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DETERMINATION OF THE EVOLUTION IN THE SHAPE OF STRESS-CORROSION-CRACKS IN SOME TYPICAL CRDM-TUBES

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ABSTRACT

Recently some longitudinal stress-corrosion-cracks have been observed to initiate at the inner surface of some CRDM-Tubes in Inconel 600 on some of the older plants operating in France. Since it is more difficult to have access to the depth of the crack than its length, a simple method was deveopped to correlate the crack depth to its length, based on Fracture mechanics methodology using computed stress analysis and the experimental material data. The objective of this paper is to present the underlying hypotheses involved in such a methodology and the results obtained at various locations of the CRDM-Tubes. These are compared with available results, obtained during inspection of the tubes.

1. INTRODUCTION

In Oct.1991, during a planned hydro-test, a leakage occured at one of the CRDM-tubes which revealed the existence of longitudinal cracks in these tubes. Since then, a huge amount of studies have been made, both theoretical and experimental, to understand the behaviour of such cracks which have been concluded to be Stress-corrosion-cracks (SCC). In fact, it is well known that under certain conditions of applied stress and temperature, Inconel 600, presently used CRDM material, develops cracks. These cracks grow according to the process which is more harmful of the two :

- either due to crack-kinetics depending on the usual fracture mechanics parameter : Stress Intensity Factor (SIF) K,
- or due to further initiation in the zone ahead of the crack susceptible to SCC.

This growth occurs all along the crack front such that, step by step, the crack develops new contours till under certain conditions, it becomer a through crack. Now, it is more difficult to measure the crack depth inside the thickeness of the tube, than the crack length at the surface. It was therefore felt that it might be useful to develop a relation between the depth and the length of the crack. However, because of the complexity of the phenomenon and the number of parameters involved, it was decided to use a simple approximate formulation which could be used only for a rapid estimation of the risk of presence of a through crack after the crack length measured at the surface. Moreover, in this approximate analysis, the defect is considered to be isolated i.e. without any interaction effects with other cracks if these are eventually present.

Although the study presented here was conducted about an year ago with a certain given data concerning computed stress and material properties, the uncertainties in these data will affect little the results of this study since it represents a comparative analysis of the surface and the deepest point of the crack front. It should be observed however that since this study, these uncertainties have been put to evidence through more refined computations and measurements ; this point will be discussed in the paper.

2. OBJECTIVE AND FRAMEWORK OF THE STUDY

As mentionned ealier, the objective of the present study is to use a simple formulation to determine the relation between the length and the depth of a longitudinal crack in a central or a hill-side CRDM-tube of a vessel head of a typical CP0-type French reactor. The result depends on various parameters including the circumferential stress-distribution. The correlation will therefore depend on the zone of the CRDM considered.

2.1. Geometry analysed

Fig.1 Shows schematically a hill-side CRDM-tube which is welded to the vessel head at the lower part.

The tube has :

- inner diameter $\Phi_i = 70$ mm
- and thickness $t = 15.8$ mm

The defect retained is a semi-elliptical flaw.

Only two points of the contour are analysed :

- the deepest point with corresponding SIF K_f
- the surface point with corresponding SIF K_s

using the "localised" propagation law to determine step by step the new shape of the elliptical defect.

An internal study showed that the subcritical growth could occur upto crack depths as far as 95 % of the thickness which represents the ligament instability condition.

2.2. Material properties

This study is based on the following properties of Inconel 600 material with respect to stress corrosion cracking :

- crack Initiation : it is based on the curve shown in fig.2, which gives initiation time ta as a function of applied stress σ.
  One can notice that the minimum stress necessary to initiale a crack is given as 300 MPa.
- crack Propagation : The equation governing the crack propagation in SCC is given by :
  $da/dt = 1.4\ 10^{-12}\ (K-9)^{1.16}$ where da/dt is in m/s and K in MPa $\sqrt{m}$.

This equation is established from the crack propagation law given at 330°C, by correcting it by a factor of 2 for application at 315°C. (P. SCOTT "An analysis of Primary Water Stress Corrosion Cracking in PWR Steam Generators", "Proceedings of NEA/CSNI-UNIPEDE Specialists Meeting on Operating Experience with Steam Generators", 16-20 Septembre 1991, BRUXELLES, paper 5.6.)

2.3. Circumferential stress distributions

This study is based on the circumferential stress distribution available in FRAMATOME internal reports at the time of this study and concerns :

- elastoplastic analysis in the central CRDM-tubes
- elastic analysis in the hill-side CRDM-tubes.

The two types of distributions which are necessary for the analysis are :

- variation in the axial direction
- variation in the thickness of the tube

The highest stresses result in the welded area and depend on the location in the hill-side nozzles (e.g top hill or down hill locations). Without going into the details of the stress-evaluation, fig.3 shows, as an illustration, the stress distribution in a central CRDM-nozzle at the inner surface along

the longitudinal axis of the tube. To simplify the present study, this distribution is considered qualitatively in all the axial planes in the thickness, with a linear variation in the peak values.
The slope of the stress distribution in the thickness corresponds to the result of the computation at the maximum stress point and is considered the same in all planes along the tube axis. It was observed that the slope is generally small except for the case of central CRDM-tube above the weld (fig.4). The more refined computations and the measurements made since this study, confirm qualitatively the data used. In any case, to evaluate some of the variation of the input data, parametric studies were conducted as discussed in §4.

2.4. Zones analysed

The results presented here correspond to four cases :

- ▩ two cases for the central CRDM-tubes
  - ▩ crack propagation above the weld
  - ▩ crack propagation below the weld
- ▩ two cases for hill-side CRDM-tubes
  - ▩ propagation on down-hill side
  - ▩ propagation on up-hill side

3. THE APPROACH RETAINED

Since there is a threshold value of SIF $K_{ISCC} = 9$ MPa$\sqrt{m}$, a crack will propagate only for values of $K > 9$ MPa$\sqrt{m}$. As a first step, therefore, one looks for initial defects which correspond to a value of $K_I \simeq 9$ MPa $\sqrt{m}$:

$a_0 \simeq 0{,}1$ mm for a hill-side CRDM-tube
$\simeq 0{,}2$ mm for a central CRDM-tube

Then, one looks for the stress σ_0 which acts upto the depth of a_0 to determine :

▩ the time to initiation t_0
and ▩ the length $2C_0$ of the defect which would initiate in the axial direction under the effect of stress σ_0.

This characterises the initial defect $(a_0, 2C_0)$.
From this initial state, one can evaluate the evolution each year by considering 8800 hrs at each step (in some cases, this time step is too large, however for this preliminary study, it is considered sufficient).
Thus for the first year for example,

$$t_1 = t_0 + 8800 \text{ hrs}$$

Using fig.2, one can determine the value of stress σ_1 which would initiate a crack in time t_1.
After the retained stress-distribution, one looks for the new extent of the zone $(a_1, 2C_1)$ in the radial as well as axial direction on which exerts the stress σ_1. This determines the new defect $(a_1, 2C_1)$. Evaluation of the SIF K_f and K_s determines the localized propagation of these points of the contour : Δa, Δc
For the evaluations for the following years :

$$t_2 = t_1 + 8800,\ t_3,\ t_4,\ \ldots..$$

One determines the predominance of the two phenomena :

- ▩ initiation
- ▩ propagation

to determine the new shapes of the defect
$(a_2, 2C_2)$, $(a_3, 2C_3)$, ...

4. RESULTS

4.1. Preliminary Remarks : Before presenting the results, it would be appropriate to make the following remarks.

For given material properties, the result crack depth "a" as a function of crack length "2C" depends only on the distribution of the stress considered.

Now, in a given x-section, one can express the stress as a function of two parameters α and β :

$$\sigma = \alpha\ (c) \left[1 + \beta \frac{x}{t}\right]$$

where α (c) represents the mean stress on the internal surface, acting on the length 2C of the crack, and β is a function of the linear distribution considered in the thickness t.

A sensitivity study shows that the curve (a Vs C) is not very sensitive to the value of α and that a variation in α leads to a different time to obtain a given pair (a, C). However, the parameter β defining the slope of the linear stress distribution in the thickness has a considerable effect on this curve. Consequently, results were obtained using three values of β corresponding to upper bound, lower bound and a realistic linear distribution of stress in the thickness.

In this way, one can bound the depth of the crack for a given length.

4.2. Results for the cases considered

Figs 5, 6, 7 and 8 show the results for :

- hill-side CRDM-tube - down-hill (fig.5)
- hill-side CRDM-tube - up-hill (fig.6)
- central CRDM-tube - below the weld (fig.7)
- central CRDM-tube - above the weld (fig.8)

In the last case, the initiated crack cannot propagate beyond a certain length (or depth) since :

- the SIF becomes < 9 MPa √m at both the surface as well as deepest point
- the stress at the crack front level is < 300 MPa.

4.3. Sensitivity study

As mentionned ealier, the curve (a Vs C) is not very sensitive to the numerical value of α, the stress acting at the inner surface of the tube. In fact, computation made on the down-hill side of the CRDM-tube with a stress 10 % lower than the computed result, changed length of the through-crack from 58 mm to 60 mm (however the time to reach the through-wall case is greatly increased : 30 % for a decrease of 10 % in stress).

The sensitivity study with respect to the slope β are shown in figs 5 to 8.

4.4. Correlation with observed results on the reactor

In fig.5, are indicated also some points corresponding to the actual observations on the reactor :

- One point corresponding to the through-wall crack for the BUGEY 3 reactor CRDM n° 54 - Down-hill.
  The length here is about 50 mm on the inner wall and the correlation with analysis seems good.
- Other points corresponding to surface defects observed on BUGEY 4 reactor - one is known to be nearly through-wall crack, while for others the exact depth is not known and lies between 50 % and 75 % of the thickness.

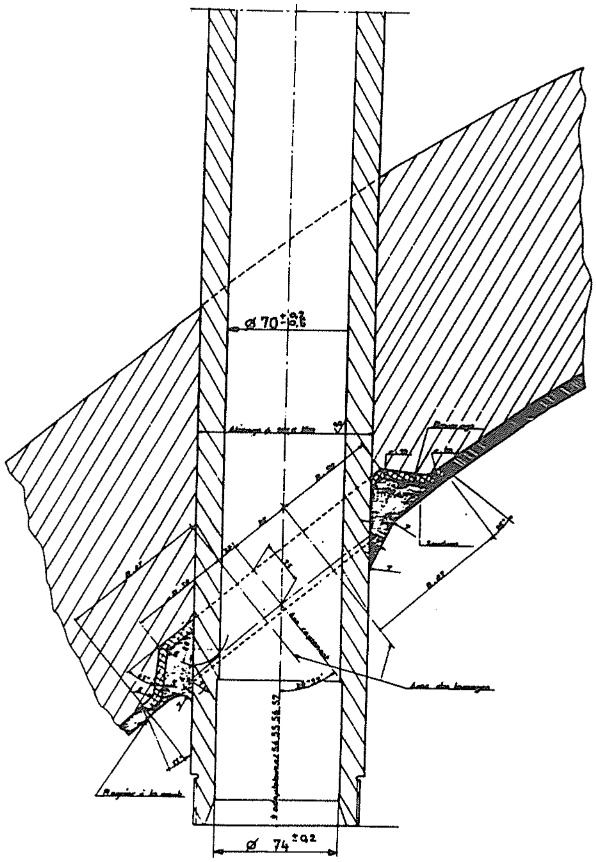

FIGURE 1

GEOMETRY OF A TYPICAL HILL-SIDE CRDM-TUBE

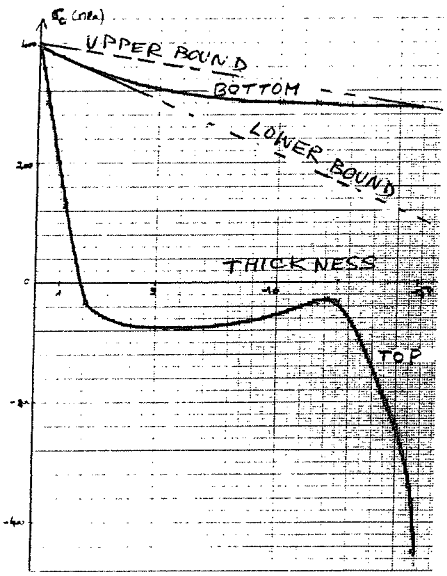

FIGURE 4

WELD CIRCUMFERENTIAL STRESS IN THE THICKNESS OF A CENTRAL CRDM-TUBE

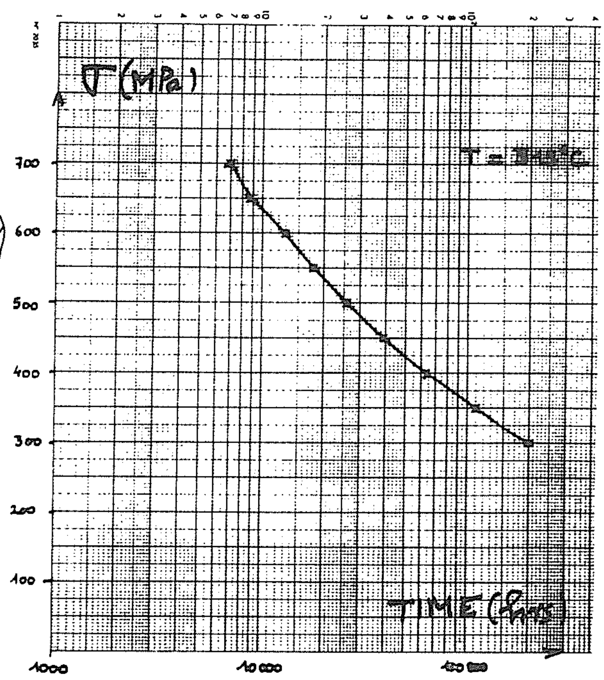

FIGURE 2

RELATION BETWEEN MINIMUM TIME TO INITIATION AND STRESS (at 315°C)

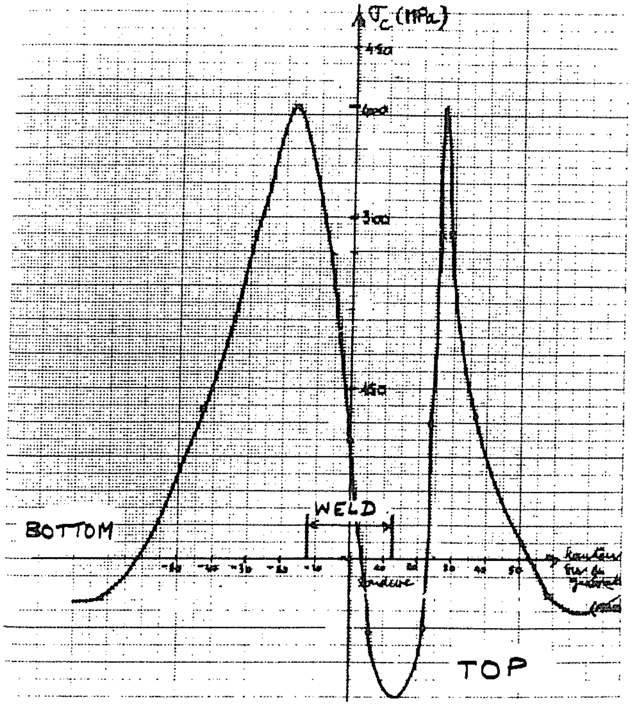

FIGURE 3

WELD CIRCUMFERENTIAL STRESS AT THE INNER SURFACE OF A CENTRAL CRDM-TUBE

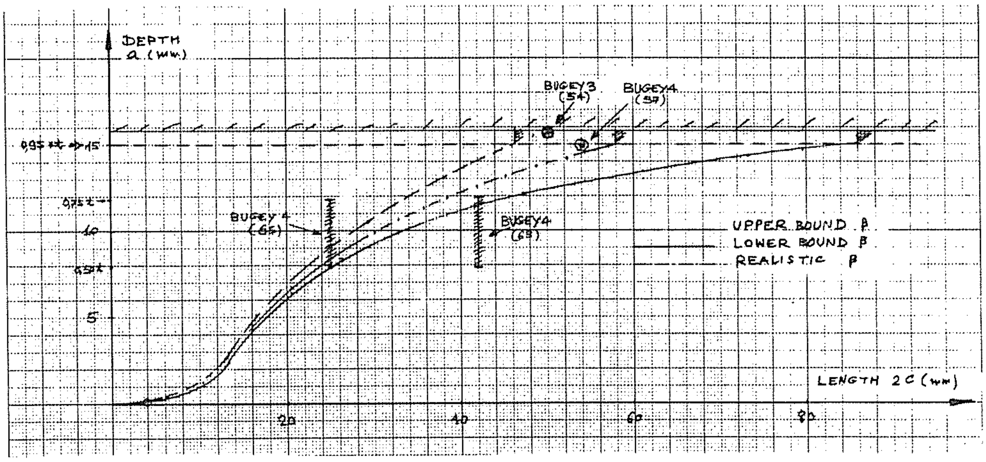

FIGURE 5 : HILL-SIDE CRDM-TUBE (DEFECT ON DOWN-HILL SIDE)

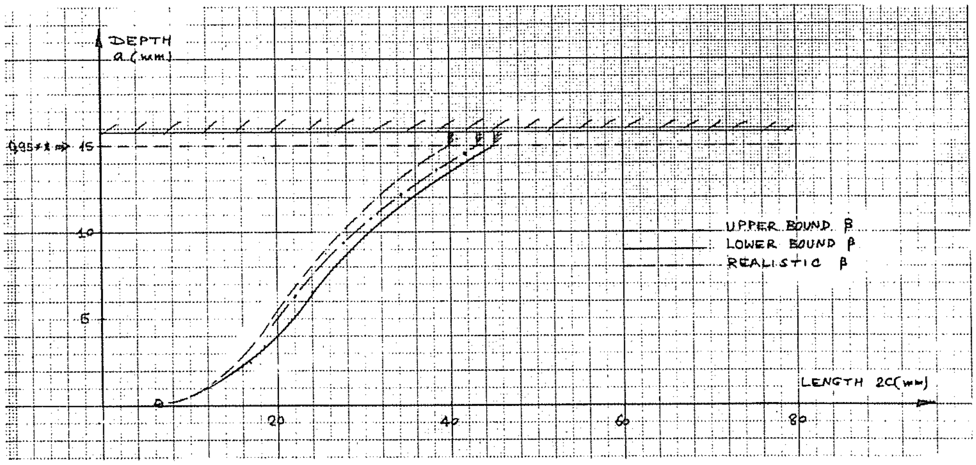

FIGURE 6 : HILL-SIDE CRDM-TUBE (DEFECT ON UP-HILL SIDE)

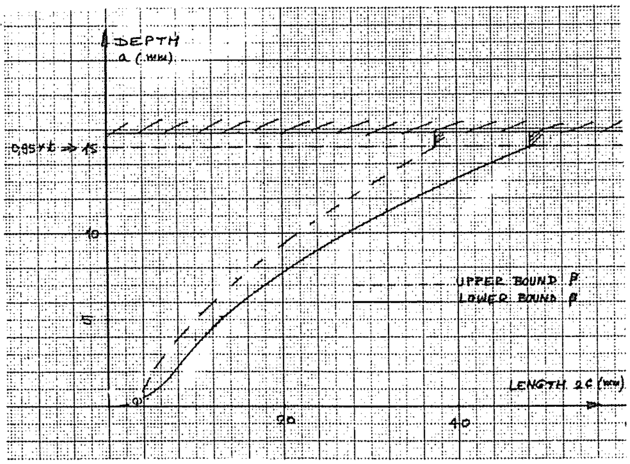

FIGURE 7

CENTRAL CRDM-TUBE
(DEFECT BELOW THE WELD)

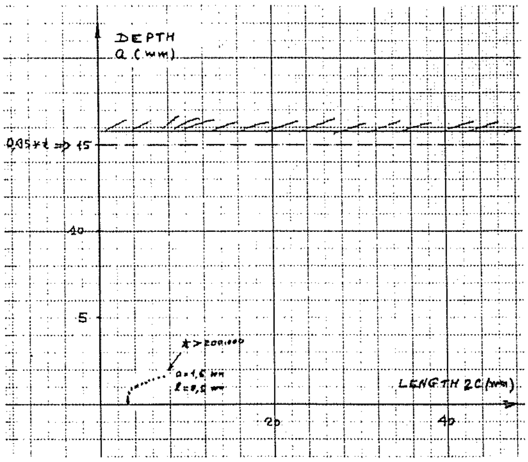

FIGURE 8

CENTRAL CRDM-TUBE
(DEFECT ABOVE THE WELD)