Fast Diagnosis and Treatment of Cracklike Defect Injuriousness in PWR Power Plant Equipment

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SUMMARY

The potential risk of cracking phenomena (initial defects or propagating cracks) in auxiliary and secondary power plant systems makes it essential to evaluate the injuriousness of such defects.

This paper presents a Defect Injuriousness Diagnosis and Treatment Package (DIDTP) which can be applied to auxiliary and secondary system analysis during manufacturing and installation work as well as during actual system operation.

Unlike the standard procedure, in which defect injuriousness is computed after detection, the DIDTP can be established beforehand for a given system, or portion of a system, so that it becomes immediately available for assessment of the injuriousness of potential defects. It furnishes on-the-spot responses to the following key questions :

- Is the defect serious ?
- How much time is available for servicing the system examined ?
- How can defect injuriousness be lessened ?
- How can defect development be monitored more effectively ?

Following a presentation of the individual elements comprising a DIDTP, a description is given of the analytical and computational methods, which are based on brittle and ductile fracture mechanics concepts fundamental to any DIDTP.

A brief description is then given of the TITAN and ANODE computer codes developed by FRAMATOME which are used for automatic compilation of DIDTP's.

Finally, a practical example is given to demonstrate the different stages involved in the compilation of a DIDTP, and the way in which the DIDTP can be used to provide results which make it possible to determine short or longterm actions : rework of faulty component, operating modifications, monitoring of critical zones, additional computations, etc..

1. INTRODUCTION

Defects detected in nuclear power plant components in the course of periodic inspections may have been formed during fabrication, at installation or in service.

In order to accelerate decision-making subsequent to defect detection and increase the effectiveness of inspection programs, it is proposed in this paper that a package be prepared for each main system at the design stage to permit immediate diagnosis of defect injuriousness and to offer guidelines for mitigating action.

The paper comprises :

- description of such a package, hereafter referred to as "Defect Injuriousness Diagnosis and Treatment Package" (DIDTP) ;
- breakdown of a DIDTP and demonstration of the computational methods used in its elaboration ;
- presentation of the computer codes (ANODE, TITAN) used for automatic compilation of DIDTP's ;
- example of DIDTP application.

2. DESCRIPTION OF A DIDTP

The DIDTP is prepared for individual regions in the system or for a hypothetical envelope region representing a portion or the totality of the system. The package can be employed to model not only piping but plant system components (valves, fittings, heat exchangers, etc.) as well.

The DIDTP comprises a series of easily interpreted tables and nomographs for each type of defect. The package is broken down into two parts :

- Part 1, "Loading Severity" contains curves showing the relative influence of each loading condition and each combination of loading conditions on defect injuriousness. Separate consideration is given to the ranges of applied loadings and to the cumulative effects of these ranges and the number of occurrences.
- Part 2, "Injuriousness Diagnosis", contains two nomographs. One of these is used to evaluate fatigue defect propagation as a function of initial defect size and operating time interval. The other is used to assess the risk of fast fracture for the most severe loading condition encountered for each category of operating condition as a function of ultimate defect size.

The data thus provided enable the user to evaluate defect injuriousness and decide on appropriate action. He may, for example, modify system operation to increase the life of a particular component, or he can pinpoint the critical stages in defect development.

3. PREPARATION OF A DIDTP

As used in this paper, the term "load" refers to the action of any environmental parameter capable of producing deformation in the system (pressure, mechanical forces, heat flux, corrosion, etc.). The superposition of a number of loads at a given instant constitutes a loading.

A "loading condition" is a loading cycle induced by a variation of operating conditions with return to the initial condition. A loading condition is characterized by two limit loadings represented by a maximum and minimum through-thickness stress distribution in the component under consideration.

3.1. Basic criteria

Methods of analysis comply with the requirements of paragraph B 3260 and appendix ZG of the RCC-M /1/and with French regulations relating to industrial safety /2/.

The package incorporates the principles set forth below which are based on brittle and ductile fracture mechanics concepts.

3.1.1. Selection of regions for analysis

For each piping run, the regions to be covered by the DIDTP are selected as a function of :

- defects liable to exist in those regions,
- possibility of crack initiation,

- possibility of local embrittlement.

Alternatively, a hypothetical envelope region may be selected to represent the most critical point in a portion of the system where the most severe loads acting in that portion of the system would be concentrated. This region is, therefore, representative of the entire portion.

3.1.2. Parametric analysis

For each region selected, a defect is postulated and an analysis is performed for variations in the parameters describing :

- site, shape and size of the defect,
- plant operating time interval.

The purpose of the parametric analysis is twofold: to ensure that the package is valid for all possible defect configurations which may be detected, and to characterize the development of each defect type under the action of different loading conditions. Accordingly, parameters may be divided into two categories: "static parameters" describing the type of defect, and "growth parameters" characterizing the development of the type of defect under consideration.

It is generally assumed that defect site and shape are described by the static parameters. Thus, a circumferential semi-elliptical surface crack is assumed to propagate along the plane of the crack with a constant eccentricity.

Defect size will always be described by one or more growth parameters representing its characteristic dimensions. A crack of the type described above would be described by a single characteristic dimension: maximum depth a. In the case of buried defects, at least two characteristic dimensions will be required.

The static parameters are defined in the DIDTP and, for each type of defect selected, injuriousness is analysed as a function of the growth parameters.

3.1.3. Criterion for selection of most severe loads

For a given defect, the most severe load is the load with the maximum associated Stress-Intensity Factor (SIF). Thus, in the case of a defect of characteristic dimension a subject to thermal shock, the through thickness stress distribution σ_j (x,t) representing the most severe load will be such that :

$$K_j(a) = \max_t \left\{ K_j \quad (a, t) \right\} \qquad (1)$$

3.1.4. Criterion for combination of loadings for all loading conditions

Loading combinations for all loading conditions represent any change from one loading condition to another. Such combinations constitute new loading conditions which are defined as follows :

The SIF distributions corresponding to the stress distributions $\sigma\ max_p$ and $\sigma\ min_p$ which represent the limit loadings of condition p, are calculated. The combinations producing the maximum SIF ranges for all loading conditions are then determined. Thus, the new loading condition produced by combination of the loadings for conditions p and q will be such that :

$$\Delta K\ (p,q) = Kmax_p - Kmin_q \qquad (2)$$

This combination will be designated (p,q), in that order, to indicate that it incorporates the maximum loading from condition p and the minimum loading from condition q.

3.1.5. Criteria for selection of most severe combinations

Two criteria may be used :

a) Maximum SIF range criterion

The most severe combination for a given defect is the combination (m,n) for which :

$$\Delta K\ (m,n) = \max_{p,q} \left\{ \Delta K\ (p,q) \right\} \qquad (3)$$

b) Maximum growth rate criterion

For a defect with characteristic dimension a increasing from a_I to a_F (p,q,Npq) under the action of Npq cycles associated with combination (p,q), this criterion is expressed as follows :

The most severe combination is the combination (k,l) for which :

$$\frac{a_F\ (k,\ l,\ N_{kl}) - a_I}{a_I} = \max_{p,q} \left\{ \frac{a_F\ (p,\ q,\ N_{pq}) - a_I}{a_I} \right\} \qquad (4)$$

This expression can easily be generalized for defects having more than one characteristic dimension by maximizing the sum of the growth rates.

3.1.6. Defect injuriousness criterion

For a given period of time, with due consideration of the cumulative contribution of all loading conditions to defect growth, injuriousness is determined as a function of :

- the extent of fatigue propagation,
- the risk of fast fracture.

3.2. Computational methods

For practical application of the above principles, linear elastic fracture mechanics (LEFM) computational methods have been used together with correction functions to account for plasticity at the crack tip and in the ligament.

The following parameters are used to describe the cracking process : defect growth parameters (generally comprising the characteristic dimensions), dimensions of the residual ligament and an equivalent SIF K_J whose validity has been extended to cover elastic-plastic material behaviour.

3.2.1. Calculation of the equivalent SIF K_J

By comparing linear elastic and elastic-plastic calculations /3/, the scope of validity of each type of calculation has been determined and the following definition for an equivalent SIF K_J has been formulated on the basis of J or modified J integral calculations :

$$K_J\ (a_k) = \alpha\ (a_k\ ,\ l)\ .\ K_{cp}(a_k) \qquad (5)$$

where :

- a_k and l are the characteristic dimensions of the defect and the ligament respectively ;
- $K_{cp}\ (a_k)$ represents the elastic SIF as corrected by Irwin ;
- the multiplication factor α varies from 1 to 1,5 /3/.

The elastic SIF $K\ (a_k)$ is calculated by the influence function method /4/. If stresses are represented by the polynomial expression

$$\sigma(x) = \sum_{\ell=0}^{m} s_\ell\ .\ x^\ell \qquad (6)$$

(where x is the abscissa through the thickness e of the component under consideration), the elastic SIF for a crack of characteristic dimension a is given by :

$$K(a) = \left\{ \sum_{\ell=0}^{m} s_\ell .\ i_\ell . \left[\frac{a}{e}\right]^\ell \right\} .\ \sqrt{\pi a} \qquad (7)$$

Influence functions i have been calculated /4/, /5/ for the following types of cracks in plates or cylinders of different radii* : circumferential or longitudinal, internal or external, plane or semi-elliptical (for different excentricities). An expression similar to eq. (6) has been formulated for buried cracks.

Where a linear approximation of through-thickness stress distributions is acceptable, the elastic SIF may be calculated using the semi-empirical formulae given in SIF handbooks /6/, /7/ or other relevant sources /8/,/9/.

3.2.2. Calculation of defect growth

Defect growth is calculated by numerical integration of fatigue crack growth laws. These laws, which are of the Paris-Forman type, represent an envelope of results obtained for a

* The ratio of inside radius R_i to wall thickness e varies from 0,82 to 20

variety of materials and environments encountered in auxiliary and secondary systems /10/, /11/.

3.2.3. Assessment of the risk of fast fracture

The risk of fast fracture is assessed by comparing SIF K_J values with critical K_{JC} values determined by measurement of J_{IC}. Fast fracture will not occur if, for a given defect,

$$\max_{\text{loading conditions}} (K_J) < \min_{\text{temperature}} (K_{JC}) \qquad (8)$$

3.2.4. Effect of temperature on material properties

Variations in material properties with temperature are taken into account at each stage of calculation : non-linear variations in mechanical and thermal properties for stress calculation, and variation in yield strength and impact strength for SIF calculations. In practice, impact strength is characterized by the lower limit of K_{JC} in the temperature range under consideration.

3.3. Computer codes

The ANODE computer code is used to prepare a DIDTP for a given system. On the basis of stress distribution data for all loadings, the ANODE code selects the most severe loadings, calculates SIF values and automatically edits the tables and nomographs used to evaluate "loading severity" and "defect injuriousness".

The ANODE code also determines the scope of validity of the methods used. It is provided with a library of material properties, influence functions for SIF calculations, fatigue crack growth and toughness laws - all determined as a function of component and crack geometry, type of material and service environment.

On the upstream side, ANODE is coupled to the TITUS-T piping code /12/ via the TITAN interface code. The TITAN code is used to calculate stress distributions for each loading in each region of the system, under the action of different loads. The code uses stress indices to account for variations in surface texture and the presence of geometrical discontinuities.

Fig. 1 shows a flow diagram representing the sequence in which computer codes are used in compiling a DIDTP for piping. It should be pointed out, however, that the ANODE code may be used separately or it may be coupled to other structural analysis codes used to determine thermal and mechanical stresses.

The modular design of the TITAN and ANODE codes ensures that the scope of application can be easily extended and facilitates updating of computational methods.

4. EXAMPLE OF A DIDTP APPLICATION

In order to illustrate the compilation procedure and potential applications of a DIDTP, the results of an analysis performed on a 900 MW plant secondary system are reproduced below. The purpose of the analysis was to evaluate the mechanical strength of the piping shown in Fig. 2 in the presence of hypothetical internal edge defects and having an initial depth a_I up to 3 mm. The diameter of the piping is 32" with a wall thickness of 37 mm.

4.1. Method

The DIDTP was compiled in 5 stages. To illustrate these stages, the most severely loaded region (Fig. 2) and the most injurious defect (continuous circumferential, edge crack) have been selected.

a) The first stage comprises modelling the system in its entirety (Fig. 2) and using the TITUS-T code to calculate the mechanical forces induced by pressure, dead weight, expansion, earthquake, pipe break, etc..., at all points on the system.

b) The TITAN code is then used to calculate two extreme stress distributions for each loading condition in the most severely loaded region and, where applicable, to calculate a series of stress distributions characterizing the associated thermal shock.

c) When these preliminary calculations have been completed, the ANODE code is used to select the instant in each loading condition when the loadings are most severe, edit the two overall extreme stress distributions defining each loading condition and evaluate severity by plotting variations in associated values of the K max (a) SIF and the K min (a) SIF (Fig. 3).

d) The ANODE code is then used to select from all loading conditions the loading combinations (p,q) producing the greatest SIF ranges (Fig. 4) and the combinations (k,l) producing the greatest relative crack propagation (Fig. 5).

e) Finally, the ANODE code edits the two nomographs used to assess the injuriousness of the cracks and described in paragraph 3.1.6. (Figs. 6 and 7). The scope of validity of the calculations is specified on each nomograph.

4.2. Application of the DIDTP

If the DIDTP is compiled prior to system inspection, the data provided on the most critical regions and the most injurious defects can aid the user in determining the regions to be inspected.

Let us assume that an inservice inspection has been performed on the piping for which the DIDTP has been compiled and that internal edge cracks* have been detected which have a maximum depth of 5 mm and a cumulative length of 60 to 70 mm. A comparison of DIDTP results for continuous longitudinal and circumferential internal edge cracks indicates that the circumferential crack is the more injurious. The propagation nomograph (Fig. 6) indicates that a crack of this type having an initial depth of 5 mm will grow to less than 5,1 mm after 40 years in service. For this depth A_F, the fracture resistance nomograph (Fig. 7) shows that $K_J(A_F)$ is less than K_{JC} even for the worst-case loading conditions. As the conditions for validity of these nomographs are satisfied, it can be concluded that there is no risk of fast fracture and defect injuriousness is slight.

If the defects detected are more critical or if the conditions for validity of the calculations are not satisfied or if the user wishes to ensure a safety margin, he may investigate the causes of injuriousness by consulting the loading severity nomographs.

Thus, Fig. 4 and 5 show that the combination (8,8) is the most severe with respect to ΔK_{max}, while combination (2,2) is the most severe with respect to ΔK and number of occurrences. By reducing the maximum loading in loading condition 8 or the number of occurrences of condition 2, the injuriousness of emerging circumferential defects on this line can be mitigated.

5. CONCLUSION

It has been shown, by reference to an actual example, how a DIDTP compiled beforehand for a given system was able to provide an immediate diagnosis of the injuriousness of defects detected during inservice inspection, and to indicate how injuriousness might be mitigated.

The analytical and computational methods used for fatigue crack growth analysis were validated on the basis of fatigue cracks detected in reactor coolant piping under operating conditions /13/. Since a DIDTP had not been compiled to enable accurate predictions to be made, this experience is considered to constitute sufficient validation at present.

It is conceivable that further modifications in DIDTP methods may be required to account for excessive plasticity in the residual ligament in severely loaded regions of pipe runs, or the refinement of detection techniques (e.g. leak-before-break method). For this reason, the interdependance between basic criteria (3.1.), computational methods (3.2.) and automation of computing sequences (3.4.) has been minimized.

Thus, while retaining the same criteria, the following improvements are being considered in the medium and long term : automatic evaluation of welding residual stresses, assessment of the risk of plastic collapse, crack growth and fracture resistance calculations under conditions of extensive plastic flow, and analysis of the stability of through-thickness defects.

* External edge cracks and buried cracks could be covered by other sections of the DIDTP.

R E F E R E N C E S

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/12/Code TITUS-T
Manuel d'utilisation : FRAMATOME, TSCS DC 0478 Rév. C du 15.3.82
Dossier de vérification : FRAMATOME, TSCS DC 0470 Rév. A du 16.6.80

/13/BOUCLE AQUITAINE, COLLABORATION CEA-FRAMATOME
RAPPORT FINAL N° 5 - "Etude de la fissuration par fatigue des tuyauteries primaires" (1979).

STAGES	COMPUTER CODES	CONTENTS
FORCE COMPUTATIONS	TITUS-T	EQUIPMENT AND PIPING ANALYSIS
STRESS COMPUTATIONS	TITAN	MECHANICAL STRESSES; THERMAL STRESSES; FOR EACH LOADING CONDITION, DETERMINATION OF TWO STRESS DISTRIBUTIONS
FATIGUE CRACK PROPAGATION AND FRACTURE RESISTANCE COMPUTATIONS	ANODE	<u>LOADING SEVERITY</u>: - FOR EACH LOADING CONDITION; - FOR ALL LOADING CONDITION COMBINATIONS <u>DEFECT INJURIOUSNESS</u>: - POTENTIAL CRACK PROPAGATION; - FAST FRACTURE RISK
D.I.D.T.P. FOR THE GIVEN POWER PLANT SYSTEM		RESULTS REPORT

Fig. 1 : General Breakdown of a D.I.D.T.P. for Piping

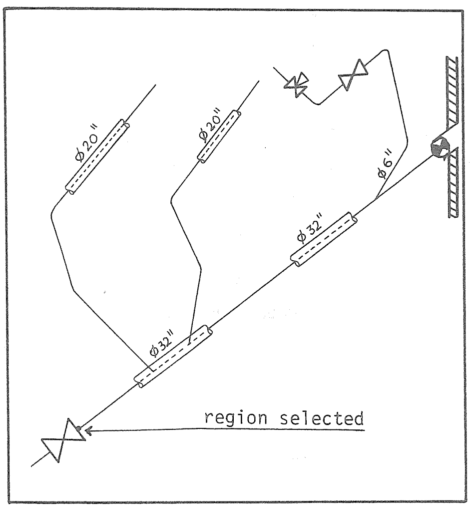

Fig. 2 : Isometric drawing of system analysed

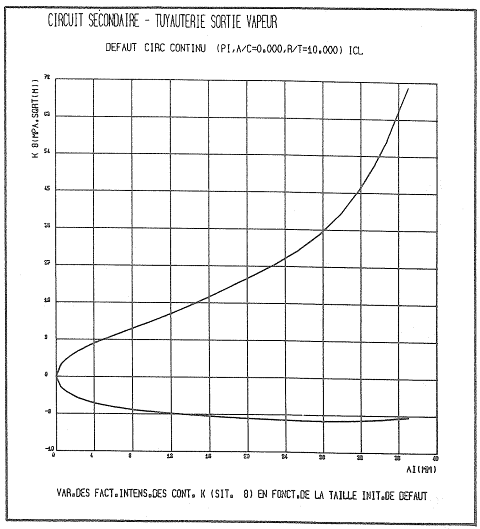

Fig. 3 : SIF variations corresponding to extreme loadings in loading condition 8.

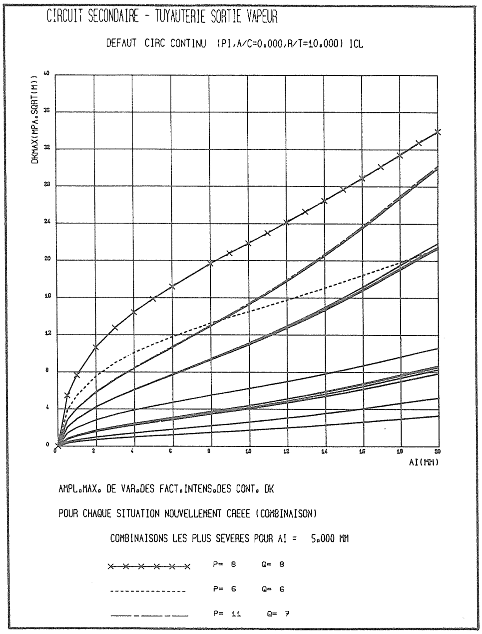

Fig. 4 : Maximum S.I.F. range nomograph.

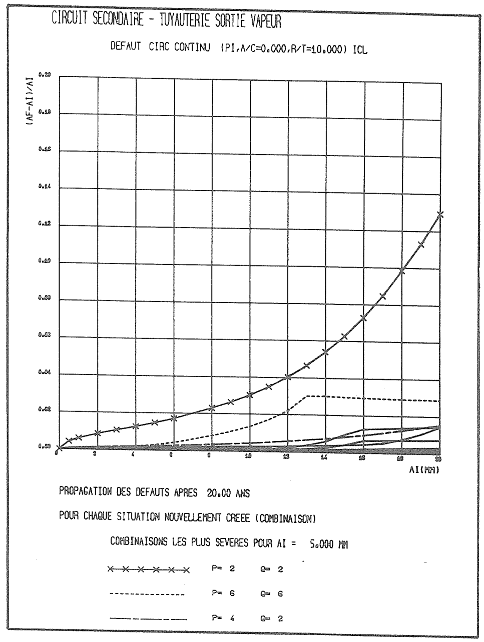

Fig. 5 : Maximum crack grouth rate nomograph.

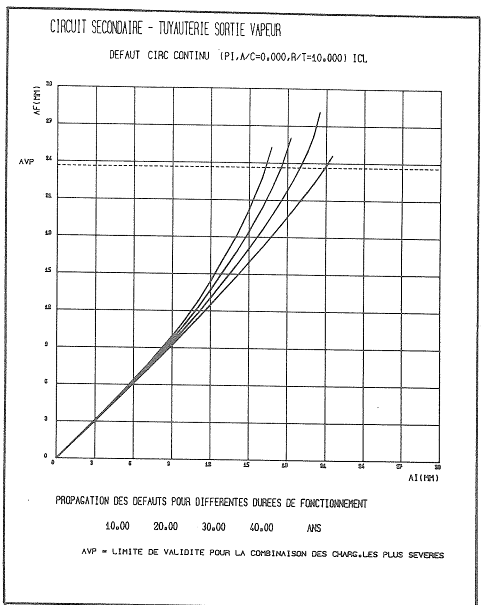

Fig. 6 : Crack grouth nomographs as a function of plant operating interval.

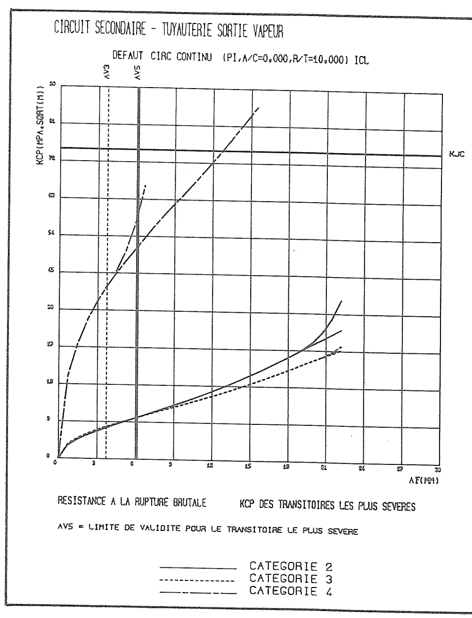

Fig. 7 : Fast fracture resistance nomographs for different categories of loading conditions.