Recent Studies on Leak Before Risk of Break in Steam Generator Tubes

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1 INTRODUCTION

Today, French power utility EDF has accumulated almost 400 PWR reactor-years of experience, with over 170 steam generators in operation equipped with tube bundles made of Inconel 600 or 690. When degradations were discovered for the first time in these tubes – generally, primary water stress corrosion cracking (PWSCC). EDF made the Leak Before Risk of Break (LBRB) concept a key element of its safety policy and the resulting surveillance philosophy. A vast study program was therefore developed in the 1980's, covering both break criteria and behavior under leak conditions (opening area, associated leakage flow rate). These studies, which focused on the most frequent cracking situations (cracks in roll transition zones) [1 to 5], were based on theoretical models and numerical calculations supported by numerous tests on models (more than 1,400 burst tests or measurement of opening areas or leakage measurements). Examinations and tests on pulled-out tubes (to date, 250) have made it possible to validate the assumptions of these theoretical studies.

During the last few years, EDF and Framatome have jointly carried out further studies in specific fields, focusing on the definition of break criteria related to degradations, either new or infrequent, which had not been studied so far, as well as on the improvement of opening area and leakage flow rate models for simple longitudinal or circumferential cracks.

This paper describes some of these aspects.

2 MULTIPLE LONGITUDINAL CRACKS

The presence of close multiple longitudinal cracks has been observed on some units in steam generator roll transition zones (RTZ). These occurred on relatively old units, or in the specific case of the Dampierre 1 power plant. A model burst test program was started in order to quantify the influence of multicracking on the critical pressure of the main crack. Main results are described in this paper.

2.1 Test program description

Fifty burst test were carried out under ambient temperature conditions on SG tubes (900 MWe) including a "main" longitudinal crack, either through-wall or part-through, located at the tube sheet exit and surrounded by "secondary", regularly spaced, adjacent cracks. If required, a uniform wall-thinning operation was superimposed on the cracks, simulating an intergranular attack (IGA) on the secondary side. Figure 1 shows a schematic diagram of these models.

2.2 Results

Interaction between several parallel, longitudinal cracks with length H_B and with spacing w, remains limited and below the scattering inherent to test conditions. In the parameter set under study, the instability pressure for the main crack (length = 2a) is not modified by the presence of secondary cracks and remains estimated conservatively by the general formula (see Figure 2 and [3]):

$$p_a . r/t\sigma_o = 1/M(\lambda^*_{ip}) \qquad (1)$$

3 CRACKS IN U-BENDS

Although EDF's current U-bend maintenance policy consists in plugging all U-bends comprising an indication, the French utility has attempted to improve its knowledge concerning the risks of break on cracked U-bends by complementing previous tests on longitudinal cracks on 900 MWe SG U-bends [2]. Additional tests on longitudinal and circumferential cracks have therefore been carried out.

3.1 Test program description

100 burst tests have been carried out under ambient temperature conditions on R1 U-bends in 900 MWe steam generators, including:
- longitudinal through-wall cracks (15 or 20mm long) located in various places in the U-bend, or
- circumferential through-wall cracks (180°, 270° or 300°), also located at different positions

In all cases, U-bend support conditions are reproduced, including gap, at the level of the last tube support plate. For certain tests, differential nominal hot leg/cold leg displacements have been reproduced. Finally, the influence of local ovalization (1% to 9%) and of stress relieving heat treatment on U-bends, has been studied.

3.2 Results

- For longitudinal cracks, present tests confirm the results of previous tests (Figure 3): U-bends with 15 or 20mm long longitudinal cracks exhibit in all cases a limit instability pressure level greater than that of the straight tube with identical mechanical end geometrical characteristics and including the same crack in the typical areas remote from discontinuities. Critical pressure rises in accordance with the angular position of the crack along the U-bend. In azimuth, the side shows the lowest gain.
- For circumferential cracks, which are not located on the side, critical pressure increases in accordance with the crack's angular position in the U-bend and seems to increase as the crack length decreases. Conversely, for circumferential cracks located on the side, a decrease in critical pressure is observed: around 20% in worst cases (at apex). Such deviations are certainly due to the different support conditions on the cracked section, to which circumferential cracks are extremely sensitive with respect to critical pressure (see Figure 4).
- Finally, in all cases, stress relieving heat treatment on cracked U-bends reduces critical pressure from 8 to 15%, depending on the crack location. Conversely, critical pressure is not affected by differential displacements, due to the secondary nature of generated stresses.

4 LEAKAGE BEHAVIOR OF CRACKED TUBES

For longitudinal cracks in the RTZ, experience feedback on EDF steam generators shows that even when the LBRB concept was not faulty [2], leakage observed while in service could be below the expected leakage predicted by models used [4], particularly in the low leakage range. It thus seemed important for EDF to find the reasons for such discrepancies and, eventually, to define leakage flow rate models that would be valid over a wide flow rate range.
EDF therefore undertook a specific study program in this field, with the following goals:

- improvement in knowledge of opening areas and types of corrosion cracking, and
- redefinition of leakage flow rate models over low, medium and high ranges.

EDF decided to add new test loops to its current series for this type of test on SG tubes (e.g., GB and QUIPROCO): the PERFIDE loop is dedicated to low flow rates and to accounting for reactor coolant chemistry, while the BRUTUS loop is designed for medium to high flow rates and high pressure burst tests (see table 1).

4.1 Opening areas

Cracks result from machining operations or stress corrosion. Several methods used to fabricate representative cracks have been reviewed (tetrathionic solution, soda, hydrogen steam, etc.). Tests have already been conducted on longitudinal (L) and circumferential (C) cracks on the typical areas or in the RTZ, mixed (L+C) cracks and low-radius U-bends. The GB and BRUTUS loops were used as test installations for validation.

Data related to "opening areas" is obtained by removing cracked tubes or U-bends to perform fine-tuned measurements once nominal (ΔP = 10MPa) or faulted (ΔP = 17MPa) operating conditions are met in steam generators.

The "residual" geometries of faults are then analyzed using image processing techniques. These techniques provide access to zones, lengths and widths, either internal or external, as well as to wetted perimeters or hydraulic diameters.

3D elastoplastic finite element calculations have been carried out (SUPERTAB meshing system, SYSTUS code) in order to interpret these tests (areas, opening displacements of faults under load, as well as residual areas corresponding to situations when ΔP = 10MPa and 17MPa). For longitudinal cracks, 20-node, 3D under-integrated elements were used. The two-layer model comprises 2888 nodes and 482 elements. As shown in Figure 5 relating to longitudinal cracks on the typical area, this calculation is consistent with test results. Moreover, for intermediate pressure values (far from critical values), opening areas are in accordance with analytical models described by Paris and Tada [6], associated with a Dugdale type plastic correction [7].

Use of fine-tuned measurements under no-pressure conditions and of plastic corrections give a precise indication of cracks under pressure and temperature conditions. These results are essential for correct interpretation of thermohydraulic data.

4.2 Loop leakage behavior

Thermohydraulic data is obtained on a continuous basis when pressure and temperature are applied to the tube. Combining measurements by weighing and turbine flowmeter makes it possible to cover a wide flow rate range (0.1 to 30,000 liters/hr). Over the whole range, the leak can be constantly fed without pressure or temperature degradation. To illustrate this, Figure 6 indicates leakage flow rate for a longitudinal crack in the typical area, as well as its interpretation for current models. The test program currently under way is designed to provide information for the "leakage flow rate" data base which includes a limited volume of information on narrow (0.005 to 0.1mm) and short (1 to 15mm) cracks. Adjustment of thermohydraulic models is achieved for situations when ΔP = 10MPa and 17MPa, at which crack geometries are well known (variations of sections with flow rate, flow convergence/divergence, etc.). Additional information (itinerary through the wall, roughness) is obtained by mechanical scanning microscopy in the tube wall at the end of the test cycle and should help improve thermohydraulic models for leakage flow rate.

5 CONCLUSION

In its recent LBRB studies on SG tubes, EDF focused on certain specific fields, including the definition of break criteria for certain specific configurations, as well as the improvement in leak flow rate models.

For multiple longitudinal cracks in RTZs, the comprehensive break criterion applied to the main crack remain valid and conservative, at least for the set of parameters considered.

For through-wall cracks located in U-bends with low bending radii, critical pressure is always greater than that corresponding to the same crack located in the typical areas, except for circumferential cracks centered on the side, for which a drop in the critical pressure is noted (20% in worst cases).

Finally, in the field of opening areas and leak flow rates, new programs have made it possible to confirm the opening area models, an essential element in defining leak flow rate models. The exploitation of mechanical and thermohydraulic data collected during these tests, using test loops dedicated to SG tubes, should help us achieve better understanding of leakage phenomena on SG tubes, particularly at low flow rates.

REFERENCES

[1] Voldoire F. (1989). Determination by the Homogenization Technique of the Overall Behavior of Steam Generator Tubes weakened by Microcrack Arrays, SMIRT 10, Vol. L, pp 103-108.

[2] Flesch B. and Cochet B. (1990). Leak Before Break in Steam Generator Tubes, Int. J. Pres. Ves. & Piping 43, pp 165-169.

[3] Cochet B. and Flesch B. (1989). Application of the Leak Before Break Concept to Steam Generator Tubes, SMIRT 10, Vol. D.

[4] Gillot E., Cochet B., Richard P. and Faidy C. (1987). Validation of Leak Before Break Analysis for Steam Generator Tubes, SMIRT 9, Vol. D.

[5] Cochet B. and Flesch B. (1987). Crack Stability Criteria in Steam Generator Tubes, SMIRT 9, Vol. D.

[6] Tada H. (1985). The Effect of Shell Corrections on Stress Intensity Factors and the Crack Opening Area of a Circumferential and a Longitudinal Through-crack in a Pipe. NUREG/CR-3464, Sections II-1 71-81.

[7] Dugdale D.D. (1960). Yielding of Steel Sheets Containing Slits, J. Mech. solids. Vol. 8, pp 79-89.

Table 1 Major characteristics of test loops in LBRB studies for SG tubes

	GB	BRUTUS	QUIPROCO	PERFIDE
Primary pressure (MPa)	5/17	8/51	6/8	4/16
Secondary pressure (MPa)	0.1	1/6.5	0.1	4/8
Primary temperature (°C)	220/270	350	300	220/350
Continuous leak flow rate (l/hr)	0.1/2500	30/30000	0/30	0/80
Specific features	Possible instrumentation on secondary side	Leakage & margin at break		Boron & lithium hydroxide possible on primary side

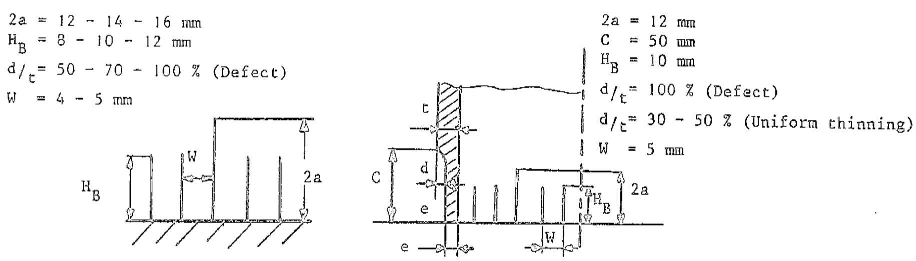


Figure 1. Test configuration for longitudinal cracks

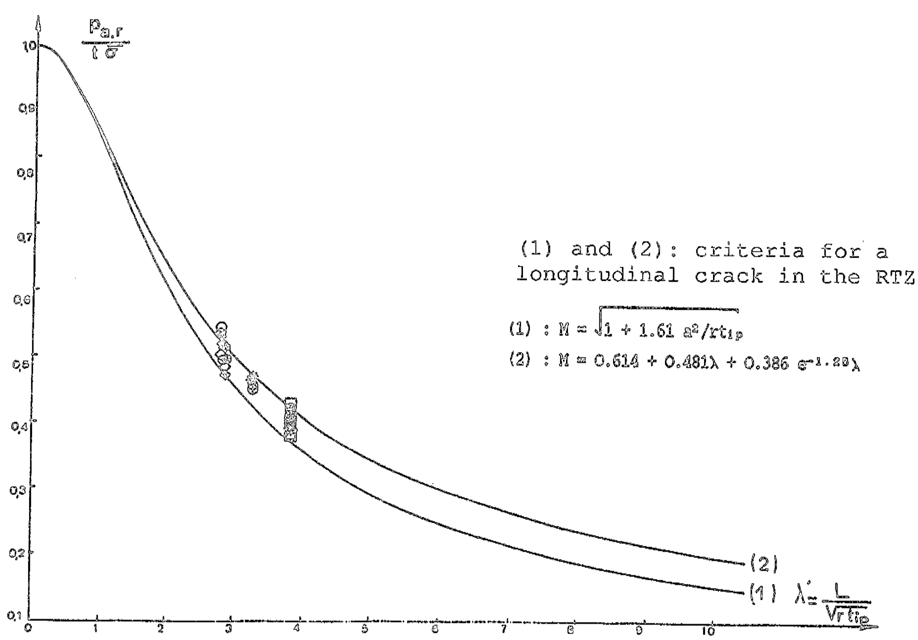
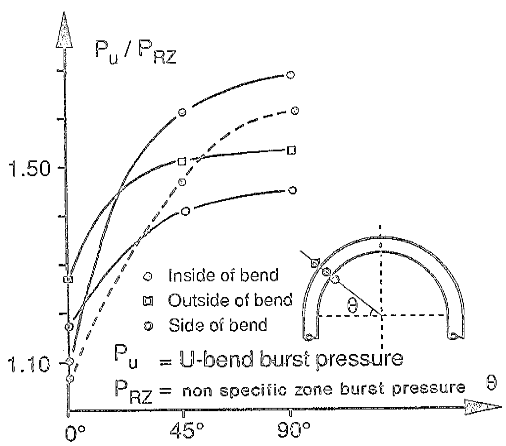


Figure 2. Burst pressure on tubes with multiple through-wall cracks in RTZ – Comparison between calculation and test results



Average values for 15mm and 20mm cracks:

------ with stress relieving
\- - - without stress relieving

Figure 3. Normalized burst pressure – Longitudinal cracks in U-bend

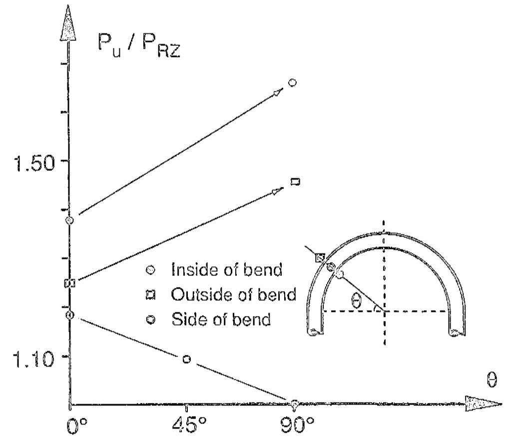


Figure 4. Normalized burst pressure – Circumferential cracks in U-bend

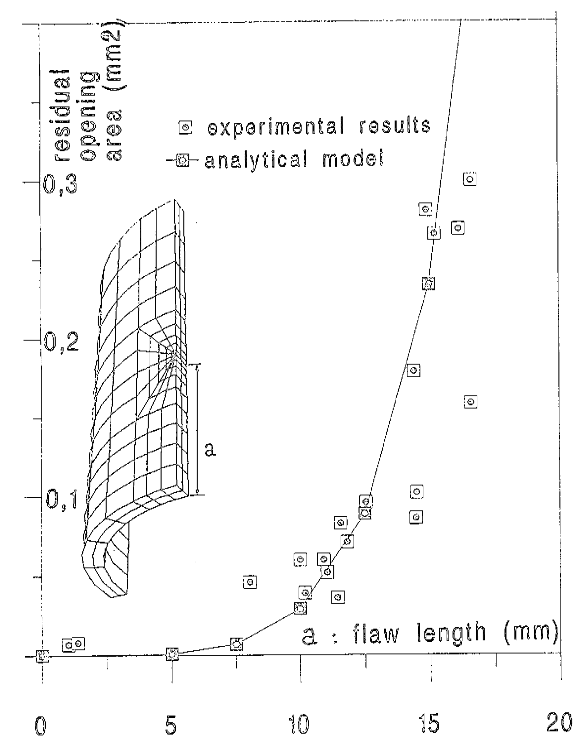


Figure 5. Longitudinal cracks – Measurement/calculation comparison

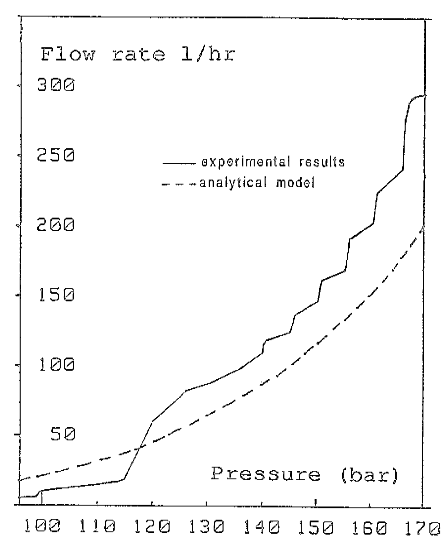


Figure 6. Flow rate restitution longitudinal crack on tube typical area