Integrity Analysis of Cracked Steam Generator Tubes

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ABSTRACT
This paper presents the flaw assessment program undertaken in France for PWR steam generator tubes affected by stress corrosion cracking. Failure criteria were deduced from burst tests on various crack configurations. Stresses and critical crack sizes were estimated for all operating conditions. The corresponding leak rates during normal operation were computed after validation of the model. Then it was shown that a significant primary to secondary leak should precede tube failure.

1 - INTRODUCTION
Steam generator tube damaging is one of the most challenging problems a PWR unit user may have to face. And one of the most difficult damaging process to cope with is stress corrosion cracking. In order to assess the severity of stress corrosion cracks detected in steam generator tube, Electricité de France and Framatome, operator and NSSS supplier of more than 30 PWR units, started a comprehensive theoretical and experimental program. The present paper will describe the main points of this program and discuss methodologies and results.

2 - STEAM GENERATOR TUBE CRACK ASSESSMENT PROGRAM
The steam generator tube crack assessment program was mainly devoted to the tube lower part where French PWR units experienced most of their problems [1]. It started with burst tests of uncracked tubes to characterize the material (inconel 600). Then, burst tests on current part of tubes with machined cracks were performed in order to establish a burst criteria which takes in account the crack length and depth and the applied stress (only pressure stress in this case). Cracks were longitudinal or circumferential, through-wall or part-through wall. Specific burst tests were conducted in order to investigate the influence of some "second order" parameters: boundary conditions, tube-sheet or support plate proximity, crack formation mechanisms, number and distance between several defects, pressure increase rate etc...

Then, pressure and thermal stresses in a tube were calculated for each operating transient (normal, upset, emergency and faulted conditions). In each case, critical crack size was estimated using the previously mentioned criteria, possibly "calmed" for some "second order" parameters. Leak areas and leak rates through these critical size cracks were computed for normal operating conditions. Laboratory leak rate measurements through stress
corrosion cracks allowed to validate these computations.

At last, numerous experiments and tests were performed to get a better knowledge of actual crack shape evolution.

The intent was to demonstrate that such cracks are unlikely to grow unstable and lead to a tube rupture without being, first, preceded by a significant primary-to-secondary leak (i.e. larger than the maximum allowable leak rate).

3 - TUBE RUPTURE CRITERIA

3.1 - Burst under pressure

Burst tests under pressure on tubes with through-wall longitudinal cracks allowed to validate an appropriate rupture criteria for this specific situation. This criteria is based on the concept of plastic instability occurring when the applied stress $\sigma^*$, amplified by the bulging (factor $M$), reaches a critical value $\sigma^*[2]$:

$$M \sigma^* = \sigma^*[1]$$

(1)

with $\sigma^* = \frac{1}{12} \left( \sigma_y + \sigma_u \right)$

For the part-through wall cracks, the approach is similar with the applied stress becoming a net section stress. Comparison between theoretical and some experimental results is shown in figure 1.

3.2 - Influence of "second-order" parameters

Below are the main findings of the part of the program devoted to the so-called "second-order" parameters:

- The pressure increase rate has no influence, at least in the realistic range.
- Crack origins has no effect on tube rupture (see figure 1, particularly tests on actual Bugey tubes).
- There is no significant interaction between several parallel longitudinal cracks (distance down to $3 \text{ mm}$).
- Presence of a support plate near a longitudinal crack may only increase the burst pressure by restraining the bulging.

3.3 - Tube rupture criteria for operating conditions

For practical application, the above mentioned criteria raises several questions: various possible rupture mechanisms are not distinguished (plastic instability and/or crack initiation and tearing which do occur in some tests); thermal stresses and large stress variations are difficult to account for; experimental and analytical results appear to be uneasy to correlate for circumferential cracks. Using a "double criteria" similar to the C.E.G.B. R-8 procedure [3] was thought to be helpful in solving some of these difficulties by extending the applicability of the first criteria. The risk of failure is, then, assessed by positionning the point $(K_R, SR)$ in the failure assessment diagram.

- $K_R$, which characterizes the risk of crack initiation and tearing, is computed from:

$$K_R = \frac{K_{ICP}}{K_{JC}}$$
with, for through wall cracks:

\[ K_{ICP} = M \sigma_m \sqrt{\pi (a + r_y)} + \lambda (\sigma_p - \sigma_m) \sqrt{\pi (a + r_y)} \]  

(2)

- \( M \): bulging factor depending on \( a \times (R \cdot t)^{-1/2} \) and crack orientation
- \( a \): half-crack length ; \( R \): tube radius ; \( t \): tube thickness
- \( \sigma_m \): membrane stress normal to the crack
- \( \sigma_p \): peak stress on O.D. or I.D., normal to the crack
- \( r_y \): plastic zone size
- \( \lambda \): peak stress participation factor.

- \( S_R \), which characterizes the risk of plastic instability, is given by:

\[ S_R = \frac{M \sigma_m}{\sigma_T} \]  

(3)

(for circumferential cracks, \( \sigma_m \) is taken as the net section stress).

\( \sigma_T \): flow stress = \( \frac{1}{2} (\sigma_y + \sigma_u) \)

Comparison between this criteria and testing results is shown in figure 2. The failure assessment diagram appears as a safe curve for flaw assessment purpose.

4 - CRITICAL CRACK SIZE EVALUATION

4.1 - Current zone in the lower part of tubes

Firstly, the analysis focused on the lower part of tubes, but far enough from the tube-sheet. Total stresses were computed for normal, upset, emergency and faulted transients using finite element method. Critical size for longitudinal and circumferential cracks were estimated for each transient. The most severe of them appears to be the feedwater line rupture. The corresponding critical size is around 16 mm for longitudinal through-wall crack and more than 180° for circumferential crack when using the minimum specified values of material characteristics (fig. 3).

4.2 - Vicinity of the tube-sheet

The case of cracks in the tube-sheet vicinity was also addressed. If the cracked part of the tube is completely or partly within the tube sheet, its bulging is restricted and so is the leak and the break capability. Then, only the length of the "emerging" part should be considered. More exactly, the "effective length" was taken as the length of the crack above the point where contact is lost between tube and tube-sheet, this point being slightly below the tube-sheet upper face due to thermal conditions. Specific burst tests were performed to validate this approach.

The proximity of the tube sheet induced a longitudinal stress gradient so that, when applying eq.2, the membrane stress is taken as the average value on the effective crack length and the peak stress is taken at the upper crack tip level. For the most severe loading, the critical effective length is then 16.5 mm.

5 - LEAK ESTIMATES

To demonstrate that a crack should induce a significant leak prior to instability, the leak rate during normal operation was estimated for through-wall longitudinal and circumferential cracks having the critical size.

The first step was to calculate the leak area as a function of crack size using a
finite element model and assuming elastic behaviour of the material. The plastic behavior of the crack tip region was accounted for by applying an Irwin type correction so that the actual crack length was increased by:

\[ r_y = \frac{1}{2\pi} \left( \frac{K_P}{\sigma_f} \right) \]

Elasto-plastic computations showed this correction to be appropriate.

Then, the leak rate was estimated through a simple analytical relationship:

\[ Q = K_S \sqrt{2} \Delta P / \rho \]

\( K \): Experimental coefficient; \( S \): Leak area; \( \Delta P \): Differential pressure.

To validate this theoretical approach, tests were performed with actual stress corrosion longitudinal cracks. Results are shown on figure 4. It can be seen that stress corrosion cracks, because of their shape, have O.D. size different from I.D. size. Taking into account the average length gives a reasonably good agreement, except for very small cracks which are of minor interest. It may be noted that the average length seems to be also the relevant parameter regarding burst tests. For critical size cracks, the predicted leak rates during normal operation are larger than maximum allowable leak rate.

6 - POINTS UNDER REVIEW

The above mentioned studies constitute an almost complete "leak-before-break" demonstration. The main point to be investigated more deeply is the demonstration that a crack will likely become a through-wall crack before reaching a critical size. This point is under review using laboratory stress corrosion cracking experiments and actual steam generator tube expertises.

Extension of the project should address some specific questions like the effect of temperature, the case of U-bend cracks etc...

7 - CONCLUSION

As a conclusion, it can be said that, before a crack induces a steam generator tube failure, a primary-to-secondary leak in excess of specifications should warn the plant operator and lead to a preventive reactor shut-down.

REFERENCES


Fig. 1: Comparison between plastic instability criteria and burst test results.

Fig. 2: Burst test results in the failure assessment diagram.

Fig. 3: Failure assessment diagram for feedwater line rupture conditions.

Fig. 4: Computed and measured leak rates for longitudinal cracks.