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Electric Power
Research Institute

Keywords:
Alloy 600
Stress corrosion cracking
Steam generators

EPRI NP-6865-L
Volume 1
Project S404-25
Final Report
Non Proprietary Version
October 1993

# Steam Generator Tube Integrity

## Volume 1: Burst Test Results and Validation of Rupture Criteria (Framatome Data)

NON-PROPRIETARY VERSION

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## ABSTRACT

The operating experience of steam generators shows that the tubes in alloy 600 are affected by stress corrosion cracking caused by the reactor coolant (PWSCC) in the roll transition area. These tubes which must fulfill under all steam generator operating conditions, the safety function while retaining sufficient mechanical integrity to preclude the risk of tube bursting, can stay in service if it is possible to determine the dimensions of potentially unstable cracks.

The burst risk assessment of steam generator tubes subjected to internal pressure, thermal loadings and external loadings representative of mechanical loadings in postulated accident conditions, requires the experimental validation of rupture criteria.

This summary report presents an overview of the relevant results which have been obtained from an extensive burst test program performed by Framatome on more than 690 burst tests carried out on 19.05 mm (0.750 inches) and 22.22 mm (0.875 inches) diameter tubes made of alloy 600 and representative of steam generator tubes in service.These burst tests have been performed with various types of damage located in the straight portion of the tubes remote from discontinuities or in the roll transition zone at the top of the tubesheet.These tests enabled validation of rupture criteria based on the concept of plastic instability.For the rupture criteria used, deviations between tests and theoretical predictions are lower than %.
Computation models have been qualified for tubes without cracks and for tubes with longitudinal or circumferential surface and through-wall cracks. These models can be reliably used to determine the critical dimensions in a damaged tube at any given temperature and stress level. The critical crack dimensions will be used to define tube plugging criteria and/or inservice surveillance requirements.

ACKNOWLEDGEMENTS

This report includes part of the results of the studies performed by Framatome for Electricité de France and the Swedish State Power Board about steam generators.

The author wishes to acknowledge Jan Engström from S.S.P.B. as well as Jean Pierre Hutin and Bruno Flesch from E.D.F. for numerous fruitful discussions and for agreeing to the publication of results reported in this report.

Bernard Cochet
Principal Investigator

NOMENCLATURE

Geometry of the tube

| | |
|---|---|
| Ø | : Nominal tube diameter |
| $D = D_1$ | : Actual outer tube diameter |
| $D_o$ | : Actual inner tube diameter |
| t | : Tube thickness |
| tr | : Local tube thickness at the level of the unstable defect (crack) |
| tmin | : Minimum tube thickness |
| R = Ro = Ri | : Inner tube radius |
| $R_1 = R_e$ | : Outer tube radius |
| r | : Mean radius |

Geometry of the defect (crack)

| | |
|---|---|
| L = 2a | : Length of the longitudinal defect (crack) |
| $L_c$ | : Critical defect (crack) length |
| d | : Depth of the defect (crack) |
| e | : Thickness of remaining ligament of the longitudinal or circumferential part-through defect (crack) |
| $e_r$ | : Thickness of remaining ligament at the level of the unstable defect (crack) |
| $2\alpha$ | : Angle of the circumferential defect (crack) |
| $N_D$ | : Number of defects (cracks) |
| W | : Width of the ligament between two parallel longitudinal cracks. |

$x$ : Distance or length of the ligament between two aligned longitudinal cracks.

$M$ : Bulging factor, function of the geometry of the cracked tube section.

$2\theta$ : Angle defining the damage sector of the tube circumference.

$\lambda$ =

$\lambda^*$ =

$S_o = A_o$ : Initial crack opening area

$S = A$ : Crack opening area due to the effect of the pressure

Physical parameters

$P = P_o$ : Inner pressure

$P_1$ : Outer pressure

Pa : Burst pressure or instability limit pressure for a through-wall defect (crack) : initiation and instability of a defect (crack) with initial length 2a.

$P_r$ : Burst pressure for a sound tube, or rupture pressure for a tube with a part-through defect (crack) - Rupture of the remaining thickness of a part-through defect (crack).

$P_f$ : Pressure applied on the sides (surface) of the defect (crack).

$\sigma r$ : Radial stress

$\sigma\theta$ : Circumferential stress

$\sigma z$ : Longitudinal stress

Rm : Tensile strength

Re (0.2 %) : 0.2 % offset yield strength

| | | |
|---|---|---|
| A | : | Rupture elongation (%) |
| E | : | Longitudinal elasticity modulus - Young's modulus |
| $\nu$ | : | Poisson ratio |
| $\sigma_0$ | : | Flow stress for material, governing rupture due to plastic instability $Re \leq \sigma_0 \leq Rm$ |
| $\sigma f$ | = | 1/2 (Re + Rm) : mean plastic flow stress for the material |
| $\bar{\sigma}$ | : | Flow stress for the material (value adjusted experimentally) constant for the material governing plastic instability. |
| s | : | Standard deviation |
| N | : | Number of tests |

ABBREVIATIONS

| | | |
|---|---|---|
| F.D.B. | : | Flow distribution baffle |
| F.L.B. | : | Feedwater line break |
| S.C.C. | : | Stress corrosion cracking |
| S.L.B. | : | Steam line break |
| T.S.P. | : | Tube support plate |
| I.D. | : | Inner diameter |
| O.D. | : | Outer diameter |

CONVERSION FACTORS

| MULTIPLY | BY | TO OBTAIN |
|---|---|---|
| mm | 0.03937 | inch |
| bar | 14.504 | PSI |
| MPa | 145.04 | PSI |

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## Section 1
## INTRODUCTION

The operating experience of steam generators shows that the tubes in alloy 600 are affected by stress corrosion cracking caused by the reactor coolant (PWSCC). A knowledge of critical crack dimensions can enable the plant operator to define either an operating surveillance requirement based on the leak before break criterion, which precludes the risk of rupture in the event of accidental overpressure, or to define tube plugging criteria which takes into consideration crack propagation kinetics (1). The critical crack dimensions can be reliably determined using rupture criteria based on the concept of plastic instability.

This summary report presents an overview of the relevant results which have been obtained from an extensive burst test program performed by Framatome on more than 690 burst tests carried out on 19.05 mm (0.750 inches) and 22.22 mm (0.875 inches) diameter tubes made of alloy 600 representative of steam generator tubes in service.
Moreover, more than 400 additional burst tests carried out recently have confirmed results presented in this report.

This report includes the following :

- Characteristics of alloy 600
- Determination of the burst pressure of tubes without defects.
- Analysis of the behavior of tubes with one defect (crack) located in the straight portion remote from discontinuities.
- Analysis of the behavior of tubes with one or several defects (cracks) located in the roll transition zone.

The study is limited to the case of tubes with defects (cracks) located in the straight portion remote from discontinuities or in the roll transition zone.

## Section 2

## PHYSICAL AND MECHANICAL CHARACTERISTICS OF BURST TEST TUBE SAMPLES

Tube samples used in the burst tests were taken from different heats which met procurement specifications for heat transfer tubes in the steam generator tube bundles of pressurized water reactors.

### 2.1 TUBE DIMENSIONS

The tube geometric characteristics are specified below :

Ø 22.22 mm
- Nominal outer diameter : $22.22 \begin{smallmatrix} + 0.13 \\ - 0.18 \end{smallmatrix}$ mm
- Nominal thickness : 1.27 ± 0.12 mm

Ø 19.05 mm
- Nominal outer diameter : $19.05 \begin{smallmatrix} + 0.10 \\ - 0.15 \end{smallmatrix}$ mm
- Nominal thickness : 1.09 ± 0.10 mm

Unless indicated otherwise, the analysis and interpretation of test results were based on the actual dimensions of tubes and defects, measured to within 0.01 mm.

### 2.2 MATERIAL

Analysis of results is carried out considering the actual mechanical characteristics of the tube samples.

- Grade : nickel, chromium and iron alloy 600
  - Brand : Nicral Z (Inconel 600)
  - Supplier : Vallourec
- Condition as supplied :
  - Mill-annealed (M.A) :
  - Thermally-treated (T.T.) :
- Chemical analysis : See Table 2.1

  The chemical composition complied with procurement specifications for steam generator tubes.

TABLE 2-1

ALLOY 600 - TUBE SAMPLES - PRODUCT CHEMICAL ANALYSIS

- Mechanical characteristics at 20°C and elevated temperature : See Table 2.2

TABLE 2-2

TUBE SAMPLES - MEAN MECHANICAL CHARACTERISTICS OF ALLOY 600

These mechanical property results were based on at least 3 tensile tests carried out on tubes which met the French NFA 49851 standard, which, in technical terms, coincides to a large extent with the international ISO 6892 standard. The characteristics obtained complied with the RCCM Code and with the ASME Code, Section III, Case 1484-3 or Case N20. The minimum characteristics have been summarized in the table below :

TABLE 2-3

MINIMUM MECHANICAL CHARACTERISTICS SPECIFIED BY ASME AND RCC-M CODES

The evolution of the 0.2 % yield tensile strength Re and ultimate tensile strength Rm with respect to temperature may be expressed by the variation of the coefficients :

$$\frac{Re\ (20°C)^*}{Re\ (\theta°C)} \quad \text{and} \quad \frac{Rm\ (20°C)^*}{Rm\ (\theta°C)}$$

* Room temperature.

The following mean values (Table 2-4) were obtained using acceptance test results for 22.22 mm and 19.05 mm diameter tubes : See Table 2-5.

TABLE 2-4

STRENGTH RATIOS - FRAMATOME RESULTS

TABLE 2-5

ALLOY 600 TUBES
TUBE MATERIAL PROPERTIES BASED ON TENSILE TESTS
AT ROOM AND ELEVATED TEMPERATURES
FRAMATOME RESULTS : MEAN VALUES

Available results did not indicate any significant difference between Re and Rm values for mill-annealed tubes and values for tubes subjected to stress-relieving heat treatment at 715°C.

Tensile tests on tubes from the same heat were carried out to ensure that the mechanical characteristics had not been significantly modified by complementary heat treatment. The maximum difference between M.A. and T.T. tubes was lower than 2 %, which is of the same order of magnitude as the scatter noted for tensile test results.

TABLE 2-6

MECHANICAL PROPERTIES : COMPARISON BETWEEN M.A. AND T.T. TUBES

## 2.3 STRESS-STRAIN CURVE - HARDENING COEFFICIENT

The strain hardening coefficient n was obtained using the tensile true stress-strain curve, with $\sigma$ and $\epsilon$ defined as follows :

Testing confirmed that the true stress-strain curve was described accurately by the formula between % of plastic strain and necking. For plastic strain lower than %, the actual stress was greater than the stress calculated by means of this formula.

The mean tensile strain-hardening coefficient value based on test results is :

## 2.4 TOUGHNESS OF ALLOY 600

The only available results to date are those from the Hanford Laboratories (4). A material with mechanical properties comparable to those listed in the materials file for tubes in alloy 600 and a similar chemical composition was subjected to tests at 24°C.

The discontinuous test method was used to determine the regression line characterizing stable crack propagation between mm. The intersection of this line and the blunting line yields a value for $J_{IC}$ at 24°C between KJ/m² and KJ/m², depending on the slope of the blunting line (See Figure 2-1). The value KJ/m² may be taken to represent alloy 600 at room temperature.

**Figure 2-1. R curve for alloy 600 tested at (4)**

The $J_{IC}$ value at 300°C was estimated using results for austenitic stainless steels similar to alloy 600 in terms of their mechanical properties and toughness. To go from the toughness value at 20°C to that at 300°C, a multiplier of has been derived from a review of literature data.

The following selected values are currently in use :

## Section 3

## BURST TESTS ON TUBES WITHOUT DEFECTS

### 3.1 RESULTS OF TESTS ON 19.05 MM AND 22.22 MM DIAMETER TUBES

86 burst tests were carried out at room temperature on 19.05 and 22.22mm diameter tubes from different heats. The results are in Table 3-1

- The mean burst pressure value, a function of tube mechanical characteristics, was :

$$\frac{Pr}{Rm} = \qquad (3\text{-}1)$$

  This mean value was based on results for 46 test specimens whose relative thickness t/Ri was between

- Complementary heat treatment to sensitize the alloy 600 tubes to stress corrosion cracking decreased the burst pressure by about %.

Generally speaking, rupture was preceded by significant, generalized plastic strain in the tube. Longitudinal rupture occurs in the straight portion remote from discontinuities, at some distance from the ends. Ductile rupture was characterized by shear lips at from the direction of the principal stresses. In some specific cases, the rupture deviated in the circumferential direction. This deviation may be due in part to the fact that tube geometry was not perfectly axisymmetrical (e.g.oval shape and variable tube thickness).

As a result, non-axisymmetrical plastic strain occurred, which can cause local distortions after breakthrough. Thus, the hypothesis that the longitudinal stress $\sigma_z$ is the intermediate principal stress is no longer necessarily justified for tubes with generalized plastic strain. The deviation may also be caused by changes in the local stress field due to generalized bending stress at the rupture brought about by the jet impingement effect after breakthrough : See Figure 3-1.

In Table 3.2, a comparison of results from 157 tests is shown. It shows that a displacement-controlled loading does not modify the burst pressure for a sound tube. Test loadings were exerted 150 mm above the fixed end in the support representing the tubesheet. The loading values employed, encompassed those values that steam generator tubes are likely to encounter.

. Plastic deformation of tube and longitudinal rupture in straight portion of the tube remote from discontinuities.

. Ductile rupture and shear lips at

. Deviation of the rupture in circumferential direction.

Figure 3-1. Photographs showing the rupture of a sound tube
Tubes in alloy 600 - Ø 19.05 mm - Ø 22.22 mm

TABLE 3-1

BURST PRESSURE - TUBES WITHOUT DEFECTS
CORRELATION BETWEEN THE FLOW STRESS AND THE CHARACTERISTICS OF THE MATERIALS

TABLE 3-2

BURST PRESSURE - TUBES WITHOUT DEFECTS
STUDY OF THE INFLUENCE OF A CONTROLLED EXTERNAL LOADING APPLIED TO TUBES

TABLE 3-3

MAXIMUM BENDING STRESS RESULTING FROM A DISPLACEMENT CONTROLLED EXTERNAL LOADING

The displacement controlled loading was applied to tubes as a pinching effect accompanied by local rotation resulting from deformation of the support plate, or as a bending stress due to a shift in the relative positions of the lower support plate and tubesheet.

When a tube was subjected to both internal pressure and an external loading, rupture occurred outside the plane in which the loading was applied.

## 3.2 ANALYSIS OF RESULTS

Test results indicate that Svensson's formula can be used to predict an accurate burst pressure value for tubes without defect.

(3-2)

with :

. (3-3)

. n : Mean hardening coefficient calculated using the true stress-strain curve.

. e : 2.71828 - logarithmic base.

The comparison of test results in Table 3-1 reveals that theoretical and test findings coincide fairly well when using the mean hardening coefficient value based on the results of 18 tests at room temperature :

When the burst pressure was calculated using this formula, theoretical and test findings did not deviate by more than % for all heats considered.

Given the scatter in the value of n, the burst pressure was calculated more accurately when the value of n used was that for the heat under consideration :

TABLE 3-4

BURST PRESSURE OF A SOUND TUBE - COMPARISON BETWEEN THEORETICAL AND TEST FINDINGS

Tests were conducted with and without the end effect to confirm that end effects do not modify the burst pressure of a sound tube. As a result, the maximum shear stress criterion (Tresca) which is valid whatever the end effect, is appropriate for use in predicting the rupture. The hypothesis that the longitudinal stress is the intermediate principal stress may be considered valid, which greatly simplifies analysis. The distribution of stresses in the tube wall may be calculated by combining the plastic flow stress :

(3-4)

and the equilibrium equation :

(3-5)

The resulting differential equation may be directly integrated to yield the pressure needed to produce the plastic flow given by the following formula :

(3-6)

Considering that rupture by plastic instability initiates when the uniform shear stresses in the tube wall reach a limiting value $\sigma_0 = \bar{\sigma}$, the above formula may be applied and the plastic flow stress $\sigma_0$ may be adjusted to $\bar{\sigma}$ as a function of the test results in Table 3-1.

The flow stress may be expressed in a form which is easier to determine :

(3-7)

with :

Here, the coefficient is approximately given by

This test result can be reinterpreted using the solution based on the Mises criterion. The threshold function associated with the Mises criterion in the plane of a stress deviator can be linearized by replacing the arc, representing the threshold of plasticity with the tangent. This is equivalent to substituting $2\,\sigma_0/\sqrt{3}$ for $\sigma_0$ in the expression of the Tresca criterion.

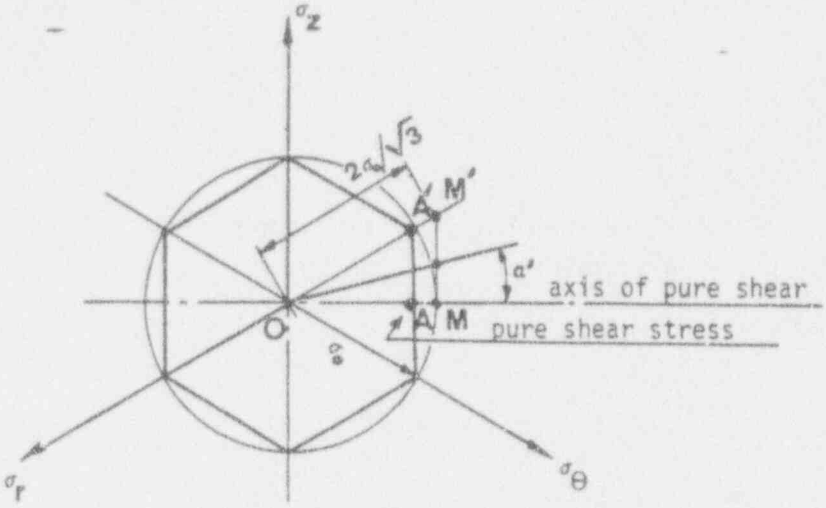


Figure 3-2. Tresca or Mises criterion in the plane of stress deviator

When a mean flow stress $\sigma_o = \sigma_f = 1/2$ (Re + Rm) was selected, the burst pressure for a sound tube was underestimated by about % when the previously-mentioned formula was used.

Section 4

# STUDY OF THE BEHAVIOR OF STEAM GENERATOR TUBES WITH A DEFECT LOCATED IN THE STRAIGHT PORTION REMOTE FROM DISCONTINUITIES - CASE OF TUBES NOT SUBJECTED TO AN EXTERNAL LOADING

## 4.1 BURST TESTS ON TUBES WITH A LONGITUDINAL, PART-THROUGH DEFECT

To study the response of tubes with longitudinal, part-through defects (cracks) located in the straight portion remote from discontinuities and to validate rupture criteria, Framatome carried out 105 tests at room temperature. The tubes tested were Ø 19.05 mm and Ø 22.22 mm and featured different types of defects with the following lengths : mm. Depths ranged from of the tube wall thickness. To confirm the results obtained, 12 tests with and without a radial thermal gradient were conducted at temperatures between at the Aquitaine test facility (CEN - Cadarache).

More recently, the results of a burst test program on the Superclaudia facility (CEN - Cadarache) at temperatures between have confirmed theoretical predictions using rupture criteria presented in this section (5).

### 4.1.1 Results of tests at room temperature

These results were obtained on tubes which were not subjected to a displacement-controlled external loading.

Generally speaking, it was observed that :

- The bulge in the tube wall was barely perceptible prior to rupture of the remaining ligament (thickness : e) of the part-through defect. For a given notch length, the bulge size at the time of breakthrough decreased as the notch depth increased.

- After ligament rupture, the crack area opened and the defect - now through-wall - showed a localized bulge. For a given length, initiation and unstable propagation of the crack after ligament rupture depended on the pressure level reached inside the tube before breakthrough : See Figure 4-1.

- The burst pressure of a " wear " type defect was greater than or equal to that of a " notch " type defect. In the latter case, defects obtained by electron discharge machining or milling were compared to confirm that the instability limit pressure was not significantly influenced by notch sharpness.

- Rupture of remaining ligament without unstable crack propagation (the surface defect becomes a through-wall crack) : crack opening is limited to the length of the initial crack (stable crack).

- Instability of the crack after rupture of the remaining ligament of surface defect.

Figure 4-1. Photographs showing the rupture in the case of a surface defect located in the straight portion of the tube remote from discontinuities.

#### 4.1.1.1 Results of tests on 22.22 mm diameter tubes

Burst test results for tubes with different types of defects (Figure 4-2) appear in Figures 4-3 and 4-4. The defect lengths used in these comparative tests were mm, and the depths were % of the tube wall thickness.

For a given defect length and depth, the " V-notch " type of defect produced by milling or electron discharge machining yielded a lower burst pressure than the " machined flat or wear " type or the "EDM square slot" type produced by electron discharge machining.

Test results for tubes " V-notch " type defects with lengths of mm are shown in Tables 4-1 and 4-2 and in Figure 4-5.

A test at bar on a tube with a crack due to stress corrosion cracking obtained in the laboratory did not cause rupture of the remaining ligament (thickness e) of the part-through crack (depth : % of the tube wall thickness). This crack was located in the roll transition zone (full-depth and kiss-rolling) : See Table 4-3 and Figure 4-5.

In Table 4-4 burst test results are given for tubes whose walls were characterized by practically uniform thinning on a length of mm over all or part of the tube circumference. Defect depths ranged from of the tube wall thickness. As a result of tube geometry and the manner in which defects were produced, a variation of between % in the thickness of the remaining ligament was obtained for each defect.

Generally speaking, before rupture of the remaining ligament (thickness e), a bulge appeared in the thin-wall area. In all cases, rupture occurred within the limits of the damaged part of the tube. A partial explanation may be that a constant pressure was not maintained after the ligament ruptured : See Figures 4-6 and 4-7.

Figure 4-2. Types of degradation - longitudinal surface defects

Figure 4-3. Longitudinal surface defects in the straight portion remote from discontinuities - Steam generator tube rupture at room temperature.
Alloy 600 - Ø 22.22 mm - Rupture pressure of the remaining ligament versus the thickness of the remaining ligament.

Figure 4-4. Longitudinal surface defects in the straight portion remote from discontinuities - Steam generator tube rupture at room temperature.
Alloy 600 - Ø 22.22 mm - Rupture pressure of the remaining ligament versus the thickness of the remaining ligament.

Figure 4-5. Longitudinal surface defects in the straight portion remote from discontinuities.
Rupture of steam generator tubes at room temperature
Tubes in alloy 600 - Ø 22.22 mm

Figure 4-6. Burst tests on alloy 600 tubes - Ø 22.22 mm : Photographs showing the rupture of the remaining ligament in the case of a local uniform thinning over an angle of $2\theta$ ($2\theta$ =

Figure 4-7. Burst tests on alloy 600 tubes - Ø 22.22 mm : Photographs showing the rupture of the remaining ligament in the case of a uniform thinning over the entire tube circumference.

TABLE 4-1

RESULTS OF BURST TESTS ON TUBES WITH A LONGITUDINAL SURFACE DEFECT
IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
TUBES IN ALLOY 600 - Ø 22.22 mm

TABLE 4-2

RESULTS OF BURST TESTS ON TUBES WITH A LONGITUDINAL SURFACE DEFECT
IN STRAIGHT PORTION REMOTE FRCM DISCONTINUITIES
TUBES IN ALLOY 600 - Ø 22.22 mm

TABLE 4-3

RUPTURE PRESSURE OF A PART-THROUGH S.C.C. CRACK

(SEE FIGURE 4-5)

TABLE 4-4

BURST PRESSURE FOR TUBES WITH UNIFORM THINNING IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
TUBES IN ALLOY 600 - Ø 22.22 mm - t = 1.35 ± 0.01 mm

4.1.1.2. <u>Results of tests on 19.05 mm diameter tubes</u>

Burst test results for tubes with longitudinal defects of different lengths and depths are shown in Figure 4-8 and Tables 4-5 and 4-6.

The following types of defects were examined :

- " Wear " type defects long produced by milling.

- " Longitudinal notch " type defects produced by milling or electron discharge machining, with lengths : mm. The results confirmed that the rupture pressure is not significantly influenced by notch sharpness. In particular, for the case of a part-through crack, in specific cases, when the rupture pressure (Pr) is lower than the burst pressure corresponding to a through-wall crack of the same length (Pa), one obtains a crack due to the rupture of the remaining ligament which has the same behavior as that of the machined notch. When pressure is increased after the ligament ruptures, instability of the defect or crack - now through-wall - occurs at a pressure level equal to that needed to cause instability in an initial through-wall defect produced by electron discharge machining (identical length, width mm) : See Figure 4-1.

Figure 4-8. Longitudinal surface defects in the straight portion remote from discontinuities. Rupture of steam generator tubes at room temperature.
Tubes in alloy 600 - Ø 19.05 mm

TABLE 4-5

LONGITUDINAL SURFACE DEFECTS
RUPTURE OF ALLOY 600 STEAM GENERATOR TUBES AT ROOM TEMPERATURE

TABLE 4-6

RESULTS OF BURST TESTS ON TUBES WITH A LONGITUDINAL SURFACE DEFECT
IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
TUBES IN ALLOY 600 - Ø 19.05 mm

### 4.1.2 Results of tests at elevated temperature

Table 4-7 shows test results for 19.05 mm diameter tubes with a defect penetrating over of the wall thickness, exposed to temperatures between In each case, test conditions were such that defect response was confirmed after ligament rupture at maximum pressure. Given the capacity of the test installation, flow was maintained through the crack for a few minutes. Depending on internal pressure at rupture, either crack stability or instability was observed : See Figure 4-1.

5 tests were carried out to evaluate the influence of thermal shock on the ligament rupture pressure obtained for a part-through defect on the outer tube wall. Its influence on the longitudinal stability of the defect - now through-wall - was also evaluated. During these tests, the pressure loading was combined with a radial thermal gradient.

Test conditions encompassed those to which steam generator tubes would be subjected under accident conditions (steam line break or feedwater line break) : Tables 4-8 and 4-9.

The test principle is as follows : See Figure 4-10 :

- Primary side pressure and temperature were increased until the internal pressure reached Pr (Pr : ligament rupture pressure estimated without a thermal gradient).

- Stabilization of the pressure and temperature for a few minutes.

- Then, simultaneous pressure build-up and injection of cold water (about ) until the ligament of the part-through defect ruptured. Test conditions were such that the thermal shock was not severe and a thermal gradient was set up in the tube wall thickness in less than second : See Figures 4-11 and 4-12.

- The ligament of the part-through defect ruptured while a thermal gradient was established in the tube wall (See Figure 4-10). After the rupture, the installation was depressurized gradually. This experiment demonstrated that one should take into account the back pressure which developed on the secondary side when the cold water was injected : See Figure 4-13.

These test results can be found in Table 4-10.

Figure 4-10. Thermal shock test : schematic diagram of test procedure

Figure 4-11. Thermal Transient - Instantaneous temperatures versus time.

Figure 4-12. Thermal transient - Temperature profile across tube wall thickness

Figure 4-13. Pressures recorded during tests : AQUITAINE facility

TABLE 4-7

RESULTS OF BURST TESTS AT ELEVATED TEMPERATURE ON TUBES WITH A LONGITUDINAL SURFACE DEFECT
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 4-8

STUDY OF THE INFLUENCE OF A THERMAL GRADIENT THROUGH THE TUBE WALL
TUBES IN ALLOY 600 - Ø 19.05 mm - TEST CONDITIONS

TABLE 4-9

DESIGN TRANSIENT FILE - CONTROLLED CONDITIONS APPLIED TO THE STEAM GENERATOR TUBES

TABLE 4-10

RESULTS OF BURST TESTS ON TUBES WITH A LONGITUDINAL SURFACE DEFECT
IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
STUDY OF THE INFLUENCE OF A THERMAL GRADIENT THROUGH THE TUBE WALL
TUBES IN ALLOY 600 - Ø 19.05 mm

- TEST 48 :

A tube containing a defect with a length of mm and depth of % was brought to a pressure of 172 bar and temperature of :. These conditions (P,T) were maintained for minutes. After test conditions were stabilized, the tube was subjected to maximum pressure and temperature levels of bar and . It was confirmed that, as expected, the ligament mm thick remained stable. At this point, cold water was injected suddenly during seconds on the secondary side, creating a back pressure and subjecting the tube to a maximum differential pressure of bar. The fluid temperature gradient was Thus, thermal stresses created by the thermal gradient of in the tube wall were added to stresses due to the pressure of bar. The difference between the fluid temperature gradient of and the tube wall temperature gradient of was due to the heat transfer coefficient. After the second injection, the tube was again brought to a uniform temperature of . Internal pressure was increased until the tube was again at a pressure of bar and a temperature of . These conditions were maintained for minutes. It was observed that the defect remained stable. Ligament rupture did not occur in a second test with a maximum differential pressure of bar and primary/secondary side temperature difference of .. Neither of the two thermal shocks caused the tube to burst.

- TEST 18 :

Based on the results of tests at elevated temperature without a thermal gradient, the ligament rupture pressure was estimated to be bar for a defect mm long with a depth of %.

. Pressure and temperature levels were simultaneously and gradually increased to bar and . These conditions were maintained at a constant level for minutes.

. Cold water was injected.

. Internal pressure was raised from bar to the rupture pressure in about seconds. The back pressure on the secondary side was such that the ligament ruptured for a differential pressure of bar.

The crack expected to remain longitudinally stable, remained stable after the ligament ruptured.

- TEST 55 :

The ligament rupture pressure was estimated to be between and bar for a defect mm long and a depth of %.

. Pressure and temperature were increased gradually to bar and . Stabilization of test conditions for minutes.

. Injection of cold water

. The rupture pressure was reached in about seconds. Back pressure measured bar.

The crack, expected to remain longitudinally stable, remained stable after ligament rupture at a differential pressure of bar.

- TEST 56 :

  The ligament rupture pressure was estimated to be between and bar for a defect whose length was mm and depth was %.

  . Simultaneous pressure and temperature build-up to bar and . Stabilization for 5 minutes.

  . Injection of cold water .

  . Rupture pressure was obtained in about seconds. Back pressure was bar.

  The crack, expected to remain longitudinally stable, remained stable after the ligament ruptured at a differential pressure of .

- TEST 58 :

  The ligament rupture pressure was estimated to be between and bar for a defect whose length was mm and depth was .

  . Simultaneous pressure and temperature build-up to bar and . Stabilization for minutes.

  . Injection of cold water .

  . Rupture pressure was obtained in about seconds. Back pressure was .

  The crack, expected to remain longitudinally stable, remained stable after the ligament ruptured, at a differential pressure of .

  For a defect of a given length on the outer tube wall, it was confirmed that the ligament rupture pressure was greater than that obtained for a tube not subjected to a thermal gradient as in tests 18-55-56-58. In the first analysis, the difference seems to be significant.

### 4.1.3 Analysis of results

For a " notch " or " wear " type defect test results show that the burst pressure for tubes not subjected to an external loading decreases in proportion to an increase in depth when the depth is in the range % of the tube wall thickness : see Figures 4-5 and 4-8.

The distribution of test points (Pr/Rm, e/t) is such that the instability limit pressure, Pr, for the remaining ligament can be determined by considering the following empirical formula :

when t/R and L are fixed. A and B are constants.

When determining Pr using this formula, there is less than uncertainty for defect depths of of the tube wall thickness : See Figure 4-5, Table 4-5. This result was confirmed by 65 burst tests, no matter what dimensions of defects were studied.

When the limit of stability of notched, worn or cracked tubes was reached, the ligament ruptured at the bottom of the defect, with or without longitudinal rupture propagation. The ligament ruptured in a plane practically perpendicular to the hoop stress.

The comparison of tests 105 and 106 (See Table 4-4) shows that, for a given ligament thickness (d/t = %), rupture pressure decreased by when the angle $2\theta$ was increased from . On the other hand, the comparison of tests 106 and 104 does not clearly indicate a decrease in rupture pressure when the angle was increased from . The difference between the latter two defect configurations of identical length can be explained in the first stage of analysis by the difference in the remaining ligament thickness.

These results are summarized in the Table below :

**TABLE 4-11**

**RUPTURE PRESSURE OF THE REMAINING LIGAMENT IN THE CASE OF A UNIFORM THINNING : SUMMARY OF THE RESULTS**

A comparison of the test results with the predictions of the Svensson formula equation 3-2 which is valid for a tube whose walls are characterized by thinning over the entire tube circumference and length, shows that this formula is very conservative (See Table 4-4). Test results indicate that it yields a rupture pressure which is low by at least in the case of defects long and from deep. This difference is due to the local reinforcement of the non-deteriorated part which prevents the thin-wall area of the tube from bulging freely. This effect is less pronounced when the defect depth is smaller or the defect length greater.

Conversely, given the instability pressure, Svensson's formula, applied to this type of defect long, defines equivalent thicknesses at least greater than the actual remaining thickness at the level of rupture.

$$e_q \geq 1.5 \text{ e min.}$$

The equivalent thickness $e_q$ depends on the length and depth of the defect.

These results are summarized in the Table below :

TABLE 4-12

**RUPTURE PRESSURE OF THE REMAINING LIGAMENT IN THE CASE OF A UNIFORM THINNING : SUMMARY OF THE RESULTS**

The comparison of test results for " locally thinned " type defects with a " notch " type defect or crack of identical length and depth shows that the former cannot be considered equivalent to a crack of identical dimensions. In some cases, the rupture pressure is overestimated : See Table 4-4.

The burst pressure for tubes with longitudinal part-through defects can be obtained using a criterion such as the plastic flow instability criterion (Tresca). The predictions agree with test findings when the material flow stress $\sigma_0 = \overline{\sigma}$ is properly adjusted on the basis of burst tests on sound tubes.

The following formula is used to calculate the burst pressure for tubes with a part-through defect with great accuracy :

(4-1)

in which $A_e$ is the notch or crack opening area, $A_0$ is the area of a tube section whose length is (2a + 2t). The instability criterion for a longitudinal part-through defect in a steam generator tube can also be expressed as follows :

(4-2)

For the defects examined, the mean deviation between theoretical and test findings remained lower than when calculating the ligament rupture pressure with the formula below (corresponding to criterion (1) in the Tables of results ) :

(4-3)

associated with the flow stress .

In all cases, and whatever the heat considered, the maximum deviation remained lower than compared to test results :

- On diameter tubes containing defects with lengths of and depths d/t of : See Tables 4-1 and 4-2.

- On diameter tubes containing defects with lengths of and depths d/t of : See Figure 4-14.

For defect depths over , this criterion is no longer appropriate since it yields an overestimated ligament rupture pressure.

The instability criterion may be expressed in another form by using the empirical formula proposed by Battelle (6).

(4-4)

23 tests were done on 19.05 mm diameter tubes with defects long and depths ranging from of wall thickness. These tests showed that rupture predictions based on the following formula (criterion (2) and (3) in the Tables of results) :

(4-5)

In association with the bulging factor M defined by formulas (1) or (2) in Figure 4-15 and Table 4-13, encompassed the test results with a degree of accuracy lower than : See Table 4-6. The lower limit for these test results is obtained by using formula (1) associated with $\sigma_0$ = Rm. Predictions for rupture at elevated temperature without a thermal gradient confirmed those obtained at : See Tables 4-7 and 4-14.

Figure 4-14. Longitudinal surface defects in the straight portion remote from discontinuities - Rupture of steam generator tubes at room temperature - Tubes in alloy 600 - Ø 19.05 mm

Figure 4-15. Longitudinal through-wall defect - Bulging factor M as a function of parameter $\lambda$.

TABLE 4-13

M BULGING FACTOR

TABLE 4-14

COMPARISON OF TEST RESULTS AT ROOM TEMPERATURE AND AT ELEVATED TEMPERATURE
TUBES IN ALLOY 600 TUBES - Ø 19.05 mm

Generally speaking, whatever the defect lengths and depths, a lower limit for test results was obtained using the maximum shear stress criterion for the ligament associated with the flow stress defined by the formula $\bar{\sigma} = K(n)\ Rm$ : See Figures 4-5 and 4-8.

This criterion was defined by means of the following formula :

(4-6)

For defects whose length and depth were given, the comparison of results obtained at room and elevated temperatures show that predictions of rupture at elevated temperature can be deduced from test results at room temperature when the mechanical characteristics are given : See Table 4-14.

Although not very significant, the influence of a thermal gradient on the instability limit pressure of a part-through defect was not negligible as shown by the results in Table 4-10. Comparing the results of tests 55 and 18 with a thermal gradient and of test 15 without a thermal gradient (See Table 4-10(a)), given the same geometry of tube and defect, shows that differences in ligament rupture pressure in comparison with the results of Test 15 can range from for a thermal gradient $\Delta T$ of and , respectively (Table 4-8). In test 15, the wall temperature was , whereas in Tests 55 and 18, with defect depths of , the respective inner wall temperatures were . These differences were due to a difference in actual mechanical properties of alloy 600 as a function of metal temperature. In conclusion, these tests indicate that the influence of the thermal gradient is not significant and is contradictory to theoretical analyses, as a minimum difference of was obtained for a maximum $\Delta T$ of .

Given the mechanical characteristics at , a close approximation of the ligament rupture pressure can be obtained for a tube with a part-through defect subjected to a radial thermal gradient by means of the following formula :

(4-7)

with : $\bar{\sigma}_{\theta th}$ : the mean thermal stress in the ligament thickness (See Table 4-15). Predicted values presented in Table 4-10 agree with test results (within ).

In all cases, applying the formula (2) in Table 4-10, we obtain the most conservative results.

Tests confirmed that the rupture pressure for a part-through defect with a depth of can be determined using a plastic flow instability criterion based on the mean hoop stress.

This criterion can be estimated closely by using the form :

(4-8)

After an adjustment in flow stress $\bar{\sigma}$ to take into account the results of 65 tests on 19.05 mm and 22.22 mm diameter tubes, a value for $\bar{\sigma}$ was obtained such that the mean difference with the value yielded by the formula .

Considering the scatter in results and criteria used, it was observed that values for $\bar{\sigma}$ based on the results of tests on sound tubes and tubes with longitudinal part-through defects were fairly consistent : See Table 4-16.

**4.2 BURST TESTS ON TUBES WITH A LONGITUDINAL THROUGH-WALL DEFECT**

To study the behavior of steam generator tubes in alloy 600 with longitudinal through-wall defects of lengths

Framatome carried out 120 tests at room temperature on 19.05 mm and 22.22 mm diameter tubes. To confirm the results obtained, 16 tests were conducted at temperatures ranging from at the Aquitaine test facility (CEN -Cadarache). More recently, the results of a burst test program at room temperature and at temperature between have confirmed theoretical predictions using the rupture criteria presented in this section.

TABLE 4-15

THERMAL STRESSES IN WALL AND LIGAMENT
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 4-16

FLOW STRESS OF MATERIAL - CORRELATION
TUBES IN ALLOY 600

### 4.2.1 Results of tests at room temperature

#### 4.2.1.1 Study of the influence of the leak-tightness device

After studying the influence of the leak-tightness device needed for room temperature rupture testing of tubular specimens with through-wall defects, Framatome developed a leak-tightness technique for each defect length which ensured that the influence of the device on rupture pressure would be insignificant. The leak-tightness device in current use does not require correction of the instability limit pressure or burst pressure. Use of this device, which is composed of a flexible plastic tube with or without " anti-extrusion " foil, has demonstrated that :

- Applying a varying degree of friction to the inner wall to limit the defect or crack opening resulted in rupture initiation at the tip of the defect at a pressure level which was higher than it would have been if the device had not been used. The development of this leak-tightness device and test technique relied on minimizing the dimensions of the stainless-steel " anti-extrusion " foil positioned at the defect and using local lubrification to reduce friction to an insignificant level. A comparison of results obtained with and without foil shows that results were identical when the flexible plastic tube was not extruded before instability was reached.

- When pressure was applied to the edges of the defect or crack, the instability limit pressure was lower than that obtained when internal pressure was not applied to the defect edges prior to rupture initiation. Tests were carried out with or without extruding the leak-tightness device through the crack.

- In addition, the test conditions which did not employ a sealing device (i.e. in the case of an initial part-through defect which becomes a through-wall crack after ligament snap-through) and which maintained a large leak rate through the potentially unstable crack (after tube breakthrough) allowed the test results using the leak-tightness device to be confirmed.

#### 4.2.1.2 Definition of the instability limit pressure of the through-wall defect

The maximum test pressure reached in the tests corresponds to the instability limit pressure Pa of a longitudinal through-wall defect with a length of 2a. This instability limit pressure or burst pressure for a tube with a longitudinal through-wall defect is the pressure level at which rupture initiation and unstable propagation of the crack occur at each end of the initial through-wall defect : See Figure 4-16.

When $P < Pa$, the defect remains stable. Maintaining the pressure constant at a level below the limit pressure does not cause defect instability. Generalized plastic collapse does not occur : See Figure 4-17.

Figure 4-16. Photographs showing a stable and an unstable longitudinal through-wall defect - Initial length :

Figure 4-17. Typical pressure versus time curve to determine the instability limit pressure of a through-wall crack

$P < Pa$ : defect stability

$P = Pa$ : Initiation and unstable propagation of the rupture

When P ≥ Pa, the defect is unstable and the tube ruptures.

Generally speaking, before the through-wall defect or crack reaches instability, significant localized bulging occurs at the defect, and the crack opening area widens. Instability is generally accompanied by considerable necking of the tube wall at the tip of the through-wall crack. When the instability limit pressure Pa is reached, rupture initiation at each end of a defect with length L and unstable propagation of the crack are observed while internal pressure is maintained constant. Stopping the fluid injection when Pa is reached does not necessarily stop crack propagation however despite a drop in internal pressure.

Let $P_i$ < Pa, the pressure at an instant t after rupture initiation. $Pa_i$ is the instability limit pressure for a crack with a length of $L_i > L = 2a$ :

- If
  crack propagation stops

- If
  the crack remains unstable and propagation continues

4.2.1.3 <u>Results of tests on 19.05 mm and 22.22 mm diameter tubes</u>

Burst tests at room temperature carried out on 19.05 mm and 22.22 mm diameter tubes with a longitudinal through-wall defect located in the straight portion of the tube remote from discontinuities revealed the following important information :

- Internal pressure caused localized plastic strain (bulging) at the defect. At the same time, the crack opened and significant necking occurred at each end of the defect.

- For a defect with a given initial length, bulging (and consequently the crack opening angle), had to be sufficient to cause defect or crack instability.

- Whatever the defect length studied, when the instability limit pressure Pa was reached, rupture initiation and unstable longitudinal propagation occurred at each end of the defect, whether pressure was maintained constant or allowed to decrease. As for sound tubes, the rupture sometimes deviated in the circumferential direction, causing a " guillotine " rupture (See section 3). For all tests, rupture was governed by plastic instability. Generally speaking, an examination of the fracture appearance showed that the rupture was ductile, and characterized by shear lips at from the axes of the principal stresses : See Figures 4-18 to 4-21.

- Longitudinal propagation of the rupture

Figure 4-18. Unstable propagation of a longitudinal through-wall defect - initial length :

- Deviation of the longitudinal crack which may lead to circumferential rupture of the tube.

Figure 4-19. Unstable propagation of a longitudinal through-wall defect Initial length

- Defect stability
- Initiation of rupture and unstable propagation of the crack at both ends

Figure 4-20. Unstable propagation of a longitudinal through-wall defect - initial length :

- Initiation of rupture and unstable propagation of the crack at both ends
- Deviation of the crack in circumferential direction : maintaining the pressure leads to a guillotine rupture.

Figure 4-21. Unstable propagation of a longitudinal through-wall defect - Initial length :

- Maintaining a constant pressure below the instability limit pressure did not cause defect instability. Generalized plastic collapse did not occur in tubes with a longitudinal crack.

- The pressure needed to cause rupture initiation and unstable propagation of the crack decreased as the length of the defect increased.

- The rate of crack propagation depended on the pressure which caused rupture initiation at each end of the defect. For a defect with a length of , the instability limit pressure was sometimes over , depending on the mechanical characteristics of the particular tube. In this case, the tube burst immediately after rupture initiation. For a defect with a length of , the instability limit pressure was lower than and slow crack propagation was observed.

- It was confirmed that a pressure build-up rate between and exerted practically no influence on the instability limit pressure of the through-wall defect : See Table 4-17.

- With the leak-tightness device, it was possible to show the effect of applying pressure to the defect or crack edges, i.e. a decrease in the instability limit pressure : See table 4-18.

For a tube whose outer diameter was 19.05 or 22.22 mm and relative thickness was , and which contained a longitudinal through-wall defect (length : ) in the straight portion remote from discontinuities, Pa corresponded to the pressure needed to cause rupture initiation and defect instability.

Tables 4-19 to 4-27 contain test results for each tube, mean values and standard deviations. These results were obtained for tubes which were not subjected to any additional external loading.

4.2.2 Results of tests at elevated temperature

4.2.1.1 Test principle

- Sample tubes containing part-through defects of given lengths and depths were subjected to a uniform and increasing internal pressure until the bursting point was reached.
  For tubes with part-through defects, the response of the defect was examined after the remaining ligament ruptured.
  For a given defect length, test definitions made it possible to select the defect depth such that the ligament rupture pressure for part-through defects was as close as possible to the pressure causing instability in a through-wall defect of identical length.
  Crack propagation might also be caused by dynamic effects following rupture of the remaining ligament and the continued leak rate through the crack which had become a through-wall crack following plastic instability of the part-through crack ligament. These test conditions which did not employ a sealing device allowed the actual test pressure to be exerted on the sides (surfaces) of the crack, thus favoring instability.

TABLE 4-17

INFLUENCE OF THE RATE OF PRESSURE BUILD-UP ON THE INSTABILITY LIMIT PRESSURE FOR A THROUGH-WALL DEFECT

TABLE 4-19

LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE
CRITERION OF PLASTIC INSTABILITY - CORRELATION : $\bar{\sigma}$

TABLE 4-20

LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE
CRITERION OF PLASTIC INSTABILITY - CORRELATION : $\bar{\sigma}$

TABLE 4-21

LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE
CRITERION OF PLASTIC INSTABILITY - CORRELATION : $\overline{\sigma}$

TABLE 4-22

LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE
CRITERION OF PLASTIC INSTABILITY - CORRELATION : $\bar{\sigma}$

TABLE 4-23

LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE
CRITERION OF PLASTIC INSTABILITY - CORRELATION : $\bar{\sigma}$

TABLE 4-24

RUPTURE OF STEAM GENERATOR TUBES : INSTABILITY LIMIT PRESSURE
LONGITUDINAL THROUGH-WALL DEFECT IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
TUBES IN ALLOY 600 - Ø 22.22 mm

TABLE 4-25

RUPTURE OF STEAM GENERATOR TUBES : INSTABILITY LIMIT PRESSURE
LONGITUDINAL THROUGH-WALL DEFECT IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
TUBES IN ALLOY 600 - D = 22.27 ± 0.01 mm t = 1,34 ± 0.01 mm

TABLE 4-26

RUPTURE OF STEAM GENERATOR TUBES : INSTABILITY LIMIT PRESSURE
LONGITUDINAL THROUGH-WALL DEFECT IN STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
TUBES IN ALLOY 600 - Ø 22.22 mm

TABLE 4-27

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

- Sample tubes with through-wall defects of given lengths were brought to a temperature of in pressurized water at . These tubes were then subjected to a maximum differential pressure Δ(PP - PS) of (primary side-secondary side) created by immediate depressurization of the secondary side. Sample tubes were not equipped with the leak-tightness device to maintain internal pressure.

4.2.2.2 <u>Results of tests on 19.05 mm diameter tubes</u>

Rupture tests carried out at temperatures between on 19.05 mm diameter tubes with longitudinal part-through defects located in the straight portion remote from discontinuities revealed the following information :

- Depending on the maximum test pressure for a defect of given length and depth, after ligament rupture either the defect reached instability or the crack opened without rupture initiation in the longitudinal direction.

- When the test parameter results in obtaining defect instability, the tube experienced a " guillotine " rupture in all cases.

- For a defect long, the difference obtained between two tests involving stable and unstable defects defined the area in which lies the limiting state of crack stability.

Test results are presented in Table 4-28, where defect response after ligament rupture is examined. The maximum test pressure Pr, equal to the ligament rupture pressure for a part-through defect, does not necessarily represent the instability limit pressure Pa for the defect, now a through-wall crack :

If $Pr < Pa$ - the crack was stable after the ligament of a part-through defect ruptured.

If $Pr \geq Pa$ - the crack was unstable after the ligament ruptured

In the case of tubes with through-wall defects long, the primary side depressurized too rapidly, so that the maximum ΔP of could not be maintained. In this case, a defect long was necessary to obtain rupture initiation and unstable propagation : Table 4-29. As depressurization was too rapid, it was impossible to draw conclusions as to the validity of this type of test.

TABLE 4-28

LONGITUDINAL THROUGH-WALL CRACKS - TUBE BEHAVIOR AFTER LIGAMENT RUPTURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 4-29

LONGITUDINAL THROUGH-WALL DEFECTS - MAXIMUM TEST PRESSURE (HOT CONDITIONS)
TUBES IN ALLOY 600 - Ø 19.05 mm -

4.2.3 <u>Analysis of results</u>

The analysis of test results shows that the burst pressure for steam generator tubes with longitudinal through-wall defects can be estimated using a plastic flow instability criterion. The rupture criterion can be expressed in a general form :

(4-9)

or (4-10)

with :

$\sigma_o$ : Stress governing plastic instability

M : Bulging factor, a function of tube geometry and crack length : See Table 4-13 - Figure 4-15

This rupture criterion was equivalent to the maximum shear stress criterion which was modified using the bulging factor M in order to take local bulging at the defect into consideration.

In Tables 4-19 to 4-23, results are presented considering the mean flow stress for the material : $\sigma_o = \sigma_f = 0.5$ (Re + Rm)

Depending on the length of the defect under examination, when the effect of applying pressure to the defect edges was not considered, the instability limit pressure was underestimated by about , with M defined by formula (2) in Figure 4-15. When the effect of applying pressure to the defect edges prior to rupture initiation was considered, the deviation between theoretical and test findings was lower than . The lower bound of the test results was predicted using M defined by formula (1) in Figure 4-15.

For a properly-adjusted value of $\sigma_o$, the theoretical and test findings coincided fairly well, depending on whether one considered M defined by formula (1) or formula (2) in Figure 4-15 and Table 4-13 in association with the results obtained with or without the application of pressure to the defect edges.

In Tables 4-24 to 4-27 and Figures 4-22 and 4-23, results are presented considering the flow stress $\sigma_0 = \overline{\sigma}$ adjusted by applying the formula

to all test results for 19.05 mm and 22.22 mm diameter tubes :

A good correlation between theoretical and test findings was obtained :

- with M defined by formula (2) when pressure was not exerted on defect edges prior to rupture initiation.
- with M defined by formula (1) when pressure was exerted on defect edges prior to rupture initiation.

The adjustment of the flow stress $\overline{\sigma}$ as a function of test results for tubes without a defect yielded an estimated instability limit pressure Pa such that the deviation between theoretical and test findings was less than .

In some cases, pressure was applied only partially to the defect edges prior to rupture initiation (caused by partial extrusion of the leak-tightness device). This explains why the test results are sometimes located between the curves defined by formulas (1) and (2) : See Figures 4-22 and 4-23.

For 19.05 mm diameter tubes (Table 4-16), an excellent correlation was obtained between the flow stress and mechanical characteristics of the material, based on test results for sound tubes and tubes with through-wall or part-through defects. Except for the scatter characterizing test results, the constant K did not depend on the heat or the geometry of tube or defect.

The results presented in Table 4-27 confirm the validity of the mean value :

based on all test results for sound tubes and tubes with a longitudinal defect.

Figure 4-22. Burst pressure on tubes with through-wall defects- Comparison between calculation and experimental data at room temperature - Tubes in alloy 600 - Ø 22.22 mm

Figure 4-23. Burst pressure on tubes with through-wall defects-
Comparison between calculation and experimental
data at room temperature - Tubes in alloy 600 - ø 19.05 mm

For 22.22 mm diameter tubes (Table 4-16), the scatter in results was more significant. As a result, greater differences were noted for the value of k.

K =      for a tube without defect

K =      for a tube with a longitudinal through-wall defect

More recent results obtained on heats WD794 (Table 4-25) and WF 422 (Table 4-26) show that the value k =      is an underestimate.

Analysis of the results of tests carried out at elevated temperature , using the plastic flow instability criterion defined by the formula :

(4-11)

confirmed results obtained at room temperature : See Table 4-28 - Figure 4-24.

These results have yielded the following information :

- After rupture of the ligament of the part-through defect, a leak flow through the through-wall crack was observed. The through-wall crack had the same length as the part-through defect. This situation is similar to that of a steam generator tube in operation with a part-through defect or crack.
  This crack can become through-wall as a result of stress corrosion cracking and/or ligament rupture due to internal pressure. A certain amount of pressure is necessarily applied to defect edges after breakthrough.

- For lengths and depths fixed by the test conditions, when the ligament rupture was accompanied by longitudinal crack instability, the rupture criterion associated with M defined by formula (2) proposed by Krenk was not satisfactory.
  However, there is excellent agreement between the criterion associated with M defined by formula (1) proposed by Folias and the test results obtained within      See Tests 8-19-14 - Table 4-28 - Figure 4-24.

- When the ligament rupture pressure Pr was lower than that based on the rupture criterion incorporating a bulging factor M defined by formula (1), it was confirmed in all cases, that the subsequent through-wall crack resulting from the initially part-through crack due to plastic instability of the ligament, remained stable. Four tests with a radial thermal gradient of between      (Table 4-8) did not show any alteration in the instability limit pressure of the through-wall defect : Table 4-28 - Figure 4-24.

Figure 4-24. Burst pressure on tubes with an initial longitudinal part-through defect - Comparison between theoretical predictions and experimental data at elevated temperature - Tubes in alloy 600 - Ø 19.05 mm

All test results presented in Figure 4-25 show that the instability limit pressure Pa for a through-wall defect or crack can be reliably evaluated with the proposed plastic flow instability criterion, incorporating the bulging factor M defined by the formula :

Test results for tube parts long containing a defect in the straight portion remote from discontinuities, show that the combination of mechanical and thermal stresses did not modify the point at which the tube reached instability after ligament rupture for an initially part-through defect.

More generally speaking, instability analysis of cracked structures in the field of elastoplasticity can be carried out by applying the CEGB "Two Criteria Approach" a method which considers two limit responses :

- The first criterion relates to brittle rupture under conditions in which linear elastic rupture mechanics are valid.
- The second criterion concerns plastic instability of the cracked structure.

In the domain ($K_R$, $S_R$), the failure assessment line proposed by Harrison, Loosemore and Milne of the CEGB in the report R/W/R6 Revision 1 is given by the formula 4-12.
The selected parameters are used to separate stability and instability zones with a single curve limited by the two axes.
It should be noted that the R6 approach, which initially covered ferritic materials, has been extended to cover more ductile materials like austenitic structures. Experience has proved that this method, in its initial form, can give rise to a certain degree of inaccuracy in results. Consequently, many studies have been carried out resulting in a modification of the method to represent the effects of plasticity : See R/H/R6 Revision 3 (6).

Figure 4-25. Burst pressure (Instability limit pressure) on tubes with longitudinal through-wall defects. Comparison between theoretical predictions and experimental data at room and high temperature.

However, the R6 approach was applied to the case of steam generator tubes considering the following formula :

(4-12)

with :

(In-Plane Stress Conditions)

For all tests, the analysis of results was carried out considering the following numerical data :

. $J_{IC}$ = Value obtained by the intersection of the J - R curve with the blunting line.

$J_{IC}$ =

. E =

. $\nu$ =

. $\sigma_0 = \sigma_f = 1/2$ (Re + Rm)

The comparison of theoretical and test findings is presented in Figures 4-26 to 4-30.

As rupture is governed by plastic instability, it was confirmed that test points were located outside the part of the curve limited by $S_R$ when considering $\sigma_0 = \sigma_f$ associated with M defined by formula (1) in Figure 4-15 whether or not pressure was applied to defect edges : See Figures 4-26 and 4-27.

Considering M defined by formula (2) in Figure 4-15, it was confirmed that all test points agreed with the rupture curve defined by the formula: . For points located inside the predicted zone of stability, the maximum deviation between theoretical and test findings remained lower than . They correspond to the results of tests during which pressure was applied to defect edges prior to rupture : See Figure 4-28.

Figure 4-26. R6 Diagram - Longitudinal through-wall defects
Tubes in alloy 600 - Ø 19.05 mm and Ø 22.22 mm

Figure 4-27. R6 Diagram - Longitudinal through-wall defects
Tubes in alloy 600 - Ø 19.05 mm and 22.22 mm

Figure 4-28. R6 Diagram - Longitudinal through-wall defects
Tubes in alloy 600 - Ø 19.05 mm and 22.22 mm

Figure 4-29. R6 Diagram - Initial longitudinal part-through defects
Tubes in alloy 600 - Ø 19.05 mm -

Figure 4-30 - R6 Diagram - Longitudinal part-through defects
Tubes in alloy 600 - Ø 19.05 mm -

Similarly, analysis of results for tests at elevated temperature using the R6 approach shows that the test points corresponding to instability are located outside the rupture curve defined by the formula :

. See Figures 4-29 and 4-30.

Experience has proved that the test points are located in the domain of plastic instability and that, in all cases, instability is reached at the maximum test pressure Pa. Thus, the phenomenon is governed by the limit-load. As a result, it does not seem useful to apply the R6 approach to tubes in alloy 600; the instability limit pressure may be determined by applying the simplified analysis criterion defined by the formula

## 4.3 BURST TESTS ON TUBES WITH A CIRCUMFERENTIAL THROUGH-WALL DEFECT

To study the behavior of tubes with a circumferential through-wall defect in the straight portion remote from discontinuities, Framatome carried out 42 burst tests at room temperature on 22.22 mm diameter tubes.

### 4.3.1 Study of the influence of the leak-tightness device

As in the case of longitudinal defects, the process of development of the leak-tightness technique made it possible to define a foil geometry, based on the defect angle. Such a geometry has a negligible effect on the burst pressure, but leaktightness is ensured, as well as the resistance of the plastic tube subjected to internal pressure. The system design is such that it may be entirely extruded through the break opening and which therefore applies pressure to defect edges prior to rupture initiation.

### 4.3.2 Study of the influence of a support plate

Comparative tests on tubes with circumferential through-wall defects of revealed the influence of support on the tube rupture pressure or the instability limit pressure of the circumferential defect : See Table 4-30.

## TABLE 4-30

CIRCUMFERENTIAL THROUGH-WALL DEFECTS IN THE STRAIGHT PORTION REMOTE FROM DISCONTINUITIES - STUDY OF THE INFLUENCE OF SUPPORT TUBES IN ALLOY 600 - Ø 22.22 mm

It was shown that providing support between above the top of the tubesheet did not significantly alter the point at which the notched tube reached instability. The influence of support was primarily evident in a modification of the tube deflection curve. Instability limit pressure deviations obtained were of the same order of magnitude as the scatter in the test results. For all tests on tubes with circumferential defects, support was provided at a distance of .

### 4.3.3 Results of tests at room temperature

#### 4.3.3.1. Ø 22.22 mm diameter tubes without lateral support - See Figure 4-31

Burst test results for tubes with circumferential defects of are presented in Table 4-31 and Figure 4-32.

Generally speaking, the following were observed :

- The bending loading due to the application of the end effect caused a deflection of the upper part of the test specimen around an axis in the plane of the notched section and perpendicular to the defect's axis of symmetry.
- The deflection of the upper part of the tube, which could move freely, increased the defect opening; significant necking appeared at each end and a plastic hinge was formed.
- When the instability limit pressure Pa was reached, the tube ruptured in the plane of the cracked section. The rupture was ductile and characterized by a rupture plane from the direction of principal stresses.

#### 4.3.3.2. Ø 22.22 mm tubes diameter with lateral support - See Figures 4-33 to 4-36

Lateral support simulating a tube support plate was applied from the top of the tubesheet : See Figure 4-37.

- Test specimens could slide inside the guide ring.
- Local rotation at the support level was limited to a angle.

Generally speaking, the following were observed :

- The support prevented the tube from bending freely. Under the effect of internal pressure, generalized plastic strain appeared in the tube with maximum deflection at the level of the notched section. Plastic bending coincided with an axis in the plane of the cracked section perpendicular to the defect's axis of symmetry, and was accompanied by defect opening and the appearance of significant necking at each end.
- When the instability limit pressure Pa was reached, initiation and unstable propagation of the rupture were observed at each end of the defect. A rupture deviation appeared in certain cases: See Figure 4-34.

Figure 4-31. Photographs showing the rupture of tubes not supported laterally
Circumferential through-wall defect in straight portion remote from discontinuities :

Figure 4-32. Burst pressure on tubes with a circumferential through-wall defect

- Bending moment imposed on tube due to end effect
- Local bulging on circumferential defect

Figure 4-33. Photographs showing the rupture of laterally supported tubes - Circumferential through-wall defect support at from fixed end

- Initiation and unstable propagation of the rupture
- Pressure applied to the sides of the defect

Figure 4-34. Photographs showing the rupture in the case of a circumferential through-wall defect : $2\alpha = 180°$
Tubes in alloy 600 - Ø 22.22 mm

- Initiation and unstable propagation of the rupture
- Pressure applied to the sides of the defect

Figure 4-35. Photographs showing the rupture in the case of a circumferential through-wall defect : Tubes in alloy 600 - Ø 22.22 mm

- Tensile rupture of net section due to end effect
- Neither bulging or bending of t )e

Figure 4-36. Photographs showing the rupture in the case of a circumferential through-wall defect : Tubes in alloy 600 - Ø 22.22 mm

Figure 4-37. Circumferential through-wall defect in straight portion remote from discontinuities
Tube supported laterally (internal pressure loading only)

TABLE 4-31

CIRCUMFERENTIAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE - TUBES WITHOUT LATERAL SUPPORT
PLASTIC INSTABILITY CRITERION
TUBES IN ALLOY 600 - Ø 22.22 mm

- The rupture pressure was greater than that of an unsupported tube. The deviation increased as the defect length increased. Providing support for a defect of increased the instability limit pressure by about

  For defects less than or equal to , the bending loading predominated with respect to pressure.

  For a defect of , the net section ruptured under traction due to the end effect.

For a 22.22 mm diameter tube with a circumferential through-wall defect of length $2\alpha$, located in the straight portion remote from discontinuities, the pressure needed to cause rupture initiation at each end of the defect is Pa. The mean values and standard deviations for all test results are contained in Table 4-32. These results were obtained on tubes which were not subjected to a displacement-controlled external loading.

#### 4.3.4 Analysis of results - tubes without a support plate

The rupture pressure or instability limit pressure of a tube with a circumferential through-wall defect in the straight portion remote from discontinuities can be estimated using a plastic collapse model (9).

The existence of a uniform bending stress field in the net section at the level of the circumferential notch (cracked section) is assumed. With the assumption that the material is rigid/perfectly plastic, the distribution of this stress field around the neutral axis of the cracked section is represented in Figure 4-38.

The angle $\beta$ ($\beta > \pi/2$) defines the position of the stress inversion axis.

When the stress field reaches a limit value corresponding to the flow stress of the material, rupture due to plastic instability occurs.

Figure 4-38. Circumferential through-wall defect : Distribution of the stress field throughout the cracked section

TABLE 4-32

CIRCUMFERENTIAL THROUGH-WALL DEFECTS IN THE STRAIGHT PORTION REMOTE FROM DISCONTINUITIES

SUMMARY OF TEST RESULTS AT ROOM TEMPERATURE - IMPOSED SUPPORT CONDITIONS

TUBES IN ALLOY 600 - Ø 22.22 mm

For a tube subjected to internal pressure only, the resolution of the equilibrium equations yielded the following results :

- The force resulting from the stress field, normal to the cracked section, balances the pressure forces due to the end effect. In other words :

  (4-14)

  The resolution of this equation makes it possible to define the position of the stress inversion axis :

  (4-15)

- The moment resulting from the stress field in the cracked section is expressed as follows :

  (4-16)

  This moment, defined with respect to the tube axis, balances that of the resultant of pressure forces with respect to the same axis, which means :

On the basis of formulas (4-15) and (4-16) with the condition , one obtains the pressure value which causes tube collapse due to plastic instability.

(4-17)

Application of this criterion shows that for defects of short length, the longitudinal stress remains lower than the circumferential stress. In this case, the tube should burst when , assuming that collapse due to plastic instability occurs when the maximum shear stress reaches a limit value $\sigma_o$.

Or (4-18)

The minimum defect opening $2\alpha$ at which the tube bursts due to plastic instability of the cracked section is obtained when Pa given by formula (4-17) equals the burst pressure for a sound tube.

When the value for $\overline{\sigma}$ is properly adjusted, theoretical and test findings coincide well for unsupported tubes with defects of .
For defects of , the rupture pressure is underestimated when this criterion is applied : See Table 4-31 - Figure 4-32.

4.3.5 Analysis of results - Tubes with a support plate

As in the case of tube without support, the instability limit pressure Pa for a circumferential through-wall defect can be determined using a plastic collapse load model.

This model is a generalization of the criterion used for unsupported tubes. Using the equilibrium equations :

one obtains :

(4-19)

The resolution of this system makes it possible to determine the burst pressure for a tube with a circumferential defect with length $2\alpha$. The calculation of the bending moment $M_z$ (A) in the cracked section depends on the boundary effect. It can be determined using a finite element model or a beam model representing the overall behavior of a tube with a circumferential crack. The finite element method using linear elastic analysis and the " spatial shell " option of the SYSTUS system is used to simplify analysis. The moment $M_z$ (A) is determined based on the calculation of the stress field in the net section : See Figure 4-39. $M_z$(A) can also be evaluated using an analytical expression for a beam model of the cracked tube : See Figure 4-40.

Figure 4-39. circumferential crack - Calculation of the stress field in the net section

Figure 4-40. Circumferential through-wall cracks
Computation of bending moment along the crack

- Finite element model : " Spatial shell " option (SYSTUS)
- Beam model : Analytical expression

The net section acts like a body with different inertia, whose axis is characterized by a shift in position with reference to the axis of inertia of a sound tube. The parameter $l_1$, a function of the defect angle, is adjusted so that the bending moment obtained using the analytical method is equal to that obtained by finite element analysis. It can also be adjusted as a function of test results.
Analytical and test results show that the bending moment due to the end effect does not vary significantly for small and large defects.
For large defects, the net section ruptured due to traction. The parameter $l_1$ can be expressed in the form :

(4-20)

For a flow stress , the comparison of theoretical and test results, depending on whether the pressure is applied to defect edges or not, shows that test results can be encompassed using the plastic collapse load model : See Figure 4-41. The results contained in Figure 4-41 are obtained considering :

Simplified analysis, which takes into account the bulging effect due to the circumferential crack, but not the bending effect induced both by the end effect and the boundary effect, yields a lower limit for the instability limit pressure. However, it is not representative of the actual behavior of a steam generator tube with a circumferential crack.

Figure 4-41. Burst pressure on tubes with circumferential through-wall defects. Finite element model and beam plastic hinge model Comparison between calculation and experimental data. Tubes in alloy 600 - Ø 22.22 mm

## Section 5

## STUDY OF THE BEHAVIOR OF STEAM GENERATOR TUBES WITH ONE OR SEVERAL DEFECTS OR CRACKS LOCATED IN THE ROLL TRANSITION ZONE

To study the behavior of steam generator tubes with one or several defects located in the roll transition zone at the top of the tubesheet, Framatome carried out 163 tests at room temperature for E.D.F. (France) and Vattenfall-S.S.P.B. (Sweden) (10). The objective of this study was to show that the plastic instability rupture criteria validated for defects located in the straight portion remote from discontinuities can be used to predict safely the burst pressure for locally-deteriorated tubes in alloy 600 at the top of the tubesheet.

A displacement-controlled external loading can be applied to test tubes to simulate the misalignment between drilled holes in the tubesheet and drilled or broached holes in the lower support plate (Figures 5-1 and 5-2). This loading, to which steam generator tubes in operation are likely to be exposed, may be due to :

- Manufacturing tolerances and drilling non-conformities
- Thermal mismatch between support plate and tubesheet, leading to differential expansion.
- Relative shift of position between tubesheet and support plate due to an earthquake or a pipe break (feedwater line break or steam line break).
- Bending of the tubesheet due to primary side/secondary side differential pressure.

### 5.1 BURST TESTS ON TUBES WITH A LONGITUDINAL PART-THROUGH DEFECT LOCATED AT THE TOP OF THE TUBESHEET - (See Figures 5-3 to 5-5)

#### 5.1.1 Results of tests on 22.22 mm diameter tubes

Tests were carried out on 15 tubes with a longitudinal defect, part of which extended inside a support representing the tubesheet. Lengths of the part-through defect were , and its depth of the wall thickness.

Tests results on non-rolled tubes are contained in Table 5-1.

Figure 5-1. Test bench - tube loading setup
Tube / tubesheet interaction

Figure 5-2. Test bench - tube loading set up
Tube / tube support plate interaction

TABLE 5-1

LONGITUDINAL SURFACE DEFECTS LOCATED AT THE TOP OF THE TUBESHEET
ANALYSIS OF RESULTS
TUBES IN ALLOY 600 - Ø 22.22 mm
BURST TEST RESULTS FOR TUBES WITH LONGITUDINAL SURFACE DEFECT

Generally speaking, before rupture, generalized plastic strain was observed in the straight portion remote from discontinuities.Strain was prevented to a great extent about above the top of the tubesheet.This boundary effect was responsible for a local reinforcement of the tube's burst resistance in the part just above the tubesheet.Consequently, for a part-through defect in this area, the ligament rupture pressure was greater than that obtained for an identical defect in the straight portion remote from discontinuities.

To simulate the external loading encountered by tubes, a lateral shift was exerted from the defect in the same plane as the loading device representing the support plate. The purpose was to promote instability in the part-through defect and, in the event of breakthrough, favor defect opening. This shift introduced a bending stress of at the top of the tubesheet (linear elastic analysis).

5.1.2 <u>Analysis of results</u>

Considering a part-through defect of a given depth and length 2a, half of which extended inside the tubesheet, the ligament rupture pressure Pr was greater than that obtained for a tube containing the same defect with length a in the straight portion remote from discontinuities :

TABLE 5-2

SUMMARY OF TEST RESULTS : SEE TABLE 5-1

Figure 5-3. Photograph showing a longitudinal part-through defect in local zone

Figure 5-4. Photograph showing longitudinal part-through defects in local zone

Figure 5-5. Photographs r ng longitudinal part-through defects in l zone.

When the defect was entirely above and outside the tubesheet, with a length of , and the tube was only subjected to internal pressure, the ligament rupture pressure was higher than that obtained for the same defect in the straight portion remote from discontinuities. For a defect long, rupture pressure increased by about because the fixed end prevented the tube from bulging freely at the top of the tubesheet.

A tube with a defect of length at the top of, and entirely outside the tubesheet had a rupture pressure equal to that obtained for a tube with the same defect in the straight portion remote from discontinuities. The difference with respect to the rupture criterion was .

For a tube without a defect, when a lateral shift of was applied at the support plate level, the deflection imposed on the tube induced a maximum longitudinal stress of at the top of the tubesheet. Comparative analysis of results in Table 5-1 shows the influence of this loading as a decrease in ligament rupture pressure, depending on defect length.

In all cases, application of the rupture criterion to a longitudinal part-through defect, validated for a defect in the straight portion remote from discontinuities, resulted in an underestimation of the rupture pressure for a defect in the local zone.

Generally speaking, the ligament rupture pressure for a part-through defect located in the roll transition zone at the top of the tubesheet was higher than that obtained for an identical defect in the straight portion remote from discontinuities.The tubesheet clearly influenced the burst resistance of defects with a maximum length of . The influence of the bending stress exerted on the tube remained limited. As a result, the plastic instability rupture criterion validated for defects or cracks in the straight portion remote from discontinuities yielded reliable burst pressure predictions. When the remaining ligament rupture pressure Pr was greater than or equal to the instability limit pressure Pa for a defect which had become through-wall, unstable longitudinal propagation of the rupture was obtained.

## 5.2. BURST TESTS ON TUBES WITH A CIRCUMFERENTIAL DEFECT, THROUGH-WALL OR PART-THROUGH, AT THE TOP OF THE TUBESHEET (See Figures 5-6 to 5-11)

5.2.1 Results of tests on 22.22 mm diameter tubes

The results of burst tests on 14 tubes with a circumferential through-wall defect of , as well as results obtained for 49 tubes with a circumferential part-through defect of with depths of are presented in Tables 5-3 and 5-4. These defects were at the top of the tubesheet (i.e. outside its bore).

To simulate the external loading, a displacement perpendicular to the tube axis was imposed at with respect to the defect. The purpose was to promote instability in both part-through and through-wall circumferential defects and favor the opening of the latter. Depending on the displacement value, bending stresses of between were created at the fixed end of the tube (calculated for a tube assumed to have no cracks). These bending stresses corresponded to displacements of about at the lower tube plate, located from the top of a tubesheet in the case of a Type 51 steam generator.

Generally speaking, the following were observed :

- For through-wall or part-through defects whose angle was less than or equal to , longitudinal rupture occurred in the straight portion remote from discontinuities in no specific plane; the plane did not necessarily coincide with the loading plane. This shows that rupture was not influenced by the bending stress to which the tube was exposed.

- For through-wall defects, a lower rupture initiation limit value was obtained. Maintaining maximum pressure for seconds, depending on the test, did not result in defect instability.

- For through-wall defects, a " guillotine " rupture due to the end effect was obtained in all cases.

- For part-through defects whose depth was less than or equal to , rupture occurred longitudinally in the straight portion remote from discontinuities, whatever the length of the circumferential defect happened to be. For circumferential defects whose depth was about , the ligament ruptured.

Figure 5-6. Photograph showing the rupture in the case of a circumferential defect in local zone

Figure 5-7. Photographs showing circumferential through-wall defects in local zone

Figure 5-8. Photographs showing circumferential through-wall defects in local zone -

Figure 5-9. Photographs showing circumferential through-wall defects in local zone -

Figure 5-10. Photographs showing circumferential part-through defects in local zone -

Figure 5-11. Photographs showing circumferential part-through defects in local zone

TABLE 5-3

CIRCUMFERENTIAL THROUGH-WALL DEFECTS AT THE TOP OF THE TUBESHEET
ANALYSIS OF RESULTS
TUBES IN ALLOY 600 - Ø 22.22 MM AND Ø 19.05 MM

TABLE 5-4

CIRCUMFERENTIAL THROUGH-WALL DEFECTS AT THE TOP OF THE TUBESHEET
ANALYSIS OF RESULTS
TUBES IN ALLOY 600 - Ø 22.22 MM AND Ø 19.05 MM

For a defect with minimum depth , the ligament rupture pressure was without initiation of rupture of the through-wall crack. This result confirmed those obtained previously for tubes with through-wall defects (Pa > ) : a through-wall defect remained stable when subjected to pressures under .

For a defect with a depth of wall thickness, the tube ruptured at the same pressure as that needed to obtain instability in a through-wall defect.

TABLE 5-5

CIRCUMFERENTIAL DEFECTS : SUMMARY OF THE TEST RESULTS

TABLE 5-6

CIRCUMFERENTIAL SURFACE DEFECTS AT THE TOP OF THE TUBESHEET - ANALYSIS OF RESULTS
TUBES IN ALLOY 600 - Ø 19.05 mm

5.2.2 Results of tests on 19.05 mm diameter tubes

The results of tests obtained on 6 tubes with a circumferential through-wall defect of , and those obtained for 28 tubes with a circumferential part-through defect of with depths of are presented in Tables 5-3 and 5-6. The defects were located at the top of the tubesheet.

As for 22.22 mm diameter tubes, a lateral displacement was imposed at with respect to the defect. This displacement created a bending stress of at the top of the tubesheet (Calculated for a tube assumed to have no cracks). This maximum stress corresponded to a displacement at the lower support plate of a type 68/19 steam generator.The ligament of the circumferential defect of 22.22 mm diameter tubes ruptured only for defects with a depth of about of the tube wall thickness. When the defect depth was less than or equal to , rupture in the straight portion remote from discontinuities occurred in a plane which did not necessarily coincide with the loading plane.

For a defect with maximum depth of , the ligament ruptured at without initiation of rupture of the through-wall crack. This confirmed results for tubes with through-wall defects : Pa =

The comparison of results for 22.22 mm diameter and 19.05 mm diameter tubes with a through-wall defect in the local zone shows that values for the instability limit pressure Pa were about the same.

Considering tube geometry and the scatter in results, differences of less than in burst pressure were obtained for defects.

TABLE 5-7

CIRCUMFERENTIAL THROUGH-WALL DEFECTS : SUMMARY OF THE TEST RESULTS

5.2.3. Analysis of results

Generally speaking, a steam generator tube of 22.22 mm or 19.05 mm diameter with a circumferential through-wall defect of - or a part-through defect deep over the entire circumference remained stable when subjected to internal pressure. Exerting a bending stress did not modify the tube rupture pressure; the tube ruptured in the straight portion remote from discontinuities in a plane which did not necessarily coincide with the loading plane : See Tables 5-4 and 5-6.

For a defect deep, the ligament ruptured, whatever the length of the circumferential part-through defect happened to be, at a pressure higher than that of a tube with the same defect in the straight portion remote from discontinuities. Exerting a bending stress did not modify this result. The same result is also valid for circumferential through-wall defects of : See Table 5-3.

The presence of the tubesheet increased the instability limit pressure for a circumferential through-wall crack of by about : See Table 5-3.

The bending stress exerted on test specimens was much greater than that likely to be encountered by steam generator tubes in operation. Under these conditions, it was confirmed that this extra loading of the secondary type did not modify the limit state of stability of the tube when a circumferential crack reached instability.

Generally speaking, tests with or without a displacement-controlled external loading showed that, for a tube with a circumferential defect in the roll transition zone at the top of the tubesheet, rupture occurred at a pressure higher than that obtained for the same defect in the straight portion remote from discontinuities. As a result, this rupture criterion, validated for defects or cracks in the straight portion remote from discontinuities can be used to obtain conservative burst pressure predictions for a tube cracked in the roll transition zone.

5.3. BURST TESTS ON TUBES WITH ONE OR SEVERAL LONGITUDINAL THROUGH-WALL DEFECTS LOCATED IN THE ROLL TRANSITION ZONE (See Figures 5-12 to 5-14)

5.3.1. Results of tests on 19.05 mm and 22.22 mm diameter tubes

Burst test results for 36 tubes with either one or 20 longitudinal through-wall defects in the roll transition zone are presented in Tables 5-8 to 5-21.

For 19.05 mm diameter tubes, the reduction in wall thickness due to the full-depth rolling operation was between . The diametral variation, ΔØ, produced by kiss-rolling was between

For 22.22 mm diameter tubes, the reduction in wall thickness was between and the diametral variation, ΔØ, due to kiss-rolling was between

Generally speaking, rupture initiation and defect instability occurred at the upper end of the defect (i.e. the part outside the tube plate). In certain cases, the rupture deviated in the circumferential direction. Considering 20 defects of identical length or different lengths, instability always occurred at the longest defect or, as in the case of defects with the same length, at the defect with the largest crack opening area. In all cases, the defect's lower end, located entirely or partially inside the tubesheet (X = 0), remained stable. In certain cases, circumferential tearing occurred at the top of the tubesheet, due to very large strain concentrations in that area.

A defect long located outside the tubesheet in the roll transition zone remained stable. Rupture occurred in the straight portion remote from discontinuities.

5.3.2 Analysis of results

For tubes taken from the same heat, comparative analysis of the instability limit pressure values Pa for a defect in the straight portion remote from discontinuities and a defect of identical length in the roll transition zone reveals the influence of the tubesheet, i.e. an increased instability limit pressure for through-wall defects.

Figure 5-12. Photographs showing the rupture in the case of a longitudinal through-wall defect in the roll transition zone

Figure 5-13. Photographs showing the rupture in the case of 20 longitudinal through-wall defects in the roll transition zone.

Figure 5-14. Photographs showing the rupture in the case of 20 longitudinal through-wall defects in the roll transition zone.

TABLE 5-8

BURST PRESSURE FOR TUBES WITH A LONGITUDINAL THROUGH-WALL DEFECT IN ROLL TRANSITION ZONE

TABLE 5-9

BURST TESTS

TABLE 5-10

BURST TESTS

TABLE 5-11

BURST TESTS

TABLE 5-12

BURST TESTS

TABLE 5-13

BURST TESTS

TABLE 5-14

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-15

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-16

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-17

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-18

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-19

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-20

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

TABLE 5-21

LONGITUDINAL THROUGH-WALL DEFECTS - TEST RESULTS AT ROOM TEMPERATURE
TUBES IN ALLOY 600 - Ø 19.05 mm

5.3.2.1 Burst pressure for a tube with a longitudinal through-wall defect (See Table 5-9)

The test results show that the burst pressure for steam generator tubes with one longitudinal through-wall defect in the straight portion remote from discontinuities can be estimated using a plastic flow instability criterion. The criterion can be expressed as follows :

with $\sigma_0$ : stress governing plastic instability

M : bulging factor

A comparison of theoretical and test results (Table 5-14 - Figure 5-15) shows that test results are encompassed by the rupture criterion, depending on whether one considers M as defined by formula M(1) or M(2) (Table 4-13 - Figure 4-15) in association with an experimentally-adjusted flow stress $\overline{\sigma}$ = .

The results, when compared to previous ones, are comparable to those obtained when pressure was not fully applied to the defect edges in order to reach instability for a defect of initial length L : the plastic pressure sealing tube was partially extruded, depending on test pressure and initial defect dimensions. Nonetheless, these results are comparable to those obtained for other heats : See Figure 4-25.

The comparison of the results appears in the following Table :

TABLE 5-22

**BURST PRESSURE ON TUBES WITH A LONGITUDINAL THROUGH-WALL DEFECT IN THE STRAIGHT PORTION OF THE TUBE REMOTE FROM DISCONTINUITIES**

Figure 5-15 - Burst pressure on tubes with longitudinal through-wall defects or cracks located in the roll transition zone. Comparison between calculated and experimental data.

The comparison of test results shows that, for tubes taken from the same heat, the burst pressure Pa was greater for a defect in the roll transition zone with respect to that in the straight portion remote from discontinuities. This increase depends on defect length. If the defect's lower end was at the top of the tubesheet, the burst pressure increased by about for a defect, for a defect and for mm defect. It was observed that, for defects over , the local reinforcement effect due to tubesheet support was no longer significant and the tube burst at the upper end of the defect. In this case, the burst pressure Pa equalled that of a tube with an identical defect in the straight portion remote from discontinuities. The results are summarized in the Table below :

**TABLE 5-23**

**BURST PRESSURE ON TUBES WITH A LONGITUDINAL THROUGH-WALL DEFECT : INFLUENCE OF THE TYPE OF ROLLING**

The comparison of a defect above the tubesheet with a defect extending inside it, shows that the latter behaved practically like a defect. The burst pressure decrease was between . The results are summarized in the following Table :

TABLE 5-24

BURST PRESSURE ON TUBES WITH A LONGITUDINAL THROUGH-WALL DEFECT : SUMMARY OF TEST RESULTS

When the rupture criterion was applied, using M defined by the formula

, and assuming a defect long, the burst pressure was underestimated by about (Table 5-16).

The comparison of test results for 22.22 mm diameter tubes shows that, for defects long, the instability limit pressure Pa was increased by about when the defect was in the roll transition zone. The results are summarized in the Table below :

TABLE 5-25

BURST PRESSURE ON TUBES WITH A LONGITUDINAL THROUGH-WALL DEFECT : SUMMARY OF TEST RESULTS

For defects in the straight portion remote from discontinuities, applying the criterion defined by the formula above yielded an instability limit pressure underestimated by about when considering a flow stress equal to $\overline{\sigma}$ = k (Re + Rm) with k = .
When the value for the constant k is adjusted from the burst test results, the value lies between for heat WD 794 (See Table 4-25).

Applying the above-mentioned rupture criterion to defects in the roll transition zone yielded an instability limit pressure underestimated by about by comparison with the test results : See Table 5-8.

For defects long, considering only the length of the defect at the top of the tubesheet, the instability limit pressure was underestimated by about .

The results were not modified when actual dimensions of non-rolled tubes were used instead of specified tube characteristics for the full-depth and kiss-rolling transition zone. Under these conditions, the burst pressure was underestimated by at most. Non-rolled tube dimensions can thus be used for analysis.

5.3.2.2 <u>Burst pressure for a tube with twenty longitudinal through-wall defects uniformly distributed over the entire tube circumference (See Tables 5-10 and 5-11)</u>

TABLE 5-26

BURST PRESSURE ON TUBES WITH MULTIPLE LONGITUDINAL THROUGH-WALL DEFECTS
SUMMARY OF TEST RESULTS

As in the case of a single defect, the increase in burst pressure in the roll transition zone depended on defect length. Taking the scatter in test results into account, this increase was for a defect long, and for a defect long. Taking the scatter in test results into account, it may be concluded that the type of rolling (full-depth or full depth + kiss-rolling) does not have a significant impact on the burst pressure.

Test results for one or twenty defects of the same length are not directly comparable, for the following reasons :

- For one defect, bulging allowed partial extrusion of the plastic tube which retained the pressurizing fluid. In this case internal pressure was partially applied to the defect edges, resulting in a decrease in the burst pressure.

- For 20 defects, the generalized, practically homogeneous strain in the entire tube section containing the defects did not cause extrusion of the plastic tube. As pressure was not applied to defect edges, the burst pressure was perceptibly higher than that of a single defect.

In the case of tubes with twenty defects in the straight portion remote from discontinuities, the test results agreed with the rupture criterion found for one defect, when using bulging factor M (2) (Table 4-13 - Figure 4-15), validated for the case when pressure was not applied to defect sides (Table 5-17). They show that the burst pressure was not influenced by the presence of twenty defects long located in the same tube section by comparison with one defect of the same length.

5.3.2.3. <u>Burst pressure for a tube with one defect long in a section containing 19 defects long - Table 5-12</u>

TABLE 5-27

BURST PRESSURE ON TUBES WITH ONE OR MULTIPLE LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS

TABLE 5-27 (continued)

BURST PRESSURE ON TUBES WITH ONE OR MULTIPLE LONGITUDINAL THROUGH-WALL DEFECTS - SUMMARY OF TEST RESULTS

In the first stage of the analysis for the defect in the roll transition zone, the presence of 19 defects long resulted in a perceptible decrease in burst pressure Pa. Instability was obtained at a pressure level comparable to that obtained for a single defect in the straight portion remote from discontinuities.

5.3.2.4 <u>Burst pressure for a tube with one defect long in a section containing 19 defects long - Table 5-13</u>

The comparison of tests S27-28-29 (Table 5-9) and of tests S30-31 (Table 5-13) shows that the burst pressures are of the same order of magnitude, (disregarding the scatter in the results).

In this case, the burst pressure for the defect with length located in a section containing 19 defects with length was identical to that for an defect outside the tubesheet in a section containing 19 defects long.Instability was obtained at a pressure comparable to that obtained for a single defect located in the straight portion remote from discontinuities.

5.3.3 <u>Determination of the instability limit pressure for a longitudinal through-wall defect located in the roll transition zone</u>

Experience shows that the instability of a longitudinal through-wall defect is, in all cases, preceded by very significant bulging at the defect, associated with necking of the tube wall at the tip of the defect.

When the tube reaches instability, rupture initiation and unstable propagation occur in a plane at from the direction of principal stresses.

On the basis of the burst tests for tubes containing defects or cracks in the straight portion remote from discontinuities, we have shown that the rupture criterion used to determine the instability limit pressure Pa for a through-wall crack can be expressed simply, in the form :

or :

$\sigma_{eq}$ : represents the equivalent stress (Tresca or Mises)

M : is the stress magnification factor (bulging factor) which is a function of the geometry of the cracked tube.

For a defect of a given length, if deformation is restrained so that it cannot take place freely, the bulging effect, and therefore the factor M, decreases. This causes a reduction in the stress concentration effect or plastic strain effect at the tip of the crack. For a given pressure level, the opening of the defect and necking at the tip of the crack will therefore be reduced; to obtain defect instability, pressure must be increased inside the tube.

As experience shows, the presence of the tubesheet prevents the tube from bulging freely up to a minimum of above the tubesheet. This boundary effect decreases progressively until, about above the tubesheet, when it becomes negligible. There is a reduction in bulging and a corresponding decrease in both the crack opening area and its angle. This reduction depends on the distance between the tip of the crack and the top of the tubesheet. On the basis of these observations made during testing, the following mechanical principles can be stated :

- The part in contact with or inside the tubesheet cannot bulge. Thus, unstable propagation initiates at the tip of the crack which is not in contact with the tubesheet.

- The boundary effect acts on the bulging factor M, which causes a decrease in the stress concentration effect or in plastic strain at the tip of the crack. Therefore, the principle adopted here is to modify the factor M by introducing an equivalent thickness in order to take into consideration the increased local tube rigidity affecting M.

The rupture criterion in the rolling zone at the top of the tubesheet can thus be expressed as follows :

with :

and :

where :

$2a_s$ : represents the length of the crack outside the tubesheet

$t_{ip}$ : represents the equivalent thickness which takes into account the interaction with the tubesheet. This phenomenon results in a change in the bulging factor M.

$t_{ip}$ is expressed in the following empirical form :

$h_{el}$ : represents the distance limit for the portion of the tube beyond which the crack will not be affected by the presence of a change in tube behavior : i.e. the presence of degradation or some type of geometric discontinuity. Experience shows that this influence can be exerted between from the top of the tubesheet.

The value :                 is chosen, determined on the basis of a model adjustment based on test results;

The comparison of theoretical and test results is presented in Table 5-28 and Figure 5-15. For all configurations examined, it was confirmed that theoretical burst pressures for through-wall cracks correlate well with test results while remaining " conservative ".

In addition, various crack configurations as a function of the location of the crack with respect to the top of the tubesheet as well as the location of the crack with respect to the last contact point between the tube and the tubesheet were also investigated to verify the limit of validity of the rupture criterion for cracks in the roll transition zone. Comparison between theoretical predictions and test findings is presented in Figure 5-16.

As mentioned previously a new version of the R6 approach has been proposed in document R/H/R6, (7) in which the failure assessment line (FAL) represents the evolution of plasticity within the structure. It is therefore a function both of the material and the geometry of the structure. In this case, an application to alloy 600 tubes tested in this program was carried out using the R6 approach (Revision 3) based on the AINSWORTH method, in which the FAL depends exclusively on the material, and not on the geometry of the structure. The FAL used is slightly modified in the R6 approach with respect to the AINSWORTH expression. It is given by the following formula :

LONGITUDINAL THROUGH-WALL DEFECTS
RUPTURE OF STEAM GENRATOR TUBES AT ROOM TEMPERATURE : BURST TEST RESULTS
TUBES IN ALLOY 600 - Ø 19.05 mm
TEST RESULTS

TABLE 5-28

THROUGH-WALL CRITICAL CRACK LENGTH - TUBES IN ALLOY 600
COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL RESULTS
DEFECT LOCATION : ROLL TRANSITION ZONE

- The reference stress $\sigma_{ref}$ and reference strain $\epsilon_{ref}$ are given by the stress-strain curve

-

-

- represents the limit load.

In the diagram ($K_R$, $L_R$), the test points are given by the following formulas :

- (In-plane stress conditions)

-

-

-

The comparison of theoretical and test results shows that all test points (Tables 5-14 to 5-21) are located outside the stability curve, beyond the limit-load $L_R$ max corresponding to the flow stress (See Figure 5-17). These results show that the $J_{IC}$ value used is probably underestimated and, also that a collapse load model is sufficient to predict instability in the present cases, since all the test points representing rupture are located beyond the limit of the parameter $L_R$.

Figure 5-17. Application of R6 Rule : Rupture evaluation curve
Tubes in alloy 600 - Ø 19.05 mm - Results from analysis of tube test data : Tables 5-14 to 5-21

### 5.4 BURST TESTS ON TUBES WITH CRACKS DUE TO STRESS CORROSION CRACKING LOCATED IN THE ROLL TRANSITION ZONE

To qualify the rupture criteria applicable to steam generator tubes in alloy 600, burst tests were carried out on tubes with one or several defects simulated by machining. The initial lengths of these defects were thus precisely determined. In particular, we showed by means of comparative tests that the sharpness of the notch does not significantly influence the instability limit pressure. The behavior of the " notch " type defect is therefore equivalent to that of a crack in a tube made of alloy 600. Rupture initiation is preceded by significant necking in the tube wall thickness at the tip of the defect, and rupture occurs by plastic instability. The rupture propagates in a plane at to the direction of principal stresses. Propagation may be longitudinal and/or circumferential. This observation clearly demonstrates the influence of a tridimensional stress field at the tip of the defect in the plastic zone, and shows that, in some cases, the longitudinal stress in the plastic zone is no longer necessarily the intermediary principal stress.

The interpretation of the tests in terms of the plastic instability rupture criterion based on the maximum shear theory according to Tresca or the application of the Mises criterion is therefore justified.

The advantage of this type of test on simulated defects is that the exact dimensions of the defect(s) can be determined, thereby minimizing uncertainty with respect to the parameters governing rupture. Thus, it is confirmed that tube rupture is governed by the longest through-wall crack. When the exact length of this defect before it reaches instability is known, the influence of this parameter can be quantified.
The examination of steam generator tubes in operation shows that tubes may, under certain operating conditions, show significant deterioration in the form of networks of parallel through-wall or part-through stress corrosion cracks. The distribution of these parallel cracks in the roll transition zone is random. Generally speaking, these longitudinal cracks are a function of water chemistry, the metallurgical state and chemical composition of the tube material, the temperature and the state of residual rolling stresses combined with operating stresses. Stress corrosion cracking depends strongly on the stress concentration and the strain heterogeneities in the roll transition zone.

In the plastic range, stress and strain concentration factors depend on the shape of the stress-strain curve and the stress or strain level.

As a result, stress corrosion cracking depends on tube geometry at the top of the tubesheet and the rolling conditions. After initiation of stress corrosion cracking, the stress concentration or strain concentration factors will be modified depending on the crack length and the propagation of one or several defects will be facilitated as a function of the local mechanical characteristics and the state of local stresses (intensity and directions) at the tip of the crack.

As instability is caused by the longest crack, the objective of the examination is to evaluate the influence of a network of stress corrosion cracks on the behavior of a principal crack. In order to do so, a longitudinal through-wall crack is produced by electron discharge machining (EDM) after stress corrosion cracking is induced in the roll transition zone.

The tubes are rolled (full-depth and kiss-rolling) inside a support representing the tubesheet (See Figure 5-18 and Table 5-29). Wall reduction ranges from . The variation in outer tube diameter in the kiss-rolling zone is between , and the variation in thickness is lower than : See Tables 5-30 and 5-31.

After rolling, the roll transition zone of the test specimens is cracked by stress corrosion cracking (SCC) : the tubes are placed in a solution of water and caustic soda at and subjected to a pressure of . Depending on how long each tube is kept in this solution, it is given an a priori classification (Types I, II or III) : See Table 5-29.

After the cracks due to SCC have been produced, a longitudinal through-wall defect long is machined (EDM) so that the lower end of the defect is located at a distance X = from the top of the tubesheet.

Figure 5-18. Sketch showing the tube in the tubesheet

TABLE 5-29

DESCRIPTION OF TESTS - TESTING OF STRESS CORROSION CRACKED TUBES

TABLE 5-30

TUBE DIMENSIONS BEFORE AND AFTER ROLLING
(SEE FIGURE 5-18)

TABLE 5-31

TUBE DIMENSIONS AFTER KISS-ROLLING

### 5.4.1 Results of tests on 22.22 mm diameter tubes

3 burst tests were carried out by S.C.M.I. CHINON (11) on tubes without any defect which were machined after cracks due to SCC were produced. The results are summarized in the following Table :

TABLE 5-32

BURST TEST RESULTS

12 burst tests were carried out by Framatome on 22.22 mm diameter tubes with a relative thickness of t/R = 0.133. The results are presented in Tables 5-33 and 5-34. Rupture generally occurred at the machined defect long. On test specimen No. 632-67, the machined defect long remained stable. Instability began at an SCC through-wall crack which was longer than the simulated EDM-machined defect. After the burst tests, micrographic and fractographic examinations allowed the state of deterioration of SCC-cracked tubes in the laboratory to be quantified : (See Figures 5-19 to 5-45) (11).

Figure 5-19. Test specimen 628-60
Rupture by plastic instability of long defect

Figure 5-20. Test specimen 628-60
Details of inner surface of half tube (b)

Figure 5-21. Test specimen 640-63
Rupture by plastic instability of long defect

Figure 5-22. Test specimen 640-63
Details of inner surface of half tube (b)

Figure 5-23. Test specimen 638-68
Rupture by plastic instability of long defect

Figure 5-24. Test specimen 638-68
Details of inner surface of half tube (a)

Figure 5-25. Test specimen 630-61
Rupture by plastic instability of long defect

Figure 5-26. Test specimen 630-61
Details of inner surface of half tube (a)

Figure 5-27. Test specimen 637-65
Rupture by plastic instability of long defect

Figure 5-28. Test specimen 637-65
Details of inner surface of half tube (a)

Figure 5-29. Test specimen 637-65
Details of inner surface of half tube (b)

Figure 5-30. Test specimen 633-57
Rupture by plastic instability of 15 mm long defect

Figure 5-31. Test specimen 633-57
Details of inner surface of half tube (b)

Figure 5-32. Test specimen 623-54
Rupture by plastic instability of long defect

Figure 5-33. Test specimen 623-54
Details of inner surface of half tube (a)

Figure 5-34. Test specimen 623-54
Details of inner surface of half tube (b)

Figure 5-35. Test specimen 639-53
Rupture by plastic instability of long defect

Figure 5-36. Test specimen 639-53
Details of inner surface of half tube (a)

Figure 5-37. Test specimen 639-53
Details of inner surface of half tube (b)

Figure 5-38. Test specimen 632-67
Rupture by plastic instability of a stress corrosion crack

Figure 5-39. Test specimen 632-67
Details of inner surface of half tube (a)

Figure 5-40. Test specimen 634-66
Leak at 600 bar - Stability of tube with stress corrosion cracks

Figure 5-41. Test specimen 634-66
Details of inner surface of half tube (b)

Figure 5-42. Test specimen 625-55
Rupture by instability of a stress corrosion crack

Figure 5-43. Test specimen 625-55
Details of inner surface of half tube (b)

Figure 5-44. Test specimen 626-51
Rupture by instability of a stress corrosion crack

Figure 5-45. Test specimen 626-51
Details of inner surface of half tube (a)

TABLE 5-33

BURST PRESSURE FOR STRESS CORROSION INDUCED LONGITUDINAL THROUGH-WALL DEFECTS
PLUS ONE MACHINED DEFECT
LOCATION : ROLL TRANSITION ZONE
ALLOY 600 D = 22.29 ± 0.01 mm T = 1.31 ± 0.01 mm

TABLE 5-34

BURST PRESSURE FOR STRESS CORROSION INDUCED LONGITUDINAL THROUGH-WALL DEFECTS
PLUS ONE MACHINED DEFECT
LOCATION : ROLL TRANSITION ZONE
ALLOY 600 D = 22.29 ± 0.01 mm t = 1.31 ± 0.01 mm

5.4.2 **Analysis of results**

Micrographic and fractographic examinations revealed the following characteristics :

- TESTS 59 AND 60 : Figures 5-19 and 5-20
  These tubes were characterized by the presence of a large number of fine longitudinal cracks whose depths, respectively for tests 59 and 60, were between of the tube wall thickness. They were distributed over the entire tube circumference, over a distance of , respectively, corresponding to the roll transition zone (full-depth + kiss-rolling).

  The upper part of the defect long was not affected by the presence of S.C.C. cracks. Circumferential tearing was visible at the top of the tubesheet in the area containing multiple longitudinal cracks. The tearing and unstable propagation of the rupture occurred simultaneously.

- TESTS 63 AND 64 : Figures 5-21 and 5-22
  These tubes were characterized by the presence of a large number of fine longitudinal cracks whose mean depths ( respectively for tests 63 and 64) were between of the tube wall thickness. They were distributed over the entire tube circumference and over a distance of , respectively, corresponding to the roll transition zone (full-depth + kiss-rolling) and kiss rolling zone.

The upper part of the main defect was only partially affected by the presence of cracks due to S.C.C. Circumferential tearing was visible at the top of the tubesheet. Tearing and unstable longitudinal propagation of the rupture occurred simultaneously. If pressure was maintained, the result was a " guillotine " rupture of the tube.

- TEST 68 : Figures 5-23 and 5-24

  This tube was highly deteriorated by stress corrosion cracking over a distance of about above the top of the tubesheet. The mean depth of these cracks was about of the tube wall thickness. As previously, a number of longitudinal cracks were observed over the entire tube circumference and over a distance of , corresponding to the roll transition zone. In many cases, circumferential branching cracks were observed at the top of the tubesheet.

The upper part of the main machined defect long was affected by the presence of many cracks due to S.C.C. When the instability limit pressure of the main defect was reached, the rupture propagated in the S.C.C region located at the tip of the defect.

* TESTS 61 AND 62 : Figures 5-25 and 5-26
These tubes were characterized by multiple longitudinal cracks distributed over the entire tube circumference in the roll transition zone. Many longitudinal cracks were also visible in the kiss-rolling zone. The distribution of this network of cracks due to S.C.C. was over a distance of respectively. The mean crack depth ( respectively for tests 61 and 62) is between of the tube wall thickness.

The upper part of the main defect was only partially affected by the presence of stress corrosion cracking.

In the specific case of test 61, circumferential tearing was visible at the top of the tubesheet.

* TESTS 65 AND 57 : Figures 5-27 to 5-31
These tubes were highly deteriorated by S.C.C. in the rolling zone. Multiple fine longitudinal cracks were distributed over a distance of , respectively. The mean crack depth was between of the tube wall thickness. Some of these cracks were practically through-wall.

A circumferential crack was revealed at the top of the tubesheet. A fractographic examination of the test specimen used in Test 65 showed that it was a circumferential corrosion crack

with a depth of .

The crack in Test 57 was .

The upper part of the main crack was located at the upper limit of the crack network.

The presence of a series of small, parallel through-wall and part-through cracks, which could either be in aligment or not was noted. These cracks, separated by narrow ligaments were able to cause the formation of principal cracks whose total length exceeded the sum of the individual cracks. In this case, the main cracks were obtained by stress corrosion and the rupture of the ligaments separating each of these individual cracks.

The instability of this type of configuration occurred at a pressure equal to or higher than that necessary to produce the rupture of a single through-wall crack whose length was equal to the greatest axial separation of aligned or nearly aligned cracks.

However, for ligaments whose lengths are smaller than about , depending on the mechanical characteristics of the tube, analysis of instability in this type of configuration should consider the total length of the two cracks separated by the smallest ligament. The rupture of one of these ligaments by plastic instability or by stress corrosion cracking can cause a series of ruptures of the various ligaments separating two cracks which are assumed to be through-wall.

- TESTS 54 AND 53 : Figures 5-32 to 5-37

These tubes were greatly deteriorated in the rolling zone by S.C.C. A number of fine longitudinal through-wall and part-through cracks were located over a distance of ,

respectively, in the roll transition zone. The mean crack depth ( respectively for tests 54 and 53) was between of the tube wall thickness.

The top end of the main defect was located at the upper limit of the stress corrosion cracking network. In the case of Test 54, when instability in the defect long was reached, the rupture propagated in the stress corrosion cracks.

A circumferential crack was revealed at the top of the tubesheet. A fractographic examination of the test specimen used in Test 54 showed that there was a crack and due to S.C.C. In test 53, the circumferential corrosion crack was .

- TEST 67 : Figures 5-38 and 5-39

This tube was characterized by a rupture produced by instability of a through-wall crack due to S.C.C. The machined defect long remained stable at the maximum test pressure.

Significant deterioration was observed over a length of . The mean corrosion crack depth of the tube wall thickness. Some cracks were practically through-wall.

Figure 5-46. Fractographic examination in the case of two stress corrosion cracks practically aligned

The length of the main crack was . The total length $l_1 + l_2 + x$ was . Due to the interaction between the two parallel, through-wall cracks, instability in the ligament separating these two cracks necessarily occurred at a pressure lower than that required for a single defect whose length was equal to the longest of these two cracks. This ligament rupture pressure was, in particular, lower than the instability limit pressure for the single defect long. After rupture of the ligament separating the two cracks, instability of the defect with total length was obtained. In this configuration, the ligament rupture pressure Pr was higher than the instability limit pressure Pa of the through-wall crack long, which explains the unstable propagation of the rupture after the ligament between the two cracks ruptured.

Visual and fractographic examinations also revealed a circumferential corrosion crack deep at the lower end of the principal corrosion crack. The initiation of a circumferential crack also appears at the lower end of the machined defect.

- TEST 66 : Figures 5-40 and 5-41
  This tube, which did not contain any machined defects, was highly deteriorated by S.C.C. in the rolling zone over a distance of . The mean depth of the network of fine, longitudinal parallel cracks was of the tube wall thickness. Rupture of the remaining ligament of a part-through defect long and occurred at a pressure of .. Longitudinal instability of the crack was not obtained because of depressurization after rupture of the remaining ligament.

  Many circumferential branching cracks were revealed at the lower limit of the deteriorated zone.

- TESTS 51 AND 55 : Figures 5-42 to 5-45.
  These tubes, which do not contain any machined defects, were highly deteriorated by S.C.C. over a distance of , respectively, in the rolling zone. The mean crack depth ( , respectively) was between of the tube wall thickness. The lengths of the stress corrosion cracks responsible for causing rupture were estimated at , respectively.Only the longest adjacent cracks were considered for analysis.

- TEST 51 :

  The stress corrosion crack was formed from individual cracks whose total length equalled about at mid-wall.

- TEST 55 :

  The stress corrosion crack was formed by individual cracks whose total length was equal to about at mid-wall.

Visual and fractographic examinations revealed the presence of a circumferential corrosion crack. This through-wall crack was in Test 55 and in Test 51 located the top of the tubesheet.

In Test 51, the examination showed that the multiple longitudinal cracks in the roll transition zone, which were distributed over the entire tube circumference could, in some cases, branch out and thereby facilitate the formation of a circumferential crack when all the branches met. For 15 cases studied using test specimens cracked in a caustic solution (i.e. with stress corrosion cracks plus a longitudinal defect produced by electron discharge machining), the circumferential stress corrosion crack, when detected, was associated with a longitudinal crack (S.C.C.) or defect (machined).

**Figure 5-47. Sketch : Interaction of a circumferential and longitudinal stress corrosion cracks**

The high concentration of stress or strain at the top of the tubesheet was such that, under the pressure loading, the bending stresses could become preponderant in the roll transition zone.
This can either facilitate tearing in the circumferential direction, as observed in some tests, or the propagation of an initially longitudinal stress corrosion crack in the circumferential direction.

Given the same test conditions (i.e. with partial extrusion of the pressure sealing device), comparative analysis of the results in Table 5-35 shows that, by comparison with tubes which have not been deteriorated by stress corrosion cracking :

- The instability limit pressure of the defect long is not affected by the presence of a partial circumferential crack, symmetrical or asymetrical with respect to the defect, or by a network of small, longitudinal cracks long with a mean depth less than of the wall thickness, distributed over the entire tube circumference in the roll transition zone. The crack network affects the tube over a distance of above the last tubesheet/tube contact point.

TABLE 5-35

BURST PRESSURE FOR STRESS CORROSION INDUCED LONGITUDINAL THROUGH-WALL DEFECT
COMPARISON OF TEST RESULTS
LOCATION : ROLL TRANSITION ZONE

- For the defect long, the instability limit pressure decreases by about in the presence of a circumferential crack and a network of longitudinal cracks with a mean depth of . These longitudinal cracks were distributed over the entire tube circumference over a distance which could vary between . The circumferential part-through corrosion crack, with respective lengths of and depths of does not significantly influence results : the difference in Pa is less than (comparison of tests 65 and 57).

- For a defect long, the instability limit pressure decreases by about in the presence of a circumferential part-through crack and a network of fine, longitudinal cracks with a mean depth of between of the tube wall thickness. Some of these cracks can be through-wall. This cracking network distributed over the entire tube circumference affects the rolling zone over an axial distance of . The dimensions of the circumferential part-through corrosion crack are :

$2\alpha = 60^\circ \quad - \quad d/t = 76\ \%$

$2\alpha = 76^\circ \quad - \quad d/t = 62\ \%$

- In the case of Test 67, instability was governed by the rupture of the ligament separating two cracks which were practically aligned. Therefore, the result cannot be directly compared with the previous results.

### 5.4.3 Application of a criterion of rupture by plastic instability in the roll transition zone

As previously mentioned in Paragraph 5.3.3., the instability limit pressure Pa of a longitudinal through-wall defect in the rolling zone, located at the top of the tubesheet, can be expressed in the form :

where $\lambda^*_{ip}$ is a function of the equivalent thickness, $t_{ip}$, which takes into account the interaction due to the tubesheet. The effect of this interaction is to modify the bulging factor $M(\lambda^*_{ip})$.

The model thus defined on the basis of test results does not take into consideration generalized deterioration of a tube due to the presence of a network of a number of longitudinal cracks in the rolling zone, which can be associated with circumferential cracking which decreases the rigidity of the tube in the roll transition zone. This decrease results in an increase in the bulging effect, and therefore the factor M.In this case, the object is to confirm the limit of applicability of this general model which makes it possible to simplify the analysis to a great extent.

The comparison of theoretical and test results is presented in Table 5-36 and Figure 5-15. In Table 5-36, the comparison has been done using the bulging factor defined by the formulas $M_1$ ($\lambda^*_{1p}$) and $M_2$ ($\lambda^*_{1p}$). However, as shown in the comparative analysis of test results between tubes with the same pressure sealing device (the comparison of results presented in Tables 4-25, 5-8 and 5-35), the application of the criterion defined by $M_1$ ($\lambda^*_{1p}$) is justified (except for Tests 51, 55, 66 and 67) by comparison with the results obtained in the straight portion remote from discontinuities. In these cases, pressure was applied to the defect edges before instability was reached, because of partial extrusion of the plastic tube sealing device :

- <u>TESTS 59 - 60 - 63 - 64 - 68</u> : 2a =

  These tubes contained a main defect long outside the tubesheet, in an area deteriorated by the presence of cracks obtained by stress corrosion over the entire circumference of the tube and over a maximum distance of . The mean depth of this network of fine longitudinal cracks reached of the tube wall thickness. Nevertheless, the theoretical predictions correlate well with test results. The instability limit pressure Pa is underestimated by when the bulging factor $M_1$ ($\lambda^*_{1p}$) is employed.

  The multiple circumferential branching cracks in the roll transition zone did not affect the results.

  On the average, Pa is underestimated by , depending on whether one considers $M_2$ ($\lambda^*_{1p}$) or $M_1$ ($\lambda^*_{1p}$). Considering the scatter in test results (s = 11) and the low theoretical deviations, depending on which formula is considered, no conclusion can be made as to which formula is better $M_1$ ($\lambda^*_{1p}$) is justified from the safety standpoint, as it sets a lower boundary for the test results.

- <u>TESTS 61 - 62 - 65 - 57</u> : 2a =

  These tubes contained a main defect long outside the tubesheet in the rolling zone, which was deteriorated by stress corrosion cracking. These cracks were distributed over the entire circumference of the tube over a distance of above the last tubesheet/tube contact point. Depending on which test is under consideration, the mean depth of this network was between . Some of these cracks were through-wall. Theoretical predictions correlate well with test results. The instability limit pressure Pa is underestimated by when using $M_1$ ($\lambda^*_{1p}$). The presence of a circumferential part-through crack whose length is and depth is does not significantly affect the instability of the defect long. $M_2$ ($\lambda^*_{1p}$) leads to an overestimation of Pa, as in the case of tests in the straight portion remote from discontinuities, during which pressure is applied to the defect edges.

- <u>TESTS 53 - 54</u> : 2a =

  The tubes contained a main defect long outside the tubesheet in the rolling zone, which was deteriorated by stress corrosion cracking. These cracks were distributed over the entire circumference of the tube and over a distance of above the last tubesheet/tube contact point. The mean depth of this network of longitudinal cracks was between and of the tube wall thickness. Some of these cracks were through-wall.

TABLE 5-36

BURST PRESSURE FOR A TUBE DEGRADED BY STRESS CORROSION IN ROLLING ZONE
TUBES IN ALLOY 600 - Ø 22.22 mm

As indicated in the previous section, the comparison of test results between sound tubes and deteriorated tubes shows that the decrease in instability pressure is about when the mean depth of these cracks is greater than . The increase in resistance given by the tubesheet to the tube is thus cancelled out by this loss of tube rigidity. In this case, the defect behavior is equivalent to that of a defect of identical length located in the straight portion remote from discontinuities. The model used for the rolling zone is then no longer conservative and Pa is overestimated by about .

- TESTS 51 AND 55 : 2a =

  These tubes contained a main through-wall crack long above the top of the tubesheet. A circumferential through-wall corrosion crack whose length was , depending on the test, was located in the roll transition zone. The mean depth of the network of longitudinal cracks distributed over the entire tube circumference over a distance of was higher than of the tube wall thickness. In this case the loss of tube resistance is significant and the model used for the rolling zone is no longer adapted for this particular case of deterioration.

  As for tests 53 and 54, it is necessary to take into consideration the loss of tube resistance due to the combined effect of the network of deep longitudinal cracks (d/t > ) and to the interaction between the main longitudinal crack, the circumferential through-wall crack, and the fine longitudinal through-wall cracks in line with the main crack.

- TEST 67

  When the rupture prediction is made considering the longest crack $l_1 \simeq$ (See Figure 5-46), the estimated value is satisfactory, because the deviation with the maximum test pressure is about .

  Comparing test results (59/60/63/69/68 and 67) with theoretical predictions, the interaction of practically-aligned cracks is revealed, which leads to a decrease in the instability limit pressure for the longest crack.

In conclusion, all of the results presented in Figure 5-15 make it possible to conclude that the proposed model (formula 3) is valid providing there is no interaction between circumferential and longitudinal cracks of the through-wall type in a network of deep longitudinal cracks (e.g. tests 53 and 54).

## Section 6

## CONCLUSIONS

Burst tests on steam generator tubes in alloy 600 with a nominal diameter of 19.05 mm and 22.22 mm, allow the following conclusions to be drawn :

- The burst pressure for tubes without any defect may be reliably estimated using a plastic instability criterion.Svensson's formula incorporating the strain hardening coefficient for the material yields a good correlation with test results. A displacement controlled external loading does not modify the burst pressure of a sound tube.

- The burst pressure for a tube with a longitudinal part-through crack in the zone remote from discontinuities may be estimated in satisfactory manner using a plastic instability criterion, whatever the length and depth of defects might be. An adequate approximation of the maximum shear stress criterion, used in association with a properly-adjusted flow stress, yields a precise evaluation of the ligament rupture pressure.

- The development of a leaktightness device and the test technique has revealed the influence of pressure applied to the sides of a longitudinal through-wall defect or crack. Generally speaking, it is shown that, by using the maximum shear stress criterion, incorporating a bulging factor defined by
  the rupture of a tube with a longitudinal through-wall crack of a given length located in the zone remote from discontinuities can be reliably predicted. This result is confirmed by tests at service temperature.
  It is demonstrated by tests at without sealing device, that a through-wall crack produced by rupture of the remaining ligament of a part-through crack is stable or unstable as predicted by the theory.
  When the crack is located in a tube region remote from discontinuities (i.e., away from the tubesheet, the support plates or the U-bend region) it can be seen that the plastic instability rupture criterion given by the expression :

  where

  and

  provides a reliable rupture prediction for alloy 600 steam generator tubes.

- In the case of tubes with circumferential through-wall defects in the zone remote from discontinuities, the influence of a support plate on the burst pressure shows up distinctly. It is confirmed that the rupture pressure may be estimated conservatively using a plastic collapse model.

- The burst pressure for a tube with a longitudinal or circumferential, through-wall or part-through defect or crack in the vicinity of the tubesheet is higher than that for a tube with the same type of defect in the zone remote from discontinuities (crack lengths ). An examination of the results reveals that a given deformation is required for the tube to burst. The presence of the tubesheet limits this deformation for the part of the tube containing the defect. This explains why the burst pressures are always higher than those obtained with an unsupported tube, given identical defects. It is confirmed that a displacement-controlled external loading, added to a pressure loading does not significantly influence the instability limit pressure.
  The plastic instability rupture criterion given by the expression :

  where

  and

  provides a reliable conservative rupture prediction for alloy 600 steam generator tubes.

- It is concluded that the type of rolling(full depth rolling or full depth plus kiss rolling)does not significantly influence the instability limit pressure of a through-wall crack.

- The effect of interaction between several (up to 20 tested) parallel longitudinal cracks remains small. This result has been confirmed with specimens containing multiple stress corrosion cracks in the roll transition region.

- The results of tests concerning the influence of stresses resulting from severe thermal loadings show that these stresses do not fundamentally affect the critical size of a longitudinal through-wall or part-through defect in a steam generator tube which is simultaneously subjected to pressure and temperature.

In conclusion, the comparison of theoretical and test results demonstrates that a rupture criterion based on the plastic instability concept can be used to predict reliably the rupture of steam generator tubes in alloy 600. Computer models have been qualified for the following cases :

- Tubes without crack.

- Tubes with longitudinal or circumferential part-through cracks.

- Tubes with longitudinal or circumferential through-wall cracks.

The critical length and depth of longitudinal or circumferential crack can be determined using these models or criteria which have been validated by extensive testing.

Section 7

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EPRI

Electric Power
Research Institute

Keywords:
Alloy 600
Stress corrosion cracking
Steam generators

EPRI NP-6865-L
Volume 2
Project S404-25
Final Report
Non Proprietary Version
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## Volume 2: Leak-Before-Break Analysis for Primary Water Stress Corrosion Cracking Near the Tubesheet (Framatome Data)

NON-PROPRIETARY VERSION

Prepared by
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ABSTRACT

This report presents the results of a theoretical analysis of the severity of cracking in the steam generator tubes of a specific plant. The results of the parametric study performed to determine the critical crack dimensions likely to affect the alloy 600 steam generator tubes are given for various parameters. Variables such as tube dimensions, flow stress and differential pressure corresponding to normal and upset operating conditions or postulated accident conditions were investigated. In the report are included the determination of :

- The burst pressure on tubes without cracks
- The critical length of longitudinal cracks located in straight portion remote from the tubesheet or support plates
- The critical length of longitudinal cracks located in the roll transition zone
- The critical depth of a longitudinal crack
- The critical length of a circumferential through-wall crack

This summary report also presents the results of the primary to-secondary leak rate through a longitudinal through-wall crack.
These results should make it possible to define reliably in-service surveillance requirements and shutdown surveillance requirements using either the leak before break criterion or the tube plugging criteria.

The purpose of these requirements is to preclude any risk of tube rupture whatever the steam generator operating conditions may be. This study is limited to the straight portion remote from discontinuities and to the roll transition zone, which are the parts of the tube likely to be affected by stress corrosion cracking caused by the reactor coolant (PWSCC).

ACKNOWLEDGEMENTS

This report includes part of the results of the studies performed by Framatome for Electricité de France and the Swedish State Power Board about steam generators.

The author wishes to acknowledge Jan Engström from S.S.P.B. as well as Jean Pierre Hutin and Bruno Flesch from E.D.F. for numerous fruitful discussions and for agreeing to the publication of results reported in this report.

Bernard Cochet
Principal Investigator

## NOMENCLATURE

### Geometry of the tube

| | |
|---|---|
| Ø | : Nominal tube diameter |
| $D = D_1$ | : Actual outer tube diameter |
| $D_o$ | : Actual inner tube diameter |
| t | : Tube thickness |
| tr | : Local tube thickness at the level of the unstable defect (crack) |
| tmin | : Minimum tube thickness |
| R = Ro = Ri | : Inner tube radius |
| $R_1 = R_e$ | : Outer tube radius |
| r | : Mean radius |

### Geometry of the defect (crack)

| | |
|---|---|
| L = 2a | : Length of the longitudinal defect (crack) |
| $L_c$ | : Critical defect (crack) length |
| d | : Depth of the defect (crack) |
| e | : Thickness of remaining ligament of the longitudinal or circumferential part-through defect (crack) |
| $e_r$ | : Thickness of remaining ligament at the level of the unstable defect (crack) |
| $2\alpha$ | : Angle of the circumferential defect (crack) |
| $N_D$ | : Number of defects (cracks) |
| W | : Width of the ligament between two parallel longitudinal cracks |

x : Distance or length of the ligament between two aligned longitudinal cracks

M : Bulging factor, function of the geometry of the cracked tube section

$\lambda$ =

$\lambda^*$ =

$S_o = A_o$ : Initial crack opening area

$S = A$ : Crack opening area due to the effect of the pressure

<u>Physical parameters</u>

$P = P_o$ : Inner pressure

$P_1$ : Outer pressure

$P_i$ : Burst pressure or instability limit pressure for a through-wall defect (crack) : initiation and instability of a defect (crack) with initial length 2a.

$P_r$ : Burst pressure for a sound tube, or rupture pressure for a tube with a part-through defect (crack) - Rupture of the remaining thickness of a part-through defect (crack).

$P_f$ : Pressure applied on the sides (surface) of the defect (crack)

$\sigma r$ : Radial stress

$\sigma \theta$ : Circumferential stress

$\sigma z$ : Longitudinal stress

Rm : Tensile strength

Re (0.2 %) : 0.2 % offset yield strength

A : Rupture elongation (%)

E : Longitudinal elasticity modulus - Young's modulus

$\nu$ : Poisson ratio

$\sigma_o$ : Flow stress for material, governing rupture due to plastic instability $Re \leq \sigma o \leq Rm$

$\sigma f$ = 1/2 (Re + Rm) : mean plastic flow stress for the material

$\bar{\sigma}$ : Flow stress for the material (value adjusted experimentally)- constant for the material governing plastic instability.

s : Standard deviation

N : Number of tests

## ABBREVIATIONS

F.D.B. : Flow distribution baffle

F.L.B. : Feedwater line break

S.C.C. : Stress corrosion cracking

S.L.B. : Steam line break

T.S.P. : Tube support plate

I.D. : Inner diameter

O.D. : Outer diameter

## CONVERSION FACTORS

| MULTIPLY | BY | TO OBTAIN |
|---|---|---|
| mm | 0.03937 | inch |
| bar | 14.504 | PSI |
| MPa | 145.04 | PSI |

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## Section 1
## INTRODUCTION

Steam generator tubes form a substantial proportion of the second fission product barrier in pressurized water reactors (PWRs). For this reason, they must, under all conditions, reliably fulfill this function while retaining sufficient mechanical integrity to preclude the risk of tubes bursting, and thus limit primary-to secondary leaks to a minimum and ensure a safe shutdown of the reactor. These tubes must perform this function with absolute reliability. Thus, it is important to establish the structural integrity of the steam generator tubes. This is accomplished on the basis of analyses, tests and in-service inspection.

The tube bundles of steam generators must therefore, sustain loads during normal operation and the various postulated accident conditions without a loss of function of safety. The operating experience of these steam generators shows that the tubes are affected by stress corrosion cracking by the reactor coolant (PWSCC), characterized by a deterioration of the roll transition zone, i.e. the full-depth rolling and full-depth + kiss-rolling zones.

Analyses of the severity of cracks likely to affect steam generator tubes focus on evaluating the rupture risks for any tube which can result from the types of damage observed in units in service.
On the basis of a large experimental program, these analyses are carried out considering the most severe accident conditions insofar as this risk is concerned, i.e. steam line break and feedwater line break conditions. These analyses make it possible to determine the dimensions of unstable cracks in accident conditions and therefore to establish tube plugging criteria. Moreover, the study also validates an in-service surveillance criterion applicable to primary-to-secondary leak rates. The reason for 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 shutdown the nuclear steam supply system as a preventive measure.

Finally, tubes likely to experience circumferential axisymmetrical cracking and those with cracking initiated at very long scratches, which might not satisfy the leak-before-break criterion, should be studied separately as part of a shutdown surveillance program.

For steam generator tubes, the problem is therefore to determine the critical crack dimensions, in the event of accidental overpressure, which lead to an allowable leak rate under normal operating conditions corresponding to a given primary/secondary differential pressure. The results of this study are given in this report :

- Section 2 recalls the objectives, principles and methodology used to apply the leak-before-break concept to steam generator tubes.

- Section 3 identifies the problem concerning steam generator tube degradations. It presents a general view of the experimental program on which the analyses are based, the logic diagram of the study and the various cases taken into consideration in the analysis.

- Section 4 contains all the relevant results of burst tests carried out on Ø 19.05 mm and Ø 22.22 mm tubes made of alloy 600 representative of SG tubes in service. It also presents the crack opening area calculation method which has been validated by experimental measurements. Section 4 summarizes the results of leak rate measurements made on stress corrosion cracks obtained in the laboratory, and the validation of the calculation model used in the analysis.
A summary of available results concerning crack propagation kinetics is also presented in this section.

- Section 5 presents the results of a leak-before-break analysis applied to tubes from the tube bundles of a specific plant. The analysis of the data used in the calculation reveals that the study is conservative.

- Section 6 presents the results used to determine the minimum critical depths in the situation where the leak-before-break criterion is not satisfied.

- Section 7 presents an overall view of general recommendations which could be used by the plant operator to establish operating surveillance requirements.

The conclusion of the report highlights the main results which could be used by the plant operator to determine in-service surveillance requirements and tube plugging criteria.

## SECTION 2

## GENERALITIES : THE LEAK-BEFORE-BREAK CONCEPT APPLIED TO STEAM GENERATOR TUBES

Among the various solutions the plant operator may opt for after discovering one or several defects in a steam generator tube in service, one is to accept the tube as it is for continued service.

The justification for allowing deteriorated tubes to stay in service is based on tube plugging criteria which take into consideration crack propagation kinetics and/or the leak before break concept, or, to be more precise, on the concept of an allowable leak rate under normal operating conditions which precludes the risk of rupture in the event of accidental overpressure.

The application of this concept to steam generator tubes to preclude any risk of rupture, whatever the operating situation may be, should be supplemented and substantiated by periodic in situ inspections (non-destructive examination and the removal of tube samples) to verify tube bundle integrity. It is necessary to identify the types of damage and to check regularly that the latter conform to the hypotheses selected to carry out behavioral analyses (from the perspective of the severity of defects and leak rates).

### 2.1 OBJECT

Generally speaking, the object is to demonstrate that any risk of rupture of a tube under the most extreme operating conditions is necessarily preceded by an allowable leak under normal operating conditions, whose detection makes it possible to shut down the nuclear steam supply system as a preventive measure.

### 2.2 LEAK-BEFORE-BREAK CRITERION : DEFINITION

The application of this concept consists in evaluating the rupture risks for steam generator tubes, taking into account the criteria imposed on leak rates under normal operating conditions.

The leak-before-break criterion applied to steam generator tubes is defined on the basis of the following considerations :

- The evaluation of the critical dimensions of through-wall cracks under faulted conditions : as the risk of rupture is associated with the most severe conditions, the critical length of through-wall defects or cracks is evaluated for accident conditions (hypothetical steam line break or feedwater line break).

  Let $L_c$ be this critical crack length and L be the actual crack length :

  If $L < L_c$ - Stability of cracks with length L, whatever the operating conditions.

  If $L \geq L_c$ - Crack instability and tube rupture

- A threshold limit is imposed for an allowable leak rate under normal operating conditions, corresponding to a threshold defect with length $L_s$. The actual crack length should conform to the following formula under any circumstances :

$$L \leq L_s < L_c$$

Verification of this criterion implies that there is an allowable leak rate under normal operating conditions for a crack with a length L which precludes any risk of tube rupture in the event of accidental overpressure.

## 2.3 APPLICATION

For tubes with part-through defects, the leak-before-break concept is only meaningful if it can be shown that their propagation kinetics are such that, at any time during propagation, including the breakthrough phase, these defects present no risk of instability when subjected to the most severe thermal and mechanical loadings. The breakthrough phase can be obtained by stress corrosion cracking (SCC), fatigue or instability of the remaining ligament caused by these loadings.

For tubes with defects which have become through-wall as a result of stress corrosion, progressive cracking, wear or instability of the remaining ligament, it is concluded that the set value for the leak rate limit fixed by technical specifications is such that the lengths of the defects corresponding to it are smaller than the lengths of the critical defects. As a result, the following formula should be obeyed:

$$\boxed{Q\ (L) \leq Q\ (L_S) < Q\ (L_C)}$$

$Q\ (L)$ represents the measured leak rate

$Q\ (L_S)$ represents the allowable leak rate

$Q\ (L_C)$ represents the leak rate corresponding to the critical defect.

For a safety evaluation, the leak rate measured in a steam generator in operation is postulated to be that corresponding to a single crack with length L. Consequently, if this leak rate is the result of the existence of several through-wall cracks in steam generator tubes, the length of the longest actual crack will necessarily be smaller than that calculated for a single crack corresponding to the measured leak rate. In the case of several through-wall cracks, the result will be a shutdown of the power plant at a leak rate $Q(L) = Q\ (L_S)$ such that the actual length of the longest crack is smaller than the threshold defect $L_S$.

## 2.4 METHODOLOGY : THEORETICAL AND EXPERIMENTAL ANALYSIS

Generally speaking, the location, type and causes of damage must be known before the leak-before-break criterion can be applied. Under these conditions, when a defect is detected in a steam generator tube, the plant operator can opt to accept it as it is, because, for the cases in which cracking is most probable, an allowable leak rate criterion precludes the risk of rupture by plastic instability in tubes made of alloy 600.

Supporting studies, on the basis of which the leak-before-break criterion is applied, are focused on the following :

- Experimental analysis used to validate tube mechanical strength criteria and to qualify numerical methods to establish a correlation between the length of the longitudinal or circumferential crack and the leak rate in normal operating conditions.
- Analysis of the integrity of longitudinal and circumferential cracks in SG tubes to evaluate the safety margins for rupture of a deteriorated tube, for either normal operating conditions or postulated accident conditions, i.e. a steam line break (S.L.B.) or feedwater line break (F.L.B.) in conjunction with a safe shutdown earthquake (S.S.E.). Based on this analysis, carried out specifically for a given nuclear power plant, it is possible to determine, in particular, the critical dimensions of through-wall cracks. These critical lengths are those below which there is no risk that the tube will burst; they are determined on the basis of test-validated criteria.
- Evaluation of primary-to-secondary leak rates, used to correlate the length of the longitudinal or circumferential through-wall crack with a leak rate in normal operating conditions.

- Determination of the minimum critical leak rate corresponding to the critical length and determination of the allowable leak rate in normal operating conditions for which the crack remains stable. Comparative analysis makes it possible to determine the existing margins between the threshold defect with a length $L_s$ correspond_ng to the allowable leak rate and the critical defect with a length $L_c$ likely to be unstable in the most severe postulated conditions (F.L.B. or S.L.B.).

- Study of crack propagation kinetics for cracks in tubes pulled from steam generators. Verification of the geometry (length, shape) of stress corrosion cracks apparent in steam generator tubes in operation has shown from tubes extracted to date that the propagation kinetics of a longitudinal crack are such that the crack remains stable when it becomes through-wall.

These experimental and theoretical studies make it possible to establish the technical specification limit on the maximum allowable leak rate during normal operation, or for a given technical specification limit to verify the leak-before-break criterion.

## 2.5 TUBE PLUGGING CRITERIA

It is noted that the leak before break (LBB) criterion applied to steam generator tubes may be a necessary but not sufficient condition for safety purposes :

- It may be necessary since, in most of the cases, the crack opening area and therefore the leak rate increases sharply when the actual crack length is close to the critical crack length. Therefore, continuous monitoring of the leak rate during normal operation will enable the plant operator to shutdown the plant before reaching crack instability.

- The above condition may be necessary but not sufficient since some crack configurations such as circumferential cracks or long axial cracks in sludge deposit areas do not lead necessarily to a leakage during normal operating conditions. As a result, tube plugging criteria based on the determination of critical crack dimensions and crack propagation kinetics must be defined and, non destructive examination during shutdown is necessary to avoid any tube rupture.

## SECTION 3

## GENERAL PRESENTATION OF THE REPORT

### 3.1 STATEMENT OF THE PROBLEM

The operating experience of pressurized water reactors has revealed the existence of several different types of damage likely to affect steam generator tubes (See Figure 3.1).

These types of damage are generally due to :

- Primary side intergranular stress corrosion of alloy 600 at the roll transition zones, and, in some manufacturing cases, at the small radius U-bends (rows R1 and R2) : PWSCC.

- Secondary side intergranular corrosion at the positions of the tube-support plates and in a localized zone above the tubesheet: IGSCC - IGA.

- Wear at the sites of the antivibration bars or wear caused by contact or insufficiently large clearances between the U-bends (large radius U-bends).

- Tube deformation at the level of the tube support plates and in the rolling zone at the top of the tubesheet : denting,

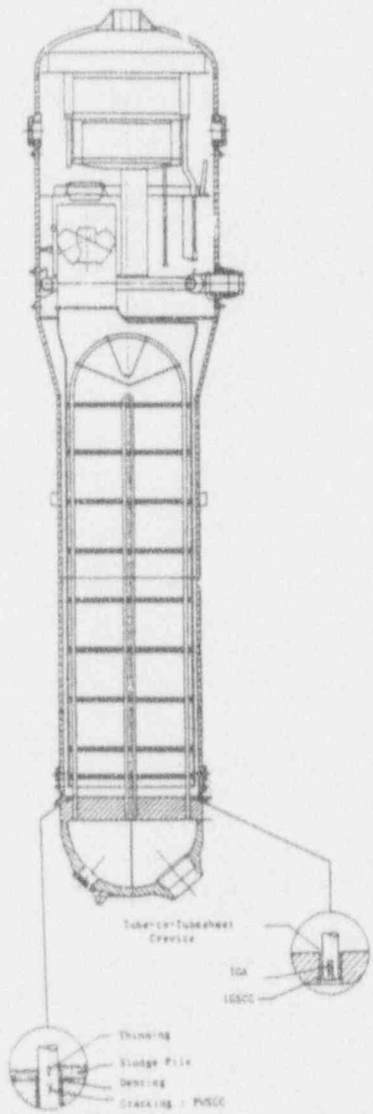
- The possible presence of loose parts in the secondary side of steam generators.

Generally speaking, for analyses of mechanical integrity conducted on damaged tubes, several different types of deterioration are distinguished:

- The " loss of thickness " or " loss of material " types of defects characterized by localized thinning over certain parts of the tubes.
  These are the " wear " or " loss of material " type of defect which appear in the form of small regions of intergranular cracks on the outer wall (IGA - IGSCC).

- " V-notch " type defects such as deep scratches and cracks oriented roughly in the same direction produced by stress corrosion cracking or fatigue cracking. These cracks, although limited in number, are generally longitudinal, but can occasionally be circumferential; they may be part-through or through-wall cracks.

- Multiple longitudinal through-wall or part-through cracks of varying lengths, distributed over a part or all of the circumference of the tube.




| LOCATION | TYPE OF DAMAGE |
|---|---|
| A.V.B. | TUBE / AVB WEAR |
| U-BEND | PWSCC ROWS 1 AND 2 |
| T.S.P. | DENTING |
| T.S.P. | ISGCC IGA |
| ROLL TRANSITION ZONE | PWSCC IGSCC |

Figure 3-1. Typical Corrosion Problem Areas in PWR Steam Generators

- Stress corrosion cracking networks. This type of damage is characterized by numerous small intergranular cracks, and may take the form of :
  - networks of small, longitudinal cracks
  - networks of small, multidirectional cracks

- Complex cracks, distinguished as :
  - multiple, cracks almost in a straight line,
  - combinations of longitudinal and circumferential cracks : L-shaped or U-shaped,
  - Multiple longitudinal cracks or circumferential cracks associated with networks of small longitudinal or multidirectional cracks,
  - The combination of a crack and a " wear " type defect or thinning over the entire circumference of the tube.

Analysis of steam generator tube behavior with reference to the different types of damage likely to threaten the integrity of the primary system leads us to distinguish between the various tubes zones in which damage has been observed :

- <u>The rolling zones or roll transition zones.</u>

  In this case, stress corrosion cracking is most commonly initiated on the primary side. Generally, the orientation of cracks depends on the level of residual manufacturing stresses in addition to operating stresses (pressure + thermal load) and stresses due to local tube interaction with the tubesheet and flow distribution baffle (or the lower tube support plate). All the results of analysis indicate that these cracks may be multiple, longitudinal in direction, frequently through-wall, and located in the roll transition zones. In some cases, they may be circumferential, especially in the case of single or double rolling not conforming to the specification; e.g. over-rolling in the case of full-depth rolling, and excessive kiss rolling. Circumferential cracks also appear in certain tubes located in the sludge-deposit zone.
  Lastly, in some very specific cases, one may observe networks of small, intergranular longitudinal or multidirectional cracks (See Table 3-1.). Multiple, longitudinal cracks initiated on the outer wall above the tubesheet have also been observed in several tubes located in the sludge-deposit zone.

- <u>Zones located at tube support plate levels</u>

  Generally, in this case, one finds tube deformation at the level of the tube support plates which could be due to :

  - Denting phenomena likely to appear in specific types of steam generator.
  - The deformation of tube support plates located near the antiseismic support blocks which transmit the loads on the tube support plates to the steam generator shell.

These deformations are likely to induce damage due to stress corrosion cracking, with the formation of longitudinal or circumferential cracks. In certain cases, " loss of material " type defects may be found.
In most cases, intergranular stress corrosion cracks (IGSCC) or intergranular attack (IGA) initiated at the outer surface of the tubes has been found in steam generators in operation. Generally cracks are oriented longitudinally and crack lengths are limited to the thickness of the support plates.

TABLE 3-1

DEFECTS ACTUALLY APPEARING IN THE ROLL TRANSITION ZONE IN FRENCH STEAM GENERATORS

- <u>The zones located near the antivibration bars</u>

  In general, these are " wear " type defects. The " worn " area is usually limited to the width of the antivibration bars.

- <u>The tube U-bends</u>

  Here, longitudinal stress corrosion cracking is found in those tubes with the smallest radius U-bends. In certain specific cases, longitudinal and circumferential, through-wall or part-through cracks could be obtained in stress corrosion cracking tests. For the most part, the direction and location of the defects depend on the level of residual manufacturing stresses in addition to operating stresses, taking into consideration the manufacturing and assembly tolerances.

As it can be shown, the knowledge of causes, types and location of degradation is necessary to apply the leak before break criterion and/or to establish a tube plugging criterion.

The results of analysis presented in this report are limited to the straight portion remote from discontinuities and to the roll transition zone, which are the parts of the tube most likely to be affected by stress corrosion cracking caused by the reactor coolant (PWSCC). Eddy current testing with a rotating pancake coil and the examination of tubes pulled from various steam generators show that tubes are sensitive to primary side intergranular stress corrosion cracking (PWSCC). This corrosion by the reactor coolant (PWSCC) is due to the combined effects of a susceptible material, chemistry, local stresses and temperature. As a result, bands of multiple axial cracks around the tube circumference are found in the roll transition zone at the top of the tubesheet. Whatever the tube geometry might be, the presence of this type of axial crack in the transition zone represents the most severe rupture conditions. It has been shown, from the results of burst tests carried out on tubes in alloy 600, that a certain amount of deformation is required for a cracked tube to burst (after plastic instability is reached). The tubesheet reduces the possible extent of deformation of that part of the tube containing the defect(s). As a result, a tube with longitudinal cracks inside the tubesheet will never burst.

As for longitudinal cracks (IGSCC) located at tube support plate level, it is demonstrated that the tube support plate has a significant reinforcement effect on the tube burst strength. Indeed, degraded tube deformation at the support plate level is clearly limited by the presence of support plates. This results in an increase in the instability limit pressure of through-wall cracks. Therefore, the limits of tube degradation beyond which tubes must be repaired or removed from service will be higher than those obtained for the same degradation located away from supports (1).

### 3.2 ORGANIZATION

The leak-before-break analysis applied to the steam generator tubes of the specific units is based on the following ideas :

- Evaluation of the burst risk for steam generator tubes to determine the dimensions of critical cracks in the event of accidental overpressure : Steam line break (SLB) or Feedwater line break (FLB).

- Determination and justification of the allowable leak rate in normal operating conditions.

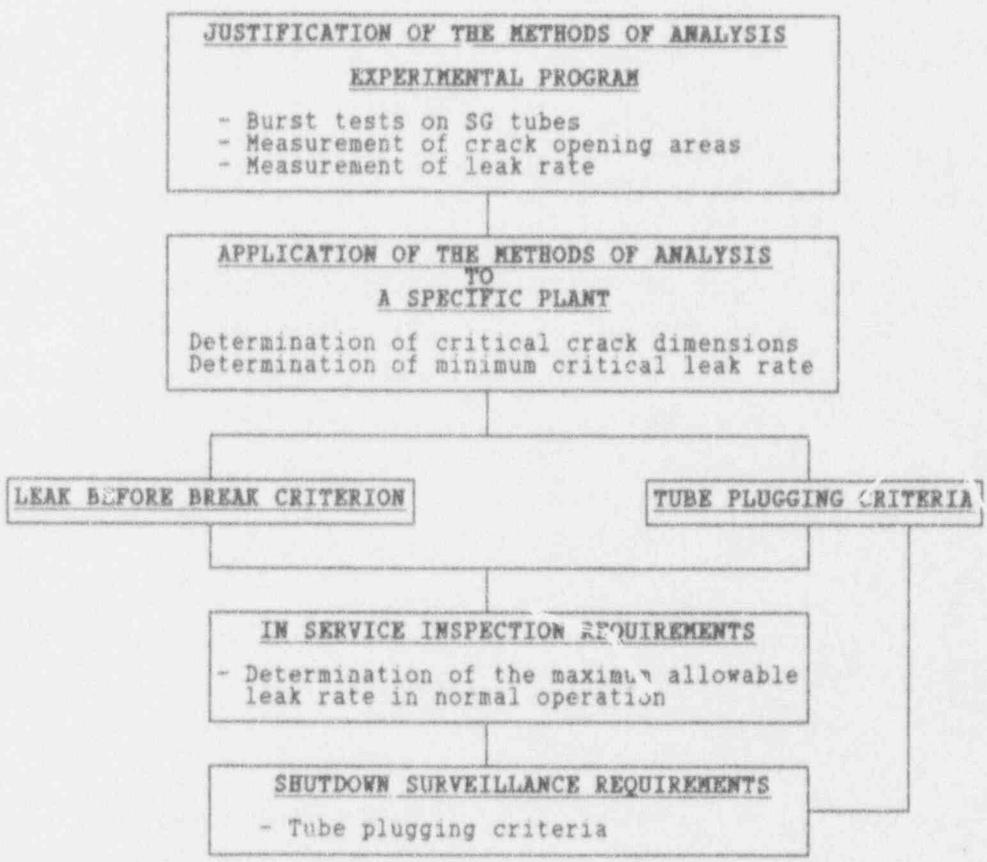



Figure 3-2. Flow diagram for steam generator tube integrity analysis

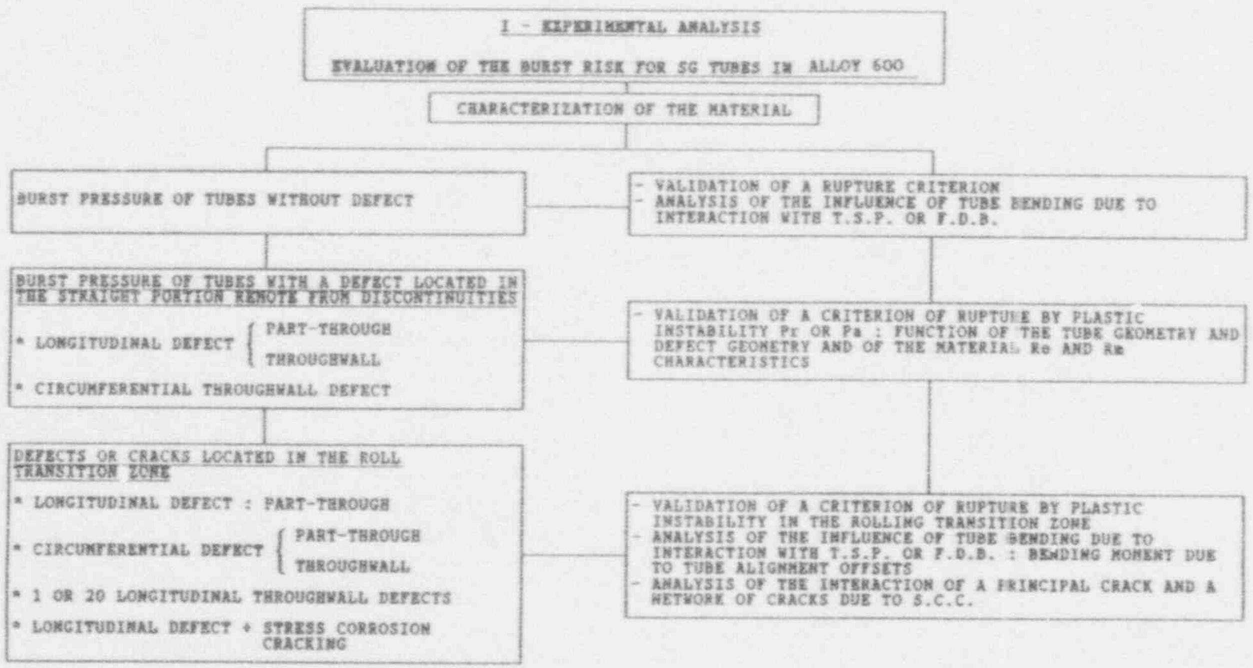



Figure 3-3. Flow diagram for experimental analysis Burst Test Program

I - EXPERIMENTAL ANALYSIS (CONTINUED)

EVALUATION OF THE BURST RISK FOR SG TUBES IN ALLOY 600

BURST PRESSURE OF TUBES WITH MULTIPLE PARALLEL DEFECTS OR COMPLEX DEFECTS LOCATED IN THE STRAIGHT PORTION REMOTE FROM DISCONTINUITIES OR IN THE ROLL TRANSITION ZONE

COMPARATIVE ANALYSIS OF TEST RESULTS

* CASE OF 2 LONGITUDINAL THROUGHWALL DEFECTS
  - PARALLEL
  - NOT ALIGNED
  - ALIGNED
* CASE OF 8 OR 20 LONGITUDINAL THROUGHWALL OR PART-THROUGH DEFECTS UNIFORMLY DISTRIBUTED OVER THE ENTIRE TUBE CIRCUMFERENCE
* CASE OF A REGULAR NETWORK OF LONGITUDINAL THROUGHWALL AND PART-THROUGH DEFECTS
* CASE OF A LONGITUDINAL THROUGHWALL DEFECT + A NETWORK OF MULTIPLE LONGITUDINAL DEFECTS
* CASE OF A CIRCUMFERENTIAL DEFECT + A NETWORK OF MULTIPLE LONGITUDINAL DEFECTS
* CASE OF UNIFORM THINNING + A LONGITUDINAL THROUGHWALL DEFECT
* CASE OF A CIRCUMFERENTIAL DEFECT + LONGITUDINAL DEFECTS : U SHAPE

BURST PRESSURE OF TUBES PULLED FROM DIFFERENT POWER PLANTS :

VERIFICATION OF THE APPLICABILITY OF PLASTIC INSTABILITY RUPTURE CRITERIA

Figure 3-4. Flow diagram for experimental analysis Burst Test Program (continued)

**II - EXPERIMENTAL ANALYSIS**

**EVALUATION OF PRIMARY SIDE - SECONDARY SIDE LEAK RATE THROUGH THROUGHWALL CRACKS**

* **DETERMINATION OF THE CRACK OPENING AREA OF LONGITUDINAL THROUGHWALL CRACKS**

  . MEASUREMENT OF THE CRACK OPENING AREA OF A LONGITUDINAL THROUGHWALL DEFECT UNTIL THE TUBE RUPTURES : PHOTOGRAPHIC OR VIDEO METHOD

  . VALIDATION OF A MODEL TO CALCULATE THE CRACK OPENING AREA

* **DETERMINATION OF THE LEAK RATE THROUGH LONGITUDINAL CRACKS**

  . MEASUREMENT OF THE LEAK RATE OF WATER THROUGH STRESS CORROSION CRACKS OBTAINED IN THE LABORATORY

  . VALIDATION OF A MODEL TO CALCULATE THE LEAK RATE

Figure 3-5. Flow diagram for experimental analysis
Leak rate test program

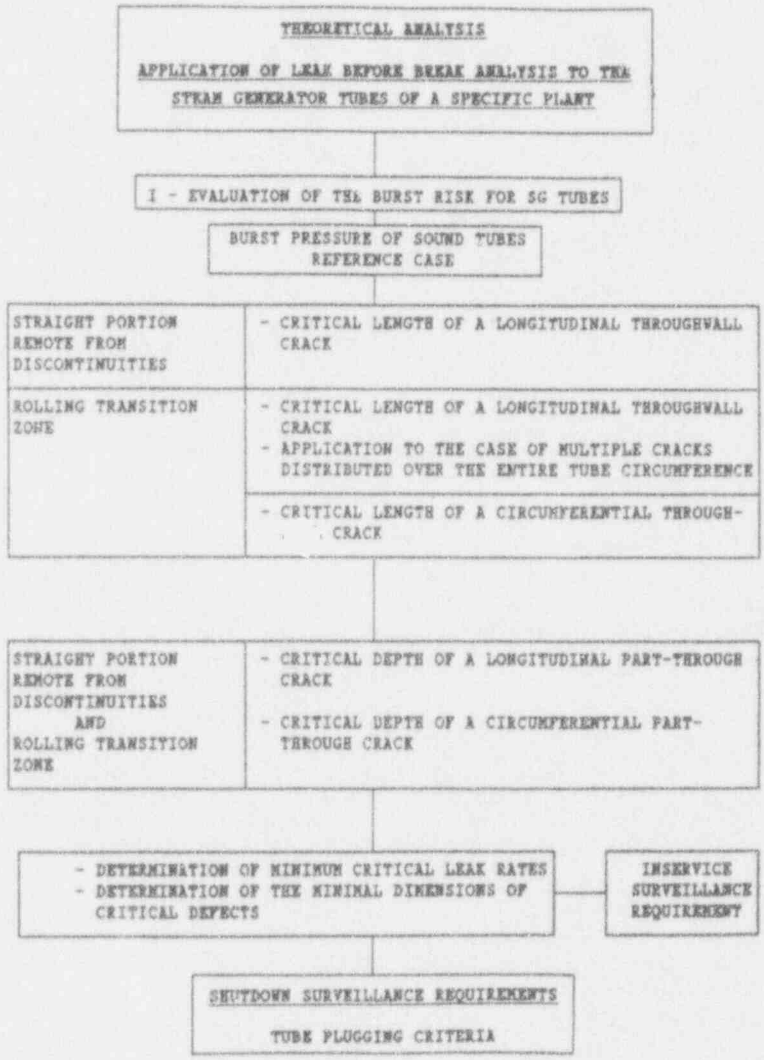



Figure 3-6. Flow diagram for theoretical analysis
Tube plugging criteria

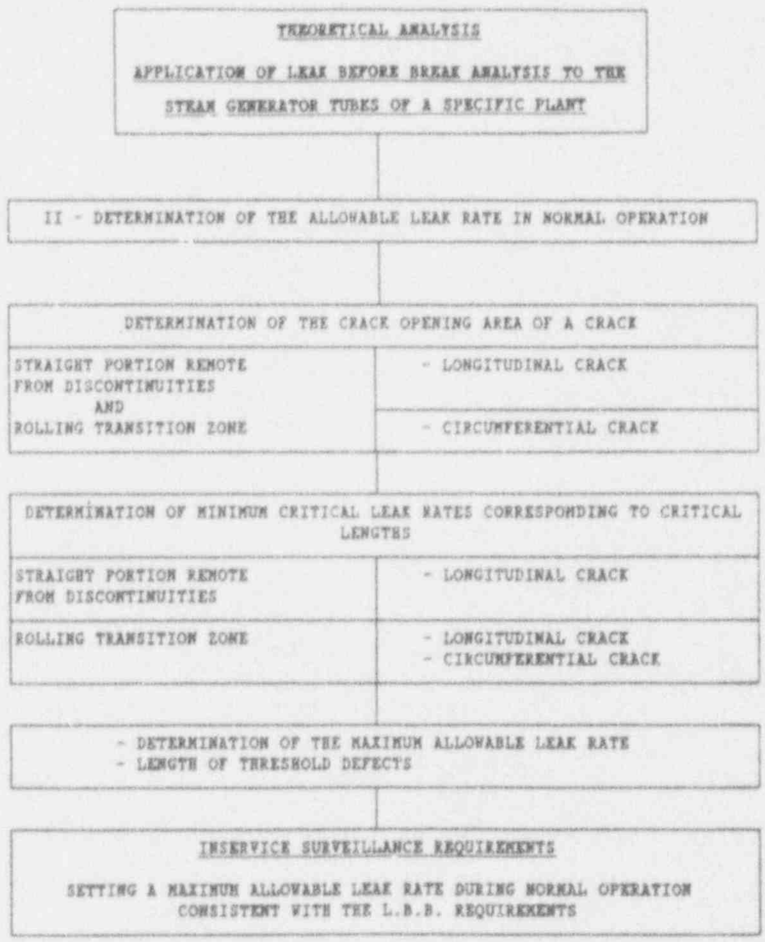



Figure 3-7. Flow diagram for theoretical analysis
Leak before break criterion

## SECTION 4

## EXPERIMENTAL PROGRAM

To evaluate the rupture risks for steam generator tubes in French 900 MW and 1300 MW nuclear power plants, taking into account the criteria set for leak rates in normal operation, a large-scale theoretical and experimental program has been undertaken in France. The results of these studies have been directly applied to the case of the steam generators of Ringhals 3 and 4 (Sweden), C.N. Almaraz and C.N. Asco (Spain), for which a specific study has been carried out to analyze the behavior of cracked tubes in the roll transition zone.

### 4.1 GENERAL OBJECTIVES

The general objectives of the experimental program are as follows :

- Validation of mechanical strength criteria.

  These criteria are used to evaluate the burst pressure of tubes with simulated defects likely to represent defects or cracks encountered in steam generator tubes in operation.
  In order to do so,

  - Determination of the burst pressure, at room and elevated temperatures, of 22.22 mm and 19.05 mm diameter tubes made of alloy 600 with defects or cracks located in the straight portion of the tubes remote from discontinuities or a local zone near a tube support plate or the tubesheet.

  - Verification that a criterion based on the plastic flow instability concept can be used to predict reliably the rupture of steam generator tubes.

- Justification of the tube behavior in accident conditions.

  To determine allowable loadings on steam generator tubes in operation, the loadings which tubes are likely to encounter in normal operation and accident conditions are reproduced on a test bench. In order to do so, one studies the behavior of a sound or deteriorated tube subjected simultaneously to :

  - Internal pressure

  - External loadings representative of the mechanical loads corresponding to accident conditions.

  A distinction is made between :

  - Loadings due to the behavior of the tube support plate when it is subjected to loadings perpendicular to its plane, such as a differential pressure or vertical acceleration. In the event of an earthquake or steam line break, bending of the support plate is likely to exert a local rotation on steam generator tubes, and thus introduce additional bending stresses.

* Loadings exerted in the plane of the support plate due to inertial forces resulting from the movement of the steam generator. In the event of an earthquake or steam line break, these loadings can cause a tube-pinching effect by deformation of the support plate in the vicinity of the anti-seismic support blocks.

* Bending loadings due to the shifts in relative positions of the lower tube support plate (or flow distribution baffle) and the tubesheet. These displacement-controlled external loadings can be due to the following factors :

  . Manufacturing and assembly tolerances, and drill run-outs in tubesheet holes.

  . Thermal mismatch between the tubesheet and tube support plate.

  . Bending of the tubesheet due to the primary side - secondary side differential pressure

* Bending loadings at the base of the tube bundle due to flow-induced vibrations and tube-baffle interaction.

Taking into account fabrication restraints for tube bundles and their supports, tubes undergo additional loadings in normal operating conditions and the postulated accident conditions. These loadings introduce bending stresses to which tubes are subjected in addition to the primary stresses due to pressure. The object of the tests is to verify that these additional loadings do not significantly influence tube burst pressure.

* Determination of the primary-to-secondary leak rate through cracks

  This is done to validate the analytical or numerical methods of calculation applicable in these analyses.

### 4.2 EVALUATION OF STEAM GENERATOR TUBE RUPTURE RISKS

Generally speaking, the evaluation of the burst risk for 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. These criteria should permit reliable estimates of the critical dimensions of cracks in sound or damaged tubes subjected to the types of loadings mentioned above.

The study is limited to the straight portions of tubes with defects located in zones remote from discontinuities or in a local zone near a support representing the tube support plate or the tubesheet. In the course of the various test programs, the following configurations have been studied :

- Tubes without defect, with or without a displacement-controlled external loading

- Tubes with longitudinal part-through defects or cracks obtained by stress corrosion cracking, located in the straight portion remote from discontinuities or in a local zone, with or without a displacement-controlled external loading.

- Tubes with longitudinal through-wall defects in the straight portion remote from discontinuities or in the roll transition zone, without an external loading.

- Tubes with circumferential through-wall defects in the straight portion remote from discontinuities or in a local zone, with or without a displacement-controlled external loading, e.g. defects located at the top of the tubesheet.

- Tubes with circumferential part-through defects in a local zone, with or without a displacement-controlled external loading, e.g. defects located at the top of tubesheet.

- Tubes with part-through defects, transverse or oblique , in the straight portion remote from discontinuities or in a local zone, with or without a displacement-controlled external loading.

- Tubes with two longitudinal through-wall defects, aligned or not aligned, located in the straight portion remote from discontinuities.

- Tubes with several longitudinal through-wall or part-through defects uniformly distributed over the entire tube circumference, in the straight portion remote from discontinuities or in the roll transition zone.

- Tubes with complex defects located in the straight portion remote from discontinuities.

This report integrates the results obtained on 690 test specimens.

The resul are presented in the following manner :

- C racterization of alloy 600.

- Determination of the burst pressure of tubes without defect.

- Analysis of the behavior of tubes with one defect or crack located in the straight portion remote from discontinuities.

- Analysis of the behavior of tubes with one or several defects or cracks located in the roll transition zone.

- Analysis of the behavior of tubes with multiple defects or complex cracks, located in the straight portion remote from discontinuities or in the roll transition zone at the top of the tubesheet.

- Analysis of the behavior of pulled tubes with respect to rupture

Detailed analysis of test results and of their interpretation is presented in reference (1). The major conclusions are summarized in the following paragraphs.

4.2.1 Characterization of the Material

It is necessary to determine the tensile mechanical characteristics of tubes in alloy 600 to validate the rupture criteria and to determine the dimensions of critical defects. In all cases, analysis of test results is carried out considering the actual mechanical characteristics of tube samples. Thus, on the basis of burst tests on sound or damaged tubes, it is shown that the burst pressure is a function of tube geometry, the dimensions of defects or cracks and mechanical properties Re and Rm of alloy 600. Consequently, when the characteristics are identical, tube origin does not affect the instability limit pressure. The values of characteristics to be taken into account in the analyses are those of steam generator tubes in service. These values, which can vary greatly from one nuclear power plant to another, are specified in acceptance test reports concerning tubes from different heats. When mechanical characteristics have not been recorded, the minimum values required by the technical specifications or the prevailing manufacturer's code are selected.

The results presented in reference (1) yield the following information :

- The mechanical properties of mill-annealed tubes are not significantly modified by complementary heat treatment. The deviations are of the same order of magnitude as the scatter in tensile test results.

- In the absence of results of tests at elevated temperature , the mechanical characteristics at can be deduced by means of the following formulas :

The coefficients applied respectively to the values Re and Rm are based on acceptance test results for mill-annealed tubes or tubes which have undergone complementary heat treatment.

- The value of the mean hardening coefficient for french supplied tubes is :

Depending on tube origin, lower values for n can be obtained.

### 4.2.2 Burst pressure of tubes without defect

On the basis of tests carried out on Ø 19.05 mm and Ø 22.22 mm tubes made of alloy 600, it is demonstrated that the burst pressure of tubes without defect can be estimated reliably by means of Svensson's formula :

(4-1)

This formula, which incorporates the material stress hardening coefficient, n, in addition to the ultimate tensile strength, Rm, can be used to obtain a good correlation with test results. The deviation between the theoretical predictions and test results is less than 5 % in all cases.

The results of burst tests show that rupture is preceded by a very large degree of deformation, which attests to the great ductility and toughness of tubes made of alloy 600. There is a good correlation between test results and a model predicting the burst pressure as a function of plastic flow stress; this reflects 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 alloy 600. One obtains :

(4-2)

Thus, the rupture criterion is equivalent to the linearized Mises criterion defined by the formula :

(4-3)

or equivalent to the Tresca criterion defined by the formula :

(4-4)

In accident conditions, steam generator tubes can be subjected to loadings due to the displacements and deformation caused by shifts in the relative positions of the tubesheet and tube support plates. To analyze the influence of these external loadings, burst tests were carried out to evaluate the consequences of :

- Tube pinching due to tube support plate deformation near the wedge supports
- Local tube rotation by tube support plate bending
- Differential displacement of tube support plates and tubesheet.

Thus, it is demonstrated that a displacement-controlled external loading does not modify the burst pressure of a sound tube. The stresses caused by the effects of the changes in relative position of support plates and tubesheet and by the pinching effect produced by the support plate, are secondary in nature. They are the result of imposed displacement or deformation. Experience in the calculation of pressure vessels, codified in the ASME and RCCM codes, shows that secondary stresses have a negligible effect in plastic instability phenomena against which protection is sought when accident conditions occur. This practice is well justified in the case of steam generator tubes in alloy 600, characterized by high toughness and ductility. The burst test results show that it is perfectly justified, for sound tubes, not to take secondary stresses into account when calculating the behavior of tubes in accident conditions.
The criterion which should be used on tubes in accident conditions is to limit the effects of interaction to those simulated in tests because, for these limiting values of external loading, experience shows that the burst resistance of straight tubes is not affected.

### 4.2.3 Analysis of the behavior of steam generator tubes with a defect located in the straight portion remote from discontinuities - Case of tubes not subjected to an external loading

Experimental studies on steam generator tubes in alloy 600 with a defect or crack in the straight portion remote from discontinuities were carried out to validate rupture criteria based on the plastic instability concept. For the criteria used, deviations between test and theoretical values were lower than .

#### 4.2.3.1 Burst tests on tubes with a longitudinal part-through defect.

117 burst tests on tubes with a longitudinal part-through defect were carried out at room temperature or elevated temperature . The length of defects is between and depth is between of the tube wall thickness. Test results yielded the following information :

- For the " V-notch " type defect produced by milling or electron discharge machining or a crack, the burst pressure obtained is lower than obtained for a " wear " type defect represented by a " machined flat " type defect produced by milling.

- It is confirmed that notch sharpness does not significantly influence the burst pressure.

- For a given length, the minimum burst pressure is obtained for the case of a tube with uniform thinning over the entire tube circumference.

- It is confirmed that a considerable thermal shock or a thermal gradient in addition to the pressure loading does not significantly influence the ligament rupture pressure for a part-through defect.

- For defect depths between of the tube wall thickness, it is confirmed that the ligament rupture pressure decreases in proportion to the increase in defect depth.

- When a notched, worn or cracked tube reaches the stability limit state, the remaining ligament of the part-through defect ruptures, with or without longitudinal crack propagation. After breakthrough of the tube wall thickness, the pressure needed to produce instability of the through-wall crack thus formed, depends on the length of the part-through defect at the time of breakthrough.

Fxperimental results show that, for tubes with longitudinal part-through defects, an accurate estimation of the burst pressure may be obtained on the basis of a criterion of the plastic instability type :

- When the defect depth is between of the tube wall thickness, the rupture pressure can be obtained using the following formula :

(4-5)

- When the defect depth is greater than of the tube wall thickness, this formula is no longer appropriate for predicting the ligament rupture pressure. In this case, the formula proposed by Battelle is used to encompass test results by considering the bulging factors defined by Krenk and Folias, associated with a flow stress $\bar{\sigma}$ equal to the ultimate tensile strength Rm. In this case, the rupture pressure is obtained by the following formula :

(4-6)

A conservative estimation of Pr is obtained using the Folias bulging factor defined by the following formula :

(4-7)

- Generally speaking, whatever the length and depth of the defect under consideration, a lower limit for the ligament rupture pressure is obtained by means of the following formula :

(4-8)

In all cases, the selection of flow stress $\bar{\sigma} = k\ (Re + Rm)$ with leads to an underestimation of the rupture pressure value for a part-through defect. Predictions of rupture at elevated temperatures are obtained by considering the mechanical properties of alloy 600 at the relevant temperature.

#### 4.2.3.2 Burst tests on tubes with a longitudinal through-wall defect

136 burst tests on tubes made of alloy 600 with a longitudinal through-wall defect were carried out at room temperature or at temperatures between , with or without a thermal gradient. The length of the defects is between . The test results yielded the following information :

- The pressure needed to produce instability of a through-wall defect decreases when the defect length increases. Rupture is preceded by large plastic deformation (bulging) at the location of the defect.

- Whatever the initial length of the defect or crack may be, when the instability limit pressure Pa is reached, rupture initiation and unstable propagation of the crack occur. In some cases, the rupture can deviate in the circumferential direction, causing a " guillotine " break. Generally speaking, propagation of the ductile rupture occurs in the shear plane from the direction of principal stresses. Below the limit value Pa, the crack remains stable.

- The influence of applying pressure to the sides of the defect or crack prior to initiation of rupture by plastic instability is manifested by a decrease in the instability limit pressure Pa of the through-wall defect.

It is demonstrated that the instability limit pressure Pa of a defect or crack through the tube wall can be accurately estimated on the basis of a plastic instability criterion. It is determined by means of the following formula :

(4-9)

with :

. (4-10)

or

. (4-11)

.

The application of the rupture criterion incorporating a bulging factor M defined by formula (4-10) gives an underestimation, whereas M defined by formula (4-11) gives an overestimation. In fact, the comparison of theoretical and test results shows that for a properly-adjusted flow stress $\bar{\sigma}$ :

- When internal pressure is applied to the sides of the defect or crack prior to rupture initiation, there is an excellent correlation between the test results and the theoretical predictions using the bulging factor defined by formula (4-10). Experimentally, pressure is applied to the sides of the crack prior to rupture initiation when the flexible plastic tube sealing the through-wall defect is extruded through the defect or when a leak rate occurs after rupture of the remaining ligament of an initially part-through defect.

- When the leak-tightness device prevents the application of pressure to the sides of the defect or crack, the test values agree with theoretical predictions using the bulging factor defined by formula (4-11).

As in the case of tubes without defect, the very high ductility and toughness of tubes in alloy 600 is attested by :

- Very large deformations manifested by considerable bulging before the defect reaches instability.

- Considerable necking in the thickness of the tube wall, at the ends of the through-wall defect.

- Perfect agreement between test results and a model used to predict the rupture pressure with reference to a plastic flow stress.

The adjustment of the flow stress on the basis of test results for tubes with a longitudinal through-wall defect gives the following results :

$$\bar{\sigma} = k\ (Re + Rm)$$

The value the case of the Ø 22.22 mm tubes is probably underestimated. Taking into account the low scatter in results, a good correlation is thus obtained between the flow stress and the mechanical characteristics of the material, based on the test results for tubes without defect and for tubes with a longitudinal defect which is either through-wall or part-through.

In conclusion, the instability limit pressure Pa of a through-wall crack can be reliably determined on the basis of the proposed plastic instability criterion (4-9) in which the bulging factor M is defined by the formula :

In addition, experiments 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, are only secondary in nature and they do not play an important role in the plastic collapse phenomena. As a result, the critical length of a through-wall crack is obtained by considering the pressure loading only. As the phenomenon is governed only by the limit load, it is confirmed that application of the CEGB R6 approach is not needed in the case of alloy 600 steam generator tubes.

4.2.3.3 <u>Burst tests on tubes with a circumferential through-wall defect.</u>
42 burst tests on tubes in alloy 600 with a circumferential through-wall defect were carried out at room temperature.The test results yielded the following information :

- The influence of providing support conditions simulating the presence of a tube support plate is manifested by an increase in rupture pressure in comparison with that obtained for an unsupported tube.

- Support conditions located between above the top of the tubesheet do not significantly influence the instability limit pressure of the circumferential defect. For a defect, it is of the same order of magnitude as the scatter in results.

- The end effect exerted by internal pressure induces tube bending which increases with the angle of the defect.
  When the angle of the circumferential defect is lower than about , the bending moment remains small and rupture is governed by the hoop stress or equivalent stress

  For an angle greater than and fixed boundary conditions, the bending moment increases with the angle of the defect. Rupture is governed by the longitudinal stress or equivalent stress .

  For an angle greater than , the bending moment is no longer dominant and rupture occurs due to tension of the net section.

- As in the case of longitudinal defects, rupture is preceded by bulging at the location of the circumferential defect.

It is concluded that the instability limit pressure of a tube with a circumferential crack may be estimated using a plastic collapse model.

### 4.2.4 Analysis of the behavior of steam generator tubes with one or several defects or cracks located in the roll transition zone

163 burst tests on tubes in alloy 600 with one or several defects or cracks located in the rolling zone were carried out at room temperature. Test results yielded the following information :

- The boundary effect represented by the tubesheet is manifested by an increase in the local rigidity of the tube.
  The presence of the tubesheet prevents tube deformation from taking place freely over a minimum distance of above the tubesheet. This boundary effect diminishes progressively until it is negligible beyond a distance of above the tubesheet. In the case of a cracked tube, this boundary effect is manifested by a decrease in the bulging effect, which causes a decrease in the stress and strain concentration factor in the plastic range, at the tip of the crack. As a result, the rupture strength of a sound or deteriorated tube increases in the local zone at the top of the tubesheet.

- In all cases, it is experimentally confirmed that the instability limit pressure of a defect or crack, or the burst pressure of a tube cracked in the rolling zone at the top of the tubesheet is higher than that of a tube with the same type of damage located in the straight portion remote from discontinuities.

- The increase in the instability limit pressure in the roll transition zone depends on the length of the defect or crack. In Ø 19.05 mm and Ø 22.22 mm tubes, this increase is when the length of the longitudinal cracks is . It becomes negligible when the length of the crack is between
  When the tip of the crack outside 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. In all cases, unstable propagation initiates at the tip of the crack which is not in contact with the tubesheet. In the case of a circumferential through-wall crack located at the top of the tubesheet, the increase in the instability limit pressure is over for a defect and over defect. For defects larger than , rupture occurs due to tension caused by the end effect (negligible bending of the tube). The boundary effect due to the presence of the tubesheet is then negligible and rupture occurs at a pressure Pa equal to that of a crack with the same length in the straight portion remote from discontinuities.

- It is concluded that a displacement-controlled external loading, added to a pressure loading, which introduces supplementary bending stresses lower than or equal to the offset yield strength of the material at the top of the tubesheet, does not significantly influence the instability limit pressure Pa of a longitudinal or circumferential through-wall crack. These test results for displacements much larger than those likely to be encountered by steam generator tubes in operation are used to assess the role of secondary stresses in the behavior of tubes in accident conditions. These effects of secondary stresses are negligible as previously mentioned for sound tubes. It is, therefore, perfectly justified not to take secondary stresses into consideration in the burst-risk evaluation for worn or cracked tubes.

- It is concluded that the type of rolling; i.e. full-depth rolling or full-depth plus kiss rolling, does not influence the instability limit pressure of a through-wall crack.

- The presence of one or several through-wall cracks uniformly distributed over the entire tube circumference does not significantly modify the instability limit pressure Pa. Rupture starts at the longest defect(s) or crack(s).

- When the end of the tube/tubesheet contact is located at - with respect to the top of the tubesheet, the instability limit pressure of a defect outside the tubesheet is equivalent to that of a defect long, of which are outside the tubesheet.

- It is confirmed that the instability limit pressure of a defect long, located in a band containing longitudinal defects with lengths of inside the tubesheet) distributed uniformly over the entire tube circumference, is only slightly affected by the presence of other defects. The decrease in instability limit pressure of the principal crack is of the same order of magnitude of the scatter in results.

- A circumferential defect, through-wall or part-through, remains stable. The tube ruptures in the straight portion remote from discontinuities; rupture occurs independently of the supplementary bending to which the tube is subjected due to the relative displacement of the tube support plate and the tubesheet.

- A circumferential part-through defect whose depth is equal to of the tube wall thickness over remains stable. Rupture occurs in the straight portion remote from discontinuities. When the depth of the defect reaches of the tube wall thickness, the rupture occurs at the location of the defect. In this case, the loss in tube resistance is about with respect to a sound tube.

On the basis of all these test results, it is demonstrated that a plastic instability rupture criterion can be used to predict the rupture of cracked steam generator tubes in the rolling zone. It is confirmed that rupture criterion validated for defects or cracks located in the straight portion remote from discontinuities can be used to predict reliably the rupture of a tube with the same type of damage in the local zone at the top of the tubesheet.

These tests show that this rupture criterion can be modified to take into consideration the increase in tube rigidity due to the presence of the tubesheet, which affects the bulging factor M.

A global approach is used to formulate the increase in instability limit pressure of a through-wall crack provided it does not exceed a certain length determined on the basis of test results. It is based on a modification in the factor M by introducing an equivalent thickness taking into account interaction with the tubesheet. The instability limit pressure of a longitudinal through-wall defect in the roll transition zone can be determined by means of the following formula :

(4-12)

with

and

where :

- $2a_s$ represents the crack length outside the tubesheet

- $t_{ip}$ represents 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 cracks distributed over the entire tube circumference or when there is a network of longitudinal cracks obtained by stress corrosion cracking in the rolling zone. All test results on tubes with cracks in the roll transition zone are situated above the limit curve defined by the proposed model.

The limits of applicability of this model are revealed when there is a network of longitudinal cracks whose depth is over of the tube wall thickness. This network " cancels " the increase in rupture strength of the tube due to the presence of the tubesheet.
Then, the tube again behaves like a cracked tube which ruptures at a pressure equal to that of a tube with a crack of identical length in the straight portion remote from discontinuities.

This model is not appropriate in the case of the combined effects of an interaction between a circumferential crack and a longitudinal through-wall crack in a network of deep longitudinal cracks.

4.2.5 **Analysis of the behavior of steam generator tubes with multiple cracks located in the straight portion remote from discontinuities or in the roll transition zone**

146 burst tests on tubes in alloy 600 with complex defects located in the straight portion remote from discontinuities were carried out at room temperature.

On the basis of plastic instability rupture criteria validated for different defect configurations or for single cracks, comparative analysis of the results obtained, reveals a weakening, which is variable in extent, of overall tube strength in the deteriorated area. This results from an interaction between cracks, and is manifested by a decrease in the instability limit pressure of the main crack depending on the type of damage, length and relative position of the various cracks.

As shown by experiment, the weakening of a tube due to the presence of a network, or an interaction between complex cracks, can be partially compensated by the boundary effect due to the presence of the tubesheet which prevents deformation from taking place freely. However, beyond a certain limit of deterioration (over      of the tube wall thickness for configurations examined), this effect is cancelled out. This limit depends on the type of deterioration observed, see (1).

The analysis of the behavior of any complex cracks identified in a steam generator tube in operation should be carried out as part of a specific study, depending on the type of deterioration observed.

4.2.6. **Analysis of the rupture behavior of tubes pulled from steam generators**

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 roll transition zone. These tests were carried out on a configuration known as " the straight portion remote from discontinuities ", where the presence of the tubesheet is not simulated. The comparison of theoretical and test results does not call into question the validity of the calculation model proposed (2), (3), (4).

## 4.3 DETERMINATION OF THE PRIMARY TO-SECONDARY LEAK RATE FOR THROUGH-WALL CRACKS

Knowledge of this parameter is necessary in order to establish an operating requirement which consists of fixing an allowable leak rate criterion corresponding to a threshold defect whose length is smaller than the critical size determined by application of the rupture criteria.

Experimental studies on test specimens or on tubes taken _in situ_ are carried out for the purpose of qualifying calculation models which can be used to establish a correlation between the length of the crack and the leak rate under normal operation conditions.

These studies make it possible to determine the sensitivity of the flow to given parameters, select hypotheses which minimize the theoretical flow and are, therefore, conservative in the demonstration of the leak-before-break criterion and to estimate the margins with respect to experimentation.

### 4.3.1 Determination of the crack opening area of longitudinal cracks

Knowledge of the crack opening area of a through-wall crack is necessary in order to evaluate the leak rate. To validate the methods of calculating the crack opening area for longitudinal through-wall cracks, the crack opening area was measured using the photographic or video method.

Detailed comparative analysis with respect to results of measurements on specimens and calculated crack opening areas has been performed. The measurements were carried out on Ø 19.05 mm tubes with a longitudinal through-wall defect with a length of in the straight portion remote from discontinuities. This analysis yields the following results :

- On Ø 22.22 mm and Ø 19.05 mm tubes, after tests at at room temperature or at , the existence of a remaining crack opening area due to bulging at the defect location is observed.This remaining crack opening area increases as the length of the defect increases.

- It is confirmed that an elastic analysis model or numerical model underestimates the crack opening area.

- By comparison with tests, it is confirmed that an elastoplastic or elastic model which is corrected for the size of the plastic zone, can be used to obtain a more realistic crack opening area than that obtained with an elastic model.

- Among the various models proposed in the literature to calculate the crack opening area, the calculations of the crack opening area based on an elastic model (analytical or numerical) with the correction of the plastic zone given by the Dugdale model are used to obtain results which correlate well with the values measured for longitudinal through-wall defects with lengths . The correction of the plastic zone to take into account the effect of plasticity is applied according to the Tada-Paris method. On the basis of the results obtained by means of the finite element method, an expression for the crack opening area ($S_{[num]}$) can be written as follows :

(4-13)

where : represents the bulging factor.

The $A_i$ coefficients determined on the basis of the values for S calculated by the finite element method for various crack lengths depend on the $M(\lambda)$ function selected.
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 roll transition zone. The advantage of the numerical model over the analytical model is manifested by the the possibility of taking into account the influence of the tubesheet which has the effect of decreasing the crack opening area, and taking into account the bending stress on the crack lips. In the straight portion remote from discontinuities, the analytical and numerical models give equivalent results.

4.3.2 <u>Determination of the leak rate through longitudinal cracks</u>

On the basis of leak rate measurements (5) (using water at and ) the following results are deduced :

- In some cases, when the length of the stress corrosion crack is less than , the leak rate at is practically nil following an obstruction of the break.

- The effect of temperature on the leak rate is not very significant. Nonetheless, for a given crack length, the leak rate is generally higher at higher temperature. As a result, there is a slight increase in the flow coefficient determined by means of the method used.

- The shotpeening operation tends to increase the leak rate. For leak-before-break analyses, the influence of shotpeening is considered to be negligible.

- Leak rates lower than about . for pure water are decreased by a factor of in an environment of borated water containing of boron. These low flows correspond to cracks whose length is less than . For high leak rates corresponding to cracks greater than long, the phenomenon does not occur.

This decrease could be due to the recrystallization of the boric acid by vaporization at the outlet cross-section of the crack. This crystallization is thought to contribute to the obstruction of small cracks whose opening, which is practically elastic, remains small.

The analysis of test results reveals two ranges of sensitivity concerning the evaluation of the leak rate which can be determined by using a simple calculation model of the perfect fluid type. This model is expressed in the form :

(4-14)

where :

Q : represents the leak rate

$\rho$ : represents the density of the primary coolant

S : represents the crack opening area of the through-wall crack when the tube is subjected to a differential pressure $\Delta P$

K : represents the flow coefficient determined on the basis of leak rate measurements on pulled tubes or tubes cracked by stress corrosion cracking in the laboratory

Given the crack opening area, the value of the coefficient K is determined for each leak rate measurement test. The value of K determined in this manner integrates all uncertainty for the various parameters, such as :

- Type of coolant : perfect or viscous
- Type of flow : laminar or turbulent
- Actual length of the stress corrosion crack, generally characterized by an inner length greater than the length on the outer wall.
- State of the surface of the crack shear lips : friction along the crack walls which modifies pressure drop.
- Differential pressure effectively applied to the crack surface.

The value of K depends strongly on the model used to calculate the crack opening area. On the basis of test results, the values of K given in this report were determined considering an elastic model with a plastic zone correction given by the Dugdale model as used in the Tada-Paris method. Taking into consideration the scatter in test results, distinction is made between :

- Cracks whose length is less than a value between for which, in some cases, the leak rate may be practically nil due to a partial obstruction of the crack whose maximum crack opening at is lower than . The uncertainty for the flow value for small cracks does not call into question the leak-before-break concept, because these cracks are generally stable. For leak-before-break analysis, it is considered that cracks under long can have a flow which is practically nil.

- For cracks greater than or equal to in length, the leak rate is measurable and a good correlation can be obtained between flow and crack length. By application of the numerical crack opening area model defined in the preceding paragraph, when considering the pressure applied to the sides of the crack, a mean flow coefficient is obtained :

  A lower limit for this flow is obtained by adopting :

## 4.4 CRACK PROPAGATION KINETICS

An estimation of crack propagation rates in alloy 600 has been made from tests performed in laboratory. This estimation is founded on two approaches :

- An experimental approach which analyses all the available data including unpublished Framatome results and utilizes those for which the error due to incubation time seems acceptable

- A theoretical approach based on the film rupture model.

This study has made it possible to estimate the primary water stress corrosion crack propagation rate in alloy 600 at steam generator operating temperatures of between .These rates lead to the formation of through-wall cracks in the tubes in short periods as compared to the corresponding incubation times (see Figure 4-1).

An analysis of all the experimental results on 119 tubes pulled from steam generators at different French nuclear power plants has been carried out. These tubes were pulled after periods of operation of 3,000 to 48,000 hours (6).

Figure 4-1. Crack propagation rate as a function of temperature for alloy 600

This study yields the following results and conclusions :

- Although the tubes whose mechanical properties are low (yield strength at between ) are less susceptible to PWSCC, one cannot exclude the possibility of encountering this type of damage in steam generator tubes in operation.

- For all cases observed, it is confirmed that the number of longitudinal cracks longer than distributed over the entire tube circumference, remains under .
  It is also confirmed that the maximum length of part-through cracks is under .

- Taking into account the relatively high propagation rates (about . on the average obtained in the laboratory), it is confirmed that tube breakthrough can occur at the end of a relatively short period of operation.

- The examination of curves showing crack length versus the normalized crack depth, d/t, presented in Figures 4-2 to 4-5, for each nuclear power plant, makes it possible to demonstrate the existence of stress corrosion cracks which are stable when they become through-wall independently of crack propagation kinetics.

- In all cases, the inner wall crack length $L_i$ is greater than the outer wall crack length $L_e$. The analysis of stress corrosion crack shape for 61 pulled tubes shows that (See Figures 4-6 and 4-7) :

  When the ID crack length $L_i$ exceeds , with a

  standard deviation

  When the length increases, the ratio $L_e/L_i$ nears

- For the maximum pressure imposed by PWR operating conditions, the critical crack dimensions in the roll transition zone at the top of the tubesheet, depend on the tube dimensions and the mechanical properties of the tube.

- The analysis of results presented on curves showing crack length versus operating life (See Figures 4-8 to 4-11) makes it possible to obtain an estimate of the mean longitudinal crack propagation rate between , depending on the power plant considered.

Figure 4-2. PWSCC in the roll transition zone : Bugey (French PWR)

Figure 4-3.  PWSCC in the roll transition zone : Dampierre (French PWR)

Figure 4-4. PWSCC in the roll transition zone : Gravelines (French PWR)

Figure 4-5. PWSCC in the roll transition zone : Tricastin (French PWR)

Figure 4-6. Typical stress corrosion crack shapes

Figure 4-7. Typical stress corrosion crack shapes (continued)

Figure 4-8. PWSCC in the roll transition as a function of operating life: Bugey (French PWR)

Figure 4-9. PWSCC in the roll transition as a function of operating life: Dampierre (French PWR)

Figure 4-10. PWSCC in the roll transition zone : as a function of operating life : Gravelines (French PWR)

Figure 4-11. PWSCC in the roll transition zone as a function of operating life : Tricastin (French PWR)

To date, the operating experience of several different power plants, in France, Belgium, Spain and Sweden shows that the evolution of longitudinal cracks determined by eddy current testing using rotating pancake coil can be between per operating cycle. The large scatter in the results is due to the fact that from one unit to an other one, the values of parameters which govern PWSCC are not the same.
Moreover, according to the Belgium operating experience (7), the evolution of the crack length distribution curve is such that long cracks tend to propagate significantly less quickly than shorter ones.
To conclude, as the stress corrosion by the reactor coolant is due to the combined effect of a susceptible material, chemistry, local operating and residual stresses as well as temperature, it is recommended that the crack propagation kinetics for each plant considered should be verified.

In conclusion, the steam generator operating experience for French nuclear power plants shows that some possibilities of in-service deterioration should be considered. Given the inevitable intervals of time between in-service inspection of tubes, some development of stress corrosion cracking by the reactor coolant can lead to a tube breakthrough 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.

## SECTION 5

## THEORETICAL ANALYSIS OF THE SEVERITY OF CRACKING IN THE STEAM GENERATOR TUBES OF A SPECIFIC PLANT

The purpose of these analyses is to define the limits for defects which can be tolerated in steam generator tubes without their presenting any risk of rupture when subjected to mechanical loadings corresponding to accident conditions.

### 5.1 GENERAL RELEVANT DATA

Leak-before-break analysis applied to steam generator tubes in alloy 600 is carried out considering the data provided in the technical specification.

As an example, results of analysis presented in this section are such that for the most severe conditions, each steam generator tube is postulated to be subjected to a maximum internal pressure of in the event of a steam line break or feedwater line break and to have simultaneously :

- minimum material properties at
- the most critical dimensions with respect to bursting, based on fabrication tolerances.

In addition, the parametric study conducted as a function of pressure, taking into consideration the physical and mechanical properties, includes the following steps :

- Burst pressure of tubes without crack
- Evaluation of burst risk in tubes with longitudinal cracks in the straight portion remote from discontinuities
- Evaluation of burst risk in tubes with longitudinal cracks in the roll transition zone.
- Evaluation of burst risk in tube with circumferential cracks

Data used for this analysis are summarized in Table 5.1

TABLE 5-1

DATA USED FOR ANALYSIS

Figure 5-1. Tube expansion

## 5.2 EVALUATION OF THE BURST RISK FOR STEAM GENERATOR TUBES : DETERMINATION OF CRITICAL CRACK DIMENSIONS

### 5.2.1 Object

The object of this study is to determine the critical crack dimensions likely to be encountered in the roll transition zone of steam generator tubes. The results of this study will make it possible to define a tube plugging criterion as well as an allowable leak rate criterion for normal operating conditions.

### 5.2.2 Analysis of the data used in calculation

| | |
|---|---|
| Tube dimensions | a) Selection of nominal tube dimensions : this corresponds to the situation which best represents the tube population |
| | b) Selection of critical tube dimensions with respect to rupture : manufacturer's tolerances are taken into account so as to minimize the rupture pressure (*) |

(*) Maximum outer diameter : Realistic figures are taken for this analysis in the roll transition zone since this parameter has little influence on results.

(*) Minimum thickness : Conservative figures are chosen in this case since one can eliminate all uncertainty with respect to manufacturer's tolerances. This parameter's influence on results is significant.

Selection of minimum mechanical properties of tubes taken at .

In most of the cases, selecting mechanical properties at is a conservative hypothesis : in accident conditions, the maximum temperature corresponding to the pressure peak taken into account for the analysis is lower than .

The evolution of the Re offset yield strength and tensile strength Rm, with respect to temperature may be expressed by the variation of the coefficients :

* Room temperature

In the absence of results of tests at elevated temperature, one may use coefficients deduced from the minimum values specified by the ASME code. The values Sy and Su are defined by the following formulas :

- (5-1)

(5-2)

- (5-3)

(5-4)

Table 5-2

YIELD STRENGTH AND ULTIMATE TENSILE STRENGTH SPECIFIED FOR ALLOY 600

In addition, FRAMATOME acceptance test results for tubes shown in Table 5-3, yield the following mean values :

Table 5-3

TUBES IN ALLOY 600
TUBE MATERIAL PROPERTIES BASED ON TENSILE TESTS AT ROOM AND ELEVATED TEMPERATURE
FRAMATOME RESULTS : MEAN VALUES

Table 5-4

STRENGTH RATIOS - FRAMATOME RESULTS

These coefficients are deduced from tensile test results for over 3000 tubes in alloy 600 with a nominal diameter of 19.05 mm or 22.22 mm.
To be conservative with respect to safety, steam generator tube burst risk analyses can be carried out by considering the actual mechanical characteristics measured at and deduced for (if not available) by using the following formulas :

(5-5)

(5-6)

Although tubes with a low yield strength are less sensitive to stress corrosion cracking, as shown in the laboratory, the French steam generator operating experience shows that tubes with a low yield strength can also be affected by PWSCC. This eventuality should also be taken into account from the safety point of view.

The minimum value for Re does not necessarily correspond to a minimum value for Rm. By choosing simultaneously the minimum Re and Rm values, a minimum conservative flow stress is obtained.
A good correlation can be obtained between the flow stress and Re and Rm mechanical characteristics of the material (Figure 5-2). By imposing a lower tolerance limit based on statistical analyses of test data from steam generator tubing of the plant, a more realistic minimum value of flow stress can be obtained in some cases. The flow stress has a considerable influence on results. It is demonstrated experimentally that the burst pressure of a tube is proportional to the value of the flow stress $\bar{\sigma}$.

Figure 5-2. Actual mechanical characteristics - Flow stress versus yield or tensile strength

Conditions for calculation at

Selection of the maximum primary to secondary differential pressure at

.

This maximum value for ΔP corresponding to the design conditions is used to evaluate the critical length of cracks in normal and upset conditions. It is used to evaluate the margin of safety during normal operation.

Selection of the maximum primary to secondary differential pressure at

.

This maximum value for ΔP which corresponds to the pressure peak in the event of a feedwater line break is conservative if the depressurization of the secondary side, which is not instantaneous, is not taken into account.

It is demonstrated, based on tests, that even very high thermal stresses do not influence the instability limit pressure of a through-wall crack. Therefore, they are not taken into consideration to determine the critical crack dimensions.

In addition to primary-pressure-induced stresses, test results show that the axial bending stresses due to misalignment resulting from a displacement-controlled external loads do not modify the instability limit pressure of a through-wall crack. Thus, as rupture is governed by primary stresses caused by pressure in the tube, the evaluation of the burst risk for locally-deteriorated steam generator tubes is carried out assuming that the maximum differential pressure of , occurs at .

In conclusion, critical crack dimensions (length and depth) can be estimated reliably by considering, simultaneously :

- maximum outer tube diameter
- minimum tube wall thickness
- minimum yield strength at
- minimum ultimate strength at
- the maximum pressure and temperature likely to be reached in postulated accident conditions

Type of rolling operation

On the basis of tests, it is concluded that the type of rolling operation, full-depth rolling or full-depth plus kiss-rolling, does not influence the instability limit pressure of a through-wall crack. As a result, residual stresses existing in the roll transition zone do not significantly influence rupture. Thus, they are not taken into account in determining the critical crack dimensions.

### 5.2.3 Method of calculation

On the basis of burst tests on tubes in alloy 600, it is demonstrated that the burst pressure of tubes with one or several cracks located in the straight portion remote from discontinuities or in the roll transition zone can be reliably determined using a plastic instability rupture criterion. Conversely, given the maximum pressure to which the tube is subjected, the application of these rupture criteria yields the critical crack dimensions leading to rupture by plastic instability.

Justifying the rupture criteria was the objective of an important experimental phase which revealed that the instability limit pressure for a through-wall or part-through crack can be estimated to within an error of less than when the geometry of the tube and crack and the mechanical properties of the tube are known.

Generally speaking, the interpretation of burst tests and its application to steam generator tubes in operation are based on a rupture criterion defined by the following formula :

(5-7)

(5-8)

### 5.2.4 Analysis of results

#### 5.2.4.1 Burst pressure of tubes without cracks :

Results of burst tests on tubes without cracks at room temperature show that the plastic instability pressure or burst pressure can be estimated on the basis of the Svensson's formula:

(5-9)

This formula, which incorporates the strain hardening coefficient and tensile strength, shows a good correlation with experimental results. For all test results, there was less than difference between theoretical and experimental results

Table 5-5

BURST PRESSURE OF TUBES WITHOUT CRACKS

In normal or upset conditions, the minimum safety coefficient with respect to rupture is :

In accident conditions, the minimum safety coefficient with respect to rupture is :

5.2.4.2 <u>Determination of the critical length of a longitudinal crack located in the straight portion remote from discontinuities.</u>

Results of tests performed on alloy 600 tubes with nominal diameters of 19.05 mm and 22.22 mm have shown that the burst pressure of a tube with a longitudinal through-wall crack in the straight portion can be accurately estimated using a criterion which is based on plastic flow. For the criteria used, differences between theoretical and experimental values were less than .

The plastic instability criterion which enables prediction of burst pressure in a tube with a longitudinal through-wall crack of a given length is written as :

(5-10)

where:

M is the bulging factor which depends on the geometry of the cracked tube.

If the pressure applied to the sides of the crack whose length L = 2a, is known, the burst pressure is reliably obtained by using the following formula :

(5-11)

Depending on which D, t and $\bar{\sigma}$ values used for the calculations, the results Pa = Pa (L) are given in Table 5-6 and in Figures 5-3 and 5-4.

Figure 5-3. Burst pressure of a longitudinal through-wall crack
Location : straight portion remote from discontinuities

Figure 5-4. Burst pressure of a longitudinal through-wall crack
Location : straight portion remote from discontinuities

Table 5-6

LONGITUDINAL THROUGH-WALL CRACKS - BURST PRESSURES
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES

Conversely, for the maximum pressure specified in the technical specification, the critical length of a longitudinal through-wall crack in the straight portion, is obtained using the following equation :

(5-12)

The results of the parametric study, which are a function of geometry, pressure applied to the tubes and flow stress, are given in Tables 5-7 and 5-8 and in Figures 5-5 et 5-6. They are given as a function of the Folias bulging factor.

The values obtained considering the Folias bulging factor M (4-10) constitute a lower limit for results. These results are applicable to the case of a leak rate through the through-wall crack.
The values obtained considering the Krenk bulging factor M (4-11) correspond to the case of a closed, obstructed crack in which pressure is not applied to the sides of the crack.

The critical length determined by considering the rupture criterion incorporating a bulging factor defined by the formula:

(5-13)

is a conservative value from the safety point of view.

By using the minimum mechanical properties imposed by the technical specification or specified by the code CASE-N20 - the main results are summarized in the Table 5-9.

Figure 5-5. Through-wall critical crack length - Tube in alloy 600
D = 19.05 mm - t = 1.09 mm
Crack location : straight portion remote from discontinuities

Figure 5-6. Through-wall critical crack length - Tube in alloy 600
D = 19.15 mm - t = 0.99 mm
Crack location : straight portion remote from discontinuities

TABLE 5-7

THROUGH-WALL CRITICAL CRACK LENGTH - TUBE IN ALLOY 600
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES

TABLE 5-8

THROUGH-WALL CRITICAL CRACK LENGTH - INFLUENCE OF FLOW STRESS
TUBE IN ALLOY 600 -
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES

TABLE 5-9

CRITICAL CRACK LENGTH IN THE STRAIGHT PORTION OF STEAM GENERATOR TUBES REMOTE FROM DISCONTINUITIES

In conclusion, when the crack is located in the straight portion remote from discontinuities, the value of the minimum critical length, whatever tube is considered, is :

This value is obtained by postulating that any steam generator tube whatsoever, subjected to a maximum internal pressure of at (the bounding value for accidental conditions) possesses simultaneously :

- a minimum yield and ultimate tensile strength at
- the most critical dimensions with respect to the burst risk, given the manufacturing tolerances.

As a result, these critical lengths constitute a lower bound, wherever the crack is located in the tube bundle. As test results show, the above results are also valid when the tube has several longitudinal through-wall cracks distributed over the entire tube circumference .

For normal and upset operating conditions, the minimum safety coefficient for the critical length is greater than . Thus, in normal operating conditions, even taking into account the most severe hypothetical conditions, there is a relatively large margin of safety which can be provided by detecting leaks and fixing an allowable leak rate criterion (See sections 2 and 5.3).

These values obtained for cracks in the straight portion of the tube remote from discontinuities do not take into account the local reinforcement effect provided by the tubesheet, which prevents tube deformation from occurring freely and results in a larger margin of safety.

5.2.4.3 <u>Determination of the critical length of a longitudinal crack located in the roll transition zone.</u>

It is concluded, on the basis of the test results presented in this document, that the influence of the tubesheet is manifested by an increase in the instability limit pressure of a through-wall crack. For Ø 19.05 mm tubes in alloy 600, this influence is limited to a distance limit between above the top of the tubesheet.

The results presented in this section are given for a defect length less than , considering the rupture criteria validated experimentally in the roll transition zone. For a length greater than or equal to , the results are those corresponding to a rupture criterion validated for a crack located in the straight portion remote from discontinuities. As the tests on Ø 19.05 mm tubes show, this upper limit of is applicable to the case of a single crack. In practice, the zone of influence is considered to be limited to to take the following into account :

- considerable deterioration in the rolling zone, characterized by the possibility of the presence of up to longitudinal through-wall cracks

- the possibility that the last point of contact between the tube and tubesheet is located at - from the top of the tubesheet. In this case, cracks can extend inside the tubesheet.

Figure 5-7 situates the domain of validity of the rupture criterion (formula 3 in Figure 5-7) corresponding to the data used for analysis.

As in the case of a crack in the straight portion remote from discontinuities, the parametric study presented in this section gives the burst pressure as a function of defect length or, conversely, the critical length for a given pressure, tube geometry and flow stress. As previously mentioned, the safety analysis is carried out considering the Folias bulging factor M which minimizes the critical crack length :

- When the crack is located outside the tubesheet, the results are presented in Tables 5-10 to 5-12 and in Figures 5-8 and 5-9 The results are summarized in the Table 5-13.

  Changes in critical length as a function of flow stress are shown in Table 5-12 and in Figures 5-10 and 5-11.

- For the case when the crack is located partly inside the tubesheet, the results are given in Tables 5-14 and 5-15 and in Figures 5-12 and 5-13.

Figure 5-7. Longitudinal through-wall defect or crack. Rupture of steam generator tubes at room temperature : Comparison between theoretical and test results
Location : roll transition zone

Figure 5-8. Burst pressure of a longitudinal through-wall crack
Location : roll transition zone (at the top of the tubesheet)

Figure 5-9. Burst pressure of a longitudinal through-wall crack
Location : roll transition zone (at the top of the tubesheet)

Figure 5-10. Through-wall critical crack length
Tubes in alloy 600 - D = 19.05 mm - t = 1.09 mm
Crack location : roll transition zone

Figure 5-11. Through-wall critical crack length
Tubes in alloy 600 - D = 19.15 mm - t = 0.99 mm
Crack location : roll transition zone

Figure 5-12. Longitudinal through-wall crack - Burst pressure
Location : roll transition zone

Figure 5-13. Longitudinal through-wall crack - Burst pressure
Location : roll transition zone

TABLE 5-10

LONGITUDINAL THROUGH-WALL CRACKS - BURST PRESSURE
CRACK LOCATION : ROLL TRANSITION ZONE

TABLE 5-11

LONGITUDINAL THROUGH-WALL CRITICAL CRACK LENGTH - TUBE IN ALLOY 600
CRACK LOCATION : ROLL TRANSITION ZONE

TABLE 5-12

THROUGH-WALL CRITICAL CRACK LENGTH - INFLUENCE OF FLOW STRESS
CRACK LOCATION : ROLL TRANSITION ZONE

TABLE 5-13

CRITICAL CRACK LENGTH IN THE ROLL TRANSITION ZONE

TABLE 5-14

LONGITUDINAL THROUGH-WALL CRACKS - BURST PRESSURES
CRACK LOCATION : ROLL TRANSITION ZONE

TABLE 5-15

THROUGH-WALL CRITICAL CRACK LENGTH - INFLUENCE OF FLOW STRESS
CRACK LOCATION : ROLL TRANSITION ZONE

The results are summarized in the following Table :

TABLE 5-16

CRITICAL CRACK LENGTH IN THE ROLL TRANSITION ZONE WHEN THE CRACK IS PARTLY INSIDE THE TUBESHEET

Changes in critical length as a function of flow stress are shown in Table 5-15 and in Figures 5-14 and 5-15.

In conclusion, when the crack is located in the roll transition zone, the value of the minimum critical length for any considered tube is as follows :

This critical length corresponds to the length of the crack, starting at the top of the tubesheet. As test results show, the above results are also applicable to a tube with several longitudinal through-wall cracks distributed over the entire tube circumference .

If one consider the possibility of the extension of stress corrosion cracking to a distance of inside the tubesheet, corresponding to the last point of contact between the tube and tubesheet, the minimum critical crack length is :

Figure 5-14. Through-wall critical crack length. Tubes in alloy 600 - D = 19.05 mm - t = 1.09 mm
Crack location : roll transition zone

Figure 5-15. Through-wall critical crack length. Tubes in alloy 600
D = 19.15 mm - t = 0.99 mm
Crack location : roll transition zone

As mentioned earlier, these results are applicable when the tube contains several longitudinal through-wall cracks distributed over the entire tube circumference . The particular configuration for this study should be taken into consideration, in view of the fabrication restraints of steam generators which may be different in other cases.

#### 5.2.4.4 Critical depth of a longitudinal crack.

The criterion which enables accurate estimation of the burst pressure of tubes with a longitudinal surface crack of a given initial length, may be written as follows :

(5-14)

A good correlation is achieved between theoretical and experimental results when the flow stress of the material $\overline{\sigma} = K(n)\ Rm = K(Re + Rm)$ is taken in consideration.

The burst pressure or the instability limit pressure of the remaining ligament of a surface crack whose depth and length 2a is given by the following equation :

(5-15)

Results are given in Tables 5-17 and 5-18.

Curves showing burst pressure versus crack length and depth are shown in Figures 5-16 and 5-17.

Since the tube is subjected to an internal pressure P, the minimum depth of a crack of length Lc, likely to cause a rupture of the remaining ligament, followed by instability of the resulting through-wall crack is expressed as :

(5-16)

See Curve A : Figures 5-16 and 5-17)

Figure 5-16. Burst pressure of a longitudinal surface crack
Location : straight portion remote from discontinuities

Figure 5-17. Burst pressure of a longitudinal surface crack
Location : straight portion remote from discontinuities

TABLE 5-17

LONGITUDINAL CRACKS - BURST PRESSURE
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
ALLOY 600 - D = 19.05 mm - t = 1.09 mm

TABLE 5-18

LONGITUDINAL CRACKS - BURST PRESSURE
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES
ALLOY 600 - D = 19.15 mm - t = 0.99 mm

For a given maximum pressure, the maximum crack depth, which does not cause a rupture of the remaining ligament, regardless of the length of the crack, is given by the formula :

(5-17)

(See Curve B : Figures 5-16 and 5-17)

For a maximum pressure of , the maximum allowable depth of the crack leading to snap - through, regardless of its length is given in the following table.

**TABLE 5-19**

**MAXIMUM ALLOWABLE CRACK DEPTH**

In the roll transition zone, the results provided by the parametric study are given in Tables 5-20 and 5-21 and on Figures 5-18 and 5-19.
At the specified pressure P = , the critical length of a longitudinal through-wall crack (see curve 1 : Figures 5-18 and 5-19) is larger than the critical length obtained in the straight portion.

The new values are used to calculate new crack depths (see curve A:Figures 5-18 and 5-19) for which there is instability of the new through-wall crack. These values correspond to the intersection (I) of curves (1) and (A) in Figures 5-18 and 5-19.

The minimum depth of a part-through crack with a length likely to cause the remaining ligament to rupture at , followed by instability of the resulting through-wall crack, is given in the Table 5-22.

Figure 5-18. Burst pressure of a longitudinal surface crack
Location : roll transition zone

Figure 5-19. Burst pressure of a longitudinal surface crack
Location : roll transition zone

TABLE 5-20

LONGITUDINAL CRACKS - BURST PRESSURE
CRACK LOCATION : ROLL TRANSITION ZONE
ALLOY 600 - D = 19.05 mm - t = 1.09 mm

TABLE 5-21

LONGITUDINAL CRACKS - BURST PRESSURE
CRACK LOCATION : ROLL TRANSITION ZONE
INCONEL 600 - D = 19.15 - t = 0.99 mm

TABLE 5-22

CRITICAL LONGITUDINAL CRACK DEPTH

In the roll transition zone, the results above are obtained even when the influence of the tubesheet is neglected. The critical depth of a longitudinal part-through crack is, in all cases, over of the tube wall thickness : Figures 5-16 to 5-19.

5.2.4.5 Critical length of a circumferential through-wall crack.

When neglecting the influence of the tube support plate, the burst pressure due to plastic instability is given by the following formula (1):

(5-18)

which is applicable as long as Pa remains lower than the burst pressure of a tube without a defect :

(5-19)

Application of the model to steam generator tubes enables determination of the critical dimensions of circumferential cracks, which depend on geometrical and mechanical tube properties. Results from applying this model are shown in Table 5-23 and Figures 5-20 and 5-21.

Figure 5-20. Circumferential through-wall crack - Burst pressure

Figure 5-21. Circumferential through-wall crack - Burst pressure

TABLE 5-23

CIRCUMFERENTIAL THROUGH-WALL CRACK LENGTH - TUBE IN ALLOY 600
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES

To determine the burst pressure of a tube with a circumferential through-wall crack in the roll transition zone, it is necessary to know :

- The location of the circumferential crack above the last tube/tubesheet contact point

- The support condition imposed by the lower tube support plate.

By applying the plastic collapse model presented in the reference (1) it is possible to determine the critical dimensions of circumferential cracks.

Even neglecting the influence of the tubesheet, which increases the instability limit pressure, one obtains a critical length longer than half of the tube circumference.
Moreover, by comparison with test results, on an equivalent geometry, the instability limit pressure is underestimated by a factor of more than (for a crack between due to the effect of the tubesheet.

TABLE 5-24

INSTABILITY LIMIT PRESSURE OF A CIRCUMFERENTIAL CRACK

Experimental results show that, beyond , the bending effect due to the end effect becomes negligible and rupture occurs due to tension. Applying the criterion of maximum shear stress in the net section, one obtains :

(5-20)

The deviation between test and theoretical results is lower than for a crack :

TABLE 5-25

INSTABILITY LIMIT PRESSURE OF A CIRCUMFERENTIAL CRACK

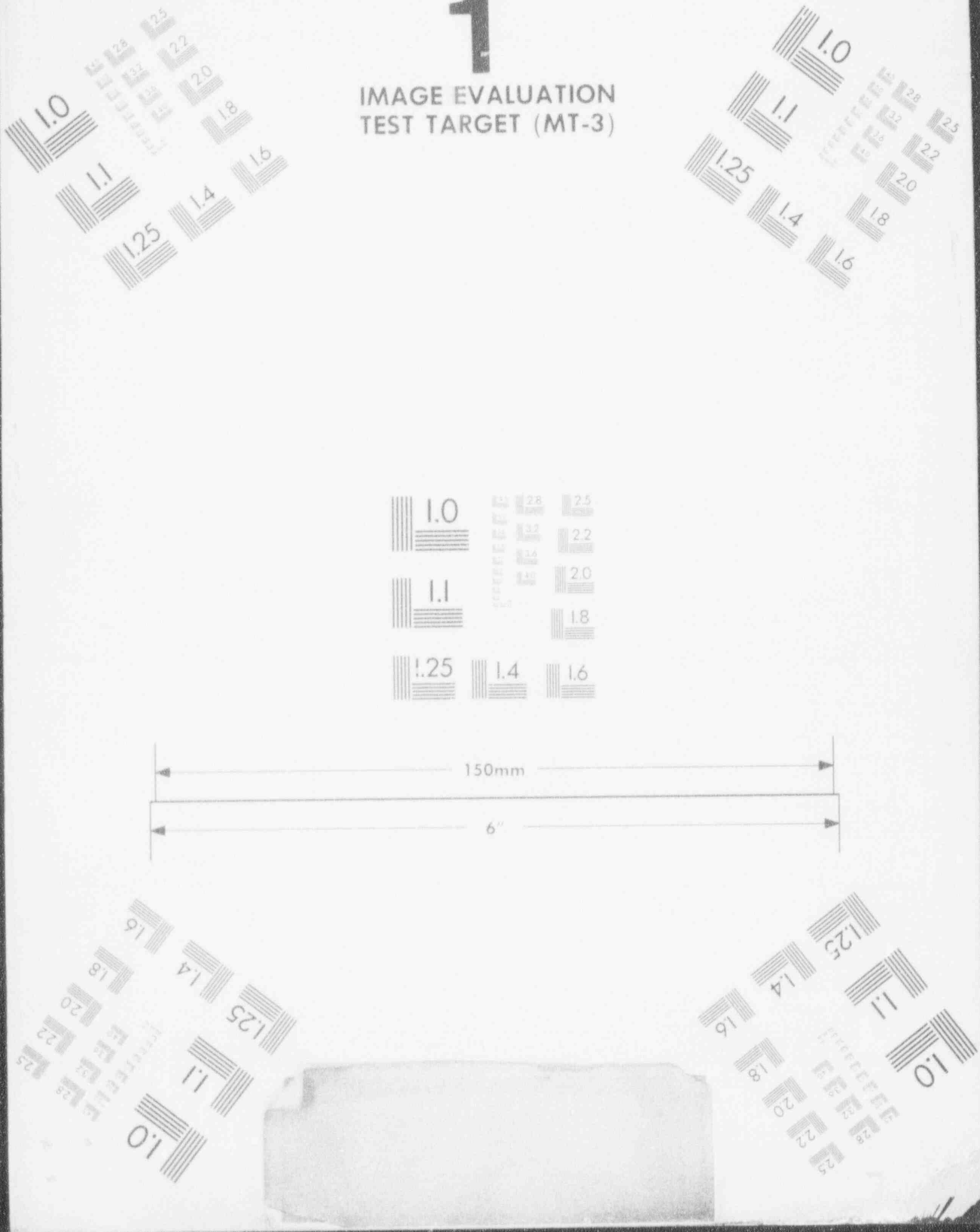
The minimum safety coefficient for defect is

Conversely, for a maximum pressure of , the minimum critical circumferential crack is , in the case of extreme tube dimensions and a minimum flow stress of MPa.

5.2.4.6 Review of all results. On the basis of data used for analysis presented in this section, the minimum critical lengths to be considered for leak-before-break analysis and to define the tube plugging criterion are summarized in the following Table :

# 1

## IMAGE EVALUATION TEST TARGET (MT-3)



# 1

## IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

# 1

## IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

# 1

## IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

TABLE 5-26

MINIMUM CRITICAL CRACK LENGTH : SUMMARY OF THE RESULTS

These results are used to deduce the limit values for threshold cracks for which there is no risk of rupture in the event of accidental overpressure.

## 5.3 EVALUATION OF THE PRIMARY TO SECONDARY LEAK RATE THROUGH A THROUGH-WALL CRACK : DETERMINATION OF THE ALLOWABLE LEAK RATE

The purpose of this study is to :

- Determine the leak rate in normal operating conditions corresponding to the dimensions of critical cracks.
- Determine the allowable leak rate corresponding to the operating conditions of the steam generators.

The maximum value of the primary-to-secondary leak rate used for normal operation should preclude any risk of accident in the event of accidental overpressure.

### 5.3.1 Principle

Figure 5-22. Leak rate versus crack length

The leak rate measured experimentally represents the actual flow corresponding to an actual crack length that cannot be measured in normal operating conditions. To be conservative for safety purposes, it is assumed that the leak rate occurs through a single crack in order to maximize the crack length.

For leak-before-break analysis, the crack length, calculated analytically from the leak rate, must be equal to or greater than the actual crack length. As a result, the theoretical flow curve must be situated below the actual flow curve, which is the same as minimizing the value of the theoretical flow given by the expression :

(5-21)

Conversely, for a length corresponding to tube rupture by plastic instability, the resulting theoretical flow, assumed to be representative of the actual flow, will correspond to an actual crack length shorter than the critical crack length.
Therefore, this analysis makes it possible to increase the safety margins with respect to the rupture of the tube.

### 5.3.2 **Analysis of data used in calculation**

Tube dimensions

The dimensions are the same as those used to calculate the critical lengths (see § 5.2.2.).

Mechanical properties of the tubes

The mechanical properties are the same as those used to calculate the critical lengths. However, it should be noted that when the mechanical properties increase, the crack opening area and, consequently, the leak rate, decreases, but the critical length of the crack increases. The results retained are those which minimize the leak rate.

Calculation conditions in normal operation

Selection of the primary-secondary differential pressure in normal operating conditions : .

Density of the primary coolant at

Stress corrosion cracking occurs mainly on the hot leg, where the primary temperature is about , which corresponds to a density $\rho$ equal to . The choice of the value for $\rho$ at yields a leak rate underestimated by about . Thus, the results take into account possible cracking on the cold leg side.

Crack opening area

The minimum crack opening area for a longitudinal crack of a given length is considered. The crack opening area is calculated for the inner tube wall, using a numerical model validated by crack opening measurements corresponding to the crack opening area on the outer wall.

Flow coefficient : K

The value of the flow coefficient is based on test results on tubes cracked in the laboratory. To minimize uncertainty, this coefficient, K, is determined by considering the same crack opening area calculation model as that used to evaluate the leak rate.

The mean flow coefficient value is :

A lower limit for the flow coefficient is obtained by choosing : .

The uncertainty characterizing the determination of the flow coefficient and the evaluation of the leak rate, leads us to conclude the following :

- : No estimation is made for leak rates which can vary between 0 and the leak rate corresponding to a defect ' long (a non-critical crack in most cases).

- : A realistic and conservative estimation of the leak rate is possible.

5.3.3 <u>Method of calculation</u>

To apply the finite element method to the case of steam generator tubes, linear elastic analysis is used to determine the crack opening areas for different crack lengths : . Calculations are based on nominal tube dimensions and conservative dimensions with respect to rupture :

19.05 x 1.09 mm
19.15 x 0.99 mm

The study takes into account the parameter $P_f$, which represents pressure applied (or not applied in certain cases) to the surface of the crack. Calculations are carried out considering a crack located in the straight portion remote from discontinuities or in the local zone at the top of the tubesheet.

Based on the results of calculations done by means of the finite element method and on elementary theoretical considerations, a numerical formulation of a crack opening area model can be obtained, in order to generalize the results of finite element calculations. This model is used to take the following into consideration :

- Bending in the crack lips
- Application or non-application of pressure to the sides of the crack
- The location of the crack : the straight portion remote from discontinuities or the local zone at the top of the tubesheet.

By comparison with experiments, it has been shown, in particular, that this elastic model, to which a plastic zone correction is applied, yields a realistic evaluation of the crack opening area.

Given the crack opening area, one determines the leak rate through a through-wall crack by applying the formula (5-21) in which the flow coefficient K is determined on the basis of test results for tubes cracked in the laboratory.

### 5.3.4 Analysis of results

The evolution of the leak rate as a function of crack length is presented in Tables 5-27 and 5-28 and in Figures 5-23 to 5-26. These different curves reveal the sensitivity of the leak rate to variations in crack length. This sensitivity depends on tube dimensions and mechanical characteristics :

- When mechanical characteristics increase, the leak rate decreases but the critical length increases.

- When one considers the critical dimensions with respect to rupture (19.15 x 0.99 mm), the leak rate increases but the critical length decreases.

- The increase in crack length can only promote an increase in leak rate. The variation in this flow is even more appreciable for tubes with extreme dimensions (19.15 x 0.99 mm) and minimum mechanical characteristics for which the critical lengths are minimal.
  In particular, in the roll transition zone, when the crack length goes from , the leak rate of a tube with the minimum mechanical characteristics increases by depending on the geometry of the tube examined. This appreciable variation in flow as a function of length, for cracks whose lengths are or longer, can only help with leak detection, monitoring of the leak evolution and the scheduling of a plant shutdown before crack instability is reached.

- The leak rate for a crack in the roll transition zone decreases, with respect to that in the straight portion, by about when the crack length is between , but the length of the critical crack increases.

On the basis of the above-mentioned considerations, one seeks the most conservative situation in determining the minimum critical leak rate in order to define the maximum allowable leak rate.

Comparative analysis of the results presented in Table 5-29 shows that the minimum critical leak rate for a crack in the roll transition zone is . This corresponds to the case of crack long of which mm extends inside the tubesheet (note that to calculate the leak rate, the length of the part of the crack inside the tubesheet is not taken into account). Taking various uncertainties into account, this computation gives a lower critical flow limit of .

Figure 5-23. Leak rate calculation -
CRACK LOCATION : STRAIGHT PORTION
CRACK OPENING AREA REFERENCE : INNER WALL

Figure 5-24. Leak rate calculation -
CRACK LOCATION : STRAIGHT PORTION
CRACK OPENING AREA REFERENCE : INNER WALL

Figure 5-25. Leak rate calculation -
CRACK LOCATION : ROLL TRANSITION ZONE
CRACK OPENING AREA REFERENCE : INNER WALL

Figure 5-26. Leak rate calculation -
CRACK LOCATION : ROLL TRANSITION ZONE
CRACK OPENING AREA REFERENCE : INNER WALL

TABLE 5-27

LEAK RATE CALCULATION -
CRACK LOCATION : STRAIGHT PORTION REMOTE FROM DISCONTINUITIES

TABLE 5-28

LEAK RATE CALCULATION -
CRACK LOCATION : ROLL TRANSITION ZONE

TABLE 5-29

TUBES IN ALLOY 600 - LONGITUDINAL CRACK - LEAK FLOW RATE CORRESPONDING TO CRITICAL CRACK LENGTH -

If one admits the possibility of stress corrosion cracking in the straight portion remote from discontinuities, in particular above or below the flow distribution baffle in a zone affected by the presence of sludge, a lower critical flow limit of is obtained.

Analysis of the limiting case for which the critical length in the straight portion remote from discontinuities is equal to

For the first step in the analysis, it is not possible to guarantee leak rate evaluation for all cracks shorter than in length, for which the leak rate can range from liters per hour to , because of the uncertainties related to the small crack opening. The risk of crack obstruction is greater for short crack lengths. As previously mentioned, the uncertainty characterizing the evaluation of the flow decreases when the length of the crack increases and this flow can be evaluated, as experiments show, on the basis of a length of about .

As shown by the results presented in Figures 5-23 and 5-24, the leak rate is very sensitive to tube dimensions for a given crack length and given mechanical characteristics. In particular, for a crack long, the leak rate increases by about when one goes from the nominal dimensions to the extreme dimensions of a tube with the minimum mechanical characteristics such as $\sigma$ = . Based on this observation, it seems appropriate to compare the crack opening of a crack long in a tube with nominal dimensions and a crack long in a tube with dimensions which are critical with respect to rupture. Comparative analysis, considering linear elastic results in order to remain conservative, shows that the crack openings are almost identical. The results are summarized in the Table 5-30 :

TABLE 5-30

MAXIMUM CRACK OPENING

It is also concluded that the crack opening area of the crack long is slightly greater than that of the crack when the effect of plasticity is taken into account.

From this comparative analysis, one may therefore conclude that the critical crack long in the straight portion remote from discontinuities behaves practically in the same way as the crack, for which the leak rate is . Taking various uncertainties into account of the parameters given in section 5.3.2., computation gives a lower flow limit of .

5.3.5 Review of all results

On the basis of data used for analysis of leak rates presented in this section, the minimum critical leak rates to be taken into account for leak-before-break analysis are summarized in the Table 5-31 :

TABLE 5-31

MINIMUM CRITICAL LEAK RATE

Fixing a value for the allowable leak rate limit $Q_B$ lower than the minimum critical leak rate values $Q_C$, makes it possible to preclude all risk of rupture in the event of accidental overpressure. As the analysis shows, the hypotheses were chosen so as to minimize the results.

The coefficient can, therefore, be chosen close to .

## SECTION 6

## ANALYSES OF CASES FOR WHICH THE LEAK-BEFORE-BREAK CONCEPT IS NOT VALID

### 6.1 CASE OF A LONGITUDINAL PART-THROUGH CRACK

A longitudinal part-through crack, whose initial length is greater than the critical length of a longitudinal through-wall crack, does not satisfy the leak-before-break criterion since, in the event of breakthrough, the resulting through-wall crack is unstable.

By applying a plastic instability rupture criterion validated by tests, it is demonstrated that the minimum critical depth of a longitudinal part-through crack is given by the formula :

(6-1)

On the basis of data used for analysis presented in section 5, the application to the case of the steam generator tubes yields a minimum critical depth of of the tube thickness, whatever the length of the part-through crack is assumed (Figures 5-16 to 5-19 - Curve B). The results are summarized in the Table below :

TABLE 6-1

MINIMUM CRITICAL CRACK DEPTH

## 6.2 CASE OF A CIRCUMFERENTIAL PART-THROUGH CRACK

A circumferential crack located in the zone at the top of the tubesheet remains stable, whatever its length, when the crack depth is between and of the tube thickness. To be compatible with experimental results, the value of the burst pressure corresponding to $\sigma =$ is estimated as . This value should be compared with the value of bar determined in § *5.2.4.1.* The deviation of about is due to the difference in geometry considered.

When the circumferential crack reaches a depth of ɩf the tube wall thickness, the burst pressure corresponding to $\sigma =$ is such that the safety margin is, with respect to the maximum value of , greater than .

The results are summarized in the Table below :

TABLE 6-2

INSTABILITY LIMIT PRESSURE OF A CIRCUMFERENTIAL PART-THROUGH CRACK

As test results show, when the defect depth becomes large, the influence of bending becomes negligible and rupture occurs as a result of tension due to the end effect. The application of the criterion of the maximum shear stress in the net section yields the following expression of the instability limit pressure :

(6-2)

where :

The comparison of theoretical and test results gives a deviation of .

TABLE 6-3

INSTABILITY LIMIT PRESSURE OF A CIRCUMFERENTIAL PART-THROUGH CRACK

For a circumferential part-through defect which is deep over the entire tube circumference, the application of test results to the case of steam generators yields the following results :

TABLE 6-4

INSTABILITY LIMIT PRESSURE OF A CIRCUMFERENTIAL PART-THROUGH CRACK

## SECTION 7

## TECHNICAL OPERATING LIMITS : INSERVICE SURVEILLANCE REQUIREMENTS AND SHUTDOWN SURVEILLANCE REQUIREMENTS

A valid demonstration of the leak-before-break concept can be made for all but a few specific crack configurations, in particular in sludge deposit areas, for which application of the tube plugging criteria will be necessary. The results of analysis enable us to conclude that tube rupture in the event of accidental depressurization on the secondary side (pipe break) is necessarily preceded by an allowable primary-to-secondary leak rate in normal operation. This leak should lead to a preventive shutdown of the Nuclear Steam Supply System (NSSS).

According to inservice surveillance requirements established by the plant operator, the only tubes allowed to remain in service until the next series of inspections are those satisfying the leak-before-break criterion. This requires the following :

- That defect configurations and dimensions be known : application of non-destructive examination methods and tube removal.
- That the nature and causes of each type of deterioration be known and that, more precisely, the crack propagation kinetics be characterised well enough to confirm that the defect remains stable in the event of breakthrough.
- That the high-performance, qualified non-destructive examination methods be available for each type of deterioration : detection of longitudinal and circumferential defects.
- That tubes be pulled out <u>in situ</u> to identify the nature and causes of deterioration, and to confirm the correlation between actual defects and the response signals obtained by means of non-destructive examination methods, in order to define the type and size of the defect. The examination of tubes pulled from the steam generators allows the propagation kinetics of any degradation mechanism to be confirmed.
- That configurations likely not to satisfy the leak-before-break criterion be eliminated as a preventive measure.
- That the evolution of primary-to-secondary leak rate be kept under permanent surveillance up to the allowable threshold value fixed by technical specifications in force.

## 7.1 CASE OF APPLICATION OF THE LEAK-BEFORE-BREAK-CRITERION

The demonstration of the leak-before-break principle can be considered valid in the following case :

- Parallel longitudinal through-wall cracks, single or limited in number to less than , in the same section of the tube : these cracks can be situated in the straight portion of tubes remote from discontinuities or in the roll transition zone.

  Rupture is caused by instability of the longest crack. The critical length depends on crack location, the dimensions and mechanical characteristics of the tubes. It is experimentally verified that through-wall defects or cracks in the roll transition zone do not significantly influence the instability limit pressure of the critical crack. However, some stable long cracks have been found in sludge deposit areas for which the leak rate in operation was smaller than the predicted value. Analysis of these cracks has shown the following :

  - The actual length was longer than the minimum critical crack length of the tube bundle determined by considering the minimum values of mechanical properties specified by the code (General case).

  - The actual length was smaller than the minimum critical crack length of the degraded tube determined using actual tube material properties.

## 7.2 CASE OF NON-APPLICATION OF THE LEAK-BEFORE-BREAK-CRITERION

All cases of tube deterioration for which the applicability of the leak-before-break criterion cannot be shown must be examined in a study specific to the type of damage observed.

A distinction is made between different cases likely not to satisfy the leak-before-break criterion :

- Longitudinal part-through cracks whose length is greater than the critical length of a through-wall crack. These cracks may be initiated by the presence of scratches.
  Steam generator operating experience shows that crack propagation kinetics are such that the longitudinal cracks are generally through-wall when the length exceeds .

- Networks of small corrosion or cracks, aligned with X approximately or not aligned, with a small leak rate.
  The interaction between cracks is such that in the event of rupture of the ligament between two adjacent cracks, the entire network behaves like a single crack equal to the sum of the lengths of cracks, aligned or not aligned.
  To date, steam generator operating experience shows that circumferential cracking which does not satisfy the LBB criterion remains limited to a relatively number of tubes. All cases of circumferential cracking observed in France have been identified on tubes located in the sludge-deposit areas.

Circumferential cracking is caracterized in most cases, by multiple independent cracks separated by small remaining ligaments. Stress corrosion circumferential cracks are, in general, initiated at the inner wall of tubes in the roll transition zone. The maximum length of the main circumferential crack observed after five operating cycles is and the degradation extends over to about of the tube circumference. These cracks are generally through-wall when the crack length becomes longer than of the tube circumference and they are located in the lower part of the full-depth rolling plus kiss-rolling transition zone.
Two cases of part-through circumferential cracks have also been observed.
However, the case of circumferential cracks initiated at the outer wall, specially in the case of full-depth rolling, cannot be entirely ruled out.

Circumferential non-axisymetrical through-wall cracks (cracking limited to a certain length) could be observed in the case where there is significant interaction between the tube and the lower support plate (or flow distribution baffle), which would introduce major changes in bending stresses. Bending stresses resulting from this interaction, which are function of the operating conditions associated with the manufacturer's tolerances, can contribute to circumferential crack formation. In that case, degraded tubes are not necessarily confined in the sludge deposit areas.

Circumferential cracking can also result from high stress or plastic strain concentrations in the area of a geometric discontinuity due to the rolling operation; the longitudinal stress is no longer necessarily the principal intermediary stress (i.e. that $\sigma\theta < \sigma_z < \sigma_r$ is not necessarily true).
In particular, in the case of denting at the top of the tubesheet or in the presence of a network of longitudinal cracks in the roll transition zone, branching cracks in areas of high plastic strain facilitate circumferential cracking, as shown in tests on tubes with cracks produced by stress corrosion cracking (1).

In the roll transition zone, circumferential part-through or through-wall cracks which are almost axisymmetrical and do not leak, can also be promoted in areas containing sludge deposits. Stress analysis in the roll transition zone, demonstrates an increase of the maximum longitudinal stress (peak) at the inner wall of the tube near the last contact point between the tube and the tubesheet when sludge effects which modify the heat transfer conditions are taken into consideration. This increase of axial stresses contributes to circumferential crack formation.
Moreover, denting phenomenon at the top of the tubesheet resulting from hard sludge piles can also promote circumferential cracks.
This type of almost axisymetrical cracking is also facilitated by rolling anomalies.
Deep circumferential part-through cracking over the entire tube circumference of a tube, or circumferential through-wall cracks from through which there is no leakage (e.g. when displacement-controlled loading tends to close up the opening) can cause tube rupture to occur by plastic instability due to the end effect.

## 7.3 OPERATING SURVEILLANCE REQUIREMENTS

In order to assess the integrity of steam generators or to define, if necessary, the nature of deterioration and to verify that they conform to hypotheses used in analyses, the plant operator supplements his dossier justifying the leak-before-break concept by a series of periodic in situ inspections.

The maintenance program relating to operating surveillance and shutdown surveillance of the steam generator tube bundles is defined by the plant operator in a technical specification as a function of the condition of the steam generators known at that time :

- Knowledge of the maximum allowable leak rate in normal operating conditions enables the plant operator to define an operating surveillance requirement.

- Knowledge of the dimensions of the critical crack size enables the plant operator to define the tube plugging criteria.

7.3.1 <u>Inservice surveillance requirements</u>

Inservice surveillance is carried out by following up primary-to-secondary leak rates. Detection of a leak progressing at a fast rate or exceeding the leak rate limit specified in the technical specification results in a return to a cold shutdown and a search to identify the leaking tube(s), see Figure 7-1.

As shown by the results of analysis presented in section 5, the large safety margins between :

- The dimensions of a critical crack at , for which a minimum critical flow is determined at .

- The dimensions of a critical crack at , corresponding to normal operating and upset conditions.

gives the plant operator a certain amount of flexibility for the return to a cold shutdown. The period of time needed to return to a cold shutdown is defined by the plant operator.

On the basis of data used for this conservative analysis, to preclude any risk of rupture for any tube which is cracked in the roll transition zone, the primary-to-secondary leak rate, beyond which the power plant must be shut down, should be strictly lower than the following values :

It will be noted that low flows observed at the site in some cases do not call into question necessarily the leak-before-break concept. The reduction of leak rates can be due to :

- The plugging or closing of the crack with debris

- A tube in sludge-deposit areas

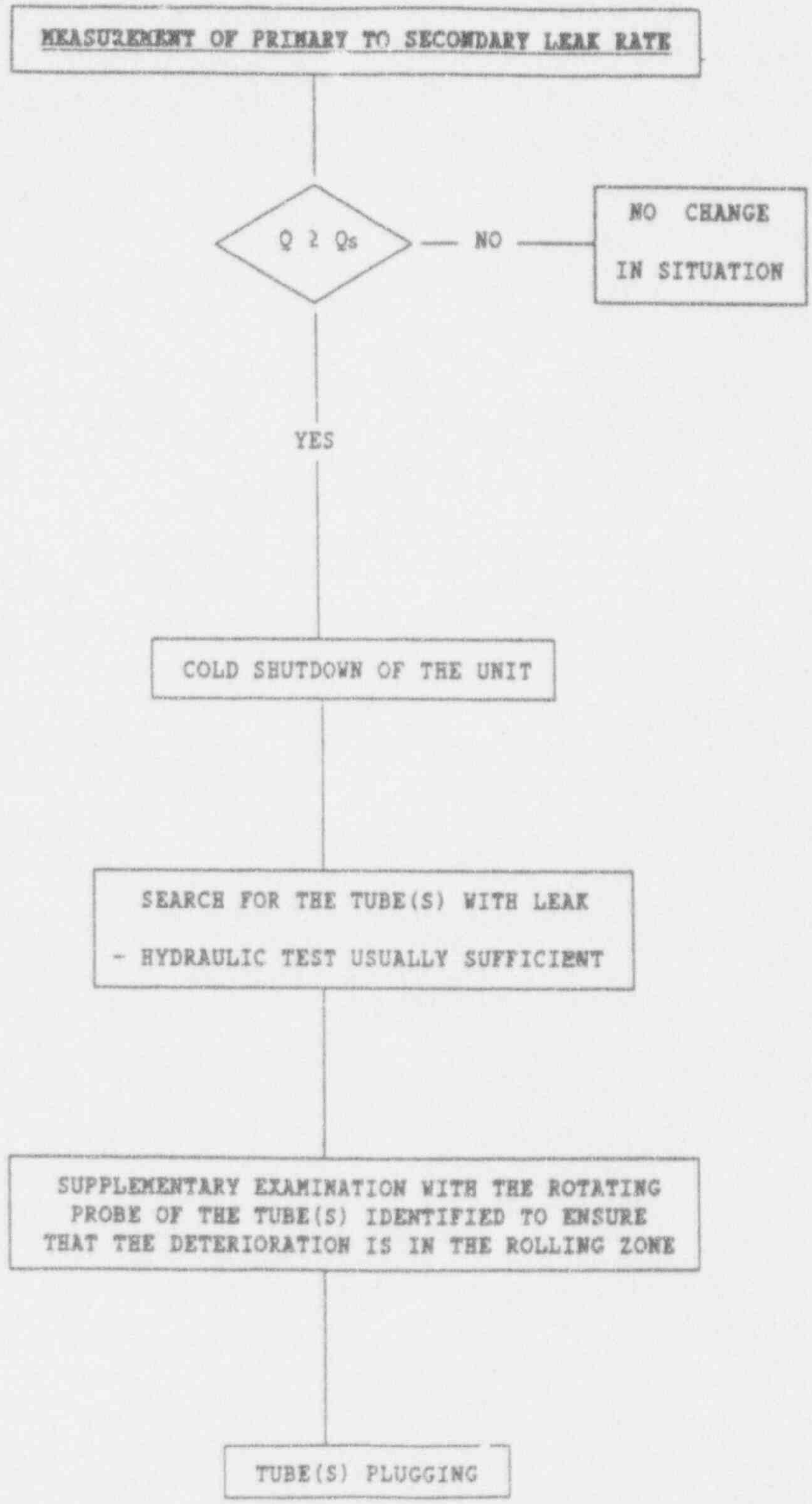



Figure 7-1. Measurement of primary-to-secondary leak rate in steam generators - Illustration of analysis procedure

For the most part, these decreases in leak rate will tend to appear in non-critical cracks less than long, located in the roll transition zone. For these cracks, the crack opening is practically linear elastic and the maximum opening is less than . This effect will be even more pronounced when the mechanical characteristics of the tube, i.e. Rm and Re, are high and the tube wall thickness is near its maximum thickness, taking into account the manufacturer's tolerances.

As a result :

- A leak rate through a crack whose minimum critical length is determined for a tube with a maximum diameter, minimum wall thickness and minimum mechanical characteristics, is easier to detect due to the effect of plasticity which promotes the opening of the defect. In this case, leak detection is also facilitated as the variation in flow is very sensitive to a slight variation in crack length.

- A leak rate through a crack in a tube of nominal dimensions or maximum thickness can be appreciably reduced in the case of cracks with lengths smaller than . For a given geometry, this decrease is greater when the tube has high mechanical characteristics. In these conditions, the critical length of the crack exceeds . The leak rate becomes significant due to a crack opening which is greater than , even without taking into account the effect of plasticity, which is, under these conditions, quite important (Table 7-1).

TABLE 7-1

POST-TEST RESIDUAL CRACK OPENING AREA

To take into account the above considerations, for analysis, a leak rate which is practically nil is considered for cracks under long which are not critical in the event of accidental overpressure. Beyond a length of , an increase in crack length promotes an increase in the crack opening area and the flow becomes measurable. A lower flow coefficient limit is fixed to account for uncertainties. The value of the maximum allowable leak rate to be fixed in the technical specification, can be close to the minimum leak rate value for the critical crack because of significant conservative assumptions built into the calculation of this value.

Nevertheless, the actual primary to secondary leak rate in steam generators can be significantly reduced in some cases, during normal operation due to various factors which are not taken into consideration by the calculation model described earlier. The reduction of leak rates for long cracks can be due to the presence of hard sludge, boiling and evaporation phenomena in the crack or the possibility of plugging of crack by solid precipitates. This decrease in leak rate will be all the more important when the actual crack length is much smaller than the critical length corresponding to operating conditions.

Indeed, in this case, the cracked tube has high mechanical characteristics and the behavior of the cracked tube will be elastic and therefore, the crack opening area and the corresponding leak rate will be smaller than in the case of crack whose length is close to the critical length. From the French experience of steam generator tubes, this situation can not be excluded. However for all cases which have been encountered the crack was stable for postulated accident conditions according to a plastic instability rupture criterion.

For these reasons, in addition to the leak rate criterion, the plant operator should take into account the potential evolution of the crack during a cycle, and also the uncertainty corresponding to eddy current measurements in order to define the tube plugging criterion.

7.3.2 <u>Shutdown surveillance requirements (refueling shutdown)</u>

Shutdown surveillance is based on carrying out periodic inspections and applying tube plugging criteria.

7.3.2.1 Periodic inspection.

Periodic inspections rely, for the most part, on eddy-current testing carried out as part of a basic program defined by the plant operator. The extent of the inspections depends on the state of deterioration observed in the steam generator.

Particular attention should be given to tubes located in the areas containing sludge deposits, where the risk of circumferential cracking is greatest.

Shutdown surveillance may be supplemented by helium or other leak tests. In the case of a large leak, it is necessary to determine the length of the crack, so as to make sure that later crack propagation does not lead to an unscheduled shutdown of the unit.

Shutdown surveillance can also be supplemented by pulling tubes from steam generators for examination.

7.3.2.2 Tube plugging criteria.

Case of stress corrosion cracking in the roll transition zone

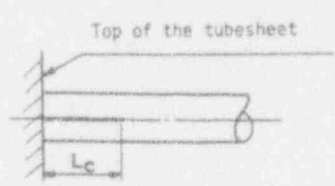
Tubes to be plugged : Those presenting one or several longitudinal through-wall cracks with a length greater than or equal to the minimum critical length : $L_c$.

The minimum critical length depends on :

- Pressure taken into consideration for analysis
- Tube dimensions
- Location of the crack
- Mechanical properties of tubes

Consider the example : $L_c$ (see section 5)

This length must be measured from the top of the tubesheet.



This minimum length takes into account a extension of the crack inside the tubesheet. An extension of the longitudinal crack longer than in the expanded part of the tube does not modify the above mentioned results. These results are established assuming that the last point of contact between the tube and tubesheet can be located between from the top of the tubesheet. As detailed analysis of the results shows, these minimum values are derived on the basis of conservative considerations. Therefore, it is not necessary to provide additional safety margins.

Tubes to be plugged :

- Those presenting circumferential through-wall cracks

- Those presenting circumferential part-through cracks which are practically axisymmetrical.

It is noted that circumferential cracks smaller than do not constitute a safety problem since degraded tube rupture occurs at the same level of pressure as a sound tube, independently of any supplementary bending likely to be imposed on the tube.

However, to date, steam generator operating experience does not enable a conservative assessment of circumferential crack propagation kinetics which can be between per operating cycle. In particular, a rapid and axisymmetrical crack propagation cannot be excluded. However, French steam generator operating experience does not reveal crack growth kinetics likely to lead to a circumferential rupture after one cycle of operation. Since the crack propagation kinetics of circumferential or complex (circumferential + longitudinal) cracks are not well-known, the following recommendations are made :

- After each cycle of operation, an examination by the eddy current rotating pancake coil or ultrasonic method of all the tubes likely to be affected by circumferential cracking should be carried out. This essentially concerns the tubes located in sludge-deposit areas. However, as it is mentioned in paragraph 7.2, the risk of circumferential cracks in areas out of the sludge piles, cannot be entirely ruled out.

- Plug or repair the tubes as soon as an indication of circumferential crack has been detected.

Case of defects or cracks located in the straight portion remote from discontinuities

Tubes to be plugged : those with one or several longitudinal through-wall cracks whose length is greater than or equal to the minimum critical length : $L_c$

Consider the example : $L_c$ (see section 5)

It is noted that the minimum critical crack length of a longitudinal through-wall crack at the tube support plate level is longer than the thickness of the support plate if the maximum axial tube to support plate relative movement remains limited to a certain value which depends on the precise steam generator parameters in the case of an accidental overpressure.

Tubes to be plugged : those with part-through defects whose length is greater than $L_c$ when the defect depth is equal to or greater than of the tube wall thickness. To fix the plugging criterion, the plant operator takes into consideration the uncertainty concerning the presumed depth of the defect, which depends on the type of measurement carried out.

Plugging criterion taking into account the kinetics of crack propagation

To avoid the unscheduled shutdown of the unit during the forthcoming cycle, it is necessary to take into account the evolution of the cracks during this period.

The plugging criterion to be applied to preclude the risk of rupture in the event of accidental overpressure, is given by the following formula :

$$L\ (PLUGGING) = L_c - X$$

Where :

$L_c$ : is the critical longitudinal through-wall crack length corresponding to accident conditions.

X : is the potential evolution of the crack during the forthcoming cycle (this value must integrate the measurement error which depends on the type of non-destructive examination method used)

As already mentioned in section 4, this evolution of the crack should be determined for each individual plant since propagation rates are not necessarily the same from one plant to another Generally speaking this rate of evolution is not well known for a specific tube. As a result, it is recommended that the maximum crack propagation rate should be used during a cycle. For one plant, this rate will be evaluated from all available results from all steam generator tubes affected by PWSCC.

To limit the number of tubes to be plugged, the following approach could be adopted : See Table 7-2.

TABLE 7-2

TUBE PLUGGING CRITERION : LONGITUDINAL CRACKS

In the case of analysis tube by tube, in order to limit the number of tubes to be plugged, the problem is only to estimate the uncertainty of material properties (ie, yield strength and ultimate strength), of the tube. For one supplier, the scatter in mechanical properties includes :

- the scatter within each batch
- the scatter of acceptance test results between all batches

TABLE 7-3

PARAMETERS LIKELY TO INFLUENCE UNCERTAINTY OF MATERIAL PROPERTIES

| ACTUAL MATERIAL PROPERTIES FOR ONE BATCH | ACCEPTANCE TESTS FOR ALL BATCHES |
|---|---|
| - Location of test sample in the furnace | - Location of test sample in the furnace |
| - Roll straightening | - Roll straightening |
| - Tensile test | - Tensile test |
| - Location of the test sample in the tube | - Chemical composition |
| | - Cold rolling |
| | - Heat treatment |

For safety purpose, one can consider that the scatter in the tensile properties for each batch is lower than, or in the worst case equivalent to the scatter between batches. Therefore, the uncertainty on material properties which can be used corresponds to the scatter between all batches which is deduced from statistical analysis.

This statistical analysis can be performed by using acceptance test results from steam generator tubing.
In this case the uncertainty which can be taken into consideration corresponds to the standard deviation of analysis performed for the specific plant steam generator tube bundle.

## SECTION 8
## CONCLUSIONS

The operating experience for nuclear power plant units has revealed the existence of stress corrosion cracking by the reactor coolant (PWSCC) which affects the steam generator tubes. The formulation and justification of safety criteria make it necessary to :

- Detect, identify the nature of and determine the causes of deterioration
- Identify the configuration, dimensions and location of cracks
- Follow the crack propagation kinetics
- Evaluate the tube rupture risk
- Measure and evaluate the leak rates through real cracks.

The study program, which should be undertaken by the plant operator, should make it possible to define the requirements for inservice and shutdown surveillance with the objective to limit the risk of steam generator tube rupture which could result from stress corrosion cracking, in particular, in the roll transition zone.
With the exception of certain crack configurations, one can demonstrate that the possibility of tube rupture, in the case of accidental overpressure and depressurization of the secondary system is necessarily preceded by an admissible leak permitting the preventive shutdown of the Nuclear Steam Supply System.

The leak before break analysis applied to the steam generator tubes of a specific plant, has yielded the main results presented in the following Table.

TABLE 8-1

LEAK BEFORE BREAK ANALYSIS APPLIED TO A SPECIFIC PLANT STEAM GENERATOR TUBES - SUMMARY OF THE RESULTS

As tube dimensions and mechanical characteristics are not catalogued for each tube, the plugging criterion is such that any tube with one or several cracks with length L located above the tubesheet, such that :

shall be plugged. L represents the length of the axial through-wall crack located outside the tubesheet. The tubes with one or several longitudinal cracks whose lengths are smaller than the above values can be allowed to remain as they are. The cracks can extend inside the tubesheet without any influence on the above results.This result assumes that the last contact point between the tube and the tubesheet is between from the top of the tubesheet.

Tubes with circumferential cracks should be plugged or repaired.

In normal operating conditions, the maximum allowable leak rate should be strictly less than the following value :

Generally speaking, the methodology and the results of theoretical and experimental studies carried out by Framatome can be applied to all PWR units with steam generator tubes in alloy 600. These results can be used to define :

- An admissible leak rate criterion in normal operating conditions and/or

- Tube plugging criteria which take into account the kinetics of crack propagation

In either case, these criteria allow for the presence of stable, longitudinal through-wall cracks in all possible operating conditions. These results are derived :

- Based on data selected so as to minimize the critical lengths and the corresponding leak rates, in order to meet safety requirements.

- Using methods which have been validated experimentally and are accurate to within less than (rupture criteria).

It is thus possible to affirm that the inservice surveillance presents an advantage from the safety standpoint in so far as 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, specifically in areas containing sludge deposits where the risk of practically axisymmetrical circumferential cracking cannot be entirely ruled out.

## SECTION 9
## REFERENCES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