Application of the Leak Before Break Concept to Steam Generator Tubes

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1. INTRODUCTION

Steam generator tubes in pressurized water reactors (PWRs) must, under all operating conditions, fulfill the safety function while retaining sufficient mechanical integrity to preclude the risk of tube bursting, thus limit primary-to-secondary leaks to a minimum and ensure a safe shutdown of the reactor. These tubes must perform this function with the highest reliability. Therefore, it is important to prove the structural integrity of steam generator tubes, through mechanical analyses, tests and in-service inspection.
Analyses of injuriousness of cracks likely to affect steam generator tubes focus on evaluating the rupture risks for any tube, according to the types of defects observed in units in service. On the basis of a large experimental program performed by EDF and FRAMATOME, these analyses are carried out considering the most severe accident conditions insofar as this risk is concerned. These analyses make it possible to determine the size of unstable cracks in accident conditions. Moreover, the study also validates an in-service surveillance criterion, applicable to primary-to-secondary leak rates. The reason to use this criterion is that any unstable crack in an accident condition should result in a leak under normal operating conditions; detection of this leak enables the plant operator to shut down the nuclear steam supply system as a preventive measure.

2. STEAM GENERATOR TUBE RUPTURE CRITERIA

The burst risk assessment of steam generator tubes subjected to internal pressure, thermal loadings and external loadings representative of mechanical loadings in accident conditions, requires the experimental validation of rupture criteria.
More than 1000 burst tests have been carried out by FRAMATOME on Inconel 600 and Inconel 690 tubing with nominal diameter of 19.05 mm and 22.22 mm. These burst tests have been performed with various types of damage located in straight portion remote from discontinuities, in the rolling transition zone at the top of the tubesheet, in the vicinity of the tube support plate and in U-bends.
It is demonstrated that the burst pressure of tubes with part-through defects and the instability limit pressure of through-wall defects or cracks due to stress corrosion cracking can be accurately estimated on the basis of plastic instability criteria. For the criteria used, deviations between test and theoretical values are lower than 5 %.

2.1. Burst pressure of tubes without defects

The results of burst tests show that tube rupture occurs after very large deformation, as a consequence of great ductility and toughness of tubes.
There is a perfect correlation between test results and a model predicting the burst pressure by referring to a plastic flow stress; this manifests the nature of rupture by plastic instability. On the basis of test results, a good correlation may be obtained between the flow stress and the mechanical properties of INCONEL.

2.2. Analysis of the behavior of steam generator tubes with defects or cracks located between supports.

According to burst tests, the burst pressure for tubes with longitudinal part-through crack can be estimated closely by using the following functional form :

(1) $$Pr = f\ (\bar{\sigma}, t, R, a, d)$$

where $\bar{\sigma}$ is the flow stress based on results of tests on sound tubes, t is the thickness, R is the inside radius, a is the crack half-length and d is the depth of the crack. When the ligament rupture pressure Pr is smaller than the instability limit pressure of the through-wall crack with the same length, the crack remains stable after rupture of the remaining ligament.
The instability limit pressure Pa of a through-wall crack can be reliably determined on the basis of a plastic instability criterion. It is determined by means of the following formula :

(2) $$M\sigma = \bar{\sigma}$$

where σ is the applied stress and M is the bulging factor defined by the formula :

(3) $$M = (1 + 1.61\ a^2/rt)^{1/2} \text{ (FOLIAS)}$$

Test results show that the combination of thermal and mechanical stresses does not modify the stability limit state of the tube with a longitudinal crack.
These thermal stresses, which result from a considerable thermal shock created by the injection of cold water on the tube wall on the secondary side, do not play an important role in the plastic collapse phenomena .
It is confirmed that the instability limit pressure of a tube with a circumferential through-wall crack may be estimated using a plastic collapse model. The influence of providing support conditions simulating the presence of a tube support plate is manifested by an increase in rupture pressure obtained for a supported tube in comparison with that obtained for an unsupported tube (figure 2).
It is demonstrated that burst pressure of a tube with longitudinal cracks located in U-bend is higher than that of a tube with the same type of degradation located in straight portion.

2.3. Analysis of the behavior of steam generator tubes with one or several defects or cracks located in the rolling transition zone.

In all cases, it is experimentally confirmed that the instability limit pressure of a tube with a crack located in the rolling zone at the top of the tubesheet is higher than that of a tube with the same type of degradation located in straight portion remote from discontinuities. The increase in the instability limit pressure in the rolling transition zone depends on the length of the defect or crack. When the tip of the crack outside of the tubesheet is located beyond the limit of local reinforcement, the instability limit pressure of the crack is equal to that of a crack of identical length located in the straight portion remote from discontinuities. Unstable propagation initiates at the tip of the crack which is not in contact with the tubesheet. The instability limit pressure of a longitudinal through-wall crack in the rolling zone, can be determined by means of the following formula :

$$M(\lambda^*)\ \sigma = \overline{\sigma} \tag{4}$$

where the bulging factor $M(\lambda^*)$ depends on the crack length outside the tubesheet and the equivalent thickness which takes into account the interaction with the tubesheet. It is demonstrated that this rupture criterion remains applicable when there are several main cracks distributed over the entire tube circumference (figure 1).

2.4. Analysis of the behavior of steam generator tubes with multiple cracks located in the straight portion remote from discontinuities or in the rolling transition zone.

On the basis of plastic instability rupture criteria validated for different defect configurations or for single cracks, comparative analysis of the results reveals a weakening, variable in extent, of overall tube strength in the deteriorated area. This comes from an interaction between cracks, and is manisfested by a decrease in the instability limit pressure of the main crack depending on the type of deterioration, length and relative position of the various cracks.
As shown by the experiment, the weakening of a tube due to a network or an interaction between complex cracks can be partially balanced by the boundary effect of the tubesheet, which prevents deformation from taking place freely. However, beyond a certain limit of deterioration, this effect is cancelled out. This limit depends on the type of deterioration observed. Burst tests on tubes pulled from various french power plants were carried out at room temperature. These tubes are cracked due to stress corrosion cracking in PWR conditions in the rolling transition zone.
The comparison of theoretical and test results does not call into question the validity of the calculation model proposed.

3. DETERMINATION OF THE CRACK OPENING AREA OF A LONGITUDINAL CRACK AND LEAK RATE EVALUATION

Crack opening area calculations on the basis of an elastic model with a plastic zone correction given by the Dugdale model enable results to be obtained that are in good agreement with the values measured on through-wall longitudinal defects. The plastic zone correction to allow for the effect of plasticity is applied in the sense used in the Tada - Paris method.
From the results of finite element calculations, an expression of the crack opening area can be written in the form :

$$S = \frac{a_1^2\ P}{E}\left\{A_0 + A_1\ x + A_2\ x^2\right\} \tag{5}$$

where : $x = M(\lambda).\frac{R}{t}$ and $M(\lambda)$ represents the bulging factor.
The A_i coefficients determined on the basis of S values calculated by the finite element method for various crack lengths, depends on the $M(\lambda)$ function selected. P is the pressure, a_i is the effective crack length and E is the Young's modulus. In this manner, one can determine the crack opening area at the inner wall, mid-thickness and outer wall for cracks located in the straight portion remote from discontinuities and in the rolling transition zone. Using the numerical model instead of analytical model gives the possibility to take into account both the influence of the tubesheet, which has the effect of decreasing the crack opening area, and the bending effect on the crack lips. In the straight portion remote from discontinuities the analytical and numerical models give equivalent results (figure 3).
From crack opening area calculations, using elasto-plastic behavior hypothesis and leak rate test results through corrosion cracks, the value of the flow rate coefficient K can be determined by using a simple calculation model of the perfect fluid type. This model is expressed in the form :

$$Q = KS\sqrt{\frac{2\Delta P}{\rho}} \tag{6}$$

where Q is the leak rate, S is the crack opening area, ρ is the density of primary coolant and ΔP is the primary to secondary differential pressure. The value of K determined in this manner, integrates all uncertainty for the various parameters such as : type of coolant, type of defect, actual length of the stress corrosion crack, state of the surface of crack lips or differential pressure effectively applied to crack surface. The value of K depends strongly on the model used to calculate the crack opening area. Using the relation (6), the leak rate can be determined as a function of crack length. The scatter of results is relatively large. On the basis of leak rate measurements performed by EDF, a lower bound of leak flow rate can be obtained with K = 0,10 (figure 4).

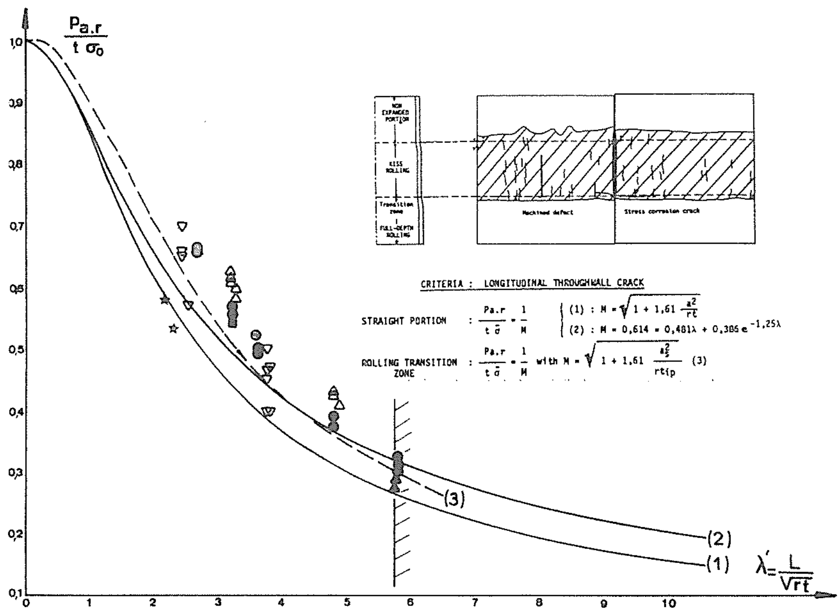

Fig 1 : Burst pressure on tubes with through-wall defect or crack located in the rolling transition zone. Comparison between calculation and experimental data.

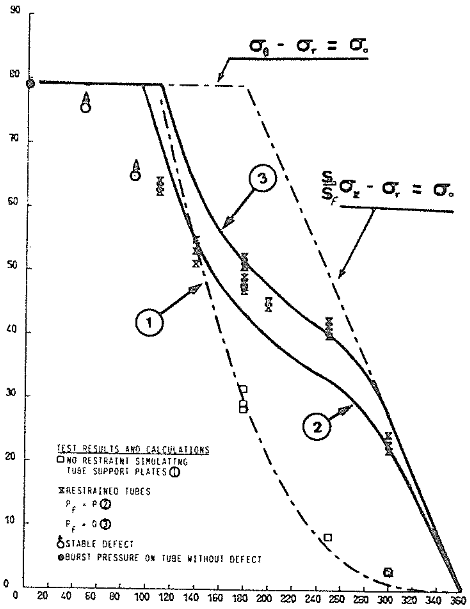

Fig. 2 - BURST PRESSURE Pr VERSUS THE ARC LENGTH 2 θ OF CIRCUMFERENTIAL THROUGHWALL DEFECTS. COMPARISON BETWEEN CALCULATION AND EXPERIMENTAL DATA . (P_f IS THE PRESSURE APPLIED ON THE SURFACE OF THE DEFECT).

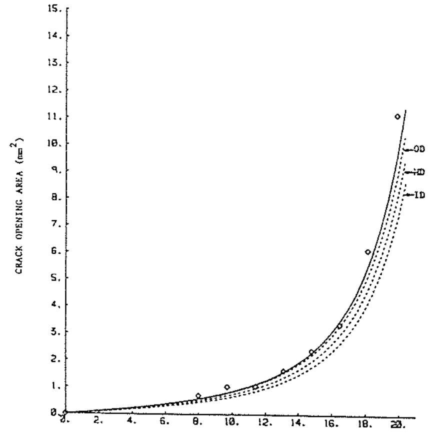

Fig.3 Comparison between experimental and theoretical crack opening areas

◇ : Experimental results (Inconel 600-Ø19.05mm-2a = 15 mm)

———— : Elastic model with plastic zone correction (Dugdale)

------ : Numerical model with plastic zone correction (Dugdale) (WITHOUT pressure on the crack Surface)

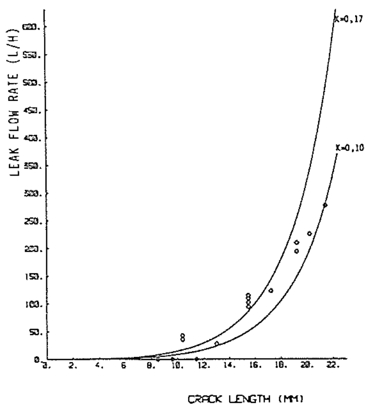

Fig. 4a LEAK RATE TEST AT ROOM TEMPERATURE
COMPARISON BETWEEN TEST RESULTS AND CALCULATIONS

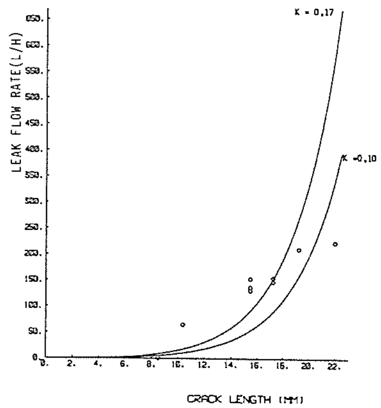

Fig4b LEAK RATE TEST AT 120°C
COMPARISON BETWEEN TEST RESULTS AND CALCULATIONS

SUMMARY AND CONCLUSION

The steam generator operating experience for nuclear power plant shows that some possibilities of in-service deterioration must be considered. Given the inevitable intervals of time between in-service inspection of tubes, a certain development of stress corrosion cracking by the reactor coolant can lead to a tube break through in a period of time which can be relatively short. Based on the examination of tubes pulled from different power plants, it is confirmed that these through-wall cracks remain stable for the operating conditions in PWR power plants.
Comparison of theoretical and experimental results has confirmed that criteria based on the concept of instability by plastic flow give reliable predictions of steam generator tube rupture. Computation models have been qualified for degraded tubes located in the vicinity of supports and tubesheet and away from supports. These models can be reliably used to determine critical dimensions in a damaged tube at any given temperature and stress level. Crack opening area measurements enabled to validate models using elasto-plastic behavior hypothesis in order to evaluate the leak rate through cracks in steam generator tubes.
The leak before break analysis applied to steam generator tubes make it possible to conclude that the inservice surveillance presents an advantage from the safety standpoint. It precludes the risk of rupture of any tube whatsoever in the event of accidental overpressure. Surveillance during refueling shutdowns also remains a preventive measure against the risk of tube rupture since the applicability of the leak before break cannot be shown for all configurations. In this case, using methods which have been validated experimentally to within less than 5 %, the critical crack dimensions will be used to define tube plugging criteria.

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