CRACK GROWTH RATE ANALYSIS IN PWR REACTOR PIPING

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SUMMARY

The survey of crack growth on PWR reactor primary circuit pipings is the subject matter of the Aquitaine-1 Program. — This program includes an experimental part on piping elements made of stainless steel AISI 316 L, scale 1/4 of primary pipings. These pipings are subject to cyclic variations of cold pressure, then to 290 °C in water, utilizing a specific test loop. At 290 °C the pressure variations are between the atmosphere and 160 bars at 4 cycles/hr. With the above conditions the experimental part constitutes a realistic approach of phenomenona pertaining to defects propagation in actual operating conditions. A first phase consisted of characterizing the material. The speed of cracking was determined on test-piece CT in the various environment conditions: air 20 °C, air 320 °C, water 320 °C. Furthermore, an evaluation of the influence of the cycling frequency on that speed had been made.

Three measurement methods for the crack depths are simultaneously utilized: a method by electrical potential, ultrasonic technics (Rayleigh waves, transversal waves). The estimate of the stress intensification factor was performed through various ways. Calculations related to finite elements in elastoplasticity with the Pastel Code were carried out for a number of infinite length internal and external crackings.

Moreover, an elastic calculation in tridimensional geometry with the Bilbo Program was made for a finite length crack. A comparison was made with the obtained results with the weight functions. Furthermore, for finite cracks, there was reliance upon formulae found in published literature (Levy & Rice, Shah & Kobayashi, Smith & Surenseen). The first results were obtained on axial cracks with infinite length and 20 to 3 ratio for notch length on wall thickness. All the notches had an initial depth equal to half of the thickness. At test completion cracks aspects are examined through microfractography.

The comparison is performed between the experimental results on the one hand and the forecastings of growth speed resulting from the characterization of material and calculations of fracture mechanics on the other hand.

The first test specimen had a long axial crack and was cycled in cold water at 4 cycles/min. Using the weight functions the results of the first test have been transformed in da/dn function of ΔK. The data obtained by this method are in good agreement with the curve obtained on *CT* specimen. Two other specimens with axial crack respectively of 340 mm and 50 mm are under cycling and we will have the results at the end of the year. At the end of June 1977, we will have three other specimens tested. These first results are very encouraging showing that it is possible to predict with *CT* specimens the crack growth in pipe.

1 - OBJECTIVE

The survey of crack growth rate in the pipings at scale 1/4 of the PWR primary pipings is the subject of AQUITAINE I program. That survey has been undertaken in the aim to refine the safety analysis of pressurized water reactors. In effect, the consequences of a reference accident on the behavior of reactors must be evaluated. That characteristically and highly improbable accident is, by definition, the complete breaking of a primary system piping. The effects on the vessel, fuel and primary supporting equipment devices thus depend on the retained location for the breaking. The safety survey considers several locations that is important to select with regard to the damage sustained by the pipings and resulting from cyclic sollicitations exerted during normal working conditions. AQUITAINE I will enable to select in a more rational manner the location and breaking type to be envisaged.

2 - CHARACTERIZATION OF MATERIAL

This steel has the characteristics of the metal utilized for the primary pipings which is the ICL 167 CN from CREUSOT LOIRE (AISI 316). The characterization of material on the test pieces and cracking speed determination have been carried out on same metal in three different laboratories :

1 - Departement of Metallurgy and Material Science University of Cambridge
GREAT BRITAIN

2 - Services de Recherche Metallurgique Appliquée du C.E.A. à Saclay - FRANCE

3 - Laboratory of CREUSOT LOIRE at Unieux - FRANCE

This exposé only considers the results concerning our work in those three surveys.

The labs 1. and 2. have worked on the same piece of primary piping, lab 3. has utilized a piece of another primary piping.

Chemical and mechanical characteristics

	C	Mn	Si	S	P	Ni	Cr	Mo
AQUITAINE	0.040	1.70	0.66	0.011	0.09	13.5	17.4	2.67
LAB 1 & 2	0.032	1.62	0.48	0.014	0.025	11.6	18.1	2.75
LAB 3	0.035	1.61	0.65	0.010	0.025	11.45	17.6	2.5

Chemical and mechanical characteristics

	Re 0.2 20°C	(N/mm2) 343°C	Rm 20° C	(N/mm2) 343° C	A % 20°C	CV J/cm2 20° C
AQUITAINE	220	160				
LABO 1 & 2	290 224		566 562		53 57	217 234
LABO 3	280	160	580	460	70	210

Number of cycles at initiation

Only the lab 3 performed the survey the results of which are those expressed by the fig. 1. The law is analogous to the one of Jack and Price $\frac{\Delta K}{\sqrt{r}}$ (variation of stress intensity factor on square root of radius with notch) in function of cycle number at initiation. The radius with notch surveyed were r = 0.1 ; r = 0.5 ; r = 1 mm. Since the points for r = 0.1 are not correctly located with regard to the curve line, it was supposed that the critical radius similar as for Jack and Price was 0.25 mm and one re-drew the points for r = 0.1 in taking for r = $\frac{\Delta K}{\sqrt{r}}$; r = 0.25 mm.

That curve line is the one which enables us to forecast the cycle number in order to initiate the cracks on the AQUITAINE tubes (fig. 2)

Speed of crack

The different results are well expressed by the Paris law where :

$$\frac{da}{dn} = 10^{-4} \left(\frac{\Delta K}{\Delta Ko}\right) m$$

This results are summarized in the hereafter table with :

$\frac{da}{dn}$ = crack growth rate in mm/cycle

ΔKo = intensity factor of cyclic stress corresponding to a speed of crack of 10^{-4} mm/cycle in MPa $\sqrt{m}$

R = ratio of minimum stress with regard to applied maximum stress.

LAB.	TEST PIECES	MEDIUM	CHANGES R	SCOPE OF MEASUREMENT OF ΔK MPa$\sqrt{m}$	ΔKo	m
3	2 20 Hz	air 20°C	0	20 - 40	31.3	4.4
1	4 1 to 100 Hz	"	0.3	12 - 40	25 - 29	4
2	1 35 Hz	"	0.09 0.1-0.2	30 - 40 25 - 40	26 - 27 25	5 5
3	2 10 Hz	air 320°C	0	20 - 40	22.6	4.9
3	3 4 cpm	PWR 320°C	0	12 - 40	17.5	2.4
	4 cpH	"	0	12 - 40	11.9	2.3

Type of test pieces

1 CT	thickness	25 mm
2 "	"	20 mm
3 "	"	15 mm
4 "	"	10 mm

The conclusions of these surveys pertaining to the speed of cracks are the following :

. The results obtained in air at 20° C by the three labs for the primary piping's steel are remarkably coherent (fig. 3)

$\Delta Ko = 28 \pm 3$ MPa $\sqrt{m}$

$m = 4.6 \pm 0.4$

. At 20°C in the air, the frequency does not seem to have any influence on crack growth rate,

. At 20°C the R ratio would not seem to have any influence on the m coefficient,

. For the low values of ΔK, the speed of cracking increases when one passes from 20°C to 320°C and from 320°C to PWR medium.(fig. 4).

3 - DESCRIPTION OF MEASUREMENT MEANS

The defects whose propagation is under examination are axial defects with various lengths. For these, three methods were tested. They are :

. Method of electrical potential,

. Ultrasonic method with transversal waves,

. Ultrasonic method with Rayleigh waves.

All these methods were tested on ferrules taken from an AQUITAINE piping. Those ferrules were notched. Those ferrules notches were initiated and propagated in cracking by means of a vibrophore.

Methods of the electrical potential

By means of a 4 pin captor or 4 welded pins, one feeds the surface of the part (fig.5 pins S1, S2) and measures the resulting potential between two other pins (S3, S4, fig. 5). The amplitude of the measured tension is tied with the perturbation of the lines of current caused for instance by a cracking. A very clear improvement on the quality of the contact was performed in welding the pins. The measurement accuracy may be estimated at ± 0.5 mm.

Ultrasonic method by transversal method

That method consists of utilizing two ultrasound palpers, an emitter and a captor working in transversal waves. Those focalized palpers are erected on a movable supporting set around the tube under test. Their tilting with regard to the tube surface and their distance are such that the waves reverberate on the tube internal wall. The reverberation may only take place when the waves passes under the crack (fig.6 and 7).

In displacing the palpers support perpendicularly to the crack plane and measuring the signal produced by the receiver in function of the displacement, one obtains curve lines such as those of the fig. 8. The appearance and extinction of the signal is proportional to the distance between the crack center and internal wall for the external cracks. The frequency of the palper is 4 Mhz. They are focalized at 100 mm in the water. The obtained accuracy, taking into account the reproductibility is about ± 0.3 mm.

Ultrasonic method by Rayleigh wave

That method has been the subject of a published material (ref. 1). It consists of inducing surface waves proximate to the notch. Those waves have the property of following the boundaries in reverberation on encountered obstacles (fig. 9). In measuring the time gaps between the various echos, one may calculated the distance separating the notch bottom from the crack center.

4 - DESCRIPTION OF THE FACILITY

The AQUITAINE I facility reproduces the working conditions of the PWR reactors ,i.e. pressurized water at about 300°C and 170 bars. The tests consist of submitting these piping components to pressure cyclings associated or not with mechanical cyclings.
The pipings components present themselves under two forms (see fig. 10) - the model A steel-made AISI 316 type is destined to fatigue tests under variable pressure,
- the model B which includes mixed weldings steel or carbon-steel AISI 316 may be submitted to sollicitations of pressure and flexion combined. In both cases, the dimensions of the tested tubes are : external diameter 219.5 mm, internal diameter 185.5 mm.
The working characteristics in variable pressure are obtained from a main circuit in stainless steel comprising a 108 kw boiler, a 27 kw thermic pressurizer, a circulation pump and a buffer tank (see fig. 11). The opening of two electrovalves enables feeding the test section in hot water under pressure. After maintaining a few minutes under pressure the test section is isolated from the main circuit by shutdown of the electrovalves and is depressurized by communication with a condensor. The condensed water is reinjected in the main circuit by means of a high pressure proportioning pump. The pressure cyclings are entirely self-acting. The duration of a cycle is about 15 minutes.
For tests of section model B, one may work with steady or variable pressure, seeing that the alternated flexion device for the piping enables to superimpose the two types of sollicitation. Prior to hot condition tests, the piping components undergo cyclings of cold pressure at a frequency of about 4 cycles/minutes. That fatigue in pressure is destined to initiate crackings at the bottom of notches machined on the inside and outside walls of the tubes. It is carried out on facility distinct of AQUITAINE I.

5 - CALCULATION OF INTENSITY FACTOR OF STRESSES

The comparison between the propagation speed of cracks on test pieces (measured during characterization tests of the material) and speed of tubes's cracks requires the as accurate as possible knowledge of the intensity factor of stresses K_I of various experimented notches.

The calculations of K_I for several geometries of notches were performed by means of various methods. The calculated geometries are :

. Inside diameter of tube	:	D = 185.5
. Tube thickness	:	h = 17 mm
. Notch depth	:	a = 8.5 mm
. Length of notch 2 C	(	infinite (2 c/h = 00)
	(	340 mm (2 c/h = 20)
	(	170 mm (2 c/h = 10)
	(	85 mm (2 c/h = 5)
	(	50 mm (2 c/h = 3)

The most convenient way for presenting the results consists of writing :

$$K_I = F\sigma\sqrt{\pi a}$$

Wherein

F = Factor of form

σ = Stress of membrane = $\frac{P \times D}{2H}$

P = Nominal pressure = 165 bars

The F coefficient also enables to easily evaluate the relative severity of the various notches.

Three methods of calculation were employed :

a) Finite elements
   Elastic and elasto-plastic calculations (program PASTEL) [2]
   Tridimensional elastic calculation (program BILBO) [3]
b) BUCKNER method of functions of weight
c) Utilization of abacuses (counting frames) furnishing the values of F in function of the cracking's geometry and proposed by SHAH and KOBAYASHI-SMITH and SORENSEN-LEVY and RICE-CODE ASME.

The results of elastic calculations obtained by the various methods are regrouped in the table 1. wherein one finds the reference of utilized publications. One sees that the results concerning the notches infinite in length are homogeneous enough and one may note that the value F = 2.8 obtained with the BILBO program is in excellent agreement with the reference 2.83 calculated in accordance with [4]. Hence, one estimates that the K_I values of notches finite in length, calculated with BILBO are the estimates which seem the most reliable at the present time. The bidimensional elastoplastic calculations (Program PASTEL) for a crack infinite in length produce K_J values obtained with the RICE integral

$$K_J = \sqrt{\frac{EJ}{1-V2}}$$

For the 165 bar pressure at room temperature, one has K_J = 38.5 MP a $\sqrt{m}$; at working temperature of loop (280°C), K_J is equal to 44 MPa $\sqrt{m}$.

6 - INITIATION AND PROPAGATION OF A CRACK INFINITE IN LENGTH

The first test of the program on tubes consisted of submitting to cyclings of cold water pressure (0 - 165 bars) a piece of tube 650 mm long comprising a notch 8.5 mm deep and infinite long (see fig.12) The main goal was to compare the propagation speeds measured with those observed on the test pieces CT. Precedingly, one has seen that the most probable value of F (table) for such a case (tridimensional calculations with program BILBO) is 2.8 A similar calculation was performed for a notch the depth of which is equal to 0.75 time the width of tube ; the F value is then equal to 8.5. One has :

depth a (mm)	$\frac{a}{h}$	F	$\Delta K = F\sigma\sqrt{\pi a}$
8.5	0.5	2.8	40 MPa m
12.8	0.75	8.5	120 MPa m

The cycling were performed by series of 100 cycles with measurements of the notch depth by ultrasonic waves (transversal waves) and by variation of electric potential at each stoppage ; these measurements were performed at A level (360 mm) see fig. 12. The test was stopped at 5.882 cycles, after local breaking of the ligament remaining at level B (520 mm). Measurements of crack depth were then performed at this level before dismounting of the tube (US measurements, transversal and surface waves). Metallographic examinations were performed on 2 samplings taken at levels A and B (macrographic examination and electronic microscope with scanning); one has measured :

. The depth of crack in function of the cycles number,

. The speed of propagation $\frac{da}{dN}$

The beginning of the cracking happens at one of the tube's far end, proximate to level B, at around 500 cycles. The fig. 13 and 14 indicate the crack depths measured by the various utilized means at levels A (during cyclings) and B (at end of tests). One sees that the measurements by ultra-sounds (transversal waves) are in good agreement with the macrographic observations the precision of which is evaluated at $\pm$ 0.1 mm. The figure 15 which results from inter-stria measurements shows that the variation law of propagation speed is not exponential. At the beginning of cracking, the measured speeds at the two levels are perceptibly different. From the 2 estimates of K previously indicated, one may compare the propagation speed observed on the tube with the one of the CT test pieces. The figure 16 shouws a pretty good concordance at the beginning of the tube cracking but one then finds out a notable divergence.

7 - CRACKING AT HOT CONDITIONS

The tests on notches finite in length started up with a tube comprising an outside longitudinal notch 340 mm long and inside notch 170 mm long (8.5 mm deep in the 2 cases). After 2000 cycles at cold condition for initiation of a fatigue pre-cracking, the tube was erected on the loop and had undergone 440 cyclings at temperature 285°C, the internal pressure varying from 2 to 165 bars.

The depth measurements were carried out after stoppage and cooling at the end of the 100 cycles series. Contrary to the satisfactory results precedingly obtained, the situation vis-à-vis the measurements performed on this tube is somewhat confusing. The tests were interrupted after 440 cycles at hot conditions on the strong assumption of a very deep cracking of the outside crack, according to indications of the ultrasonic measurements. The first results of a micrographic examination under progress produce the dimensions of the actual cracking which is much more reduced than the one indicated by the U.S measurements. The crack depth measured on the first examined sampling is in the order of 0.7 mm from the notch bottom ; the propagation speed is at this time estimated at :

$$0.5 < \frac{da}{dN} < 4 10^{-6} \text{ mm/cycles}$$

for a K_I estimated at 30.9 MPa $\sqrt{m}$ (table 1. calculation by program BILBO). These figures are in good agreement with the speeds measured on the CT test pieces (fig. 4).

8 - CONCLUSIONS

The main results already acquired within confine of the AQUITAINE program concern the following :

. The characterization of the utilized steel (AISI 316) vis-à-vis initiation and propagation speeds of cracks in various conditions (environment, temperature).

. The research of measurement methods for crack depth, the ultrasonic methods have provided good indications for propagations at room temperature. Difficulties appear when the cyclings are performed at hot conditions.

. The calculation of K_I for defects finite in length by different methods ; the results obtained with the BILBO program (tridimensional elastic calculations) at this time seem the most reliable.

. The correlation between the propagation speeds $\frac{da}{dN} = F(K_I)$ observed on the CT test pieces and tubes.

The first obtained result shows a satisfactory concordance.

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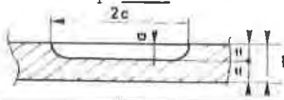
F and K_I elastic assessment



$F = \frac{K_I}{\sigma\sqrt{\pi a}}$

K_I in $MPa\sqrt{m}$

2C=50mm 2C/h=3			2C=85mm 2C/h=5			2C=170mm 2C/h=10			2C=340mm 2C/h=20			2C=∞ 2C/h=∞		
Method	F	K_I	Method	F	K_I	Method	F	K_I	Method	F	K_I	Method	F	K_I
Rice Levy [5]	1,13	16,7	Finite elements (Bilbo-Tri dim)	1,6	23,5	Elastic Calcul	1,15	17	Weight functions	2,25	33,1	Weight functions	2,2	33
Shah.Kob [5]	1	14,7				Rice-Levy [6]	1,97	29	Rice-Levy [6]	2,09	30,8	Rice-Levy [6]	2,45	36
Smith [5]	1,16	17,1				Shah.Kob [5]	1,26	18,5	Smith-Sor^n [8]	1,53	22,5	Finite elements (Pastel)	2,4	35,5
Finite elements (Bilbo-Tri dim)	1,4	20,6				ASME [7]	3,08	4 5	Shah.Kob [5]	1,19	17,6	Finite elements (Bilbo-Tridim)	2,8	41,2
						Finite elements (Bilbo-Tri dim)	1,9	27,9	Finite elements (Bilbo-Tridim)	2,1	30,9			

TABLE 1.

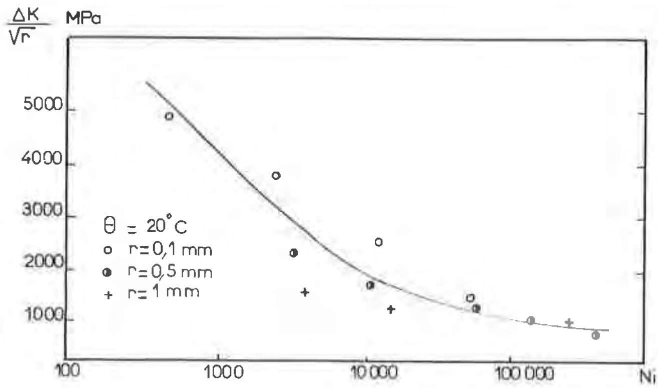


FIGURE 1. Variation of $\frac{\Delta K}{\sqrt{r}}$ with the number of cycles for initiation at 20°C

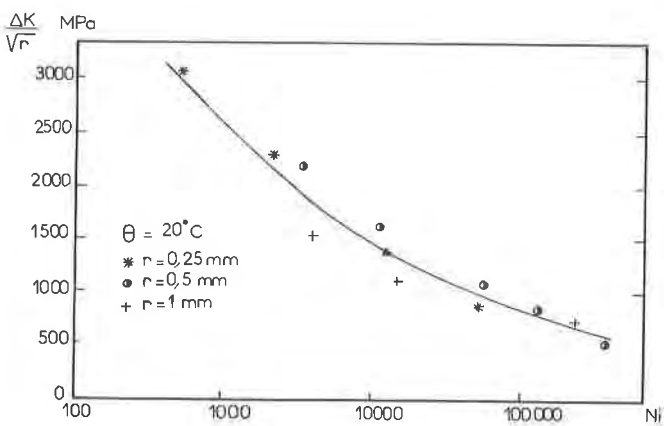


FIGURE 2. Variation of $\frac{\Delta K}{\sqrt{r}}$ with the number of cycles for initiation at 20°C

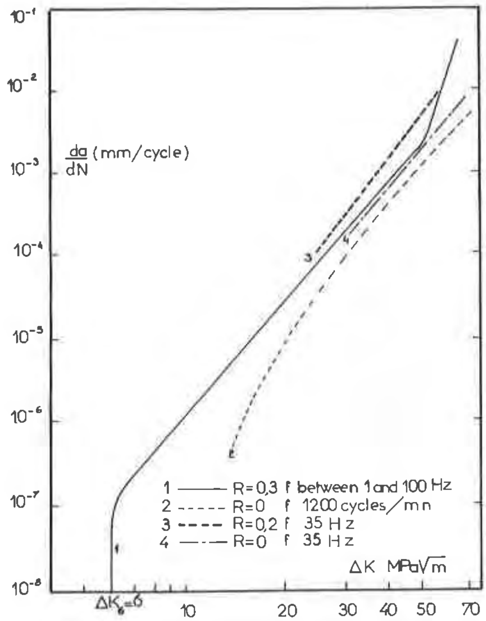


FIGURE 3. Crack growth rate of 316L at 20°C in air

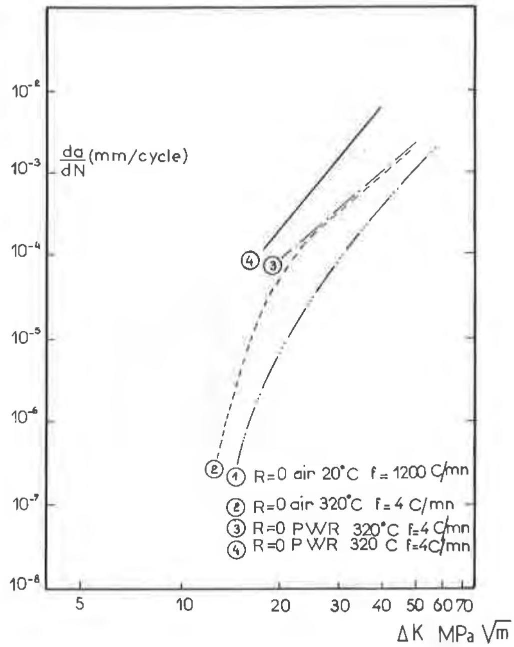


FIGURE 4. Crack growth rate of 316L at 20°C and at 320°C

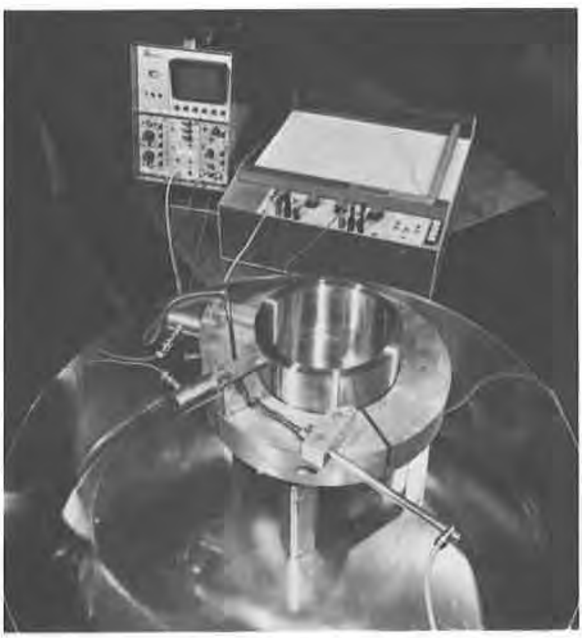


FIGURE 7.

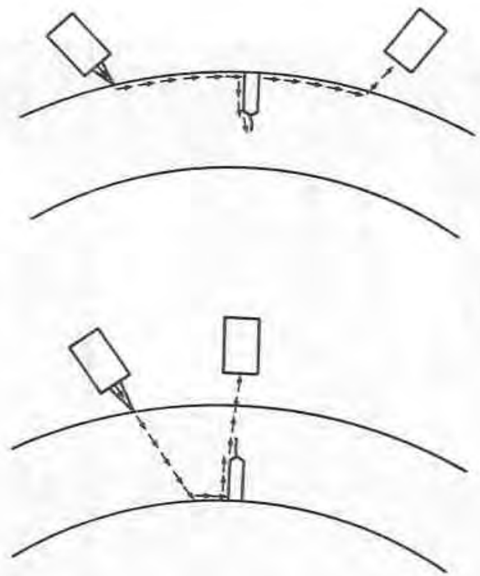


FIGURE 9. Measurement by RAYLEIGH waves

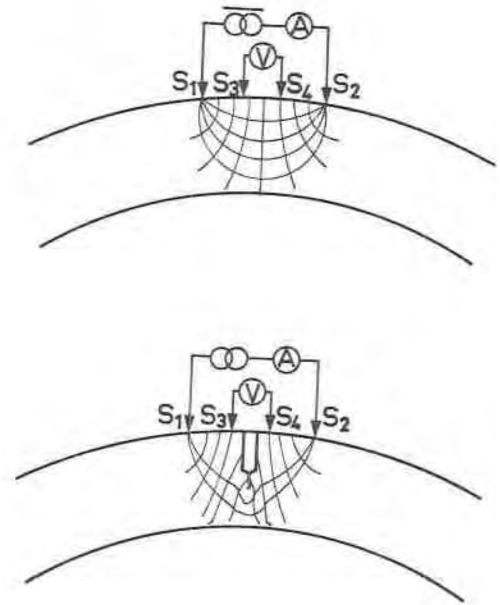


FIGURE 5. Measurement by electrical method

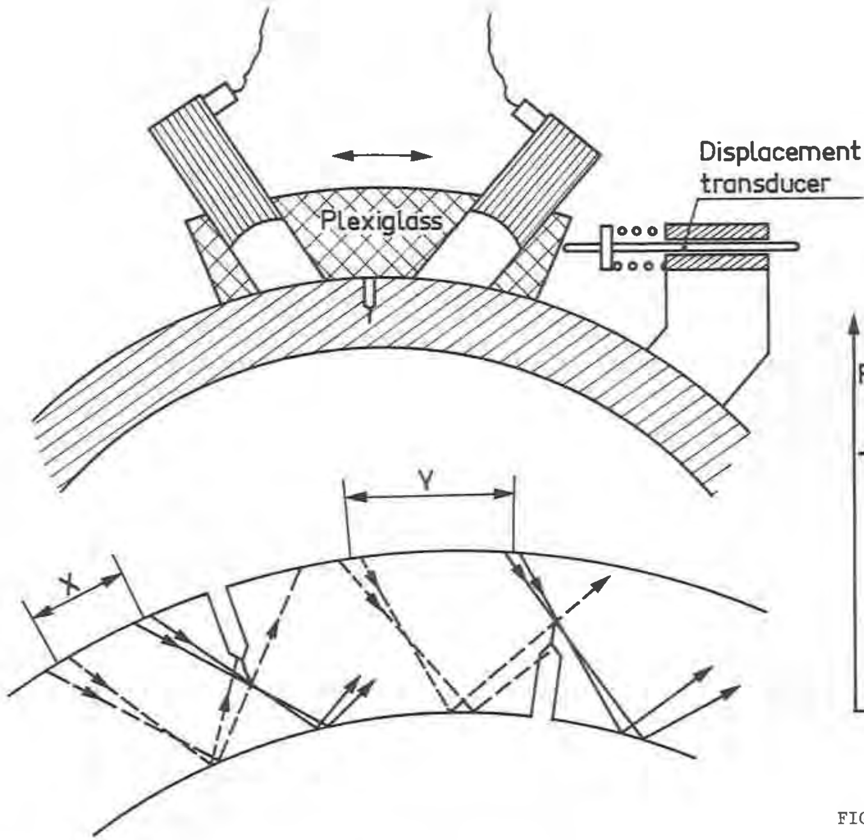


FIGURE 6. Crack depth measurement by ultrasonic waves

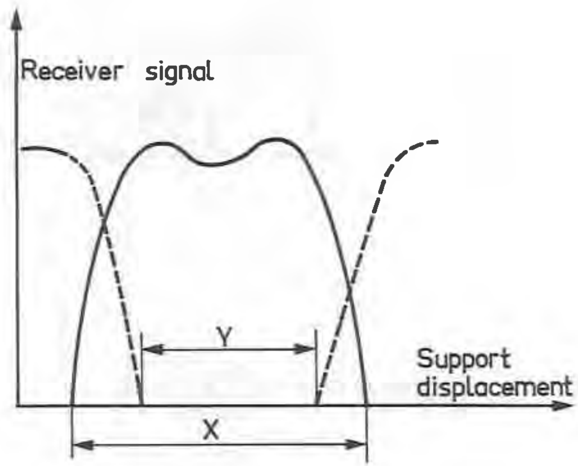


FIGURE 8. Crack depth measurement by ultrasonic waves

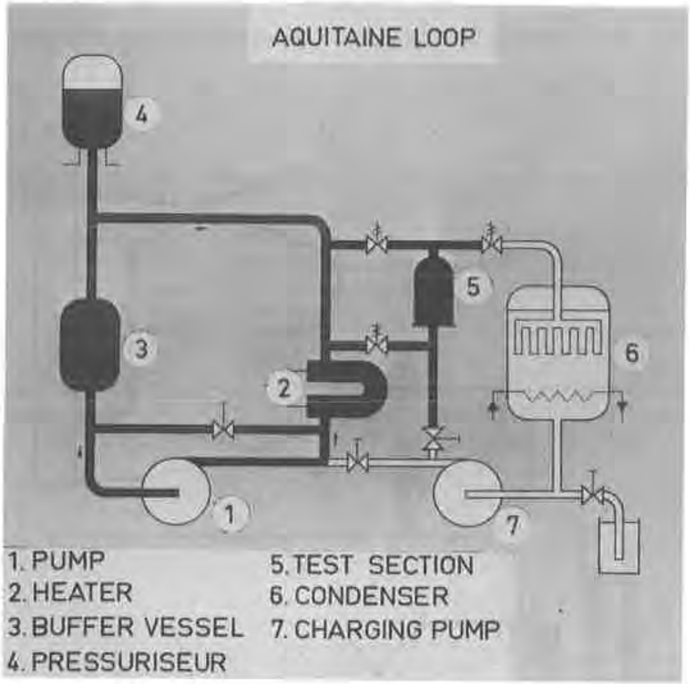
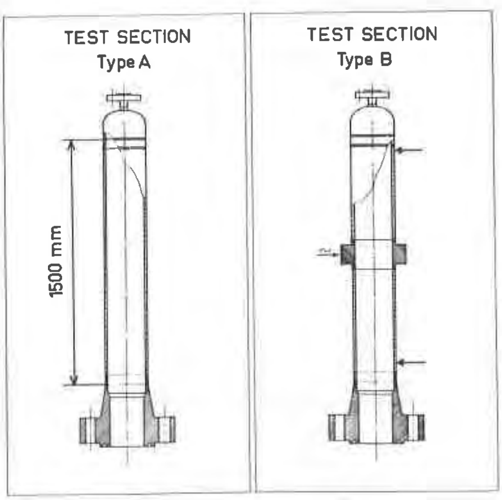


FIGURE 11. AQUITAINE loop



Tube diameter 186 x 220 mm

FIGURE 10. Test section (type A) -
Test section (type B)
Tube diameter 186 x 220 mm

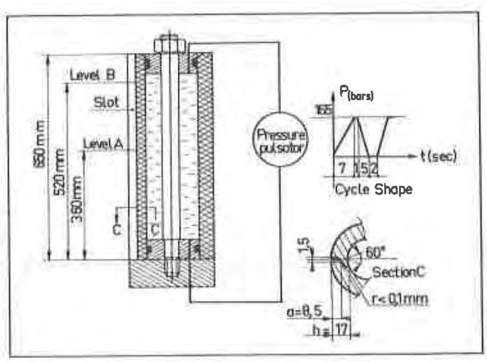


FIGURE 12.

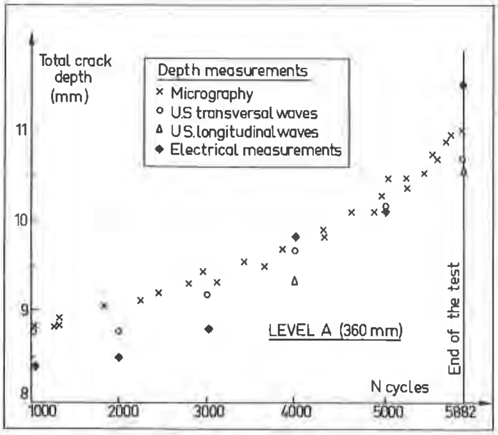


FIGURE 13. Depth measurements (level A)

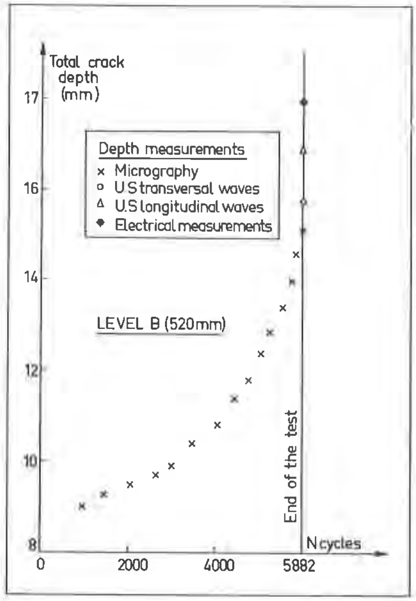


FIGURE 14. Depth measurements (level B)

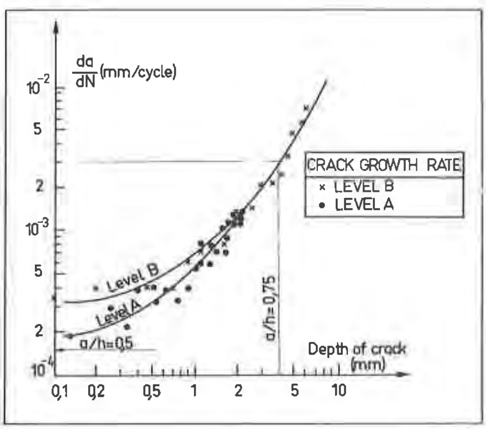


FIGURE 15. Crack growth rate

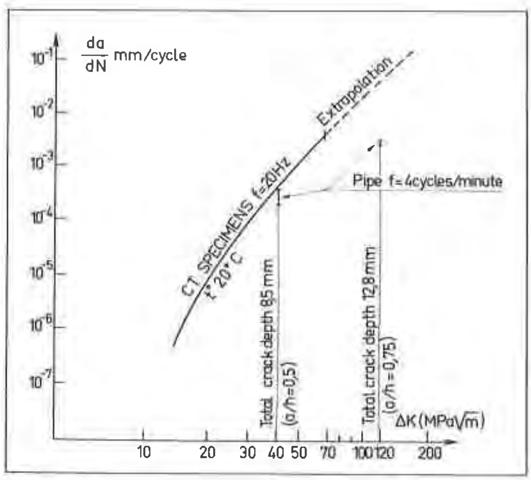


FIGURE 16.