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"THERMAL SHOCK EXPERIMENT ANALYSIS, THE USE OF CRACK ARREST TOUGHNESS MEASUREMENTS"

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A Thermal Shock Experiment (TSE) has been performed by FRAMATOME, with the support of EDF.

The first part of this presentation will describe the characteristics and the main results of this experiment. The second part will describe the crack-arrest tests carried out by the CEA.

I - Brief presentation of the TSE.

The numerous american TSE's performed by ORNL [1] are well-known, the french approach is rather similar. The main purpose of such an experiment is to assess the procedure codified in the ASME XI appendix 1 or RCC-M-B appendix ZG, and allow comparisons with numerical simulations. The analysis of the integrity of the PWR vessel belt line under accidental transients (a LOCA for example) is based on reference curves (K_{Ic}, K_{Ia} or K_{IR}) whose position is given by the RT_{NDT}.

II - Test set-up and material properties.

The test-piece is a cylinder (height = 1 m, Inner Radius = 0,46 m , thickness = 0,23 m) of SA 508 cl.3 steel. A longitudinal surface crack, 17 mm deep, is obtained by the electrolytically charging with hydrogen of an electron beam weld.

The temperatures at six different depths were measured by four sets of six thermocouples.

The fast propagation events were identified in time by the simultaneous increases of the opening measured at the inner surface by clip gauges (cf. figure 1).

The test cylinder is coated with a synthetic rubber enhancing the heat transfer. Its surface is sufficiently rugose in order to promote nucleate boiling instead of film boiling. But these two modes coexisted sometime during the experiment.

The cylinder, toped by a 1 meter high cylindrical extension was completely filled with liquid nitrogen in 13 seconds ; additional liquid was poured later.

The material is a SA 508 cl.3 steel, its chemical composition and mechanical properties are given in table 1. The cylinder is a PWR nozzle whose thickness was reduced from 360 mm to 230 mm (i.e. the PWR's vessel thickness) by machining the inner part. This operation removes a great part of the toughness gradient located near the quenched inner surface.

The impact toughness properties of this cylinder have been measured at different depths.

Charpy V and Pellini tests have been performed. Table 2 gives the values of the reference temperature obtained according to the rule given to determine the TCV of ASME III. At 1/3 thickness of the original forging, the RT_{NDT} is - 7° ± 4°C. The toughness gradient in the thickness is partly estimated by the Pellini and Charpy V tests made near the center and the external outer region of the test cylinder. The NDT temperature increases from - 15° to + 5°C, with the depth. But the trend followed by Charpy V conventionnal temperatures is reverse : TCV in TS orientation (like the crack) decreases from + 22°C to + 12°C, FATT is rather constant.

The fracture toughness has been measured at - 60°C on CT 75 specimens (3T CT), with fatigue precrack or electron beam with hydrogen charging. The eight results gave an acceptable scatterband, ranging from 50 to 90 MPa$\sqrt{m}$. Additional tests at - 10°C on CT 100 specimens (4 CT) are under progress.

III - Results of the TSE.

Three crack propagation events took place at 169 s, 209 s and 356 s after the end of the filling. These events were indicated by the clip gauges set across the crack mouth (cf. figure 2). At these moments, the temperature distributions across the thickness were known. The post-test examination of the broken surfaces (the cracked region having been extracted and broken open) gave the successive profiles of the crack. The figure 3 shows the initial straight front (17 mm deep) and the three steps of the propagation. The fracture was totally brittle (cleavage only), and occured by very fast advances (discrete steps cf. Figure 2) followed by periods of stillness during which the temperature field changed continually (ascending trend between 209 and 356 s, cf. Figure 2).

The measure of the crack-fronts depths at the center, allowed the approximate determinations of the temperatures of interest. The table 3 presents these values.

Thermal elastic stress analyses have been performed on an infinite cylinder loaded by the through-wall mean temperature distributions of the three events. The K_I stress intensity factors have been determined by using the weight-functions of the infinite cylinder with longitudinal crack. The results are given in table 3.

The three events (initiation and arrest) are shown on figure 4, in conjunction with the ASME XI (and RCCM-B-Appendix ZG) reference curves K_{Ic} and K_{Ia} (or K_{Ir}). The imprecisions on the toughness (± 5 %) and on the reference temperature (± 4°C) are taken into account. Moreover, we adopted different values of RT_{NDT}, function of the event's location (cf. table 3). Figure 4 shows that the 2nd initiation's K_I SIF is slightly below the K_{Ic} reference curve (RT_{NDT} equal to - 10°C). An explanation of this result is given in [2] . In this paper, emphasis will be put on the interpretation of the arrest's results. The three arrest's K_I SIF values are practically on the K_{Ia} reference curve.

It's must be recalled that in fracture mechanics analyses the RT_{NDT} is conventionnally constant through the forging's thickness, and measured at the quarter thickness location (- 7°C for the TSE cylinder). With this assumption the 2nd and 3rd initiation points, and the 1st and 2nd arrest points should be moved by 3°C toward the right on figure 4, and the 3rd arrest point should be moved by 12°C toward the left.

Table 2 shows that for the two first propagations, the arrest occured in a slightly decreasing K_I field and in an increasing temperature field, while the third occured in a strongly decreasing K_I field with a nearly constant temperature field.

The 2D computed K_I values at initiation are in the experimental scatterband of toughness meausrements made on similar materials (SA 508 cl.3).

The influence of dynamic effects is expected in this Thermal Shock Experiment ; in order to better understand this, K_{Ia} tests were undertaken. Dynamic computations are also under concern.

IV - The crack arrest toughness of the SA 508 cl.3 steel.

Crack arrest toughness has been determined on specimens cut in the TSE cylinder according to the presently proposed ASTM test method [3] at the temperature of 5°C with a wedge loading rate of 5 $mm.mn^{-1}$. The specimens' width (210 mm) is nearly equal to the thickness of the test cylinder (230 mm), their front faces being tangent to the cylinder's inner surface. The notched brittle weld crack starter is produced by depositing a weld, with Murex-Hardex-N electrodes of 4.8 mm diameter at 180 A, in several passes, machining according to a circle and then notching. Due to supplementary instrumentation for measuring velocity with electrical gages, one lateral notch has the conventional 45° pattern and the other one 90° or 60°. Results of the tests are given in table 4. The worthnoting comments are as following :

- 1. Cycling is necessary and lubrification is supplied before each cycling.
- 2. Good lubrification is required : with a bad lubricant (Test 2A3, first cycle), the wedge has to be withdrawn manually ; with a good lubricant (Tests 2A3,second cycle, 9A4 and 1A3), the wedge is withdrawing naturally. Moreover, with good lubrification, lower load is required and records (figure 5) are nicer.

- 3. During the first cycle, a pop-in may be displayed on the record (tests 2A3 and 1A3). To this pop-in a "subcritical" crack growth of about 15 mm, as detected after testing on the crack surface, can be associated. Moreover, the weld bead displays microcracking in and outside the starting notch.
- 4. The initial imposed displacement was 0.9 mm. Afterwards, the displacement was incremented at each cycle by 0.1 mm. This is out of the recommended procedure.
- 5. For the 1A3 test, an unexplained compliance increase occurs between the third and fourth cycles.
- 6. For the 1A3 test, crack propagation occurs during unloading when the opening displacement is still constant.
- 7. Probably due to the multiple initiation sites in the weld, crack growth initiates out of the lateral notch plan (figure 6).
- 8. Due to the out of plane propagation, the crack growth monitoring at lateral notch tip has not succeeded.

Results are given in table 4. The crack propagation jumps are respectively 85.6, 71.9 and 67 mm. The starter notch depth is nearly 95 mm under the inner surface. The mean arrest point depth in the specimens is 168 mm under the inner surface of the test cylinder. The jump conditions in the test specimens are very similar to the second jump of the TSE (cf. table 3). The static crack arrest toughness values (measured with the thickness B at the crack front at arrest) are respectively 39.1, 73.6 and 76 MPa$\sqrt{m}$. These results are shown in figure 4, the RT_{NDT} being evaluated in the range - 10°C, + 5°C according to table 3. The lowest toughness value is associated with a smooth fast fracture surface, while the two other values are associated with a rough fast fracture surface (figure 7).

Conclusion.

The arrest toughness measured on this TSE falls close to or on the K_{Ia} ASME XI, or RCC-M, reference curve.

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The K_{Ia} measured values' scatterband encompasses the three computed static K_{Ia} values. These values and the lowest measured one are on the K_{Ia} reference curve. The static analysis of the crack arrest codified in ASME XI is applicable in this experiment but without overconversatism.

Acknowledgement.

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References.

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Heavy Section Steel Technology Program Quarterly Progress Report.
NUREG/CR 1305 and NUREG/CR 1477.
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[2] A. PELLISSIER-TANON, P. SOLLOGOUB, B. HOUSSIN, F. ROBISSON.
Crack Initiation and Arrest in a SA 508 cl.3 Cylinder Under Liquid Nitrogen Thermal Shock Experiment.
7th SMIRT - Paper G/F/1/8.

[3] Proposed ASTM Test Method for Crack Arrest Fracture Toughness of Ferritic Materials. September 1983.

Table 1 : Chemical composition and mechanical properties (at 20°C) in the circonferential direction (at mid-thickness of the original forging, 80 mm depth of the test cylinder).

% weight	C	Mn	Ni	Mo	Cr	S	P	Si	Al
	0.178	1.310	0.740	0.500	0.170	0.007	0.009	0.310	0.044

0,2 % yield stress	tensile strength	total elongation	reduction of area
493 MPa	633 MPa	19 %	66 %

Table 2 : Toughness gradient in the test cylinder.

Position in thickness		T_{NDT} (°C)	Reference temperature as ASME III TCV (°C) and FATT (°C) V.S. orientation					
in vessel forging	in test cylinder		T L		T S crack orientation		L T	
			TCV	FATT	TCV	FATT	TCV	FATT
1/3	20	- 15	+26	≃ +20	+22	≃ +20	-10	≃ 0
1/2	80	- 10	+17	≃ +20	+18	≃ +20	-22	≃ 0
3/4	170	-	0	+20	-	-	0	≃ 0
9/10	210	+ 5	-	-	+25	≃ +25	-	-

Table 3 - Computed K_I , temperatures at initiations and arrests and RT_{NDT} assumed across the thickness.

Event	N° 1		N° 2		N° 3		
Time	169 s		209 s		356 s		
Crack depth at center	K_I (MPa √m)	Temp. (°C)	K_I (MPa √m)	Temp. (°C)	K_I (MPa √m)	Temp. (°C)	RT_{NDT} (°C)
17 mm	50.6	-40					-7
88 mm	49	8	64.8	4			-10
150 mm			58.5	13	98	8.8	-10*
208 mm					48	12	+5

* Non available. Estimated value, -10°C.

Table 4 - Crack arrest toughness results at 5°C. Test specimens with $W = 169$, $B = 50.6$, $B_N = 38.4$, $a_o = 59.1$ mm

Specimen	Cycle N°	δ'_{MAX} mm	δ'_{REM} mm	δ'_f mm	a_f mm	B_{Nf} mm	K_o (δ_o,mm) $MPa\sqrt{m}$	K_a (δ_a,mm) $MPa\sqrt{m}$	K_D $MPa\sqrt{m}$
2 MRL A3 (90°notch angle)	1	(.25*) .898	.136	(.26*)	15				
	2	1.05		1.07	144.7	50.61	132.8 (0.914)	39.1 (0.934)	82.9
9 MRL A4 (90°notch angle)	1	.888	.106						
	2	1.11	.160						
	3	1.21	.195						
	4	1.42	.246						
	5	1.46		1.505	126.04	50.58	173 (1.214)	73.6 (1.259)	119
1 MRL A3 (60°notch angle)	1	(.35*) .87	.160	(.36*)	15				
	2	1.12	.207						
	3	1.29	.247						
	4	1.43	.290						
	5	1.59		1.62	131.09	45.00	188.6 (1.30)	76 1.33)	127.1

* *pop-in*

δ'_{MAX} = cumulated opening displacement at each cycle
δ'_{REM} = remanent displacement
δ'_f = opening displacement after arrest
B_{Nf} = width at the arrest midpoint
K_o = crack initiation toughness
K_a = static crack arrest toughness
K_D = dynamic crack arrest toughness
δ_o = displacement at initiation
δ_a = displacement at arrest

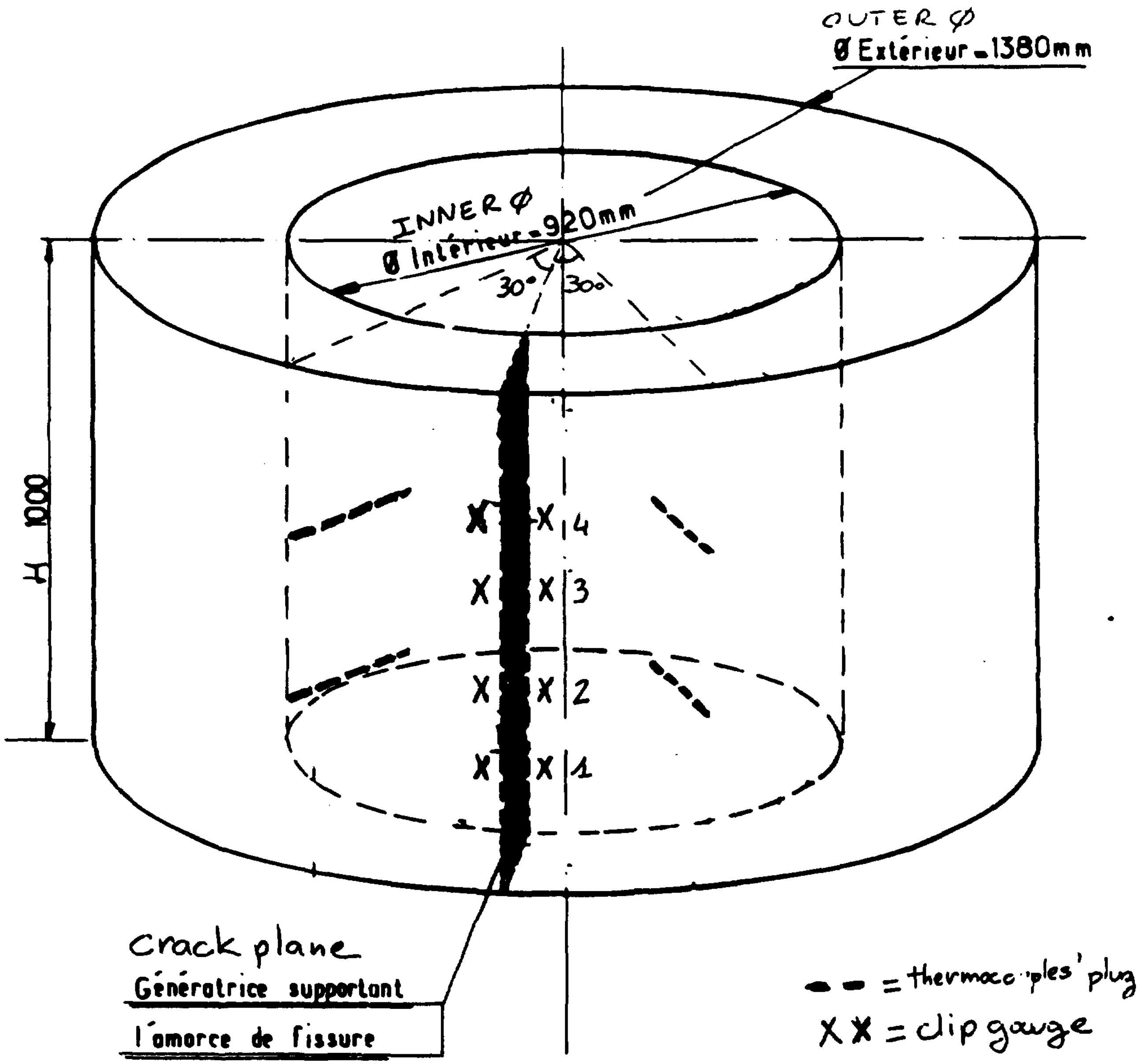

FIGURE 1 : TEST CYLINDER AND INSTRUMENTATION (CLIP - GAUGES - THERMOCOUPLES)

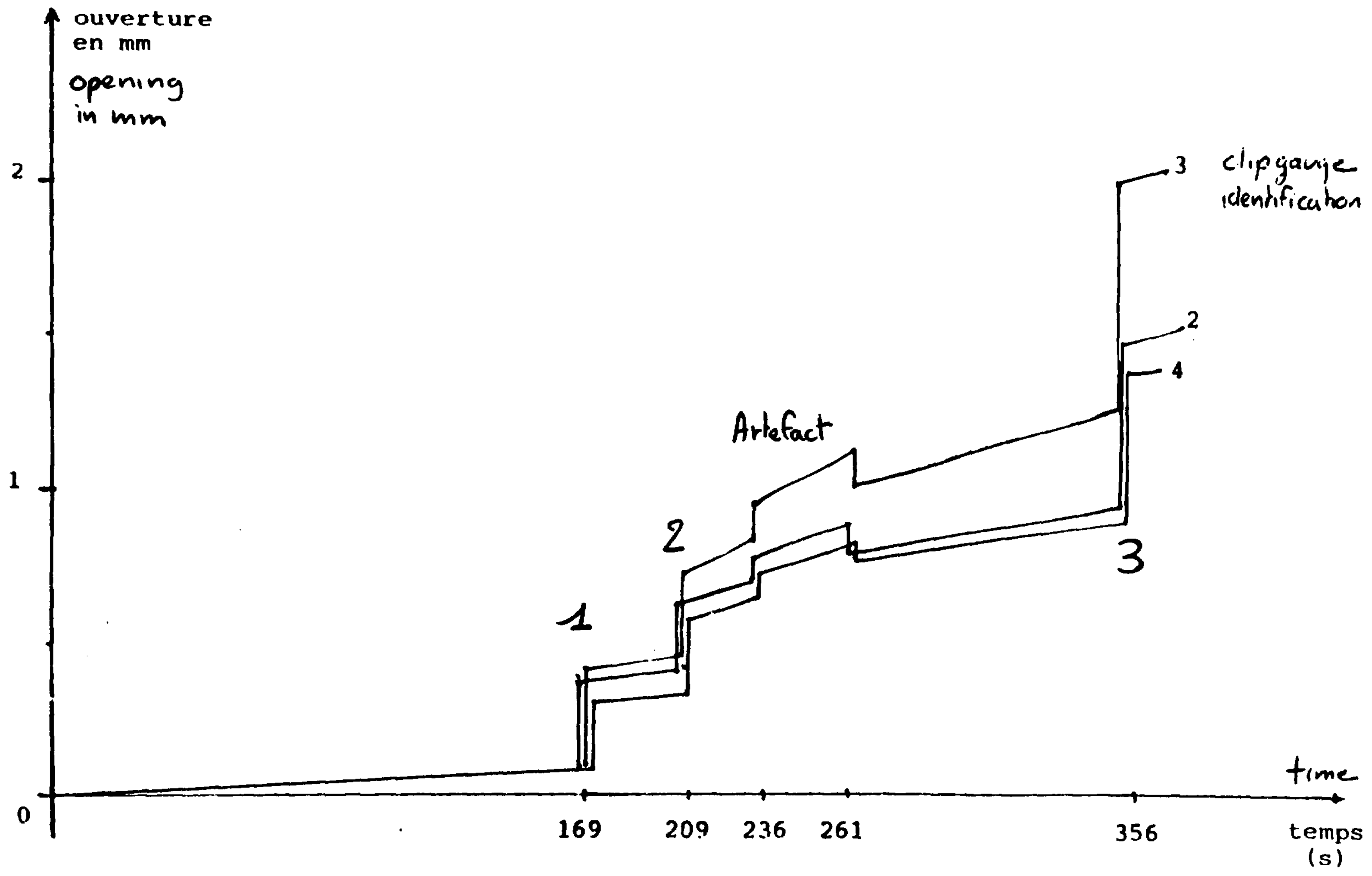

FIGURE 2 : CRACK OPENINGS DURING TSE (EVENTS ARE NUMBERED 1, 2, 3)

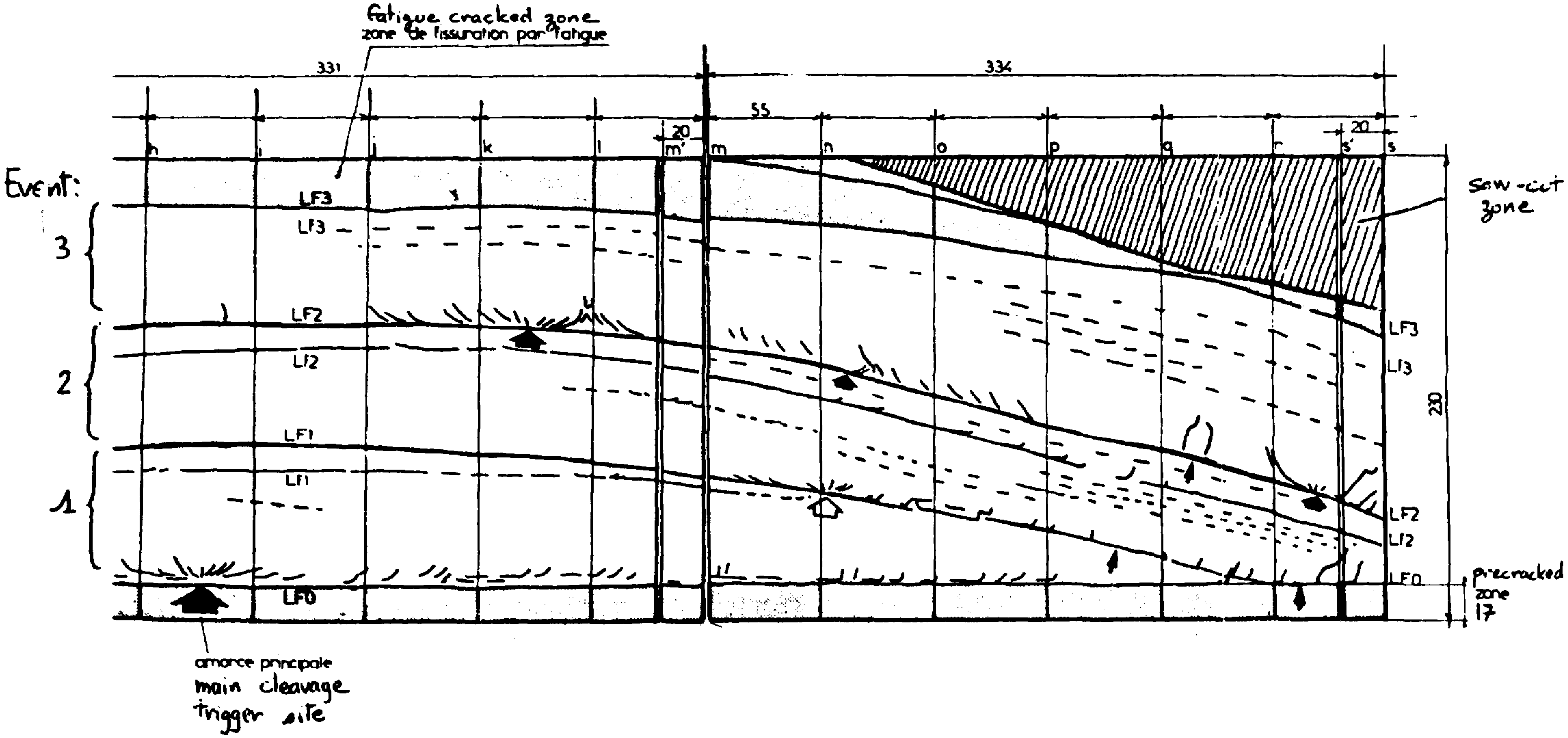

FIGURE 3 : POST-TEST EXAMINATION, MAIN LINES OF INITIATION AND ARREST (HALF HEIGHT)
(ARROWS INDICATE CLEAVAGE TRIGGER SITES)

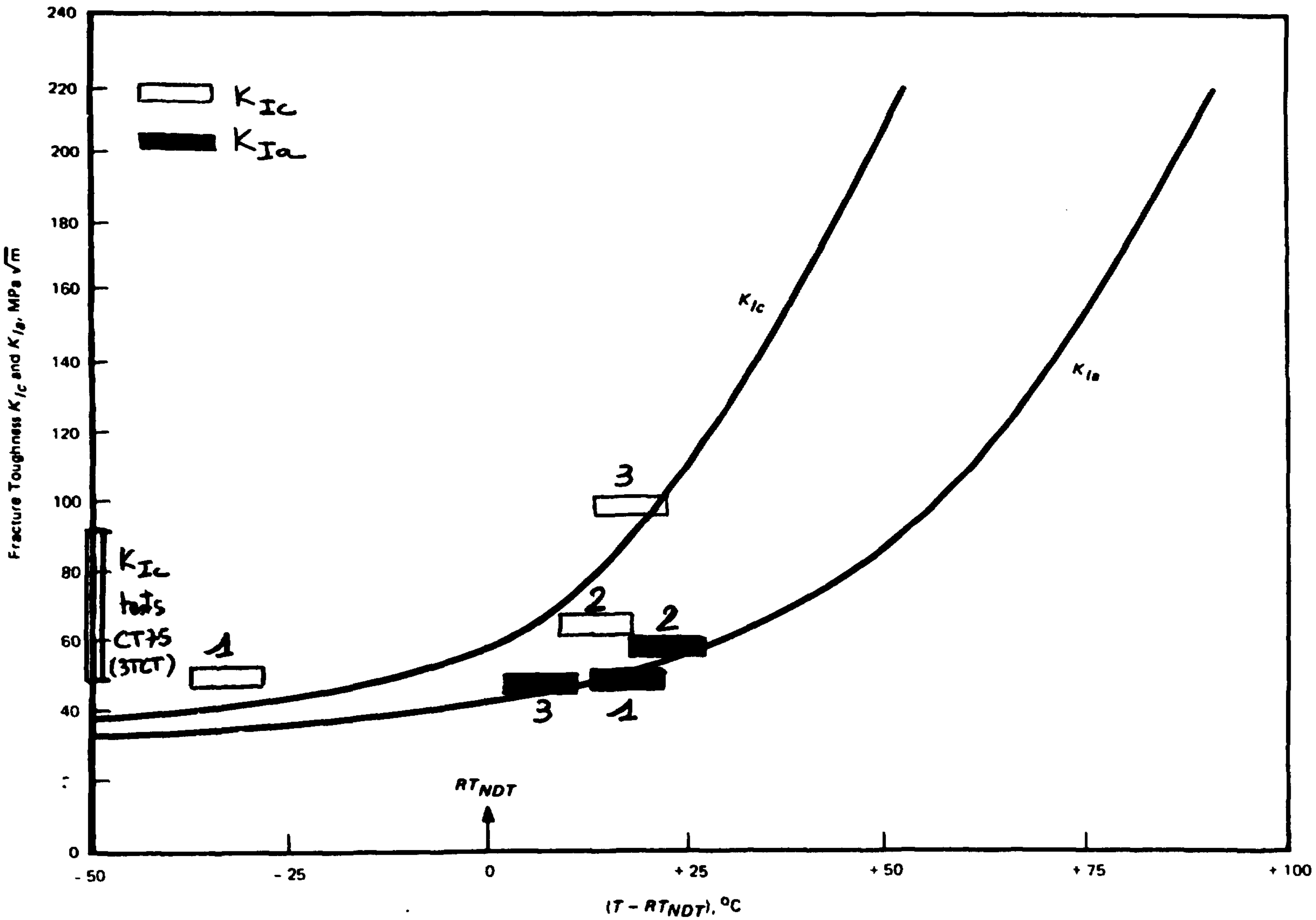

FIGURE 4 : COMPARISON OF COMPUTED INITIATION AND ARREST TOUGHNESS TO THE ASME K_{IC} AND K_{IA} REFERENCE CURVES – AND K_{IC} VALUES MEASURED AT – 60°C

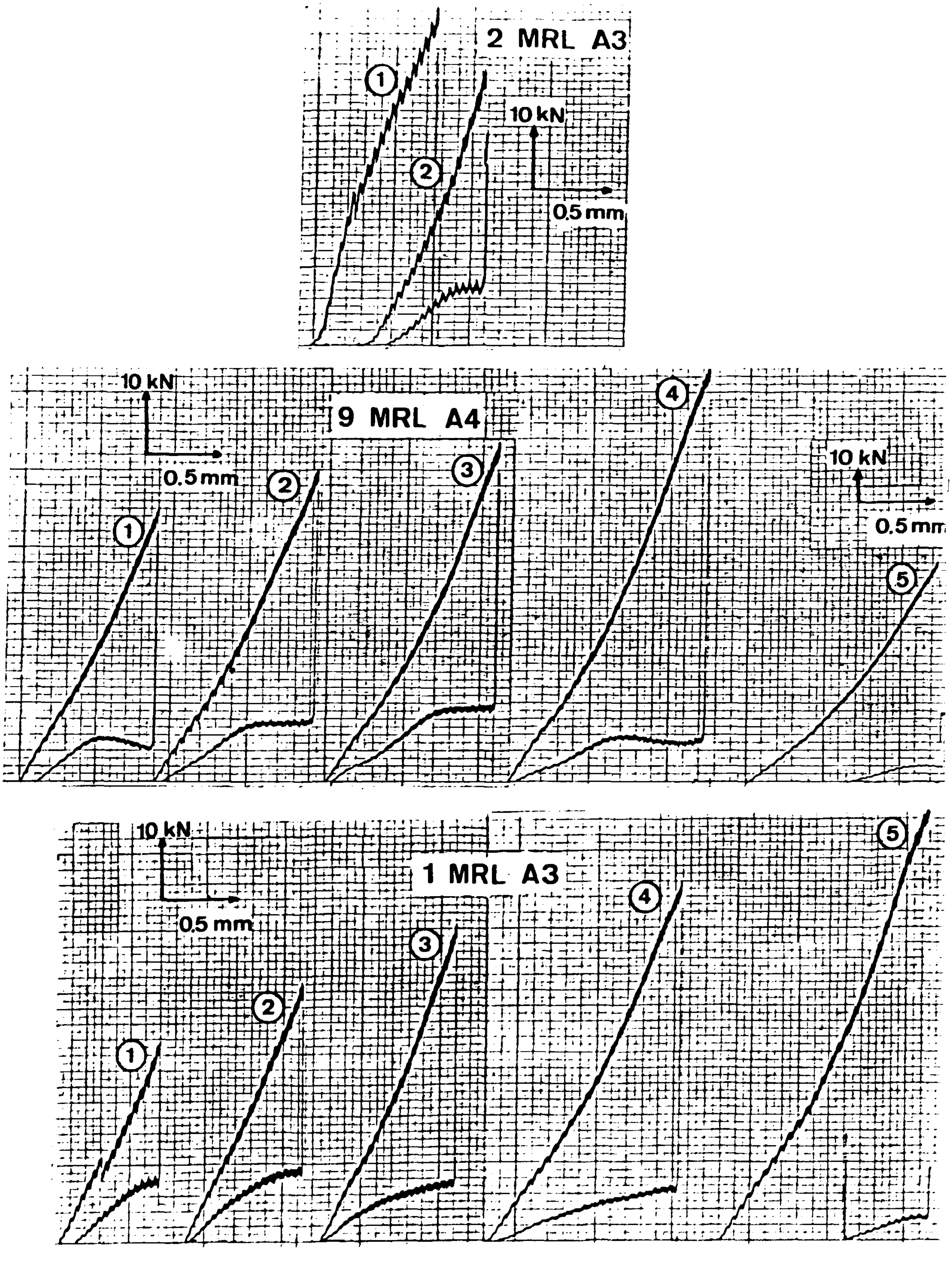

FIGURE 5 : RECORDS OF LOAD VERSUS OPENING DISPLACEMENT AT .25 W
FOR THE CRACK ARREST TESTS.
(0 NUMBER OF CYCLE)

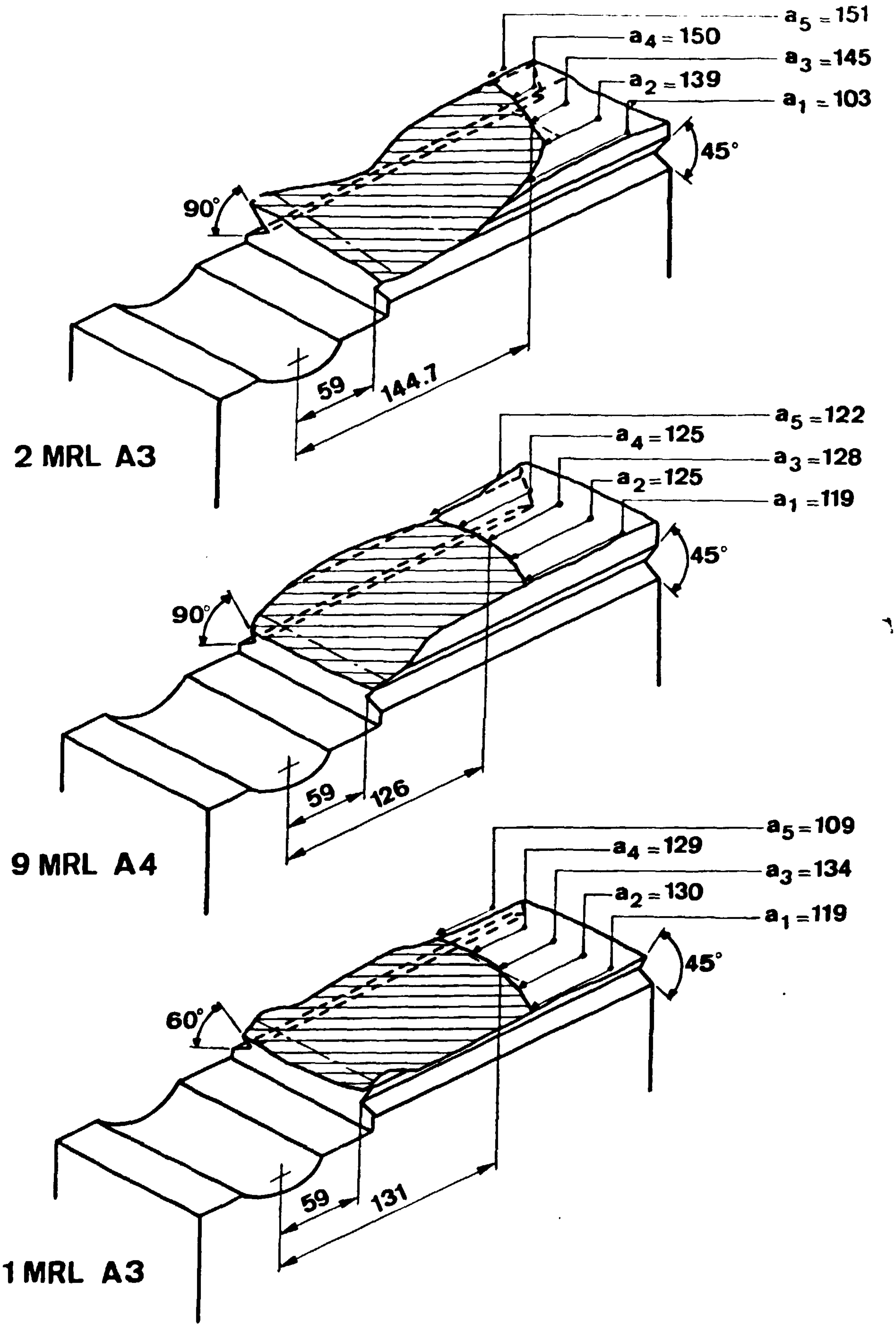

FIGURE 6 - CRACK ARREST SPECIMENS AFTER HEAT TINTING AND FINAL FRACTURE IN LIQUID NITROGEN.

FIGURE 7 : APPEARANCE OF FAST FRACTURE SURFACE OF A533 TESTED AT 5°C.