CRACK GROWTH RATE OF PWR PIPING

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Safety analysis in pressurized water reactors must take into account the growth of possible defects in the reactor coolant components, particularly in the reactor coolant piping.

The Aquitaine 1 Program, carried out jointly by FRAMATOME and the CEA is intended to improve knowledge about cracking mechanisms in AISI 316 L austenitic stainless steel under conditions similar to those of the PWR environment (irradiation excluded).

Experiments of fatigue crack growth are performed on piping elements, scale 1/4 of primary pipings, by means of internal hydraulic cyclic pressure.

Interpretation of results requires a knowledge of the stress intensity factor K_I at the front of the crack.

Results of a serie of calculations of K_I, obtained by different methods for defects of finite and infinite length (three dimensional calculations) are given in the paper. The following have been used : calculations by finite elements, calculations by weight functions.

Notches are machined on the test pipes, which are subjected to internal hydraulic pressure cycles, under cold conditions, to initiate a crack at the tip of the notch (frequency = 4 cycles/minute, ΔP = 160 bars). They are then cycled at a frequency of 4 cycles/hour on one water demineralised loop at a temperature of 280°C, the pressure varying at each cycle between approximately 160 bars and 3 bars.

After each test, a specimen containing the defect is taken from the pipe for micrographic analysis. The shape of the crack can be determined and the crack growth rate is measured through the thickness of the pipe. The results of the three tests are reported in this paper.

For the first test the length of the longitudinal external defect is assumed infinite. The number of cycles carried out is 5880 cycles.

Two defects are machined in the tube for the second test. The length of the external longitudinal defect is L = 340mm, L = 170mm for the internal longitudinal defect. The number of cycles carried out is N = 440. The tests are performed under hot conditions (T = 280°C).

For the third test two defects are analysed under cold and hot conditions, one being an internal longitudinal notch (L = 50mm) and the other an external longitudinal notch (L = 50mm). The number of cycles carried out for the external defect is 7000 when hot and 90000 when cold. The number of cycles for the internal defect is 1650 when hot and 68000 when cold. In each case, initial depth is 0,5 times the pipe thickness.

In order to interpret the results, the data da/dN are plotted on an diagram versus ΔK. Comparisons are made between these results and the curves from laboratory tests.

1. Introduction

The purpose of the Aquitaine 1 Program is to analyse the fatigue crack growth rate in PWR primary piping. It has been undertaken in order to verify the adequacy of the fatigue crack growth predictions made by Lincar Elastic Fracture Mechanics concepts with data,obtained on laboratory specimens, which relate the crack growth rate to the variation of the stress intensity factor.

The ultimate aim of this work is to define a more rational criterion for the selection of dimensions and locations of the breaches to be taken in account for the primary loop LOCA analysis.

This paper presents the first tests performed on longitudinal external and internal cracks.

2. Experimental procedure

2.1. Aquitaine Loop

A schematic view of the AQUITAINE Loop is presented in Figure 1. The working conditions of the PWR reactors are reproduced by pressurized water at about 300°C and 160 bars. These characteristics are obtained from the 108 KW boiler and the 27 KW pressuriser on the main circuit. The opening of two electrovalves makes it possible to supply the test section with hot water pressure. After maintaining the test section under pressure for a few minutes, it is isolated from the main circuit by shutdown of the electrovalves and is depressurized by communication with a condenser. The duration of a cycle is about 15 minutes.

2.2. Material and test sections

Before testing, chemical and mechanical characteristics have been studied. The fatigue crack propagation curves $da/dN = f(\Delta K)$ have been plotted in various environment, frequency and temperature combinations (see Ref [6]).

Experimental pipes are made of 316L stainless steel and are designed at 1/4 scale of actual primary piping (i.e.: ID = 185,5mm, OD = 219,5mm and L = 1500mm). (see Fig. 2)

These dimensions concern two pipes which have been tested under hot conditions of AQUITAINE Loop. In a preliminary approach, a pipe with a shorter length(i.e.650mm) has been tested at room temperature. Internal and external longitudinal surface notches with a depth of 8.5mm have been machined in the test pipes. The experimental lengths are $2c = \infty$, 340, 170 and 50mm, as specified in Table 1.

2.3. Crack growth measurements

As was the case in Ref [1] , an attempt has been made to measure crack propagation by ultrasonic waves. This method ultimately involves some experimental difficulties and proves to be unreliable. Therefore, the knowledge about crack growth has been determined after tests, by micrographic examination (inter-stria measurements). From these measurements it is possible to determine the crack growth rate da/dN versus crack depth.

2.4. Test Program

Three pipes were tested. Each test is described in detail in Chapter 4. In every case, before testing in hot conditions, cold pressure cycles are performed on the tubes to initiate crack propagation. Later, hot tests are performed with the exception of the test on pipe 1, which was carried out until crack leakage occured in cold conditions.

3. Calculation of Stress Intensity Factor

The calculation part of this program is conducted with a view to interpreting the crack growth rate da/dN in function of the stress intensity factor range ΔK in pipes.

Three methods of calculation were used :

1) Finite Elements direct calculations
   - Elastic and elasto-plastic calculations (program PASTEL) [2]
   - Tridimensional elastic calculation (program BILBO) [3]
2) Use of Weight Functions determined by finite elements [4]
3) Utilization of abacuses proposed by HELIOT [5]

This latter method has the advantage of covering all the crack geometries tested. However, the values given by this method are only approximate.

Calculations of weight functions were made for a variety of crack depths in limited number of cases i.e. infinite longitudinal crack length and semi-elliptical cracks where $a/c = 1/3$. With finite element calculations, the actual shape of crack is taken in account but the results available up to now do not cover all crack geometries tested on this experimental program. The most convenient way to present results is to give the values of F equal to :

$$F = \frac{\Delta K}{\Delta\sigma\sqrt{\pi a}}$$

with $\Delta\sigma = \Delta\sigma_H$ (for an external notch)

$\Delta\sigma = \Delta\sigma_H + \Delta\sigma_P$ (for an internal notch)

$\Delta\sigma_H$ is the hoop stress range value due to internal pressure. When internal crack is involved, supplementary stress $\Delta\sigma_P$ due to the effect of pressure on the crack areas is added to $\Delta\sigma_H$.

A good approximation for the hoop stress is

$$\sigma_H = \frac{P \times D_m}{2t}$$

with : D_m = mean diameter of pipe

t = pipe thickness

P = nominal pressure

The stress applied on crack surfaces is $\sigma_P = P$.

Different values of F are presented for infinite and finite crack lengths in Tables 2 and 3. From Table 2 it appears that the factor F is larger in the case of an infinite crack length in a plane plate than in a pipe. Results of PASTEL code and Weight Functions are similar. The results also largely correspond to describe the $2c/t = 3$ and $a/t = 0.50$ crack. Moreover, these calculations were made by Weight Functions, for a pipe where the ratio diameter to the thickness is equal to 20, where as this ratio is equal to 11 in the case of actual pipes.

The only available results for $2c = 170$ and 340mm crack length (with $2c/t = 10$ and 20) are the approximations after HELIOT, which assume cracks in an infinite plane plate.

4. Test results

4.1. Pipe 1 :

The entire first test was performed under cold conditions (see Table 4), the pressure varying between 165 and 3 bars at a frequency of 4 cycles/minute . The external longitudinal crack machined all along the pipe (650mm) can be assumed to be infinite in stress intensity factor calculations. The pipe was tested until a leak occured. Then micrography was used for measuring da/dN (inter-stria measurements) and counting the number of striae.

Figure 3 shows a plot of crack depth versus the number of cycles at two different levels.

It can be seen that in spite of a theoretically constant stress intensity factor all along the crack tip, the crack growth is quite different at the two observed levels. The crack growth rate da/dN versus crack depth is plotted on the diagram of Figure 4.

4.2. Pipe 2 :

Two notches were machined on this pipe. The length of the internal notch was 2c = 170mm and 2c = 340mm for the external one. At first, 2,000 cold cycles with ΔP = 157 bars were performed before the 440 cycles in hot conditions with ΔP = 157 bars. An error led to the tester to believe that a leak had occured on external crack after these 440 hot cycles. The test was stopped and micrography revealed a 0,7mm crack propagation only and a crack growth rate of about 0,95μm/cycle.

4.3. Pipe 4 :

Pipe 4, like the previous one, was machined with two internal and external notches, both 50mm long . In order to initiate the crack, six thousand cycles were first performed at room temperature with a pressure fluctuation of 197 bars. Then hot cycles were performed. As no propagation was observed at the tip of the external notch after 1650 cycles and after an approximative ΔK calculation was made, it was decided to continue some cycles on cold conditions. This test was continued until a leak occurs behind the internal notch which was not inspected. The through crack surfaces were examined by microfractography and the results can be seen in Figures 5 and 6. The test was continued as described in Table 4 with the purpose of obtaining more crack propagation at external notch. This objective was not achieved after 28,000 cycles. The test was stopped and micrography showed a crack propagation over 1,7mm only. The counting of striae was not finished at the time this paper was written. However, some indications about crack depth versus N cycles are given in Figure 7.

It should be said at the outset that such tests are not easy to perform especially when hot cyclings are involded. Many operating defects occured on the loop in view of the stringent conditions to which the valves are subjected.

5. Discussion

The lack of precision of the crack ultrasonic measurements did not make it possible to gain a good knowledge of crack depth during tests. The only satisfactory way of doing so was to use the "post-mortem" micrographic examinations.

Since the main aim of this study is to verify the suitability LEFM criterion to predict crack propagation in pipes, the analysis of the results consists of comparisons between (da/dN, ΔK) curves from CT specimens [6] , [7] , [8] and [9] and those obtained with these tests. Such comparisons are made in Figures 8 and 9.

It can be seen that the "CT curves" can be used as a reference for estimating pipe behavior. ΔK was calculated from the F values given in Table 2 and 3, and from the crack depth.

It can be seen that the uncertainties on the F values are of an order of magnitude within the scatter of the crack growth rate obtained during the laboratory tests.

Figure 8 illustrates close correspondence between the results of the test and the laboratory reference curves. CEA and obviously Bamford's curves are upper bound for these results of tests in cold conditions.

In the case of a smaller defect, as in Pipe 4, the crack growth rate measured in hot conditions is slightly higher than the reference results. This may reflect an actual behavior.

Elsewhere, further tests are necessary to corroborate these results.

6. Conclusion

A close correspondence has been obtained between the crack growth rate at 20°C measured on the test sections by striation counting and those predicted by LEFM calculations from the crack growth rate measured on laboratory specimens. However, at 300°C the results from pipes are slightly higher than those predicted from the laboratory specimens. Further measurements are needed to clarify this point.

The program will be continued by carrying out tests which combine pressure and bending loadings on pipes with circumferential cracks.

References

[1] J.J. DOYEN, M. LEBEY and M. VRILLON
"Crack Growth Rate Analysis in PWR Reactor Piping".

[2] GOLDSTEIN S. Systeme CEA SEMT - Programme PASTEL - Notice d'utilisation - Rapport CEA n° 1932.

[3] CHARRAS T. Systeme CEA SEMT - Programme BILBO - Notice d'utilisation - Rapport CEA n° 1936.

[4] LABBENS R.,PELLISSIER-TANON A. and HELIOT J. "Practical Method for Calculating Stress - Intensity Factors through Weight Functions".
Mechanics of Crack growth ASTM STP 590 pp. 368-384.

[5] HELIOT J. : Formules de calcul de facteurs d'intensité de contrainte pour des fissures semi-elliptiques débouchant dans une paroi.
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[6] RABBE P. AMZALLAG C. RAOUL J.P. "Influence de la température et du milieu primaire de réacteur à eau légère sur la tenue en fatigue d'aciers du type Z3CND17-12", Rapport Creusot Loire n° 1128, Août 1974, Contrat FRAMATOME n° EAD/73.2881.

[7] YAHIAOUI B. et GAUTHIER J.P. "Etude de la propagation de fissures par fatigue dans les matériaux de tuyauteries primaires de PWR - Programme AQUITAINE Octobre 1974, Rapport CEA - D. Tech. PMA (74) 610.

[8] BAMFORD W.H. "Fatigue crack growth of stainless steel reactor coolant piping in a pressurized water reactor environment" WCAP-8953, February 1977.

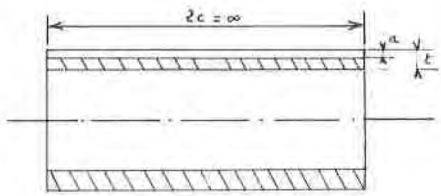
[9] BERNARD J.L. , HOUSSIN B., SLAMA G. " Validation des caractéristiques de calcul des matériaux constituant le circuit primaire des réacteurs PWR" Int. Symp. on Application of Reliability technology to nuclear power plants (Vienna 10-13 Octobre 77).

TABLE I

Pipe n°	Type of crack	CRACK SIZES				F		
		a (mm)	2C (mm)	a/t	2C/t	Finite elements	Weight functions	HELIOT [5]
1	External	8.5	∞	0.5	∞	1.6	2.18	
2	External	8.5	340	0.5	20	2.1	-	1,79
	Internal	8.5	170	0.5	10	2.05	-	1,59
4	External	8.5	50	0.5	3	-	-	1,14
	Internal	8.5	50	0.5	3	1.22	1,17	1,14

Type and size of cracks experimented, and corresponding values of F.

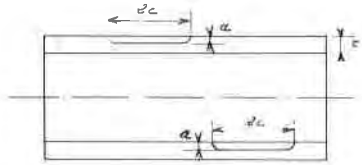
TABLE II : VALUES OF $F = \dfrac{\Delta K_I}{\Delta\sigma\sqrt{\pi a}}$ FOR INFINITE CRACK LENGTH



a/t	Analytic (TADA)	FINITE ELEMENTS PASTEL	FINITE ELEMENTS BILBO	WEIGHT FUNCTIONS
0.25	1.51		1.6	1.43
0.50	2.83		2.85	2,22
0.56		2.09		2,51
0.60				2.80
0.70				3,26
0.75	8.48		9	3.64
0.80				3.97
0.90				4.58

In dark boxes, F calculations are made by assimilation of pipe to a plane plate subjected to a uniform tensile loading.

TABLE III : VALUES OF $F = \frac{\Delta K_I}{\Delta \sqrt{\pi a}}$ FOR FINITE CRACK LENGTH



2c/t	a/t	FINITE ELEMENTS (BILBO)	WEIGHT FUNCTIONS	AFTER HELIOT [5]
3	0.25	-	-	1.22
	0.50	1.22*	1.17*	1.14
	0.80	-	-	1.08
5	0.50	1.52		1.27
	0.75	1.10		1.31
10	0.50			1.59
	0.75			1.94
20	0.50			1.79
	0.75			3.16

In dark boxes, F calculations are made by assimilation of pipe to a plane plate subjected to a uniform tensile loading

* Case of an internal longitudinal crack

TABLE IV

<table>
<tr><th>PIPE N°</th><th>NOTCH</th><th colspan="6">CONDITIONS OF TESTING
START OF TESTS → END OF TESTS</th><th>OBSERVATIONS</th></tr>
<tr><td>1</td><td>INFINITE EXTERNAL</td><td colspan="6">5880 Cycles at T = 20°C
ΔP = 162 bars</td><td>LEAK AT CRACK</td></tr>
<tr><td>2</td><td>INTERNAL 2c = 170
EXTERNAL 2c = 340</td><td colspan="3">2000 cycles
at T = 20°C
ΔP = 157 bars</td><td colspan="3">440 cycles
at T = 285°C
ΔP = 157 bars</td><td>NO LEAK</td></tr>
<tr><td rowspan="2">4</td><td>INTERNAL 2c = 50</td><td rowspan="2">6000 cycles
at T = 20°C
ΔP = 197 bars</td><td rowspan="2">1650 cycles
at T = 285°C
ΔP = 157 bars</td><td rowspan="2">62,500 cycles
at T = 20°C
ΔP = 197 bars</td><td colspan="3">← End of internal crack testing</td><td>LEAK AT INTERNAL CRACK</td></tr>
<tr><td>EXTERNAL 2c = 50</td><td>5000 Cycles
T = 20°C
ΔP = 197 bars</td><td>[illegible]
[illegible]
= 157 bars</td><td>16,670 cycles
T = 20°C
ΔP = 197 bars</td><td>NO LEAK</td></tr>
</table>

DESCRIPTION OF TESTS

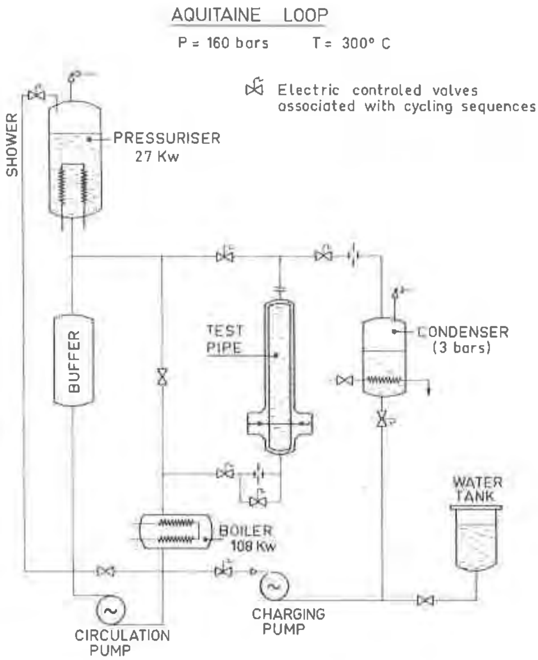


Figure 1 : AQUITAINE Loop

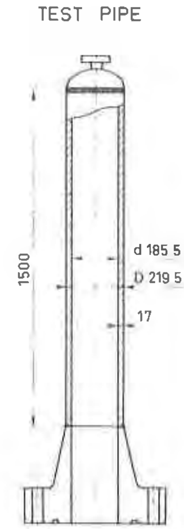


Figure 2 : Test Pipe

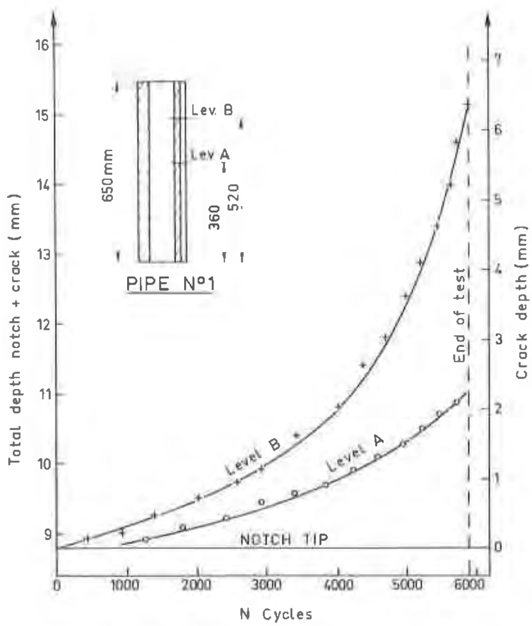


Figure 3 : Crack Propagatio n

(Pipe 1)

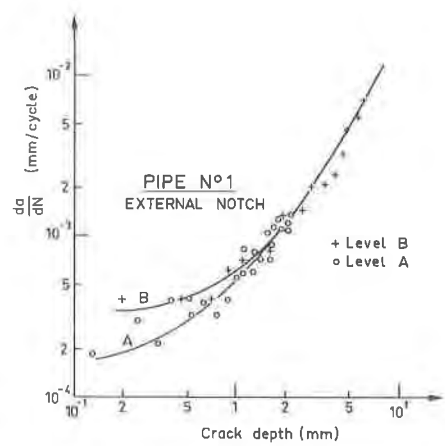


Figure 4 : Crack Growth Rate

(Pipe 1)

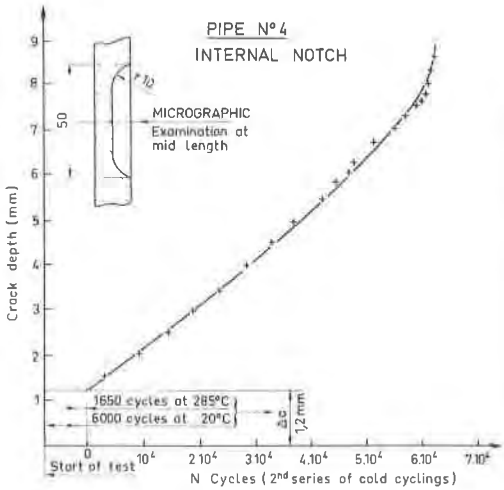


Figure 5 : Crack Propagation
(Pipe 4)

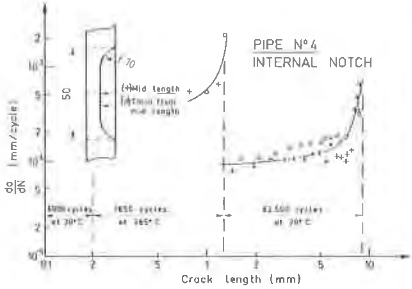


Figure 6 : Crack Growth Rate
(Pipe 4)

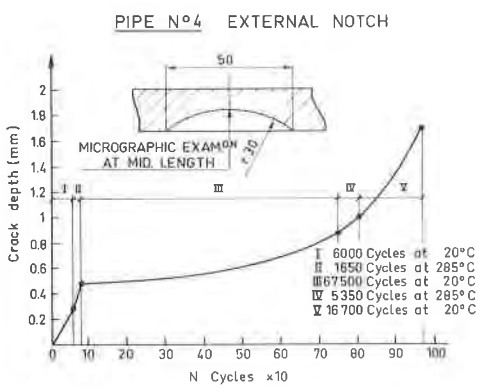


Figure 7 : Crack Propagation
(Pipe 4)

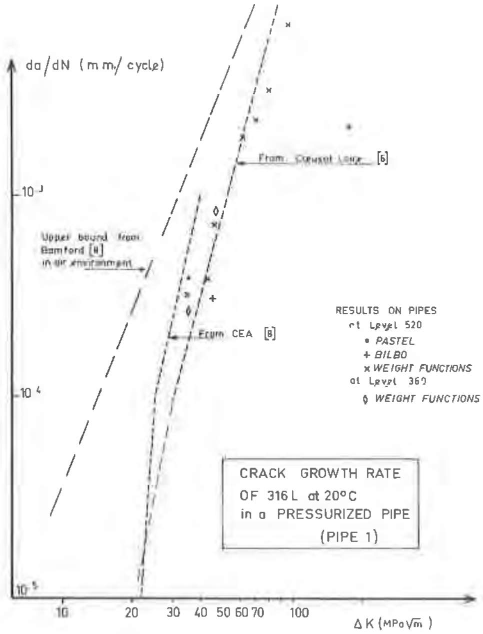


Figure 8 : Crack Growth Rate
at 20 °C

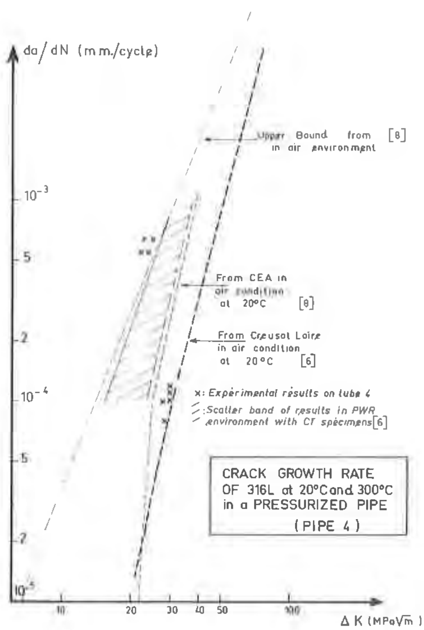


Figure 9 : Crack Growth Rate
at 20 and 300 °C