PROPAGATION OF INADEQUATE JOINT PENETRATION DEFECTS OF WELDED ELBOWS

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SUMMARY

Auxiliary piping elbows of PWR reactors are assembled by longitudinal submerged arc weld of two halves. The elbows are made of ICL 167 CN similar to AISI 316. During fabrication and erection on site some of them have been cut and repaired because of lack of penetration, causing important costs and delays. The studies performed and presented here were conducted in order to evaluate the nocivity of this defect and allow predicting for the future in case of existence of such defect in a weld: how it will cause a crack propagation and how it will be possible to detect and measure it from the outside.

Tests have been performed on fatigue specimens cut in the weld of an elbow (with real defect, and with artificial machined crack) in air and PWR environment. It results that:

— the number of cycles for crack initiation in air at 320 °C and in PWR environment seems to be of the same order of magnitude;

— decreasing the frequency of cycling from 60 to 4 cycles/mn has no influence on crack initiation;

— for the same $\Delta\sigma_{nom}$, the number of cycles corresponding to crack initiation Ną decreases by going from an artificial machined defect with K_t: 5.5 to the same with K_t: 8.3, and finally to the real defect;

— crack growth rates are of the same order of magnitude in the basic material and in the weld itself.

Fatigue tests have been performed on 3 inches schedule 160 defective elbows themselves in PWR environment (320 °C and water pressure difference variation of 200 bars).

Every 5000 cycles the installation is stopped and the weld is inspected by UT techniques in order to control the crack propagation. During cycling an acoustic emission monitoring was performed on some elbows.

After 25 000 cycles, destructive tests and macrographic examination of defects as well as NDT results permit us to conclude that for the lack of penetration of less than 1 mn no propagation occurs.

Finally, a comparison with the experimental results and theoretical results obtained using Linear Fracture Mechanics has been carried out. The theoretical results using weight functions to calculate the ΔK, as well as experimental values of crack growth rates obtained on small flexion specimen confirm our experimental results on 3 inches schedule 160 elbows.

1. Introduction

In a PWR type nuclear reactor, there are many circuits made of stainless steel ; and during the life time of such a power plant, foreseen for 40 years, they are subject to a variety of sollicitations. One may foresee about 200 to 300 cyclings between the 155-bar working pressure and atmospheric pressure. Parallely also, the temperature varies between about 320°C and room temperature. These cyclic stresses, of pressure and thermic origin, should be taken in consideration for the survey of pipings behavior in fatigue.
During the manufacturing of some pipings and erection on site, a manufacturing defect of lack of penetration type may appear.
The work that we present here represents a contribution to the "nocivity" evaluation of such a defect. The survey results that we are going to review first concern those characterizing the material itself with regard to its fatigue behavior in PWR environment. The results obtained on test specimens are then brought into a mathematical model that we have made in order to predict the behavior of the actual component and evaluate the propagation probabilities of a lack of penetration in a welded joint. The theory is then confronted to a few experiments of cycling capacity performed on defective piping elbows.

Parallely to the start-up of these tests, we have refined an ultrasonic non destructive method of control in order to follow the defect evolution in case of propagation and tried an acoustic detection method of that propagation.

2. Characterization of the welded joint

Mechanical and chemical characteristics

The material and welding possessed the mechanical characteristics and chemical compositions which are displayed in tables 1 and 2.

This base metal was hyper-tempered with water from 1070°C and up. The content of ferrite, as measured in the welding by a magnetic method, produced a value of 1.4 per cent.

Description of the defect

The dimensions of piping elbows do not permit an inside welding. The assembling procedure then requires performance of a first TIG welding at the chamfer bottom and complete the fill-up by manual welding. The defects are located in the longitudinal welding of the two shell-halves forming the elbow. The defect which is here surveyed concerns a lack of penetration at the root of the TIG operation (fig. 1).

Fatigue tests

On bending test-pieces, three points (fig. 2) with an actual defect or including 2 mm machined notches (fig. 3) the following tests were carried out :

. survey of the initiation at 320°C in air and PWR environment with a ratio $R = \frac{Pmin}{Pmax} = 0.05$ (Pmin and Pmax are respectively the applied mini and maxi strength)
. measurement of crack growth rate after initiation
. at 320°C in air with $R = \frac{Pmin}{Pmax} = 0.3$ at frequencies of 1 Hz and 4 cycles/min.
. at 320°C and under 155 bars in PWR environment with a ratio R = 0.05 at the frequency of 4 cycles/hour and 4 cycles/min.

Results on test-pieces

Figure 4 shows that in air at 320°C and PWR environment, the numbers of cycles necessary to the defect's initiation, under the form of a fatigue crack, are in the same dimension order. One equally notes that the decrease from 60 to 4 cycles/min of the cycling frequency has no influence on the initiation (fig. 5). For a variation amplitude of given $\Delta\sigma_{nom}$ (nominal stress), the cycles number necessary to the N_a initiation diminishes when one passes from a machined defect characterized by a coefficient of theoretical stress concentration /2/K_t of 5.5 to a machined defect having a K_t of 8.3, then to the real defect (fig. 4).

On the other hand, in PWR environment, one notes a good concordance between the crack growth rate in the base metal and welded joint. In both cases, the crack growth rate increases when the frequency diminishes from 4 cycles/min to 4 cycles/hour (fig. 5 and 6). These last curves, in the following paragraph, will be useful to make the calculation of defect propagation by the linear fracture mechanics theory.

3. Prediction of defect propagation by the linear fracture mechanics theory

The piping elbows which are the subject matter of this survey are constituted of two shaped and welded shell-halves (fig. 1).

Our theoretical survey relies on the linear fracture mechanics to study the evolution of a defect that one assumes already at a state of fatigue crack (after initiation) during a cycling test in pressure. After hypotheses exposê of fracture mechanics taken into account, we shall consisely describe the analytical calculation and subsequently FISCOUD calculation program.

a) Utilized hypotheses of fracture mechanics

Under the effect of cyclic stresses, the Δ_a evaluation of a crack a in depth, located in a piping element W in thickness subject to these thermal cyclings and pressure cyclings, may be evaluated if one knows the crack growth rate $\frac{da}{dN}$ corresponding to sollicitations.

One knows that the crack growth rate is a function of the ΔK variation of the stress intensity factor : $\Delta K = K_{max} - K_{min}$ with $K = \alpha\sigma\sqrt{\pi a}$ in MPa$\sqrt{m}$

in which : α = coefficient of geometrical form (without dimension)

σ = nominal stress perpendicular to the crack (in MPa)

a = depth of the crack (in m.)

According to the experimental results explained in the preceding paragraph, it is possible to determine the $\frac{da}{dN}$ function corresponding to the crack growth rate in PWR environment by :

$$\frac{da}{dN} = \frac{(\Delta K)^A}{C} \quad (3)$$

in which : A and C = constants

N = number of cycles.

In the calculations that we shall make, the experimental curves will be taken into account and one always may take for A and C such values that the most conservative conditions may be taken into consideration. The table 3, on the other hand, gives the value of the α coefficient in function of $\frac{a}{W}$ for a longitudinal crack infinite in width and located in a cylinder. In the case of an elbow, we shall make the hypotheses that these values are applicable.

The tangential stress as a result of the pressure in a piping elbow is written as follows : $\sigma_T \left[\frac{Do - 0.8\ (W)}{2\ W}\right] \left[\frac{0.5\ (2\ R + r \sin \emptyset}{R + r \sin \emptyset}\right] \quad P$

Do = piping outside diameter

W = piping thickness

R = giration radius of elbow

r = mean radius $\frac{Do - W}{2}$

p = pressure

Ø = angle as defined on drawing of figure.

This stress is maximum for Ø = - 90°. The maximum variation of stress in then written as follows : $\Delta\sigma = \left[\frac{Do - 0.8\ W}{A\ W}\right] \left[\frac{0.5\ (2\ R - r)}{R - r}\right] \quad \Delta P$

In the case of undertaken cycling tests, we make pressure variation between 100 and 300 bars, i.e., ΔP = 200 bars. The principle of analytical calculation that we have applied to make this theory is the following : from experimental results determining the fissuration speed in function of ΔK, the law $\frac{da}{dN}$ becomes linear and one calculates, for each a-depth, its fissuration speed. After integration, one obtains the relation giving the growth of a crack a_o in initial depth, after an increase ΔN in cycles.

b) Analytical application to the case of 6 inch schedule 160 elbows

Do = 170 mm

W = 16 mm

R = 230

$r = \frac{170 - 16}{2} = 77$

$\Delta\sigma = 6.1486\ \Delta P$

and for ΔP = 200 bars, $\Delta\sigma$ = 123 MPa.

For this stress variation, let us calculate ΔK for different crack depth.

$\Delta K_{(\frac{a}{W} = 0.1)} = 244\sqrt{a}$

In taking in the formula (3) A = 4.57 and C = 168 corresponding to the experimental curves obtained on test pieces, one has :

$$\frac{da}{dN} = \left(\frac{244}{168}\right)^{4.47} a^{2.285} = 5.50 \quad a^{2.285}$$

Likewise, one may calculate the fissuration speeds relative to each value of $\frac{a}{W}$. The table 4 gives these values. One thus sees that the fissuration speed progressively increases as the fatigue phenomenon goes on.

In order to calculate the depth reached by a crack in function of the number of performed cycles, one may approximate the curve $\log_{10} \frac{da}{dN}$ in function of a through portions of straight lines.

For instance, between a_o = 1.6 m and a_o = 3.2 m, one will have :

$$\log_{10} \frac{da}{dN} = 0.534\ a - 6.502$$

After integration, one obtains : $e^{-1.23\ a} = e^{-1.23\ a_o} - 3.871\ .\ 10^{-7}\ \Delta N$ which is the expression that gives a-depth reached by a fatigue crack a_o in initial depth which is subjected to ΔN - cycle increase (between 100 and 300 bars).

The preceding analytical calculation of which we have given the outline was programmed and was the subject of the FISCOUD program. The hereunder table gives a scheme of this program :

inputs of FISCOUD program

geometrical data : outside diameter of elbow
elbow thickness
giration radius
crack position : intrados
extrados

experimental data : pressure variation during a cycle
cycling frequency

metallurgical data : coefficient A and C of law $\frac{da}{dN} = (\frac{\Delta K}{C})^A$

outputs of FISCOUD program

For initial depths $0.1 < a_0 < 5$ mm, one obtains :

- the fissuration speed and the number of cycles cumulated at each progression 0.1 mm in depth of the crack.

Fig. 7 gives an example of obtained prediction.

4. Description of the test facility and experimental results

The experimental check of these theoretical forecasts is performed in a test facility including a stove programmable in temperature, in which were arranged the capacities to be cycled, the latter being constituted of defective elbows. The cycling is carried out by means of a programmable oleohydraulical installation enabling to perform the desired cyclings. The figure 8 shows a scheme of cycles to which the capacities are subjected at 300°C.

At high pressure cycles, one superimposes low 30-bar cycles, which purpose is to simulate the influence of vibration in service. At every 5,000-cycle, the test facility is stopped and the evolution of the defects progression is analyzed by means of ultrasonic control of defect depth /9/.

During the cycling operation, it is also carried out a surveillance of the crack growth by means of acoustic emission. The latter is put to work only when the stress is high (and the crack open) so that to avoid the acoustic emission due to friction against each other of the crack's sides during the decrease in pressure.

The maximum depth of the natural defects that we have surveyed in this cycling test was 0.3 mm. The performed number of cycles is 20,000 high cycles. The results of ultrasonic controls during shut downs, as those obtained through acoustic surveillance seemed to predict no propagation of defects. After destructive analysis, this is in effect what we could ascertain. One will equally be able to verify that the theoretical analysis enables to predict no propagation of these defects.

5. Conclusion

In stainless steel welded elbows used for auxiliary piping of PWR reactors, lack of penetration defect does not propagate in PWR environment if the defect depth is small. The theory made as well as the experimental results obtained confirms that under conditions simulating those which could happened during the life of the Power Plant small defect do not need to be repaired.

REFERENCES

/1/ C. AMZALLAG, P. RABBE, "Etude de l'initiation et de la propagation des fissures de fatigue dans l'acier inoxydable ICL 167 CN", Rapport D.R.U. n° 1121 - Creusot-Loire.

/2/ R.E. PETERSON, "Stress Concentration Design Factors", John Witey and Sons Inc. New-York.

/3/ P.C. PARIS - G.G. SIH, "Stress Analysis of Cracks" Fracture Toughness Testing and its application, ASTM STP 381, 1965.

/4/ W.K. WILSON, S.E. GABRIELSE, "Elasticity Analisis of Blunt Notched Compact Tension Specimens", Westinghouse Research Laboratories.

/5/ C. AMZALLAG, P. RABBE, "Essais complémentaires de fatigue corrosion sur l'acier inoxydable austénitique ICL 167 CN", Rapport D.R.U. n° 1212 - Creusot-Loire.

/6/ C. AMZALLAG, P. RABBE, J.J. DOYEN, "Etude de l'amorçage et de la propagation des fissures de fatigue à partir de défauts sur coudes de tuyauteries auxiliaires", Rapport Framatome n° 1244, Septembre 1976.

/7/ J. MARINI, J.J. DOYEN, D. ROMY, "Etude théorique de la propagation de fissures de fatigue dans des coudes", Rapport Framatome DT/D - 76.465, Avril 1976.

/8/ J. MARINI, J.J. DOYEN, A. LEDOSSEUR, "Etude des défauts trouvés dans les soudures des tuyauteries auxiliaires - Résultats obtenus après la première campagne de cyclage", Rapport Framatome DT/D - 76.28, 1976.

/9/ J. MARINI, "Surveillance of internal cracks growth in steel", VIIIème Conférence Mondiale sur les Essais Non Destructifs, Cannes, Septembre 1976.

/10/ J. MARINI, M. ROULE, "Contrôle par ultrasons d'assemblage d'angle en acier austénitique" VIème Conférence Internationale sur les Essais Non Destructifs, Hanovre, 1970.

/11/ L.A. JAMES, "Estimation of crack extension in a piping elbow using fracture mechanics techniques", Journal of Pressure Vessel Technology, Novembre 1974, p. 273.

/12/ L.A. JAMES, "Fatigue crack growth in type 304 stainless steel weldments at elevated temperatures", Journal of Testing and Evaluation, Vol. 1, n° 1 (1973) p. 52-57

/13/ MC. EVILY A.J., C.H. WELLS, "On the applicability of fracture mechanics to elevated temperature applications", Philadelphia, Septembre 1973.

/14/ J. HOLT, IG. PALMER, "The use of acoustic emission for monitoring the integrity of steel pressure vessels", Conf. on periodic inspection of pressurized components, Londres, June 1974.

/15/ J. EISENBLÄTTER, W. HEIDE, P. JAX, H. HOST, R.V. KLOT, "Acoustic emission as an inspection method for nuclear reactor vessels", Conf. on periodic inspection of pressurized components, Londres, June 1974.

/16/ M. MIRABILE, "Application de l'émission acoustique à la rupture des aciers", Mémoires Scientifiques de la revue Métallurgie n° 9, 1974, p. 495-507.

	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	N_2	Co
base material	0.035	1.61	0.65	0.010	0.025	11.45	17.6	2.5	0.112	0.082	0.125
weld	0.029	1.03	0.74	0.008	0.024	11.28	18.72	2.16	0.06	0.063	0.05

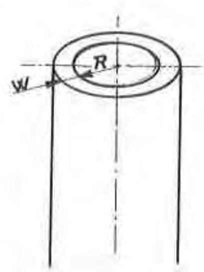
Table 1 : Chemical composition

	R 0.02 N/mm^2		Rm N/mm^2		A %		Z %		KCU j/mm^2
	20°C	320°C	20°C	320°C	20°C	320°C	20°C	320°C	20°C
base material	280	146	580	455	70	46	77	68	210
weld	289 308	185 199	600 531	396 409	50 49	27 28	53 66	42 51	66-86-80-92

Table 2 : Mechanical characteristics

a/W	Ri/W = 2	Ri/W = 5
0.1	1.12	1.13
0.2	1.22	1.3
0.3	1.34	1.7
0.5	1.7	2.7

Table 3



a	1.6 m	3.2 m	4.8 m	8 m
$\frac{da}{dN}$	$3.30\ 10^{-6}$	$1.6\ 10^{-5}$	$6.3\ 10^{-5}$	$6.00\ 10^{-4}$

Table 4

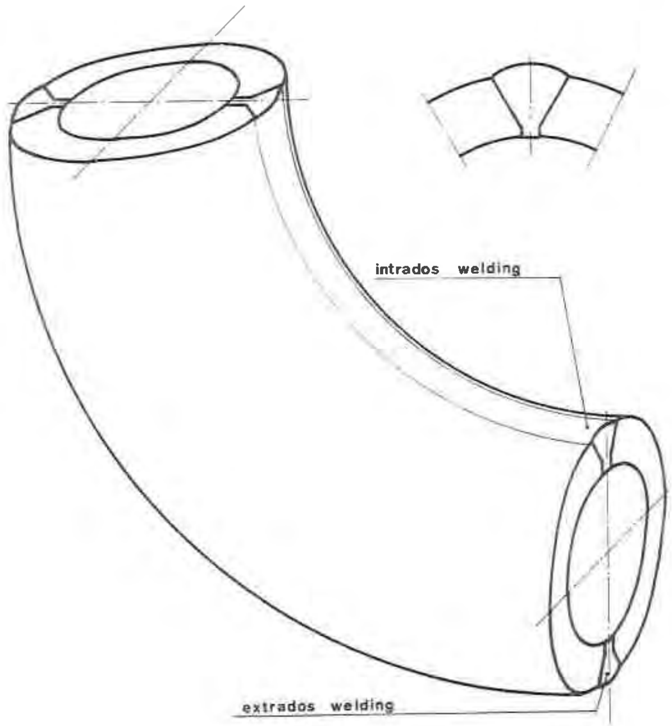


Fig. 1 ELBOW OF AUXILIARY PIPINGS AND MACROGRAPHY OF THE WELDED JOINT

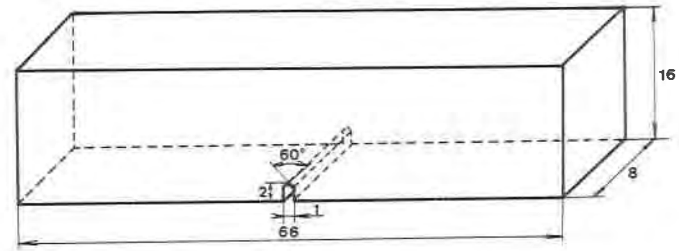


Fig. 2 THREE POINTS FLEXION SPECIMEN

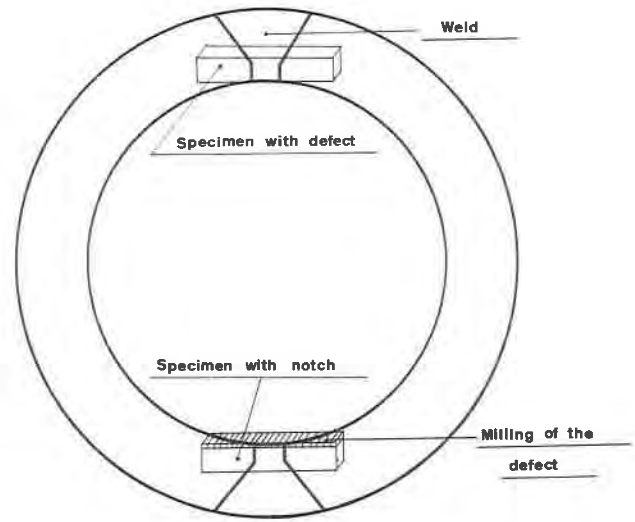


Fig. 3 CUTTING OF SPECIMENS

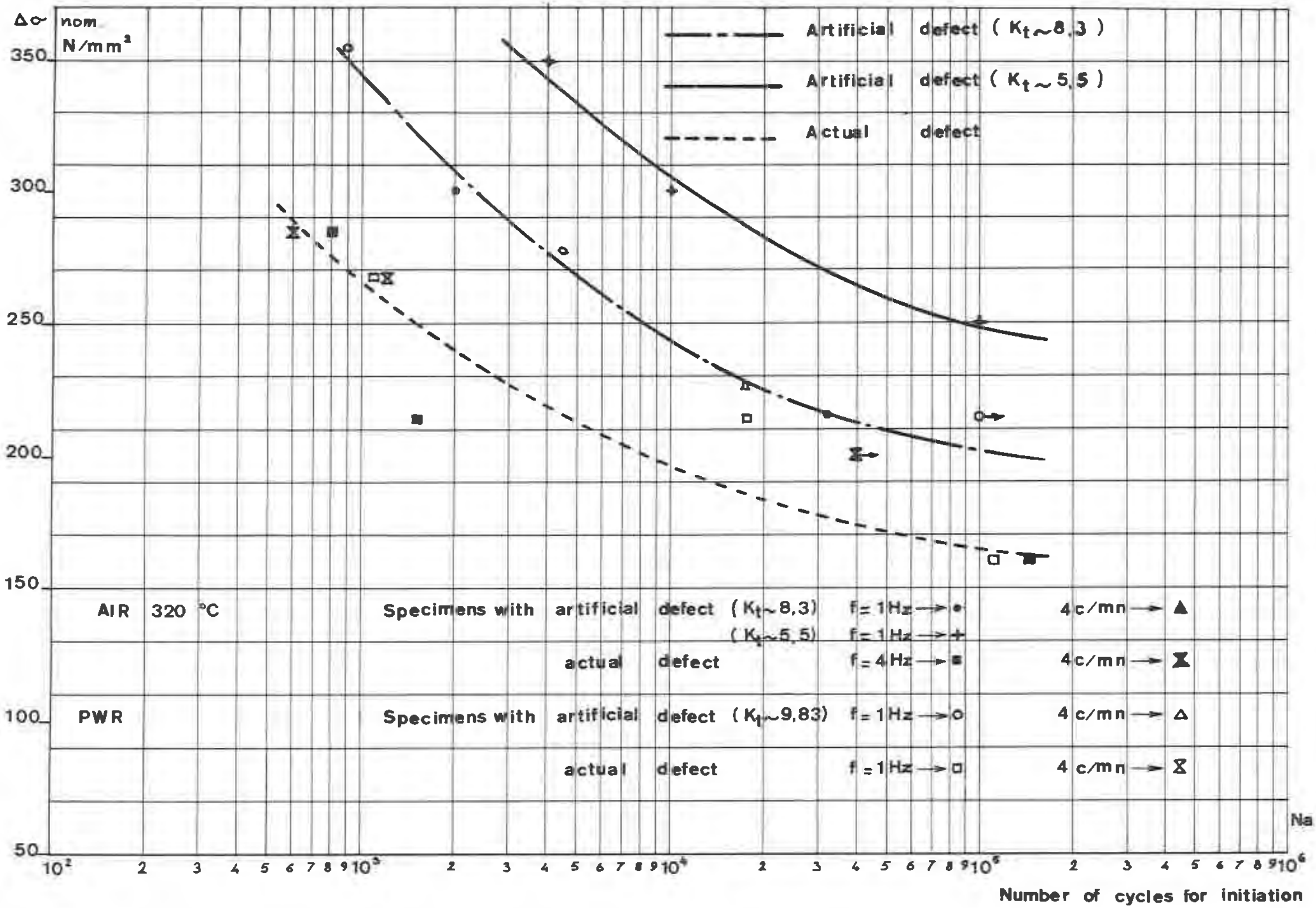


Fig.4 VARIATION OF NOMINAL STRESS VERSUS INITIATION CYCLE NUMBER

F 1/3

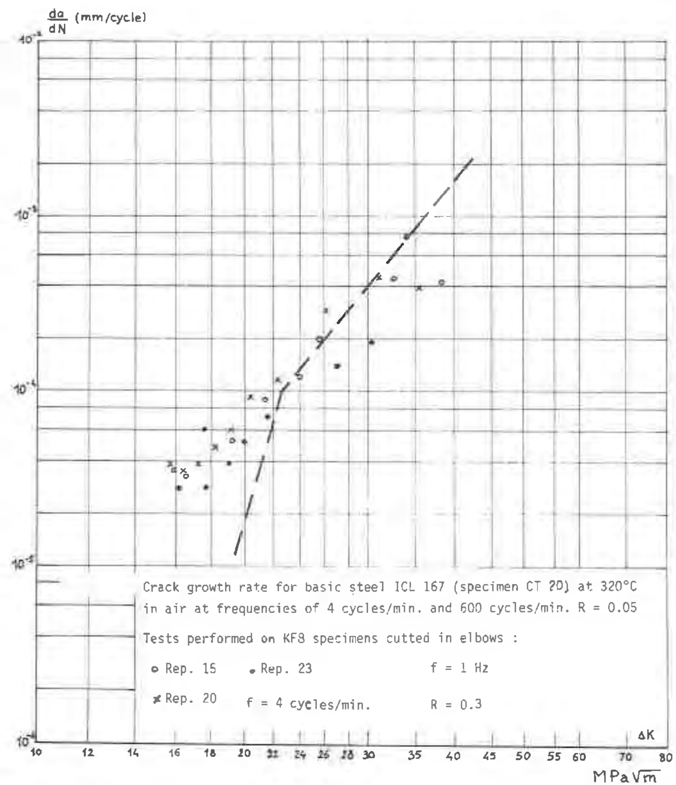


FIG. 5 : RESULTS OF TESTS PERFORMED IN AIR AT 320°C

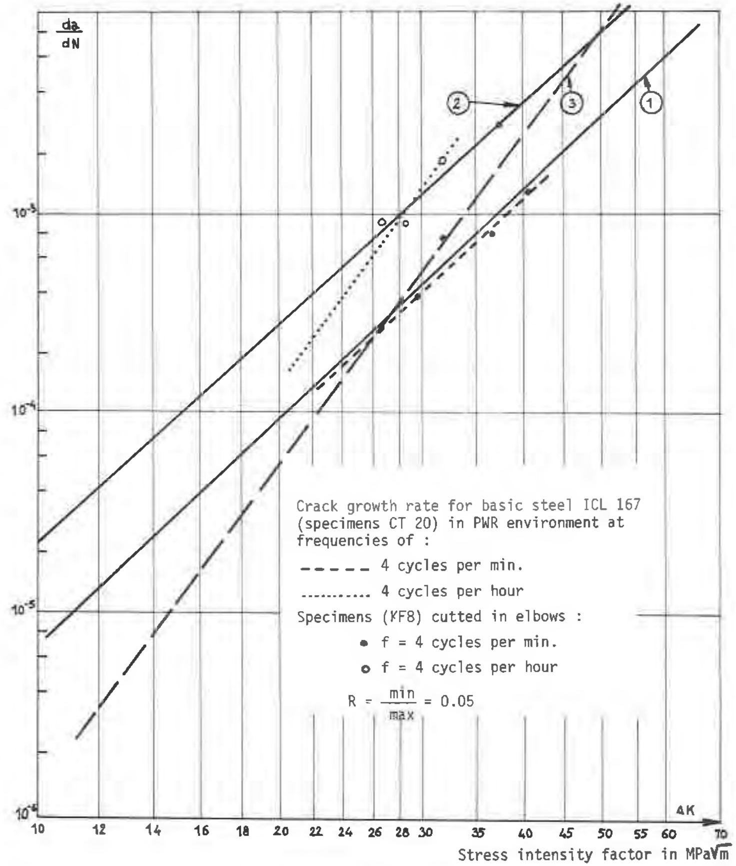


FIG. 6 : CRACK GROWTH RATE IN WELDED JOINT.
TESTS PERFORMED IN PWR ENVIRONMENT

$$\frac{da}{dN} = \left(\frac{\Delta K}{C}\right)^A$$

line 1 : A = 3.81 ; B = 228.4
line 2 : A = 3.64 ; B = 188.2
line 3 : A = 5.42 ; B = 122.3

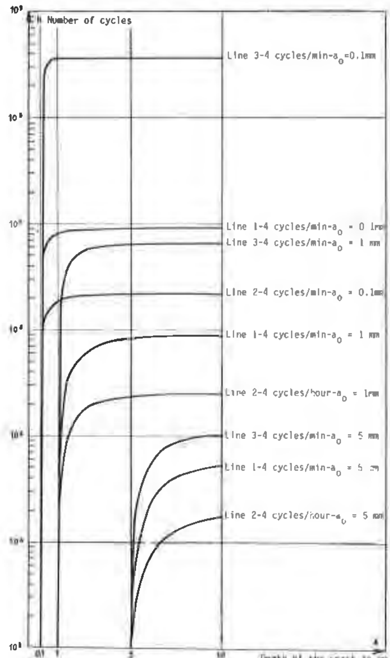
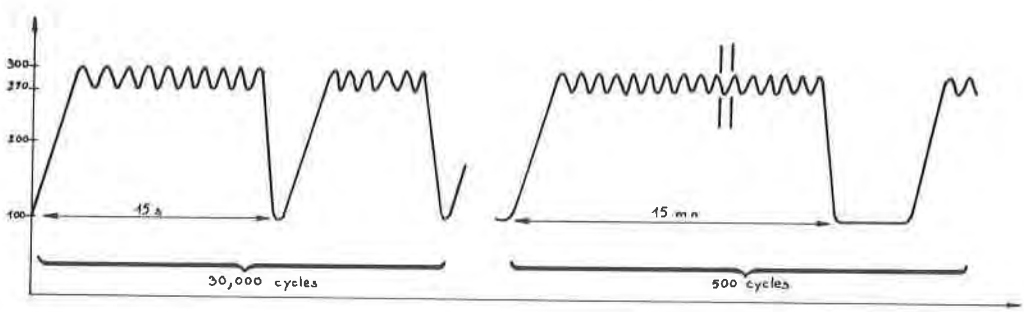


FIG. 7 - CRACK DEPTH VERSUS NUMBER OF CYCLES
6 inches piping elbow (Ø ext. 170 mm) - Thickness : 20 mm



15 s. cycle
- Increasing pressure from 100 to 300 within 1 second
- Level pressure varying between 270 and 300 bars for 13 seconds
- Decreasing pressure from 300 to 100 bars within 1 second

15 min. cycle
- Increasing pressure from 100 to 300 bars within 10 seconds
- Level pressure varying between 270 and 300 bars for 14 min.
- Decreasing pressure from 300 to 100 bars within 10 seconds
- Level pressure at 100 bars : 40 seconds.

FIG. 8 : DIAGRAM OF CYCLES (in the first 30,000 cycles period
pause every 5,000 cycles).
- Initial program -