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FRACTURE PROBABILITY EVALUATION OF A LWR PRESSURE VESSEL

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INTRODUCTION

Fracture probability evaluation, of a LWR pressure vessel have been performed in the past, using statistical data from conventional plant. A more accurate evaluation has been requested in 1976 from the SCSIN to the CEA. With this object, a joint collaboration agreement has been signed between CEA, EURATOM/ISPRA and FRAMATOME. The whole program proceeding from this agreement is managed by a joint board including the three partners. This programme has been presented in [1].

In addition to the evaluation of fracture probability of a nuclear pressure vessel, this program is carried out, in order to get the following informations :

- assessment of the individual effects of the main parameters on the final result,
- comparison of the various possibilities in the field of fabrication or operation,
- basis for the determination of the intervals for in-service inspections.

It is expected to extend this work to a comparison of the failure probability of the differents components of the reactor coolant pressure boundary (RCPB).

The basic objective of this program is to develop a method which integrates, or makes it possible to integrate at a later stage, the greatest number of significant parameters. Also, in order to prepare the practical applications, a special effort is being made to collect the data corresponding to these parameters.

Parallel basic research program have been launched in order to clarify our knowledge on some important parts of the main factors contributing to the evaluation. The results of this research will be progressively introduced into the method or will help checking its validity.

II METHODOLOGY

1. Analytical criteria

The analysis involves expressing the conventional concepts of fracture mechanics in a probabilistic form, as proposed previous by [2] [3] [4] : the fatigue crack growth rate, calculated for conditions of repeated loading, the initiation of unstable crack propagation, calculated for faulted conditions, and the possibility of arrest of the cracks which have begun to propagate, before the vessel fails. The analysis treats all defects as cracks liable to propagate under fatigue without a period of crack initiation.

The da/dN crack growth rate is expressed on the basis of the variation in the stress intensity factor ΔK during the cycle.

The initiation of unstable crack propagation is expressed both by the condition $K_I > K_{IC}$ in small scale yielding situations, and by a criterion of local plastic instability in general yielding situations.

The analysis therefore requires the statistical expression of the factors and parameters which appear in the expressions of the law of crack growth and of toughness, and also those which are used in the calculation of the K_I, that is the defect sizes and the applied stresses, which depend on the defect location and the load sustained for each loading condition.

2. Defect size

Previous research [5] on incidents occuring with conventional industrial pressure vessels has shown that in 90 % of cases the manufacturing defects, which lead to the failure, were initiated in the welded joints. For this reason, this analysis consider only the defects in the welds and their growth, using the length of the weld as basic parameter. However, in view of the particulary large loads to which the inner angles of the nozzles are subjected, the nozzles are included in the analysis.

The distribution of defects in a vessel before and after repair has been taken as the basis for the prababilistic evaluation, these data were obtained from non-destructive inspections performed by three European manufacturers, representing a total of approximately eleven reactor vessels.

The results of these manufacturers'data is given in a histogram showing, for the total length of weld analysed, the number of defects having a length or width included within each class of the histogram. Preliminary results are presented in Figure 1.

Before the distribution obtained by this method is introduced into the computer program, it must be processed in order to take into account the following factors :

- the sample size,
- the accuracy of the measurement equipments,
- the reliability of the inspection methods and equipments,
- the size of the acceptable defects,
- the critical defect related to the hydrotest.

3. Properties of the steel

a. Crack growth rate. An overall statistical interpretation of all the available (da/dN) ΔK measurement points has been made for the SA 508 and SA 533 B steels, using the four laws : Paris, Forman, Priddle and Walker [6]. Numerical coefficients have been calculated for each of these formulas by linear regression from experimental results and by several partitions of the measurement range. Then the reduced mean deviation, the standard deviation between calculated values and measured values, and the coefficient of determination have been evaluated for each law and each partition.

Paris'law $da/dN = C \Delta K^n$ has been found to be the most suitable for this first application to reactor pressure vessels. The values of the parameters have been defined, in 3 different domains, as a function of the values of ΔK and of the environment, from the experimental data in each domain. The values of the n coefficient giving the best determination coefficient have been chosen, and the C corresponding values have been established into histograms.

The propagation rate under water environment, is higher than in air, above a threshold ΔK_t given by an histogram. It has been assumed that for the values of $\Delta K < \Delta K_t$, the propagation rates are equal to those in air, for which no threshold has been considered. The values of ΔK_t are depending on R, with $R = \sigma min / \sigma max$.

b. Toughness of the steel. The K_{IC} toughness of ferritic steels shows a wide dispersion in the transition zone, which is reduced by locating it with respect to the RTNDT as defined in the ASME code. It also depends on the irradiation which has the effect of varying the RTNDT. This RTNDT variation, which depends on the fluence and the content of impurities in the steel (Cu and P), is calculated on the basis of the ASME XI curves. All these factors are taken into consideration for the determination of the equivalent temperature $T_E = (T - RTNDT - \Delta RTNDT)$ given by histograms.

The K_{IC} distribution in relation to T_E is obtained from the statistical analysis of available experimental data on non-irradiated SA 508 and SA 533B steels. The lower shelf, transition zone and upper shelf must be treated seperately.

4. Conditions

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Two categories of conditions are considered. The first category includes Observable Conditions corresponding to the scheduled operation of the power plant and to normal operating incidents (ANS Conditions I and II, and Second Category Conditions according to the French standard "Arrêté du 26 02 74"). These are taken into consideration in the analysis of fatigue crack growth. The second category encompasses Faulted conditions (ANS Conditions III and IV, and Third and Fourth Category Conditions according to the French "Arrêté du 26. 02. 74"). The probability of occurence of these latter conditions during the life of the power plant is much lower, and they are therefore not taken into consideration for crack propagation. However, these conditions are involved in the probability of fast fracture calculated at any given moment in the plant operating life. A total of 24 observable conditions have been defined with their probability of occurence. For each of these conditions, the number of cycles, the water temperature and pressure variation, in the vessel have been determined.

A LOCA has also been defined : rupture of a main piping and ACCS operation at 10°C.

5. Stress analysis and calculation of K

For all the Conditions thus defined, a transient thermoelastic analysis is realized in the zones of the components under consideration.

For Conditions which contribute to fatigue crack growth, the maximum and minimum values for the main stresses during the transient are calculated in relation with the location in the wall thickness.

The $\Delta\sigma$ taken into account for the calculation of the ΔK_1 entering into Paris'law is the biggest value of the three variations in each of the principal stresses.

For faulted conditions, the evolution of the three main stresses and of the metal temperature in relation to the thickness must be specified for the different stages in the transient. The value of K and Δ K are calculated assuming that the cracks have an elliptical shape, and using conventional formulas.
The transition from an elliptical internal crack to a semi-elliptical surface crack is assumed to occur when $a/h > 1$, keeping the same value for the major axes, and wet conditions are assumed for the cracks having their center distant from 9 mm or less from the crack surface Figure 2 and 3. The cladding is taken into account for the temperature analyis, but is ignored for the stress and Δ K analysis.

6. Onset of unstable propagation

In a deterministic situation, the onset of unstable propagation occurs when "request" K_I becomes higher than "capacity" K_{IC}. When these two parameters are time depending, propagation can occur when this condition is fulfilled at the same time and in the same location.

In the present case, K_I and K_{IC} are known only under probabilistic form. It can be assumed that in this case, the probabilistic analysis can be divided into a series of deterministic analyses associated with a probability density function.

In a given location in the thickness, the preceeding evaluation makes it possible to establish a set of curves of the stress intensity factor and toughness as function of time. A probability is assigned to each type of curve.

$P_i = g\,(K_I^i)\,dK_I$ or $Q_i = h\,(K_{IC}^i)\,dK_{IC}$.

The partial probability of onset of unstable propagation at the given point and at the given time is equal to the sum of the $P_i \,.\, Q_j$ products computed for all the couples of K_I^i and K_{IC}^j curves verifying the condition $K_I > K_{IC}$ at the given time.

This criterion is applied in the following manner :

- for an internal crack : at the tip of the minor axis of the ellipse, the closest to the internal surface,
- for a surface crack : at the tip of the minor axis of the semi ellipse , (Figure 2 and 3).

III COMPUTATION PROCEDURE

All imput data are introduced in the computation code under histogram form.

Two computer programs have been developed : COVAL 3 and COVASTOL. The COVAL computer program processes all the problem variables specified as histograms, in a purely statistical manner. All the possible combinations of the histogram classes are taken into account, at each stages of the computation, the program is therefore in this respect very close to the Monte-Carlo method. The COVASTOL computer program however, is closer to the physics of the phenomena since it takes into account the degree of correlation between the flaw dimensions a and b, and the coefficient of Paris'law during fatigue propagation. This leads to propagation histogram showing the same extremes found by COVAL but with higher probabilities. The organigram of the code is presented in Figure III.

IV EXAMPLE OF COMPUTATION

The part of the computation program concerning the crack growth and the criterion of the onset of unstable propagation during thermal shock in a belt line weld is set up. Due to the fact that the evaluations of the flaws distribution in weld by European manufacturers are not completed, the defect sizes after fabrication are taken as imput parameter.

The following example gives the probability of onset of unstable crack propagation for a belt line weld in a RPV for a LOCA occuring after 40 years of operation without in service inspection.

A discrete number of defect sizes has been arbitrarily chosen according to the following mesh.

a = 1.5	3.	6.25	12.5	mm
b =15.	30.	62.5	125.	mm

Numerical results

Numerical results are presented in Figure 4 and 5, which show for the given weld, and each defect size, the partial probability of onset of unstable crack propagation. Figure 4 shows, for the given weld, and for a given defect position, the partial probability of onset of unstable crack propagation at 40 years as a function of the initial defect size. It can be seen on this Figure that the influence of the excentricity of the ellipse is very small, and that the influence of the position of the initial defect through the thickness is very high.
Figure 5 shows, for the same weld and for a defect located close to the internal surface and supposed to be under water environment, the partial probability as a function of the time. The probability is increased by a factor 10^3 when the life of the reactor increases from 10 to 40 years.

V FINAL COMMENTS

1. In order to obtain the probability of the onset of unstable crack propagation in the given weld, the preceeding results must be completed by taking into account two additional probabilistic factors :

   - the probability for having in the pressure vessel weld, after fabrication, the given defect size,
   - the probability for having a LOCA (the WASH 1400 report suggest a probability of 10^{-4} per year). .../...

2. The adopted criterion relates to the onset of unstable crack propagation. This does not means that a disruptive failure or even a leakage would follow. It will be necessary to take into account a crack arrest criterion in order to complete this evaluation. The computed results give, from this point of view, an upper limit.

3. The proposed method requires a rather small computing time (about 30 seconds with the IBM 760-65 for one defect size and one position). It will therefore be possible to undertake a systematic sensivity evaluation of the relative weight of the different parameters.

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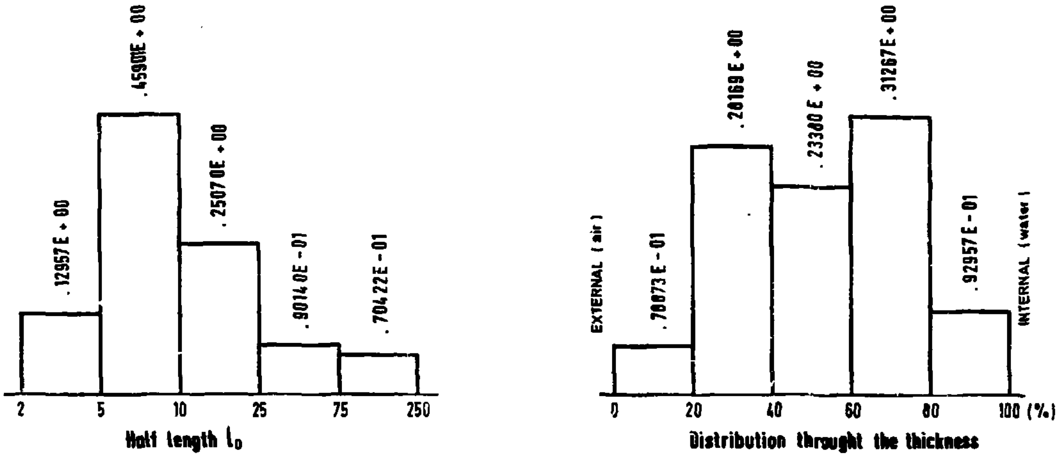

Fig. 1 – Distribution of defects

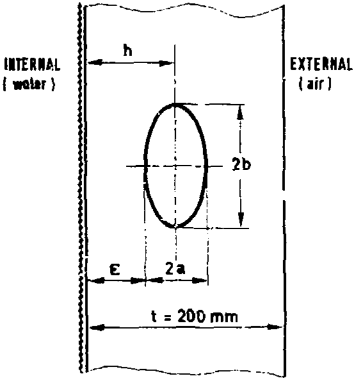

Fig.2 - Transition between dry & wet condition

ε > 8 mm dry condition

ε < 8 mm wet condition

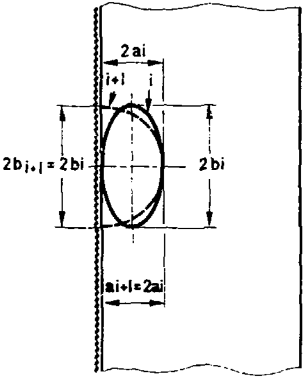

Fig. 3 Transition between:

Internal flow i

Surface flow i + 1

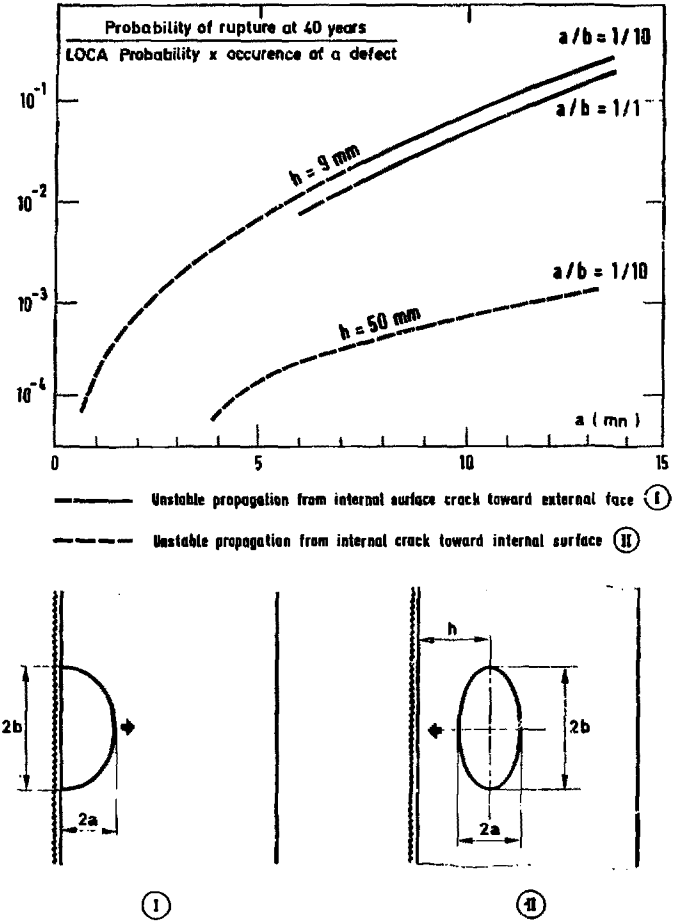

Fig. 4 – Conditional probability of rupture as a function of the size of the initial defect

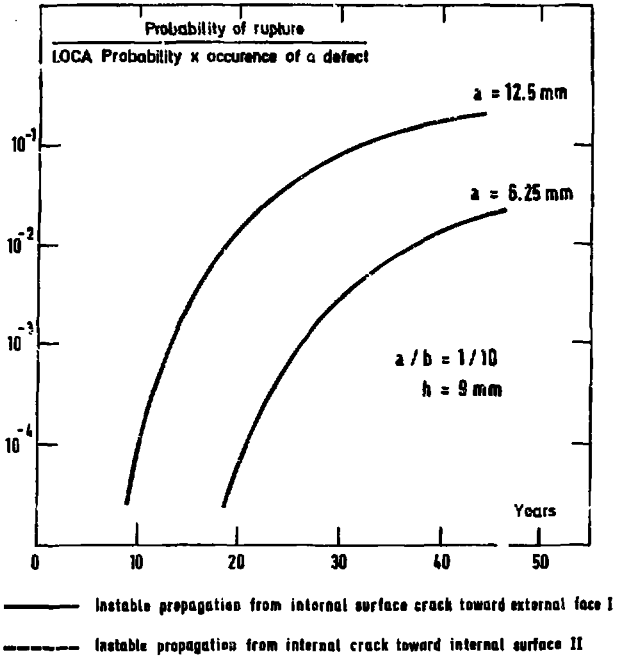

Fig. 5 _ Conditional probability of rupture as a function of time