Operating Stresses and Stress Corrosion Cracking in Steam Generator Transition Zones (900-MWe PWR)

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1 INTRODUCTION

The increase in cracking phenomenon in roll transition zones on steam generator (SG) tubes of the 900-MWe and 1300-MWe PWR series operated in France has led French power utility EDF to undertake studies aimed at improving the knowledge of operating stresses in roll transition zones. These studies have three main goals: firstly, to direct both preventive and corrective maintenance actions, while maintaining both safety and availability, secondly, to contribute to the definition of tube stress corrosion damage models, in order to create an aging prediction tool for steam generators, and thirdly, to improve design in terms of corrosion resistance.

This paper describes the main points of studies conducted by EDF with support by Framatome.

2 SUMMARY OF INSPECTIONS AND TUBE EXAMINATION

This section contains the main findings of inspection and examination results that may help analyze stresses in roll transition zones.

- Stress corrosion in roll transition zones accounts for the largest part of damage noted on SG tubes; for example, on the 900-MWe series, which at the end of 1990 showed an average rate of affected tubes of 13% - representing some 44,000 tubes with indications - only 2,200 tubes have indications that may have appeared outside the roll transition zone.
- In almost all cases, cracks in roll transition zones are longitudinal and located on inside diameter.

Only a limited number of tubes (less than 60 for all 900-MWe reactors) are affected by circumferential cracks; and these concern, almost exclusively, tubes featuring rolling faults, or tubes that have been subjected to the specific explosive expansion treatment (Westex process), or tubes located in the central sludge area, or tubes suffering from denting. Circumferential cracks are generally located on inner walls. However, a few cases where cracks are located on outer walls have nonetheless been noted outside the sludge area. For tubes that show no anomalies and no denting, cracks may appear in 5 to 6 cycles and develop at a rate of 20° to 30° per cycle.

Except for the above-mentioned cases, circumferential cracks are always located in the central part of the bundle. This zone has been identified as a preferential zone for sludge deposit, due to the thermohydraulic conditions that prevail on the secondary side (low-speed zones, boiling zones) [1].

3 OPERATING STRESSES

Operating stresses result in fact from several different actions on the tube, such as:

- residual manufacturing stresses (drawing, forming, dressing),
- residual roll stresses,
- permanent assembly stresses (due to a tube geometry before assembly which does not perfectly match its compulsory routing through its supporting elements),
- operating stresses (pressure and temperature affecting tube walls, either directly or indirectly, through interaction with supporting elements),
- possible denting stresses.

Operating stresses and residual stresses have been studied separately, using mathematical analysis for operating stresses and mathematical and experimental analysis for residual stresses.

Studies related to denting stresses are not discussed here; refer to document [4].

4 RESIDUAL STRESSES

The basis for determination of residual stresses is essentially experimental: corrosion tests and X-ray diffractometry measurements have enabled determination of stress levels, essentially on the inner wall, for different rolling configurations, both normal and abnormal.

Results concerning tubes with and without kiss rolling are shown in Figure 1: maximum stress levels on the inner walls are of the same order of magnitude (approximately 350MPa) and concern the circumferential component at the bottom of the roll transition zone for both types of transition, as well as the axial component at the top of the roll transition zone for tubes without kiss rolling.

At the same time, EDF has developed numerical models in order to have light tools for residual stress computation [3] and [4]. These tools enable systematic analysis of the various rolling types by enabling parametric studies of major data elements characterizing the rolled link.

5 OPERATING STRESSES

The term "operating stresses" covers stresses resulting from both conditions of assembly and SG operating conditions, as they are of the same type. These stresses have been determined by means of two sets of finite element calculations: one is related to axisymmetrical stresses, the other to non-axisymmetrical stresses.

Operation at nominal power, with and then without sludge on the secondary side, and certain particularly severe transients have been analyzed.

Results concerning the central tube of a 900-MWe steam generator are given below. Similar results are available for other configurations and for the 1300-MWe series.

5.1 Calculation models

The evaluation of so-called "axisymmetrical" stresses (direct action of pressure and thermal loading on tube walls) is carried out using a two-dimensional axisymmetrical and non-linear model, which represents a tube section that takes into account the geometry of the rolled zone and an equivalent ring representing the tube sheet (Figure 2a). The model can be used to simulate any separation in the tube-sheet assembly and to take into account the influence of rolling, while integrating the tube-to-sheet interface pressure.

The evaluation of "non-axisymmetrical" stresses (external movements imposed on the tube) is carried out using a three-dimensional model representing a tube section and an equivalent ring representing the tube sheet (Figure 2c). The load set typical of these non-axisymmetrical effects is applied at the model end; it is generated by a comprehensive steam generator model which makes it possible to simulate the interaction of tubes with their supporting elements (Figure 2b).

5.2 Operation at nominal power

- Axisymmetrical stresses are not significant. The maximum level is obtained on the outer wall for the circumferential component and reaches 150MPa
- Non-axisymmetrical stresses evaluated under unfavorable assembly and external stress conditions result in values of about 80MPa for axial stress on the outer wall of the peripheral tube. For the central tube under study, this value is less than 10MPa.
- evolution of resulting stresses along the tube is given in Figure 3.

5.3 The effect of sludge

Certain steam generators in service are found to have deposits of sludge on the secondary side of the tube sheet. These deposits adversely affect heat transfer through tube walls. The previous numerical models enabled simulation of these effects (Figure 3):

- in the vicinity of the last point of contact on the inner wall there is a large increase in the axial component (+150MPa) and a slight drop in the circumferential component (-10MPa).
- on the outer wall, in the vicinity of the last point of contact, there is a virtually identical drop in the stress level of the two components, while 2mm higher, that drop applies mainly to the circumferential stress, with the longitudinal stress being only slightly affected.

These findings may contribute to explaining the appearance of circumferential cracks, with phenomena being accelerated by increases in wall temperature and by the deterioration of the local chemical conditions on the secondary side. A denting might significantly increase these effects [4].

5.4 Operating transient effect

Under transient conditions, the change over time of pressure and temperature may have more or less impact on stresses, according to the speed and amplitude of parameter variations. The structure's response under two transient operating conditions, selected according to their mechanical severity, has been calculated in order to make sure that such evolutions would not result in redistribution of residual stresses.

Results given in Table 1 show that certain stresses, both in terms of extreme values and amplitude, may exceed the minimum specified yield point. Although, due to initial cold rolling, this limit is higher, certain transients may lead to a redistribution of residual stresses, which would thus modify basic conditions for cracking risks.

6 TOTAL OPERATING STRESSES

Due to the high values of residual stresses and operating stresses with respect to the minimum yield point specified, accurate determination of total operating stresses would theoretically require a complete elastoplastic calculation involving calculation of stress levels previously subjected to the rolling cycle. These complex calculations can be carried out in the medium-term. It is however possible to give a correct estimation

of total stresses in the roll transition zone where cyclic strain hardening resulting from the rolling operation dramatically increases the initial yield point of the tube. It thus remains reasonable to simply add up residual stresses and operating stresses to obtain an evaluation of total operating stresses. Table 2 gives such estimates with and without sludge, for a 900-MWe PWR steam generator.

The table shows that on the inside diameter of a tube with kiss rolling and without sludge, the circumferential stress predominates, whereas, in the presence of sludge, longitudinal stresses bridge the gap with respect to circumferential stresses. The slight difference between the two components may explain the simultaneous presence on certain tubes of longitudinal and circumferential cracks. Conversely, for full-depth rolling without kiss rolling, maximum total stresses are only slightly affected by sludge on inside diameter.

7 CRACKING RISKS

While longitudinal cracks do not pose major safety-related problems in roll transition zones, mainly because the concept of Leak Before Risk of Break (LBRB) applies in most cases, this is not true of circumferential cracks, which often exhibit poor LBRB behavior.

It is therefore of prime importance for the operator to list situations likely to lead to circumferential cracks, in order to prevent such cracks from occurring, or, if this is not possible, to strengthen their inspection policy.

In this respect, the above-mentioned results show that when sludge is deposited on the secondary side, even when they do not cause tube denting, risks of circumferential cracks are increased. Also, stress conditions (particularly on the inside diameter) are modified "for the benefit" of the longitudinal component. Should this imbalance be further increased by non-nominal rolling, for example, cracking would certainly be circumferential.

8 SUMMARY AND CONCLUSION

Circumferential cracking on inside diameter of roll transition zones in Model 51 steam generators affects only a limited number of cracked tubes. With the exception of causes so far identified (rolling faults, specific rolling, denting), it is clear that tubes with circumferential cracks are all located in the central part of the tube sheet, a zone which favors the deposit of sludge.

The correlation between sludge and the circumferential orientation of cracks can be explained by the modification of thermal stresses in the roll transition zone, resulting from the alteration in heat transfer: an estimate of total operating stresses has enabled quantification of the respective significance of longitudinal and circumferential components and shown that due to the presence of sludge, prevailing stress conditions may switch from circumferential to longitudinal, particularly on inside diameter.

When associated with the increases in wall temperature induced by the external presence of sludge, such stresses are likely to cause a circumferential crack on the inside diameter. Stress deviation may even be inverted under the influence of a weak complementary effect.

It would then be reasonable to try to limit sludge zones in steam generators in order to minimize the occurrence of circumferential cracks. These cracks are more difficult to manage than longitudinal cracks due to uncertainties in terms of propagation kinetics and to problematic application of the LBRB concept.

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Table 1. Operating stresses maximum values and amplitudes (Peripheral tube)

Unit: MPa	I.D.		O.D.	
	σ_L	σ_C	σ_L	σ_C
Maximum stress	90	180	460	510
Maximum amplitude	470	180	470	530

Table 2. Total operating stresses maximum values on I.D. (Central tube)

Unit: MPa	I.D.	
	σ_L	σ_C
FDR without KR		
without sludge	310	390
with sludge	330	400
FDR with KR		
without sludge	220	430
with sludge	380	400

FDR: Full-Depth Rolling
KR: Kiss Rolling

Fig. 1. Residual stresses - Inside diameter

Fig. 2. Finite element models used to calculate stresses in steam generator tubes above the last contact point between the tube and the tube sheet.

Fig. 3. Steady-state power operation. Stress evolution along the tube