

Crack stability criteria in steam generator tubes

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1 INTRODUCTION

Steam generator tubes form a substantial proportion of the second fission product barrier in pressurized water reactors (PWRs). These tubes must perform this function with absolute reliability.

EDF (Electricité de France) applies the leak-before-break concept to its steam generators to preclude any risk of tube rupture, whatever the operating conditions. Vérification of the concept that leaks occur in normal operation, and provide warning of possible ruptures in the case of accidental overpressure, is supplemented and substantiated by periodical in situ examinations (non destructive examinations and taking of tube specimens). These programs are designed to monitor steam generator integrity, determine the type of damage or degradation and check regularly that such damage conforms with stress analysis assumptions (in terms of leakage and hazard to the plant).

The "Leak-before-break" concept requires that the mechanical laws governing leakage and rupture of damaged tubes be thoroughly understood.

To date, EDF and Framatome have recorded a number of cases of damage actually occurring on operating steam generators, or which could occur in the future based on foreign experience. This has enabled a wide-ranging program of experimental and theoretical investigations to be defined. The main results achieved in the first part of the experimental program are presented in this article.

2 DESCRIPTION OF TEST PROGRAM

900 burst tests were conducted at room and elevated temperatures on INCONEL 600 and INCONEL 690 tubing with nominal diameters of 19,05 mm (0.75 inch) and 22,22 mm (0.87 inch) and nominal wall thicknesses of 1,09 mm (0.043 inch) and 1,27 mm (0.050 inch) respectively. These burst tests were performed with flaws or cracks located as follows : in the roll transition area at the top of the tubesheet, in the vicinity of the tube support plate and between supports.

The following points were investigated :

1. Tube bursting pressure as a function of crack depth and length.
2. Critical length of a through-wall crack.
3. Evaluation of the effect of a tube locally degraded by uniform thinning, wear or cracking.

4. Behavior of longitudinal and circumferential cracks.

5. Behavior of multiple axial flaws or cracks distributed around the circumference.

6. Bursting pressure at elevated temperatures and evaluation of effects on bursting pressure of a thermal gradient through the tube wall.

7. Substantiation of steam generator tube behavior using experimental setups reproducing local rotations or squeezing of the tube near the tubesheet or at the tube support plate.

The experimental setup was designed to provide any required rate of pressure rise. The tube sealing system was designed to allow the maximum test pressure reached to be maintained momentarily in the case of through-wall flaws.

Framatome first undertook preliminary studies to define a method which did not significantly influence the bursting pressure for different flaw lengths. This study also demonstrated and quantified the effect of pressure applied at the flaw or crack edges. The flaw tip rupture initiation pressure was detected experimentally by comparing the pressure versus time recording with the time of flaw tip rupture initiation recorded on cassette by video cameras.

3 STEAM GENERATOR TUBE RUPTURE CRITERIA

The effect of various types of damage on the bursting pressure of Inconel 600 and Inconel 690 tubing was investigated in the experimental program. Criteria based on the plastic instability concept for axial and circumferential through-wall and surface flaws or cracks were found reliably to predict tube rupture.

3.1 Burst strength of straight virgin tubing

100 burst tests on defect free straight tubing were performed to investigate the failure mode and to validate the failure criterion given by the Svensson relation :

$$(1) \quad P_r = K(n) \sigma_u \text{Log} \left(1 + \frac{t}{R} \right) = \bar{\sigma} \text{Log} \left(1 + \frac{t}{R} \right)$$

where t is the thickness, R is the inside radius and $k(n)$ is a constant function of the strain hardening exponent. The best correlation between the flow stress $\bar{\sigma}$ and material properties was obtained by either :

$$(2) \quad \begin{aligned} \bar{\sigma} &= k(n) \sigma_u \\ \bar{\sigma} &= k(\sigma_y + \sigma_u) \quad \text{with } k = 0,58 + 0,01 \end{aligned}$$

where σ_y is the yield strength and σ_u is the ultimate tensile strength.

Studies of the effect of tube interaction with support plate were conducted in order to evaluate the consequences of squeezing of the tube due to deformation of the support plate near the wedge supports, local tube deformation due to out-of-plane bending of the support plate and bending due to alignment offsets. These tests have shown that the burst pressure is in no case decreased.

3.2 Study of steam generator tubes behavior with flaws or cracks located between supports.

Experimental investigations on steam generator tubes with single flaws or cracks located between supports were performed to validate criteria based on the plastic instability concept. Predictions were within 5 % of experimental values.

100 burst tests on tubes with axial surface flaws were conducted at room temperature and in hot conditions ($290^{\circ}\text{C} \leq \theta \leq 335^{\circ}\text{C}$). Flaw lengths ranged from 5mm (0.20 inch) to 60 mm (2.36 inch) and flaw depth was between 20 % and 90 % of wall thickness (figure 1).

Various types of degradation (machined notch, EDM slot, uniform thinning, lunar wastage, wear and cracks were investigated and it was found that the most limiting damage was obtained with the EDM slot or cracks and with uniform thinning around the entire circumference of the tube.

For flaw depths between 20 % and 85 % of wall thickness, instability pressure can be evaluated with the criterion given by the relation :

$$(3) \quad \sigma_{\theta} / \bar{\sigma} = 1 - a(t-e) / t(a+t)$$

where σ_{θ} is the circumferential stress, a is the flaw half-length and e is the thickness of the remaining ligament. For these burst tests, the best correlation for the flaw stress was obtained by relation (2) with $k = 0,59$ whatever the geometry of the tube and flaw. But for flaw depths greater than 85 %, this criterion was not appropriate to predict bursting pressure and the best predictions were obtained with an empirical equation developed from experimental results on thin-wall pipes (Battelle) :

$$(4) \quad \sigma_{\theta} / \sigma_u = (t/d - 1) / (t/d - 1/M)$$

where M is the bulging factor varying with tube and crack geometry and d is the flaw depth.

100 burst tests were conducted on tubes with through-wall flaw lengths between 7 mm (0.28 inch) and 55 mm (2.17 inch), and the effect of pressure on the slot or crack edges was investigated. During testing, large ductile deformations were observed with necking at both ends of the flaw or cracks. When the maximum pressure was reached, crack initiation and instability occurred with rupture of the tube. These burst tests were used to validate and appropriate failure criterion which predicts failure where the applied stress, σ , multiplied by the bulging factor, M , reaches a critical value :

$$(5) \quad M\sigma = \bar{\sigma}$$

with M given by either :

$$(6) \quad M = (1 + 1.61 a^2/rt)^{1/2} \quad (\text{Folias})$$

$$(7) \quad M = 0.614 + 0.481 \lambda + 0.386 \exp(-1.25 \lambda) \quad (\text{Krenck})$$

$$\text{and} \quad \lambda^2 = a^2/rt [12 (1 - \nu^2)]^{1/2}$$

It was found that, for a suitable flow stress $\bar{\sigma}$, given by relation (2), a good agreement was obtained between predictions and experimental data. The value of $\bar{\sigma}$ depends on the definition of M and also on the flexibility of the tube sealing system according to which pressure was or was not applied to the edges of the flaw or crack (figure 2).

The applicability of criteria given by equations (3), (4), (5) was determined at room temperature. For high temperature they have been confirmed by burst tests conducted at temperature ranging from 290°C to 335°C on tubes with axial surface flaws. Crack behavior after rupture of the remaining ligament was studied for various flaw lengths and depths. Thermal shock effects and the influence of thermal gradients through the tube wall ($\Delta T = 100^\circ\text{C}$) on bursting pressure were also investigated. Test results showed that thermal stresses superimposed on pressure stresses did not modify the stability of cracked tubes after rupture of the remaining ligament.

To summarize, if a steam generator tube has a through-wall longitudinal flaw of given length, and if material mechanical properties are known at the temperature of interest, the rupture initiation pressure or instability limit pressure can be safely predicted for any given temperature on the basis of the plastic instability criterion associated with the bulging factor M , where M is given by the relation (6).

Behavior of tubes with circumferential through-wall flaws was studied in 50 burst tests on tubes with flaw lengths between 45° and 300°. Tests were performed on free tubes and on tubes with tube support plate which restricts the lateral displacement. Comparison between calculation and experimental data shows a good agreement with a beam plastic hinge model in which the bending moment accounts of the interaction with the support plate (figure 3).

3.3 Study of steam generator tubes behavior with flaws or cracks located in the vicinity of tube support plate.

Study of behavior of steam generator tubes with surface and through-wall flaws or corrosion cracks located in the vicinity of the tube support plate required that 290 burst tests be performed at room temperature. Flaw lengths were between 5 mm (0.20 inch) and 30 mm (1.18 inch).

The experimental setup has been designed in order to simulate squeezing of tubes due to deformation of the support plate near the wedge supports and tube rotation due to out-of-plane bending of the support plate. The values of squeezing and rotation were these which are determined during steam generator accidental transients analysis. In all cases, bursting pressure was higher than bursting pressure obtained on tubes with the same flaws located between supports. This is because the bulging deformation of the tube which occurs during the burst process is locally constrained by the support plate interaction (figure 4).

3.4 Study of steam generator tubes behavior with flaws or cracks located in the roll transition area at the top of the tubesheet.

Study of steam generator tubes with flaws or cracks located at the top of the tubesheet in the roll transition area involved 110 burst tests conducted at room temperature on tubes with axial and circumferential through-wall and surface flaws. Various flaw lengths and flaw depths were investigated in the program. Loadings imposed on the tubes during normal operation and accident conditions were reproduced in the experimental setup. It was found that the bursting pressure on locally damaged tubes is higher than bursting pressure on tubes with the same damage located between supports.

For cracking in the vicinity of the tubesheet, the tubesheet has a reinforcing effect on tube bursting strength. This means that criteria

valid for cracks located between supports provide reliable predictions of bursting pressure.

3.5 Steam generator tube burst tests with multiple flaws

A comparison between burst tests on tubes with a single flaw or crack and tubes with two or several parallel longitudinal surface and through-wall flaws of the same length with their tips on the same circumference was conducted. Study of crack behavior after rupture of the remaining ligament of surface flaws, evenly distributed around the tube, demonstrated that the bulging at one of the cracks becomes larger than the others and this crack is the one which becomes unstable and governs the burst pressure. The burst pressure was very close to those measured with only one crack of the same length and therefore there is no significant interaction between parallel longitudinal cracks (minimum distance between cracks : 3 mm (0.12 inch)).

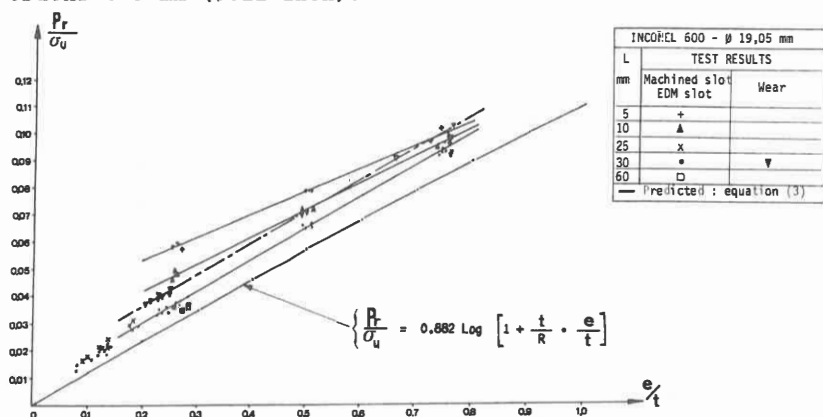


Figure 1 : Burst pressure on tubes with axial surface flaws - Comparison between calculation and experimental data.

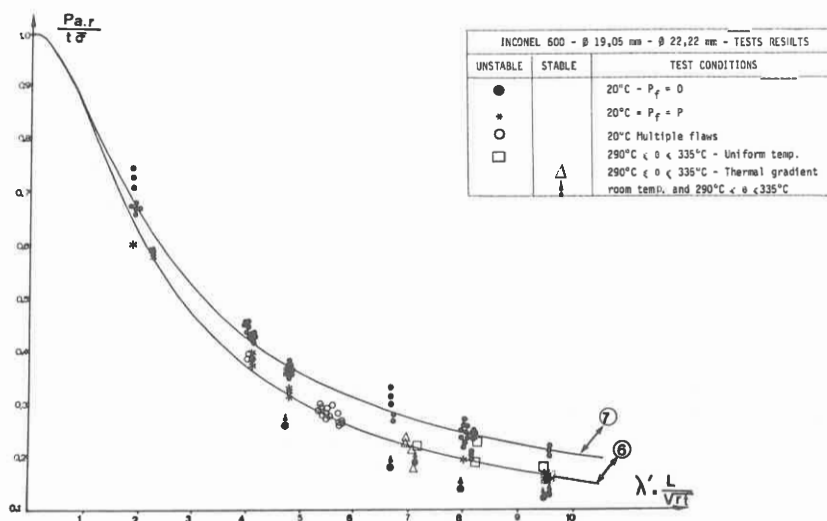


Figure 2 : Burst pressure on tubes with through-wall flaws - Comparison between calculation and experimental data at room temperature and high temperature (P_f is the pressure applied to the edges of the flaw)

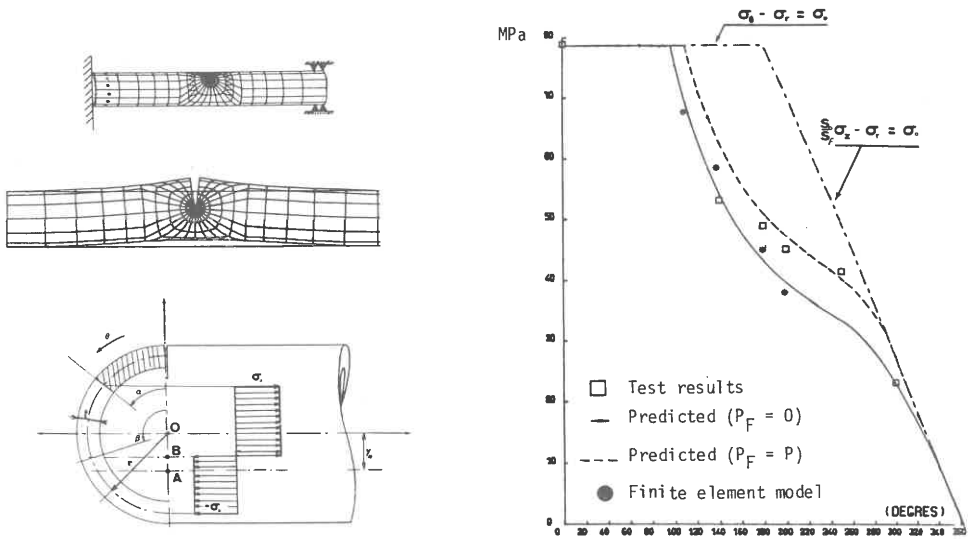


Figure 3 - Burst pressure on tubes with circumferential through-wall flaws - Finite element model and beam plastic hinge model - Comparison between calculation and experimental data (P_F is the pressure applied to the edges of the flaw).

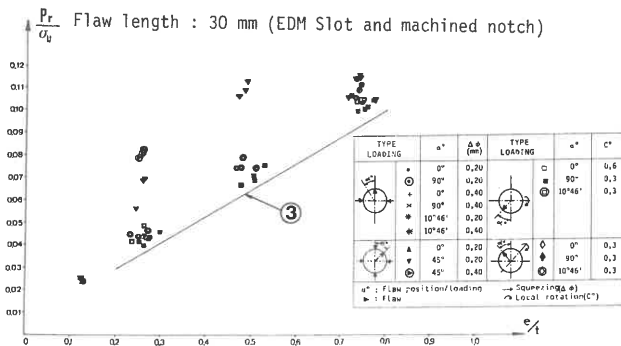


Figure 4 - Burst pressure on tubes with axial surface flaw located in the vicinity of the tube support plate - Test results with loading imposed on locally degraded tubing.

3.6 Continuation of the programm

Tests are in progress to assess the damage caused by specific defect configurations such as cracks in U-bends (to quantify effects of parameters like ovality, bend radius, flaw location, etc.) and anti-vibration bar wear flaws under representative steam generator operating conditions. Colinear or offset multiple cracks are also in course of investigation and a method for measuring crack opening area is developed in view of leakage rate evaluation. These tests will also be used to qualify computer models for calculating elastic-plastic opening area.

4 SUMMARY AND CONCLUSION

Comparison of theoretical and experimental results has confirmed that a criterion based on the concept of instability by plastic flow gives reliable predictions of steam generator tube rupture. Computation models have been qualified for tubes without defect, and for tubes with longitudinal or circumferential surface and through-wall flaws located in the vicinity of supports and tubesheet and away from supports. These models can be reliably used to determine critical dimensions in a flawless or damaged tube at any given temperature and stress levels.

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