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PWR REACTOR PRESSURE VESSEL FAILURE PROBABILITIES

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INTRODUCTION

The most severe disaster that can happen in a nuclear LWR plant is probably a large failure in the reactor pressure vessel. The most important consequences are the risks regarding the emission of large quantities of radioactive products. It is, therefore, of great interest to estimate the failure probability for this vital part of a nuclear plant. An accurate and realistic evaluation of the structural reliability of a nuclear pressure vessel requires the development of a suitable model of the structure behaviour and the knowledge of the statistical distributions of all the main parameters and variables affecting the structure.

Two methods have been developed in the past to evaluate the rupture probability of a LWR vessel :

- a statistical approach using data from conventional plants: a synthesis of relevant data has been published in 1974 (1) and the proposed value : 10^{-6} to 10^{-7} has been used in WASH 1400. Since different standards have been used in manufacturing the vessels this method is questionable,
- a probabilistic method using the fracture mechanics under probabilistic form. This method has been proposed previously (2-6), but it appears that more accurate evaluation is possible.

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The latter method has been the object of a joint collaboration agreement signed in 1976 between CEA, EURATOM, JRC Ispra, and FRAMATOME, which set up and started a research program covering three parts :
(i) a computer code development, (ii) data acquisition and processing, and (iii) a support experimental program which aims at clarifying the most important parameters used in the computer code.

PRESENTATION OF THE COMPUTER CODE

A description of the computer code has been published previously (7-8). The conventional concepts of fracture mechanics, expressed in a probabilistic form, are the following :

- Size and position of defects. These data were obtained from LWR manufacturers and are discussed below ;
- Crack growth rate. This is computed using the Paris formula with various distributions of the C coefficient 'Fig.1' for air and water environment ;
- Load history of the vessel. The load variations are defined for 24 normal and upset conditions and for three faulted conditions : Table I. For each of them the pressure and temperature of the reactor primary coolant are determined, and the corresponding stress, across the thickness, are computed at different times during each transient ;
- Onset of unstable propagation is determined, at different times of each faulted condition, using LEFM in the transition and the Dowling and Townley criterion (9) at upper-shelf . The upper-shelf plastic instability pressure (Pu) is computed using the Merkle formula (10).

The basic principle of the computer code is to introduce the main parameters, of the fracture mechanics, with a statistical distribution.

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Various methods have been proposed : BECHER and MARSHALL (2,3) use a Monte Carlo method, HARRIS and NILSSON (4,5) use an analytical one. The Monte Carlo method appears fairly realistic since it enables statistical data to be used directly. However, it has the disadvantage of requiring considerable computing time. The analytical method has the disadvantage of establishing, a priori, a distribution law for all parameters introduced in statistical form. The method used in the present computer code is based on the utilisation of histograms,in a purely statistical manner. The COVASTOL computer program has been developed, taking into account all the possible combinations of the histogram classes, at each stage of the computation with a certain degree of correlation. This method, therefore, keeps closer to the physics of the phenomena. For example, in the fatigue crack growth, once an association between a given defect and a given interval of the Paris law coefficient histogram has been predetermined for the first transient, it is maintained during the following transients.This means that the material quality does not change during the growth of the flaw.

DISTRIBUTION AND SIZING OF THE DEFECTS

Previous research (11) on incidents occuring with conventional pressure vessels has shown that in 90 % of cases, the initial defects were located in the weld. For this reason, present analysis considers only defects in the weld.

Data were collected from 3 European manufacturers : BREDA (Italy) - FRAMATOME (France) and ROTTERDAM NUCLEAR (Netherlands). Each of whom has filled, for each weld, a standard form, before and after repair, giving complete information on NDT results (US or XRay) : calibration

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description of the weld size and position of the defect in azimuth, in depth and in relation to the symmetry plane of the weld as shown on 'Fig.2'. All information has been sent confidentially to the Ispra J.R.C. which carry out processing and harmonization of data.

Large undetected defects are of paramount importance for arriving at the final probability value. It has been decided to determine, in a first stage, the distribution of defects before repair and, in second stage, to correct data so as to take into account the actual reliability of the NDT methods. Therefore all the following data concern the defects detected before repair.

A total of 338 metres of PWR and BWR shell weld were analysed. A first statement shows that results are sensitive to the method used for calibration of US transducers.

Two different methods were used for this calibration :

- Cahier des Prescriptions de Fabrication et de Contrôle (CPFC) from "Electricité de France" : transducers are calibrated using a reference block with a hole of 2mm diameter for plates thicker than 100mm.
- ASME Section 11 : the diameter of the hole in the references blocs is 7.94 mm for the thickness between 152 and 203 mm and is 9.53mm for the thickness between 203 and 254mm.

It being necessary to set up a correlation between these two procedures, an experimental measurement has been performed transposing calibration diameter for each procedure. Results are presented in Table II.

In conclusion of these measurements, we can say, roughly, that the reference echo for CPFC is 9dB lower than for ASME.

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Density of defects : for each manufacturer the density of defects is the average number of defects per metre of weld, whatever the defect dimensions. This density of defects is connected to the calibration method of the transducer. The Cumulative Distribution Functions (CDF) were determined, before repair, for both calibrations. Results are presented on 'Fig. 3'. In the figure, transposition of the data was performed using the above mentioned correlation. In the 20 % - 100 % DAC, range according to ASME calibration, the density of defects for both methods is practically the same. For lower amplitudes, the density of defects is higher with the CPFC method ; it would obviously be still higher if a more precise calibration method were used.

Data obtained from manufacturers showed a wide differences from one weld to another. This is probabily due to an occasional misadjustement of a welding parameter wich may affect one or several pass during the welding process. The corresponding CDF is presented on 'Fig. 4.

Position of the defects in the weld : Data obtained from the completed from indicate the position of each defect in relation to a reference system especially worked out for that purpose. The general conclusions are the following :

- position in depth : a rough examination of the data sheet does not show a clear distribution of the defects according to their depth. Nevertheless, one must make the following remarks : (i) sensivity is weakened in the vicinity of the transducer and (ii) the shape of the weld may differ from one weld to another. In fact, an evaluation, performed with welds having the same geometry, shows that the density of defects is slightly higher in the vicinity of the root of the weld.

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- position in relation to the symmetry plane of the weld : the corresponding distribution is also influenced by the shape of the weld ; it can be observed that the density of defects is larger in the interface between base material and weld. In fact, the density of defects in the symmetry plane of the weld is very low, except near the root.

Length of the defects : The manufacturers have obtained their data either by US or by XRay. Generallly, the lengths measured by the US method are greater than by XRay as may be seen on 'Fig. 5'. Accordingly in the following discussions, only US measurements will be considered. Nevertheless in the final distribution introduced in the computer code XRay data will be used as complementary information.

All defects have been collected according to their length and the maximum amplitude of the corresponding echo. Results are presented on 'Fig. 6' for both the ASME and CPFC methods of inspection. Regarding Fig. 6 the following remarks may be made :

- as the length of the defect decreases, the amplitude of the echo grows larger.
- with the ASME code, the greater number of defects are in the 0 - 12 %, range whereas this number ranges between 25 and 50 % with the CPFC method. This discrepancy is due to the difference in the methods of calibration ; multiplying the ASME amplitude by a factor 3 (9dB), the length and density of defects are in the same percentage range.
- Once this correction applied to the different NDT methods of calibration has been made, the data obtained by manufacturers gives roughly equivalent results as regard the general distribution of the length of the defects.

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The cumulative distribution function of the length of defects before repair is represented on Fig. 7. It can be seen on this figure that in the range of interest (i.e. defects longer than 20 mm) the Log-Normal distribution is a good approximation of the actual distribution.

The CDF of the length of defect, before repair, seems to depend slightly on the depth of the defect inside the weld. More than halfway through the wall (starting from the outside) the length distribution is independent of the depth. In the remaining half, the defects are usually longer as may be seen on 'Fig. 8'.

Distribution of the width of defects : The width of the defects in an important parameter for evaluating the probability of vessel failure but the constructors provide very few information about this parameter. The maximum width observed was 3.5 mm, so we tried to evaluate the width distribution of defects from the information collected on their number and length.

If one considers the elementary structure of a welding, it is constituted by a superposition of beads ; a section of wich is represented on Fig. 9. If a defect occupies a single bead, its width is the 2a diameter of the bead, but if two defects are located in two adjacent beads, they can be considered as one defect with a more important width (4a or 6a). Therefore the number and distribution of defects wider than 2a are calculated by estimating the probability that two or more defects are in overlapping, both in azimuth and transversal section. The width of defects has an importance in our problem only if the defect is located in the radial plane of the weld ; that is why the interesting coincidences to be calculated are the configurations represented on the'Fig. 9'. On the bases of the previously provided experimental data, this probability is calculated by the Monte

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Carlo method. Under the realistic assumption that the number of multiple defects is negligible as compared with the number of single ones, the collected histograms are used for choosing at random the number and the length of elementary defects. In the present paper a uniform spatial distribution of defects is assumed. This assumption could be revised in the future. The computation of coincidences gives the number and length distribution of multiple defects.

'Fig. 10' gives the resulting CDF of the lengths for defects of different widths. As could be foreseen the wide defects correspond to long defects, and the probability of occurence decreases very rapidly with the width.

Distribution of defects to be introduced in the computer code : The US and XRay NDT methods are complementary. In order to obtain conservative data, the following method will be applied :

- When a defect has been detected by one of the two methods, this defects is taken into consideration,
- When, on the other hand, both methods haves made it possible to identify a defect, the longer of the two lengths thus measured shall be adopted.

Different correction factors must be used before introducing the distribution law of defects into the computer code. A review of these correction factors shows that some are important while others are not.

. The sample size correction takes into account the total length of weld inspected, and gives a multiplication factor to be used to obtain data with a certain confidence level. The correction factor has been computed using the χ^2 law. For a confidence level of 99 %, the length of each defect has to be increased by 15 - 20 % ;

. The accuracy of the NDT equipment : few data have been published with representative material and thickness. From them it can be concluded that

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the length of defects is generally 5 % underestimated ;

- Defect detection probability : the present work has considered defects detected before repair by manufacturers so as to be able to assign to them a non detection probability. A large international program (PISC) is presently under way in collaboration with 34 organizations. Results of this programme are not yet published. They are sure to be taken into consideration after their publication ;
- The size of acceptable defects : defect distribution before repair, must be modifed, according to the acceptance criterion used for each vessel by the manufacturer. Elimination of a defect must be done while taking into account the corresponding non detection probability. The acceptance criterian are different according to which of the two sets of specifications is used. Due to the fact that the present publication concerns mainly the French reactor plant evaluation, only the CPFC criteria will be used (see 'Fig. 11').

FRACTURE ANALYSIS

The growth of each defect is computed during the life of the plant using the Paris law in a probabilistic form (Fig. 1). The procedure used for passing from dry to wet condition was presented in a previous publication (8) : any defect having its crack front closer than 8mm from the inner surface is assumed to be in wet condition. For each given size and location of an initial defect, an histogramm of defect size is obtained at the end of the plant life.Table III gives some maximum values for growth in different cases. It appears that the proximity of the internal side of the vessel increases tremendously the growth of the defects during the life of the plant ; this is due mainly to

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the assumption made for the transition between wet and dry condition, which practically means that all defects located at 9 mm in depth within the wall are considered under wet condition during the entire fatigue life.

Application of three faulted conditions, as defined in Table I, has been performed on defects after their growth during 40 years of life of the plant. The Dowling and Townley criterion (9) has been used to evaluate the onset of unstable propagation. Embrittlement of the material due to irradiation is considered (7).

Due to the extreme difficulties in characterizing crack emergence, particularly owing to the material heterogenity due to the presence of the cladding, a conservative assumption has been introduced in the modelling of crack emergence :

- an internal crack becomes unstable when K_1 exceeds K_{1c} at the crack tip of the small axis situated closest to the inner surface; it is then transformed into a semi-elliptical emerging crack having the same excentricity, and keeping its inner front at the same position as the initial crack ;
- a semi-elliptical, emerging crack becomes unstable (i) when K_1 exceeds K_{1c} at its minor axis or (ii) when K_1 exceeds K_{1c} at its major axis on the inner wall surface. It is then transformed in a longitudinal infinite surface crack having the same depth. A crack arrest criterion is then calculated for this new defect by comparing K_1 to K_{1a} . It thus becomes possible to find out whether the defect propagates laterally, through the wall, or both.

The conditional probabilities are presented in Table IV for a set of original defects with given size and position without considering the influences of periodic inspection and proof test. These probabilities

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include both types of instability as defined above. The probability of having the instability run through the wall without lateral propagation contributes in a small way to the overall probability of rupture (10 to 20 %).

This analysis involves only a criterion of initial crack instability. It does not preclude the possibility of subsequent arrest in a warmer, less irradiated zone inside the wall. It is known that the occurrence of such an arrest forms the basis of the deterministic demonstration of absence of fracture risk in the vessel belt line during a LOCA. Therefore, this analysis, in the present stage of development of the program, deals only with a partial aspect of the fracture analysis.

A sensivity study has been performed on the toughness criterion : the variation fo the conditional fracture probability is four time the variation of the K_{Ic} value, on the other hand, a variation of the crack arrest value entails an identical variation of the conditional fracture probability.

CONCLUSION

In the present time, only conditional probabilities of failure can be determined ; this is mainly due to the lack of information on the probability of occurrence of faulted conditions (LOCA-Steam break-over pressure etc...) and on the defect detection probability.

Data obtained from three manufacturers concerning the distribution of defects in LWR pressure vessels welds show the great importance of the calibration procedure of the ultrasonic method. For the most sensitive method, the density of defects is 1.2 defects per metre of weld. The length of the defects observed before repair ranges between 3 mm and 1.4 m . These defects are mainly located at the boundary between weld and base metal. The lack of information on the width of defect has been overcome using a statistical procedure. This procedure, wich uses the Monte Carlo method, gives the probability to have an overlapping between two or more defects located in two or more adjacents, 3 mm width, weld beads, in the radial direction. The probability of occurrence of a large defect decreases drastically with the number of overlap, e.g. by more than 10^{-6} for four overlaps (corresponding to a width of 12 mm).

The COVASTOL computer code is presently running. It may be used to determine by means of a sensivity analysis, the important parameters and the order of magnitude of the conditional probabilities. The work up to now performed has provided the following information :

- The fatigue crack growth computed after 40 years of life of the plant is not significant for defects having a width smaller than 12 mm and located at more than 15 mm from the internal side of the vessel.
- The length of defect does not influence significantly the failure probability.

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- Small, medium and large LOCA's lead to the same order of magnitude for the conditional fracture probability, given an initial defect having a width between 12 and 30 mm.
- For one defect of 12 mm width, located at 9 mm from the inside, the corresponding conditional failure probability of onset of propagation in the belt line, is in the order of magnitude of 10^{-3} per vessel year. It must be borne in mind that these results correspond to a fatigue crack growth in wet conditions and without considering periodic inspection and proof test.
- The failure probability decreases almost linearly when K_{1a} or K_{1c} increase, within a range of 10 %. The values of the proportionality factor are then respectively one and four.

REFERENCES

(1) 'Analysis of pressure vessel statistics from fossil-fueled power plant service and assessment of reactor vessel reliability in nuclear power plant service' WASH 1318.

(2) BECHER, P.E. and PEDERSEN, A. 'Application of statistical linear elastic fracture mechanics to pressure vessel reliability analysis' 2nd SMIRT, Berlin 1973, M6/4.

(3) MARSHALL, W. 'An assessment of the integrity of PWR pressure vessels' UKAEA, October 1, 1976.

(4) HARRIS, D.O. 'An analysis of the probability of pipe rupture at various locations in the primary cooling loaps of a B W PWR' SAI.050.77.PA.

(5) NILSSON, A. 'A model for fracture mechanical estimation of the failure probability of reactor pressure vessel' Third International Conference Pressure Vessel Technology, Tokyo 1977.

(6) VESELY, W.E. LYNN, E.K. and GOLDBERG, F.F. 'The Octavia computer code : PWR reactor pressure vessel probabilities due to operationaly caused pressure transients' NUREG-0258, 1978.

(7) DUFRESNE, J. and all 'The CEA sponsored research program on PWR reactor vessel failure probability calculation'
Probabilistic analysis of nuclear reactor safety (ANS), Los Angeles 1973.
(Fig. 3 of this reference must be corrected by the fig. 1 of the present paper).

(8) DUFRESNE, J. 'A model for the estimation of the failure probability of pressurized water reactor vessels'
ENS/ANS International Meeting on nuclear power reactor safety, Bruxelles, October 1978.

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(9) [illegible]ING, A.R. and TOWNLEY, C.H.A.

(10) MER[illegible], J.G. 'An evaluation of the HSST program intermediate pressure vessel test in terms of LWR pressure vessel safety' ORNL-TM-5090,p. 38.

(11) SMITH, T. [illegible] WARWICK, R.G. 'The second survey of defects in pressure vessels built to high standards of construction and its relevance to nuclear primary circuits' SRDR 30.

(9) DOWLING, A.R. and TOWNLEY, C.H.A.

(10) MERKLE, J.G. 'An evaluation of the HSST program intermediate pressure vessel test in terms of LWR pressure vessel safety' ORNL-TM-5090,p. 38.

(11) SMITH, T.A., WARWICK, R.G. 'The second survey of defects in pressure vessels built to high standards of construction and its relevance to nuclear primary circuits' SRDR 30.

TABLE I LIST OF TRANSIENTS

N°	TRANSIENTS	Postulated frequency for 5 years
	Normal and upset conditions	
1	Heat-up at 55 °C/h	25
2	Cool-down at 55 °C/h	25
3	Unit loading at 5 % of full power/minute between 15 % and 100 %	1500
4	Unit unloading at 5 % of full power/minute between 100 % and 15 %	1500
5	Step load increase of 10 % of full power	20
6	Step load decrease of 10 % of full power	15
7	Large step load decrease with steam dump	20
8	Steady state fluctuations	2.5×10^5
9	Feed water cycling at hot shut-down	240
10	Shutting-down of a loop	10
11	Start up of out-of-service loop	10
12	Unit loading between 0 % and 15 % of full power	310
13	Unit unloading between 15 % and 0 % of full power	270
17	Turbine trip without scram	10
18	Loss of external power	5
19	Partial loss of primary flow	10
20	Reactor trip from full power without excessive cool down.	40
21	Reactor trip from full power with excessive cool down, without safety injection	20
22	Reactor trip from full power with excessive cool down and safety injection	1
23	Inadvertent reactor coolant system depressurisation	3
24	Inadvertent start up of an inactive loop	1
26	Inadvertent ECCS actuation	10
	Faulted conditions	
27(i)	Small LOCA (50^{mm} diameter) with two emergency cooling injection pompes, two auxiliary feed water pompes and water storage tank at 10 °C.	
27(d)	Intermediate LOCA (150^{mm} diameter) with the same situation as 27 (i)	
31(1)	Large LOCA with one ECI pompe, two auxiliary feed water pompe and water storage tank at 10 °C.	

TABLE II

TRANSPOSITION OF THE REFERENCE ECHO FOR DIFFERENT METHODS OF CALIBRATION

Thickness	120 mm		200 mm	
Code	ASME	CPFC	ASME	CPFC
Hole diameter	6,35	2	7,94	2
100 % ASME correspond to	100 %	280 %	100 %	300 %
100 % CPFC correspond to	36 %	100 %	34 %	100 %

TABLE III

MAXIMUM GROWTH Δa OF THE DEFECTS DURING 40 YEARS LIFE OF THE PLANT

DEPTH (mm) SIZE (mm)		9	15	30
2a	2b			
12	120	1.3	0.15	0.13
12	24		0.09	0.07
18	180	4	1.8	0.23
18	36		0.8	0.15
30	300		6	0.52
30	60		1.8	0.3

TABLE IV

CONDITIONAL PROBABILITY OF RUPTURE FOR ONE DEFECT OF GIVEN SIZE FOR THREE ACCIDENTAL SITUATION OCCURING AFTER 40 YEARS

Defect size and position			Accidental situation (see Table I)		
2a (mm)	2b (mm)	h (mm)	27 (d)	27(i)	31 (b)
12	120	9	8×10^{-4}	2×10^{-3}	2×10^{-3}
12	120	15	$<10^{-6}$	2×10^{-5}	2×10^{-5}
18	180	9	8×10^{-3}	9×10^{-3}	9×10^{-3}
18	180	15	1.5×10^{-3}	8×10^{-4}	1.2×10^{-3}
30	60	15	3.5×10^{-3}	10^{-2}	1.5×10^{-2}
30	300	15	2×10^{-2}	6×10^{-3}	10^{-2}
30	300	30	5×10^{-4}	2.5×10^{-6}	7×10^{-5}

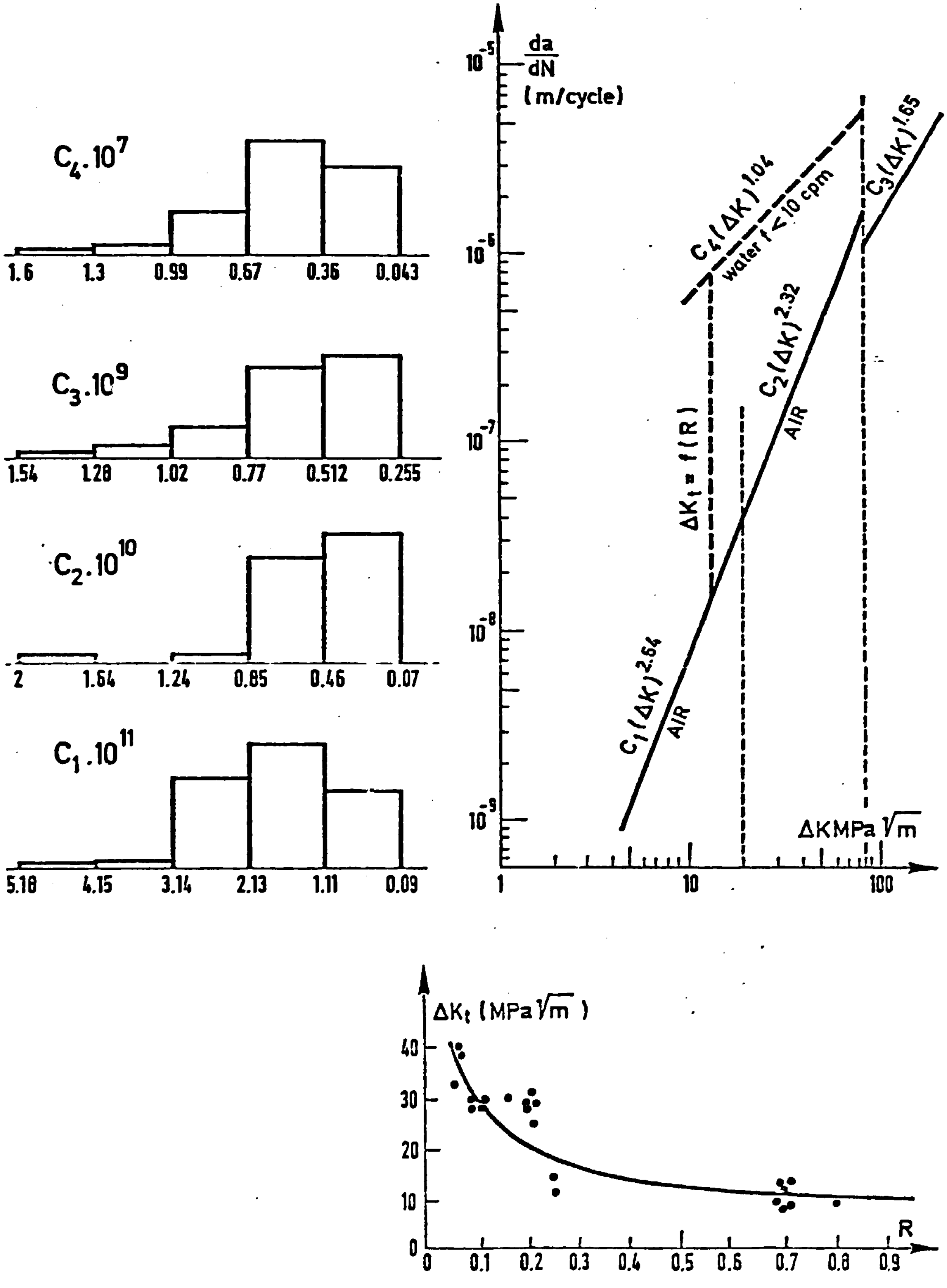
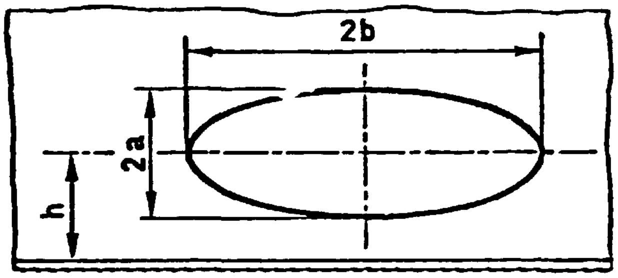

$C_4.10^7$
1.6
1.3
0.99
0.67
0.36
0.043
$C_3.10^9$
1.54
1.28
1.02
0.77
0.512
0.255
$C_2.10^{10}$
2
1.64
1.24
0.85
0.46
0.07
$C_1.10^{11}$
5.18
4.15
3.14
2.13
1.11
0.09
$\frac{da}{dN}$ (m/cycle)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$C_4(\Delta K)^{1.04}$
water f < 10 cpm
$C_3(\Delta K)^{1.65}$
$C_2(\Delta K)^{2.32}$
AIR
$\Delta K_t = f(R)$
$C_1(\Delta K)^{2.64}$
AIR
ΔKMPa $\sqrt{m}$
1
10
100
ΔK_t (MPa $\sqrt{m}$)
40
30
20
10
0
R
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Figure : 1



Internal side of the vessel

Figure : 2

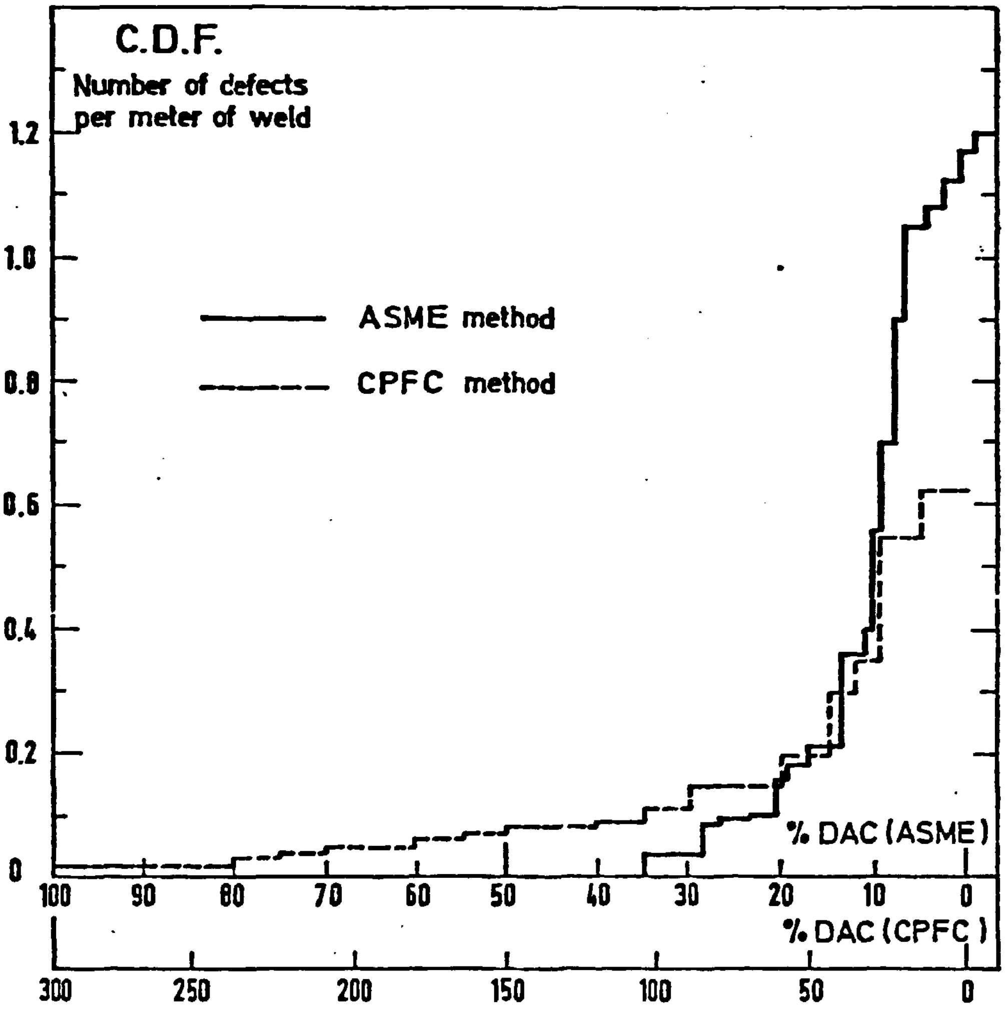

C.D.F.
Number of defects per meter of weld
1.2
1.0
0.8
0.6
0.4
0.2
0
ASME method
CPFC method
% DAC (ASME)
100
90
80
70
60
50
40
30
20
10
0
% DAC (CPFC)
300
250
200
150
100
50
0

Figure : 3

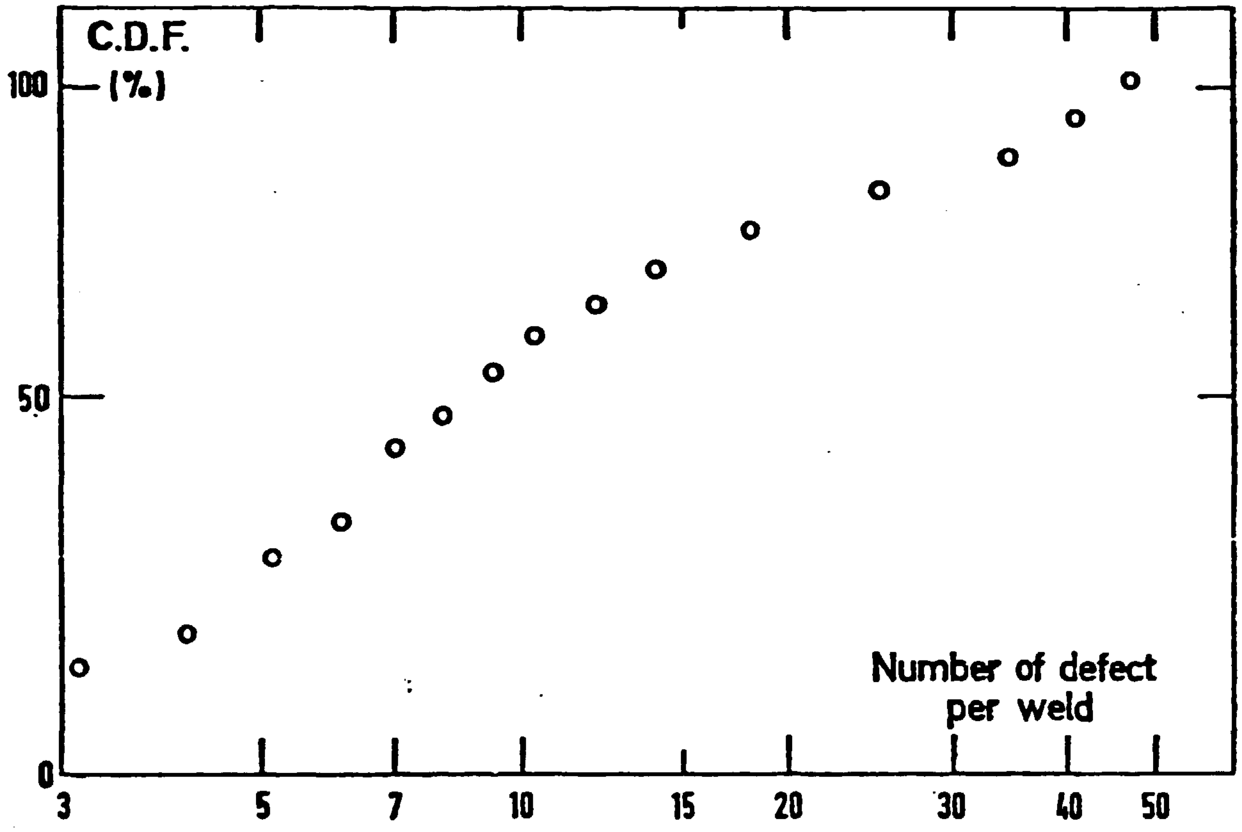
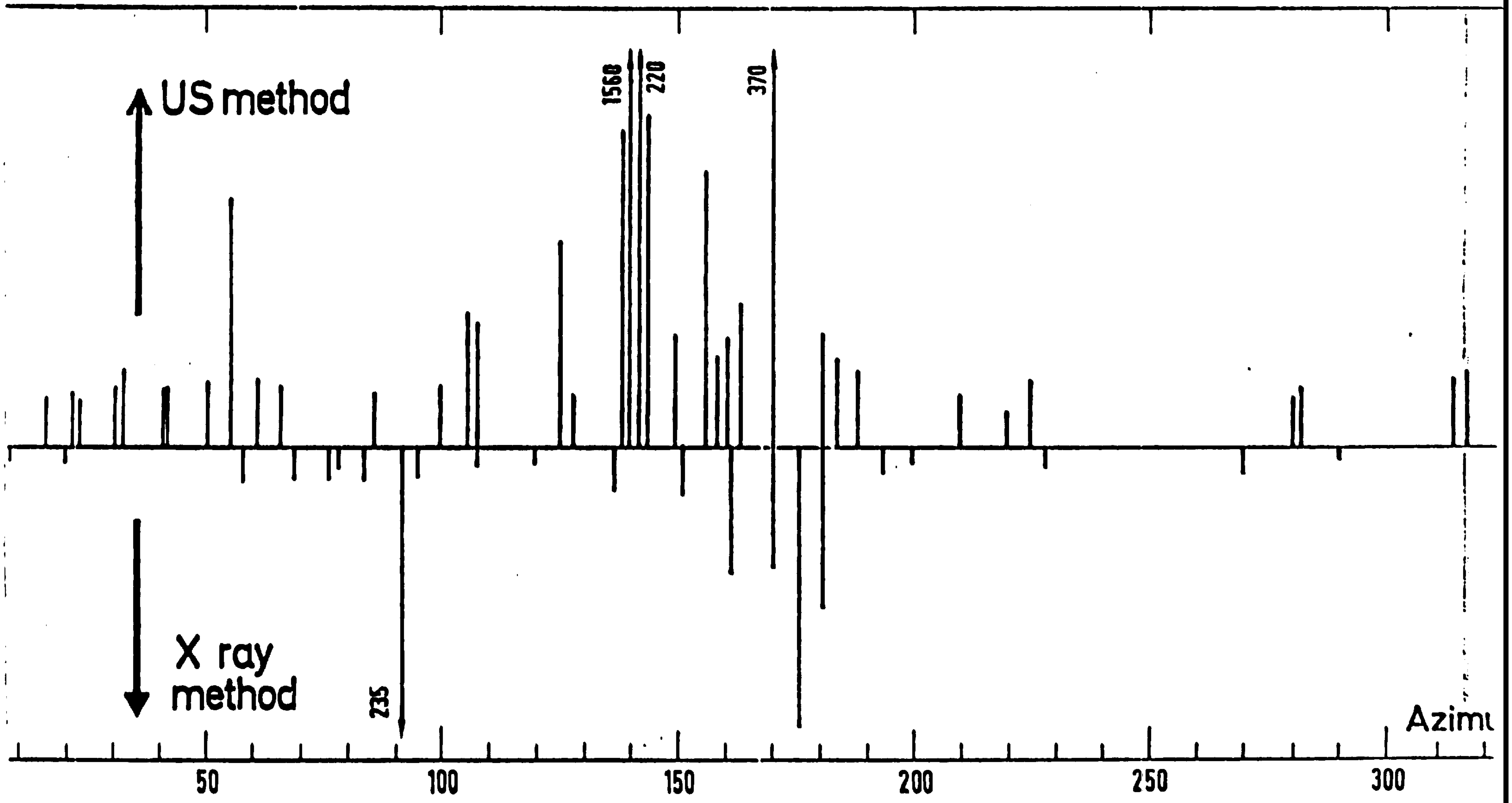


Figure : 4


US method
X ray method
1568
220
370
235
Azimu
50
100
150
200
250
300

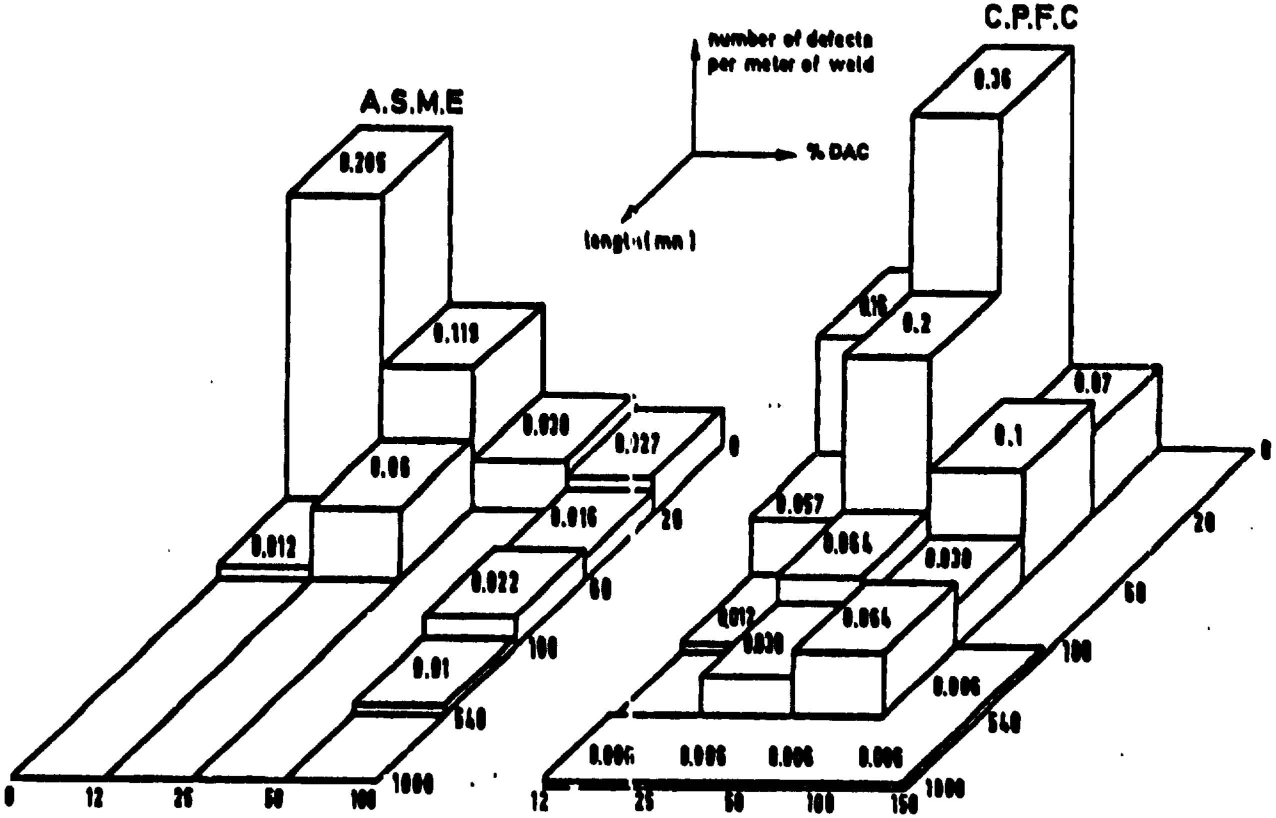

A.S.M.E
C.P.F.C
number of defects per meter of weld
% DAC
length (mm)
0.205
0.119
0.06
0.012
0.030
0.027
0.016
0.022
0.01
0
12
25
50
100
1000
20
60
100
540
0.36
0.16
0.2
0.07
0.1
0.057
0.064
0.030
0.012
0.030
0.064
0.006
0.006
0.006
0.006
0.006
12
25
50
100
150
1000
540
100
60
20
0

Figure : 6

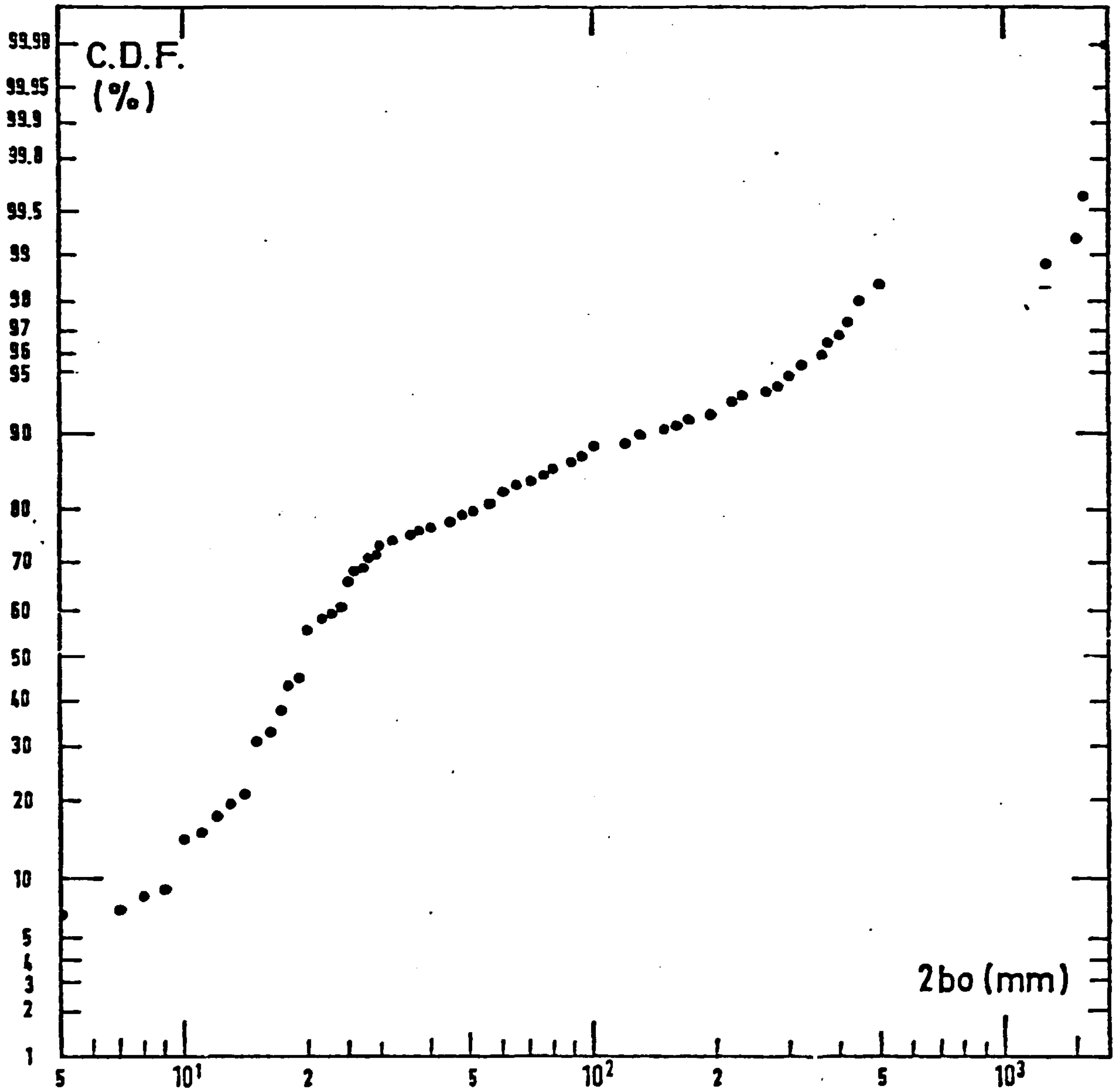

C.D.F.
(%)
99.98
99.95
99.9
99.8
99.5
99
98
97
96
95
90
80
70
60
50
40
30
20
10
5
4
3
2
1
2bo (mm)
5
10¹
2
5
10²
2
5
10³

FIGURE : 7

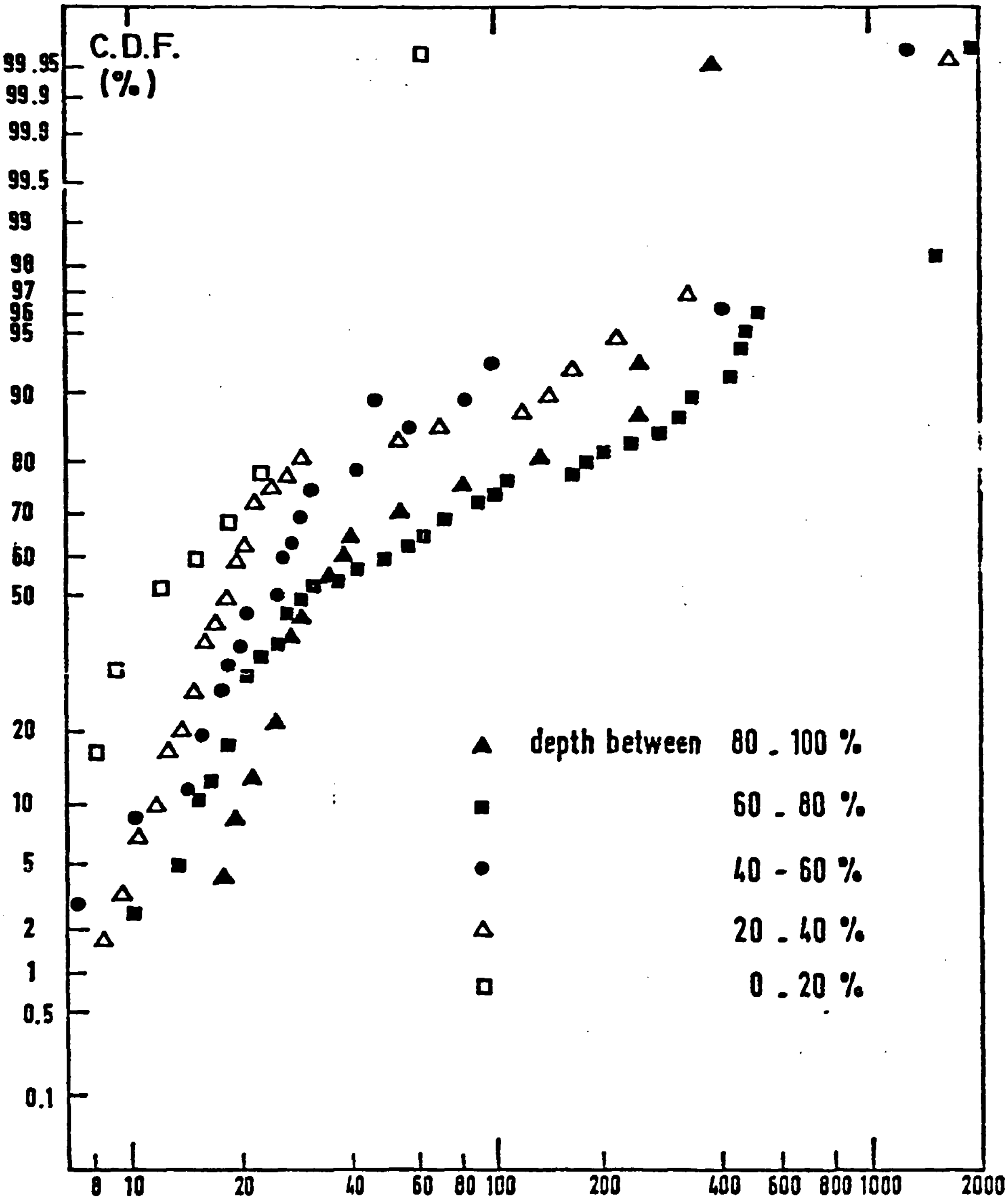

C.D.F. (%)
99.95
99.9
99.8
99.5
99
98
97
96
95
90
80
70
60
50
20
10
5
2
1
0.5
0.1
8
10
20
40
60
80
100
200
400
600
800
1000
2000
▲ depth between 80 - 100 %
■ 60 - 80 %
● 40 - 60 %
△ 20 - 40 %
□ 0 - 20 %

FIGURE : 8

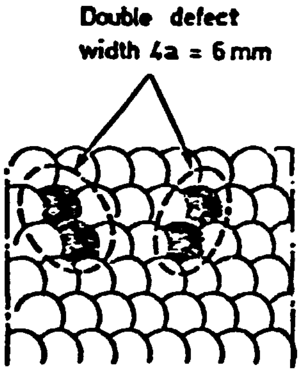


Figure : 9

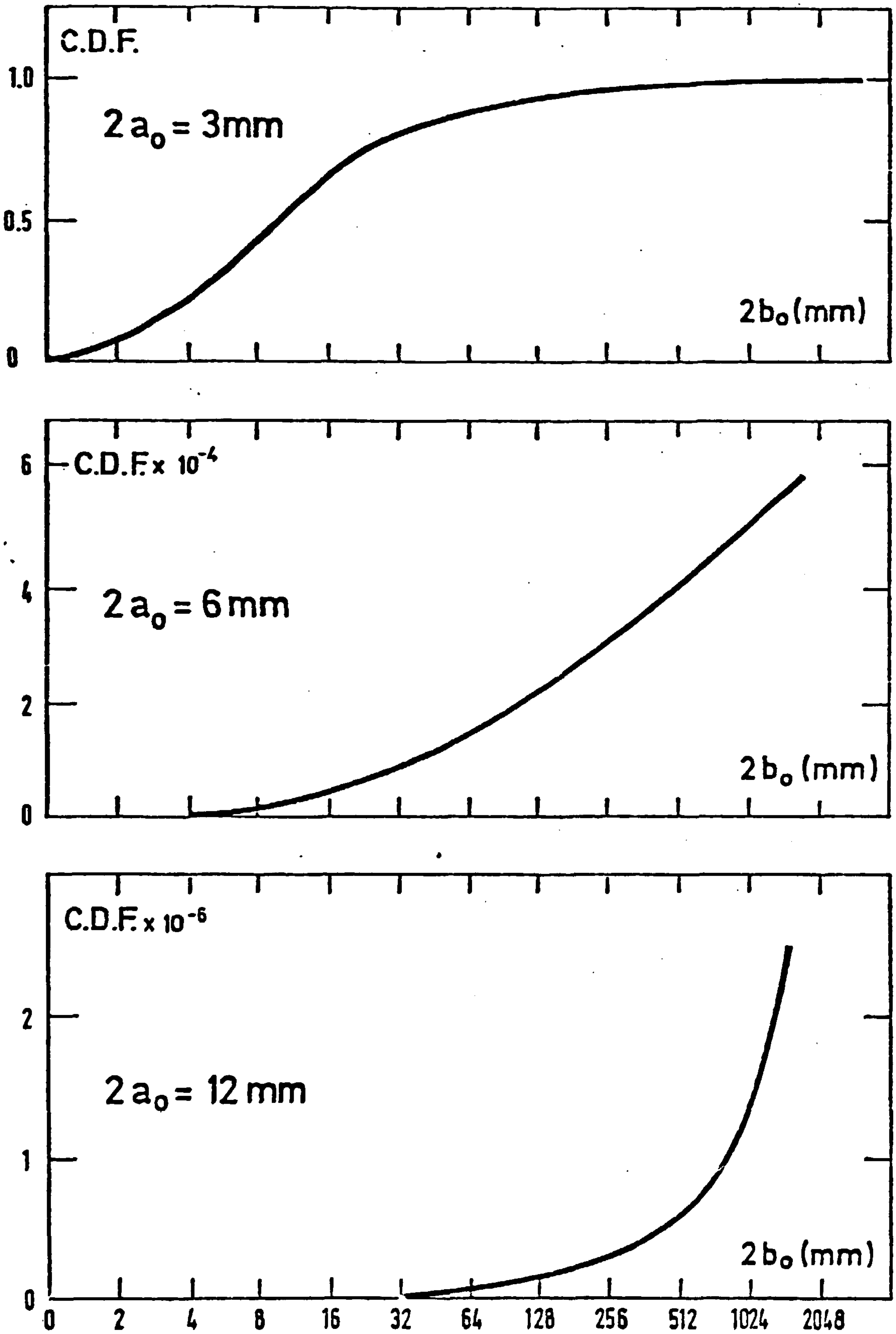

C.D.F.
1.0
0.5
0
2 a₀ = 3mm
2b₀(mm)
C.D.F x 10⁻⁴
6
4
2
0
2 a₀ = 6 mm
2 b₀ (mm)
C.D.F x 10⁻⁶
2
1
0
2 a₀ = 12 mm
2 b₀ (mm)
0
2
4
8
16
32
64
128
256
512
1024
2048

FIGURE : 10

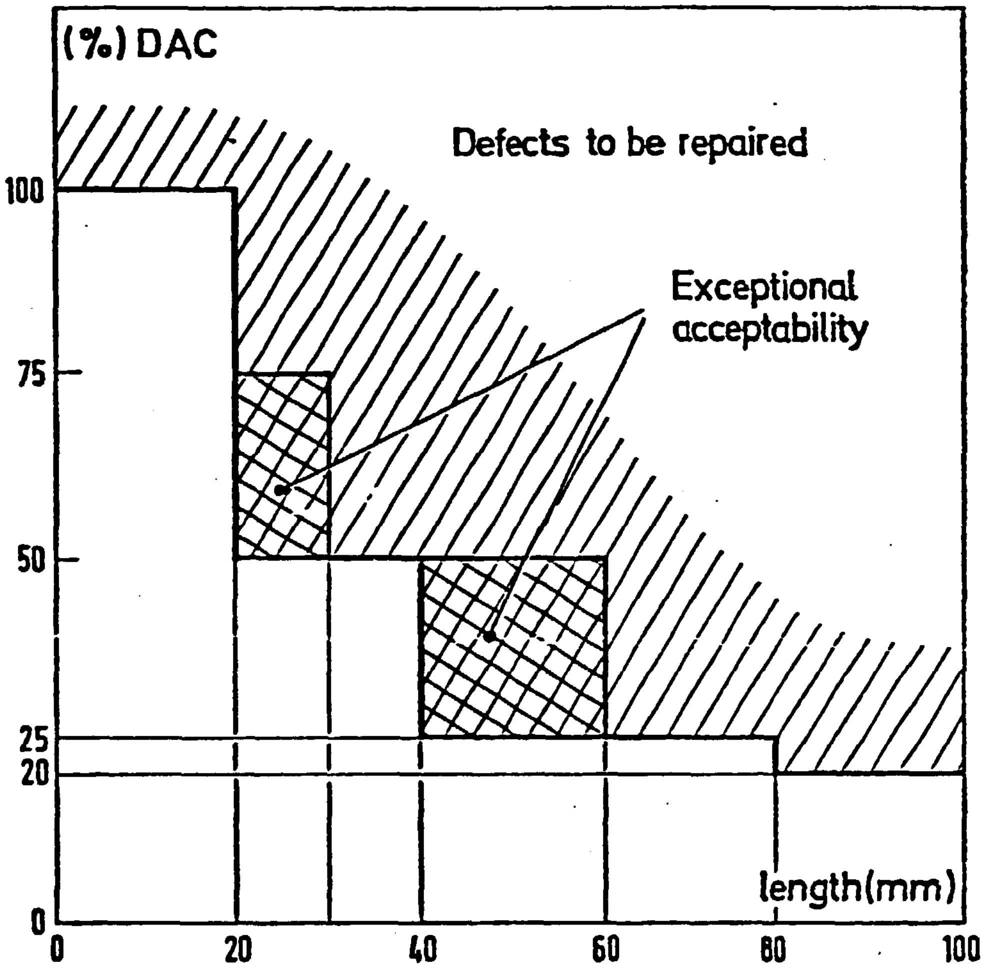

(%) DAC
Defects to be repaired
Exceptional acceptability
100
75
50
25
20
0
length(mm)
0
20
40
60
80
100

FIGURE : 11