

This probabilistic approach, an example of which is given in Table 1 for a specific unit in the 900 MWe series, is calculated using the following data:

- Sy + Su: manufacturing data banks,
- k: normal law centered on average value obtained by means of tests,
- ϕ, t, δ: normal laws based on manufacturing specifications and validated on several manufacturing histograms,
- for Pf, a deterministic envelope (Pf = Pp) is selected, since the sensitivity study has shown the limited influence of this parameter.

4 FIRST APPLICATION: SENSITIVITY STUDIES

Whereas a simple deterministic approach gives a first impression of the influence of various parameters governing the critical size, a probabilistic calculation provides something "extra", since it makes it possible to quantify the influence of these parameters on the probability of tube rupture risks for any tube in a given population. This analysis provides higher accuracy for significant parameters in the risk of break, i.e., those requiring a higher priority in terms of study.

On each curve in Figure 2, the rupture probability for a tube with a crack of a given length has been evaluated by applying a probabilistic approach to all parameters listed above, except one (the influence of which is to be tested), to which three characteristic values are successively assigned (two extreme values in the range and the average value).

These results show, for example, that it would be more important to know the distribution of thicknesses or mechanical characteristics, rather than diameters or parameter δ. For example, for a tube with average mechanical characteristics and with a longitudinal crack of 40mm, the rupture probability may rise from less than 5% to more than 85%, depending on whether its thickness is at the average or minimum thickness distribution value.

5 SECOND APPLICATION: DISTRIBUTION OF CRITICAL SIZES

The second application is, in fact, in a "standard" application of the COMPROMIS code which outputs the critical size distribution for a given operating situation based on a probabilistic definition of the above-mentioned parameters. The distribution is then compared with the distribution of actual sizes at a given moment in the operating cycle.

This distribution of critical sizes is evaluated using the stratified Monte Carlo method: a large number of random sampling operations is performed on all input parameters which have already undergone a probabilistic analysis. Each sampling operation (five parameters, in fact) corresponds, for a selected operating situation, to a critical length obtained using the analytic equation (1). This length is then recorded in the critical size histogram. In order to minimize the number of sampling operations without affecting distribution accuracy at extreme values, sampling density is differentiated ("stratified") according to sampling fields.

Figure 3 gives an example of critical size distribution for two operating situations: normal (ΔP = 100b) and faulted (ΔP = 172b, where ΔP represents the differential pressure on tube walls). These histograms show the effect of the probabilistic approach applied to critical size: for example, under faulted conditions, the average value is 27mm with a typical deviation of 3.5mm.

6 COMMENTS - DISCUSSION

The above-mentioned histogram concerning faulted conditions, for instance, can be compared to the deterministic value calculated by assigning the worst case distribution value to each input parameter. In our example, this value is 17mm, for an average histogram value of 27mm. This comparative result shows the advantage offered by the probabilistic approach in evaluating critical sizes.

Another evidence of the benefits of such studies is given in Figure 4, where the probability for risks of rupture on a given steam generator tube (along with change over time), depending on whether criteria parameters (1) have undergone a probabilistic analysis or were assigned the previously defined envelope values. Between the two simulations, break probabilities differ on the order of four decades, which shows how conservative deterministic studies can be.

7 CONCLUSION

Examples described in this paper using the failure module in the COMPROMIS code show the advantage of a probabilistic analysis in studying break risks on steam generator tubes.

By complementing deterministic values, probabilistic studies shed further light on the evaluation of break risks on steam generator tubes. They enable:

- making a quantitative comparison between how two sets of tubes are affected,
- evaluating the weight of the various parameters in evaluating the risks of steam generator tube break, thereby indicating fields where our knowledge must be improved,
- relativizing the notion of critical size when calculated in a deterministic manner, by distributing critical sizes,
- quantifying the degree of conservatism of purely deterministic studies.

Current and future developments in this area concern other steam generator tube degradations and should make it possible, in the long run, to better assess the safety level of operational equipment.

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[2] Pitner P., Riffard T., Granger B. and Flesch B. (1991). Probabilistic Break Mechanics Code for PWR Steam Generator Tube Maintenance, SMIRT 11, Tokyo.

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Table 1. Tube rupture criterion - Probabilistic laws for input parameters.

Parameter	Description
t (mm)	normal law: m = 1.27/σ = 0.04/truncated at ± 3 σ
ϕ (mm)	normal law: m = 22.22/σ = 0.06/truncated at − 3 σ and + 2.2 σ
Re+Rm (MPa)	normal law: m = 956/σ = 50.3 /truncated at ± 3 σ
k (-)	normal law: m = 0.58/σ = 0.01/truncated at ± 3 σ
δ (mm)	normal law: m = 0 /σ = 0.5 /truncated at + 3 σ

m: mean value σ = standard deviation

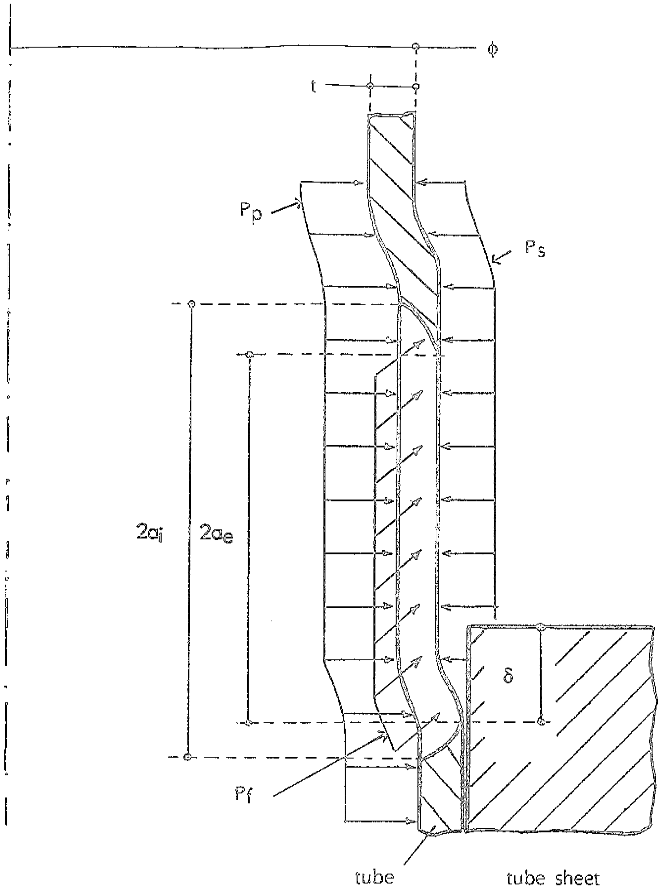

Fig. 1. Roll transition zone. Parameter definition

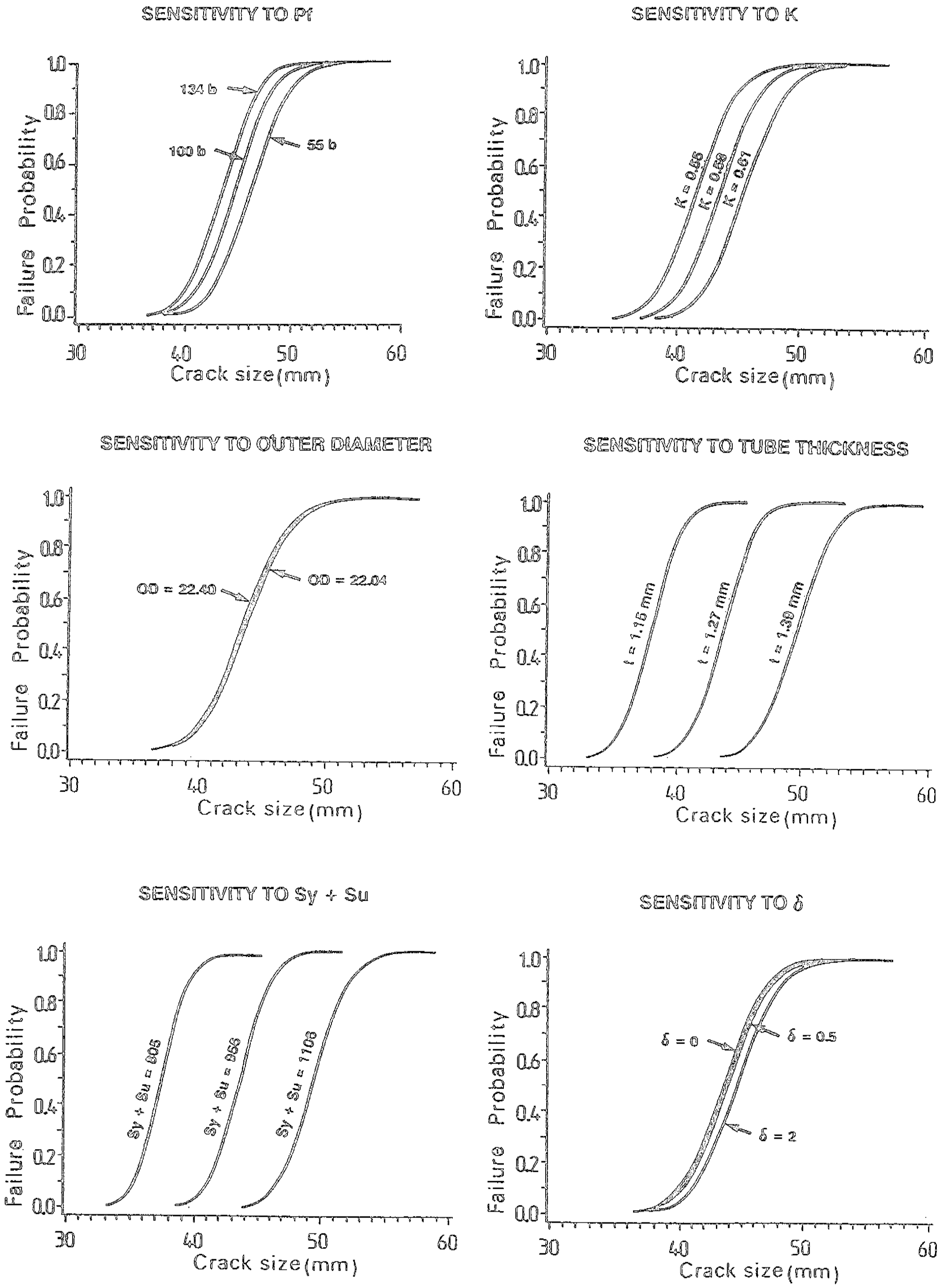

Fig. 2. Sensitivity study: Probability of cracked tube rupture for various values determined for probabilistic approach

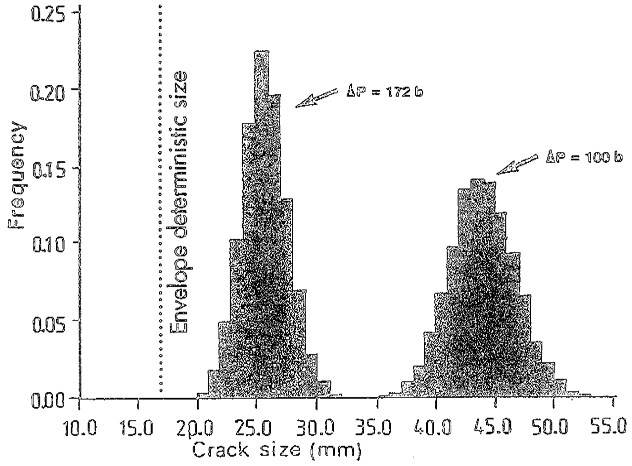

Fig. 3. Histogram of critical sizes under normal and faulted conditions.

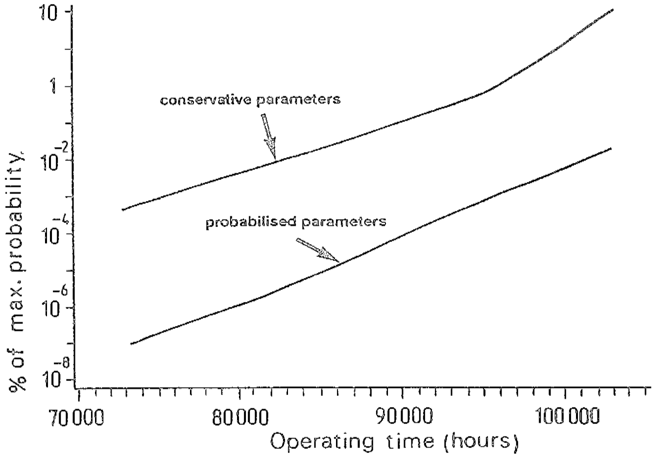

Fig. 4. Comparative evolution of rupture probability over time with and without probabilistic analysis of failure criterion.