PROBABILISTIC APPLICATION OF FRACTURE MECHANICS

J. Dufresne, CEA/DSN, Fontenay-aux-Roses (FRANCE)

ABSTRACT

The different methods used to evaluate the rupture probability of a pressure vessel are reviewed. Data collection and processing of all parameters necessary for fracture mechanics evaluation are presented with particular attention to the size distribution of defects in actual vessels. Physical process is followed during crack growth and unstable propagation, using LEFM and plastic instability. Results show that the final failure probability for a PWR pressure vessel is 3.5 10^{-8}, and is due essentially to LOCAs for any break size. The weakest point is the internal side of the belt line.

KEYWORDS

Rupture probability - nuclear pressure vessel - sizing of defects - NDE reliability.

INTRODUCTION

The increasing cost and consequences of failure of pressure vessels ranging from consumer products to nuclear power reactors have resulted in the increased need for assuring the structural reliability and consequently for evaluating the probability of failure.

One method used to determine reliability simply extrapolates from past failures found in conventional pressure vessels and ignores many physical details of the system. This approach has been taken by several investigators. A general review of published papers has been performed by S.H. Bush (1), the 99 percent confidence upper bound failure rates are presented, including the extrapolation to nuclear pressure vessel by a selection of representative pressure vessels. The disadvantage of such an approach is that the capability to predict the effects of systematic changes in key parameters is quite limited. For example, the influence of irradiation and the use of quality assurance programs encompassing design, fabrication and materials cannot be considered, but the most important disadvantage of this method is the limitation of a representative population and consequently the high value of the upper bound failure rate corresponding to a 99 % confidence level. It can be shown that a probability of rupture of 10^{-6} with an upper bound confidence level of 99 %, can be obtained only if no rupture has been observed with a population representative of nuclear pressure vessel of 5.10^{6} vessel years. At the present time, the population of nuclear pressure vessel totals up to 1.5 10^{3} vessel years.

Nevertheless this statistical approach gives important information concerning the causes of the rupture. Lancaster (2) indicates that the causes of most failures is the presence of cracks due to welding, often combined with embrittlement due to defective heat treatment. This is confirmed by Smith and Hamilton (3), Smith and Warwick (4) and Burgess and co-workers (5).

A second approach to the evaluation of pressure vessel rupture probabilities involves the development of physical models based on an understanding of the failure modes and the statistical distributions of the controlling parameters. Such models can give more than the absolute probability of failure, and are able to answer questions such as : what is the weakest point of the structure, what is the influence of a modification of the fabrication process or of the operation of the plant, what is the most adequate frequency of in service inspection, what is the relative weight of the different parameters. The disadvantage of such an engineering probability approach is its relative complexity, which requires more input parameters hence errors introduced due to lack of data and poor assumptions.

On the other hand, due to the necessity to follow as closely as possible the physical process leading to the failure, it is necessary to use best estimate data and formulae without any safety factor or conservative assumption.

Several authors have proposed to use fracture mechanics under probabilistic form. Wilson (6) makes an estimate of pipe reliability by "the distribution of time to damage method", Becher (7), Besuner (8) and Kitagawa (9) use a Monte Carlo method. Marshall (9), Harris (10) and Nilsson (11) use an analytical method. However, most of these authors use simplified methods, in particular they do not take into account the effect of the irradiation on the toughness of the material, the position of the defect through the thickness, the different crack growth rate in the case of flaws under wet or dry condition, the crack arrest during unstable crack propagation. To be as close as possible to the physical process, a computer code has to take into account all these parameters.

A computer code has been developed jointly by CEA, Euratom, Ispra and Framatome. This code is based on the linear elastic fracture mechanics and is all along as close as possible to the physics of the phenomena. It has been designed for application to nuclear reactor pressure vessels. According to the observations found in the literature (Ref. 2-3-4 and 5) the only areas considered are : all the welds of the pressure vessel, including nozzle attachment welds, and the inner side of the nozzle including the internal corner. The main assumptions introduced in the code are the following : only unintentional incidents are dealt with, no manufacturing errors are committed in the workshop, wear and stress corrosion are not considered as a crack initiation factor, irradiation has no effect on the crack propagation rate, the presence of inner stainless steel cladding is taken into account for thermal analysis, but not for stress calculation, the load application order has no effect on the total crack propagation, there is no incubation period before a crack begins to run, there is no minimum threshold in the crack growth rate, real defects are represented as ellipses and are always oriented perpendicularly to the maximum stress, and relaxation heat treatment eliminates all residual stresses.

We must turn now to the method used to collect all data to be introduced in the computer code.

DISTRIBUTION OF ACTUAL SIZE OF DEFECTS

The starting point is the collection of the defects likely to remain, following fabrication and control, according to a certain rule. This distribution of the defects on a vessel entering service includes the defects considered acceptable according to the rules, as well as those remaining undetected during manufacture. In view of the quality control and quality insurance, most defects arising during manufacture will be detected and then repaired. Some publications give information with defect distributions :

- Nichols (12) reports 153 defects for 2,236 meters of weld without giving any information on their dimensions,
- Becher (13) has identified 242 defects for 347 radiographies corresponding to 72 meters of weld performed on hull plate from 22 to 26 mm thick, and gives the length and depth distribution,
- Caplan (14) has observed 738 weldments corresponding to 36 vessels ; the number of defects per vessel varies from 0 to 66 and the size is given for 6 of them,
- Kihara (15) reports 1630 defects for 22,000 m of weld of 30 mm thick spherical vessels and gives two histograms of their length and deptn,
- Marshall (9) indicates that in 44 vessels, 12 defects were found with depths in the range 0.5 to 1 inch, and no defects of depths larger than 1 inch were observed.

In our case, we have sponsored three contracts with 3 European nuclear pressure vessel manufacturers. Each of them has given all information on NDE results (UT or X Ray) before repair. The processing of this information has been published previously (16) and the main conclusions are the following :

- density of defects : the number of defects per weld varies from 0 to 50,
- position of the defects in the weld : there is no clear distribution of the defects according to their depth and to their position in relation to the symmetry plane of the weld, but, for a given weld, defects are frequently gathered in some limited areas of the weld, this is probably due to an occasional misadjustment of a parameter during the welding process,
- length of the defects : the cumulative distribution function before repair shows that, for defects larger than 20 mm, the Log-Normal distribution is a good approximation.

As regards the width distribution of the defects, unfortunately no data have been obtained from manufacturers. After discussion with experienced welding operators, it seems that a defect larger than a single bead is very unlikely. Therefore, the number and distribution of defects wider than one bead has been calculated by estimating the probability that two or more defects are overlapping, both in azimutal and transversal section. This probability is calculated by a Monte Carlo method.

The distribution of length and width so obtained corresponds to the observed defects in a weld after fabrication and before repair, but the distribution to be introduced in the code must be processed in order to take into account the following factors : the sample size, the accuracy of the measurement equipments, the reliability of the NDE methods and equipments and the size of acceptable defects according to the rule to be considered.

Concerning the accuracy of the NDE equipments, three experiments have been performed, using welds having significant thicknesses :

- Caplan (14) has extracted 7 defects from nuclear pressure vessels during fabrition and compared their actual size with NDE measurements,
- Chiret et Varcin (17) have performed systematic measurements with thick grooved blocks,
- Lautzenheiser (18) presents three different NDE measurements performed on a nuclear

pressure vessel and compares them with in site size measurement.

From these publications, it can be concluded that the length of defects is generally 5 % underestimated.

Concerning the reliability of the NDE methods and equipments, a large program has been developed in aircraft and satellite design, but the thickness is always very small. On the other hand, two documents present the synthesis of all results published up to now : one from OCDE (19) and other from Bush (20). Marshall (9) has estimated the efficiency of ultrasonic detection by means of a questionnaire sent out to 20 experienced operators asking each individual for his estimate of the efficiency he would expect in searching for defects of a specific type. The results are presented Fig. 1 with the results of the PVRC 201 plates, EPRI, Welding Institute and Nilson hypothesis.

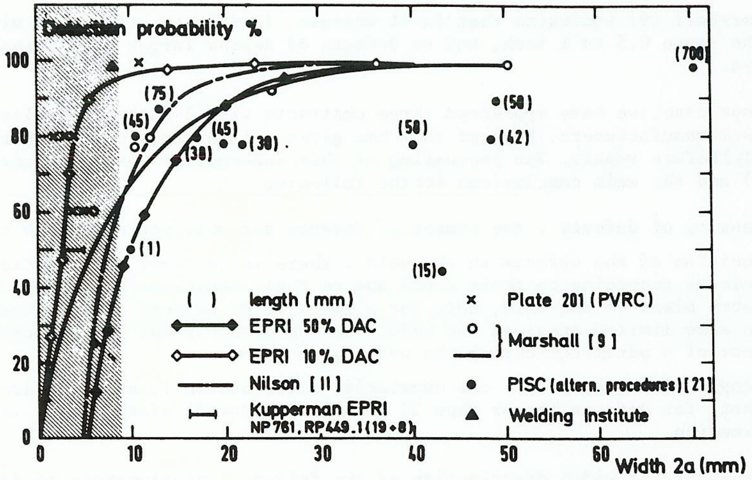

Fig. 1 Reliability of NDE methods : collected data

Three other plates from PVRC have been sent in Europe in the frame of the PISC program. Conclusions have been published (21) and alternative procedure results are presented Fig. 1. These results show that for a width less than 9 mm, the detection probability is not correlated to the width, whatever the length may be. For a width exceeding 9mm, PVRC and PISC results show a correlation between width and detection probability.

In fact, it can be assessed than the longer the defect, the greater the number of crossings of the ultrasonic transducer ; consequently, the risk of missing a defect is reduced, and the probability that the reflectivity will be more favorable is higher. Assuming P_1 to be the probability to detect a flaw at each crossing and P_n the probability to detect after n crossing along a defect. We have : $P_n = P_1 + (1 - P_1) P_{n-1}$ corresponding to $P_n = 1 - (1 - P_1)^{2b/\phi}$ 2b is the length of the defect and ϕ the diameter of the beam which is assumed to be roughly equal to the pitch of investigation. For a large defect we assume that the detection probability is ever higher than 0.99.

The detection probability vs. Defect length and width is presented on Fig. 2, where the probability to detect a 9 mm-long defect is taken as 50 %, the beam diameter as 40 mm, and where the detection probability as a function of the width, as given on Fig. 1, is used.

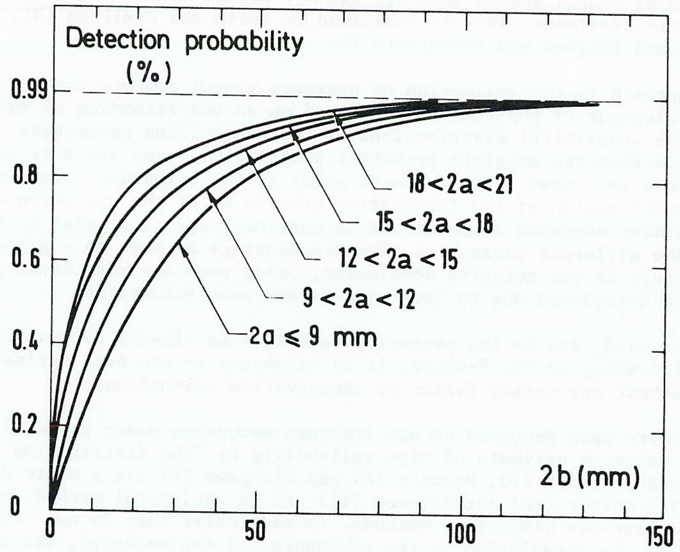

Fig. 2 Reliability of NDE methods : assumed values

The distribution obtained from manufacturers must be corrected to take into account the accuracy and the reliability of NDE methods. The distribution so obtained is the likely distribution of defects after fabrication and before repair (Table 1). This new distribution must be processed again to simulate the repair criterion according to the rule considered. All defects larger than the acceptable size are to be removed with the exception of the overlooked defects according to Fig. 2. The final distribution of defects after fabrication and repair is presented in Table 2. These values are not very sensitive to the diameter of the beam (ϕ). A sensitivity study has been performed for ϕ = 20 mm and 100 mm, and the results differ by a maximum of 60 %. Table 2 shows that for a width between 3 and 9 mm, the defects are relatively short and for a width larger than 9 mm, the defects are very long.

It is to remember that the methodology used to evaluate the final distribution assumes a complete independence between defects ; in particular, common mode, such as bad adjustment of the torch, poor preparation of the plate, wrong operation during repair, has not been considered.

CRACK GROWTH RATE

An overall statistical interpretation of all the available (da/dN) vs. ΔK measurement points has been made for the SA 508 and SA 533 B steels, using the four laws : Paris, Forman, Priddle and Walker. Numerical coefficients habe been calculated for each of these formulae by linear regression from 3,150 experimental results and by several partitions of the stress intensity measurement range. Then the reduced mean deviation, the standard deviation between calculated values and measured values, and the coefficient of determination have been evaluated for each law and each partition. Paris law has been found to be the best correlation for this application, the distribution of the parameters C and n of the Paris law has been published previously(16), it takes into account the environment of the crack : air or water.

Loading of the vessel has been computed for 22 observable conditions anticipated to the scheduled operations of the power plant and to operating incidents (ANS Conditions I and II and second category conditions according to the French standard "Arrêté du 26.02.74"). The frequency of occurrences of these conditions (16) is determined on the basis of statistical data from nuclear and, in some cases, from fossile power plant operation. The evaluation of these frequencies has been chosen "best estimated" rather than "envelope" such as those considered for design safety evaluation.

TABLE 1 Number of defects per weld before repair

2a \ 2b	8	16	32	64	128	250	500	1000	2000
3		5.3	11	1.49	0.9	0.58	0.58	0.25	0.19
6		0.0034	0.036	0.036	0.02	0.024	0.04	0.04	0.06
9			0.017	0.017	0.01	0.012	0.02	0.02	0.03
12			10^{-4}	$2.4\ 10^{-4}$	$2.8\ 10^{-4}$	$5.5\ 10^{-4}$	$1.6\ 10^{-3}$	$3.7\ 10^{-3}$	$8.5\ 10^{-3}$
15			$3\ 10^{-5}$	$6.0\ 10^{-5}$	$7.2\ 10^{-5}$	$1.4\ 10^{-4}$	$4.0\ 10^{-4}$	$9.4\ 10^{-4}$	$2.0\ 10^{-3}$
18				$1.4\ 10^{-6}$	$1.7\ 10^{-6}$	$4.5\ 10^{-6}$	$2.0\ 10^{-5}$	$6.7\ 10^{-5}$	$2.5\ 10^{-4}$
21				$2.2\ 10^{-7}$	$2.8\ 10^{-7}$	$7.0\ 10^{-7}$	$3.3\ 10^{-6}$	10^{-5}	$4.0\ 10^{-5}$

TABLE 2 Number of defects per weld after repair

2a \ 2b	8	16	32	64	128	250	500	1000	2000
3		5.3	7.3	0.56	0.07	$5\ 10^{-3}$	$5\ 10^{-3}$	$2\ 10^{-3}$	
6		$3\ 10^{-3}$	0.023	0.013	$1.7\ 10^{-3}$	$2\ 10^{-4}$	$4\ 10^{-4}$	$4\ 10^{-4}$	$5.0\ 10^{-4}$
9			0.011	$6\ 10^{-3}$	$5.0\ 10^{-3}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$2\ 10^{-4}$	$3.0\ 10^{-4}$
12			$5.6\ 10^{-5}$	$7\ 10^{-5}$	$1.2\ 10^{-5}$	$6\ 10^{-6}$	$1\ 10^{-5}$	$5\ 10^{-5}$	$8.0\ 10^{-5}$
15			$1.4\ 10^{-5}$	$1\ 10^{-5}$	$3.0\ 10^{-6}$	$1\ 10^{-6}$	$4\ 10^{-6}$	$9\ 10^{-6}$	$2.0\ 10^{-5}$
18				$2\ 10^{-7}$	$4.2\ 10^{-8}$	$4\ 10^{-8}$	$2\ 10^{-7}$	$6\ 10^{-7}$	$2.5\ 10^{-6}$
21				$4\ 10^{-8}$	$7.0\ 10^{-9}$	$7\ 10^{-8}$	$3\ 10^{-8}$	10^{-7}	$4.0\ 10^{-7}$

The maximum and minimum values for the main primary and secondary stresses during each transient are calculated in relation with the location in the wall thickness. The $\Delta\sigma$ taken into account for the calculation of the ΔK entering in the Paris' law is the largest value of the three $\Delta\sigma$ variations in each of the main stresses.

For the calculation of the ΔK, the stress is calculated at both ends of the small axis. The ΔK is computed using an analytical formula specially developed for long cracks.

- For embedded cracks at the small axis

$$\Delta K_x = \frac{\Delta\sigma \sqrt{\P a}}{E\,(k)} \quad \exp\left[\,0.25\ (a/d)^4 \quad \sqrt{b/a})\right] \qquad \text{for } b/a < 11 \qquad (1)$$

When b/a is larger than 11 we take $b/a = 11$

- For embedded crack at the long axis $\Delta Ky = \Delta Kx \quad \sqrt{a/b}$ (2)
- For surface crack on the small axis at the deepest point

$$\Delta K = \Delta\sigma \sqrt{\P a} \left[\,1.14 - 0.48.a/b + \frac{1}{0.2 + 4.9\ (a/b)^{1,2}} \left(\frac{a}{h}\right)^2\right] \qquad (3)$$

- For surface crack on the emergence point

$$\Delta K = \Delta\sigma\ a \sqrt{\P/b} \left[1.3 - 0.57.a/b + (1.8 - 1.46\ a/b)\ (a/h)^2\right] \qquad (4)$$

These formulae have been derived from finite elements computation using the weighting function method (22). The maximum discrepancy is 10 % (Fig. 3 and 4).

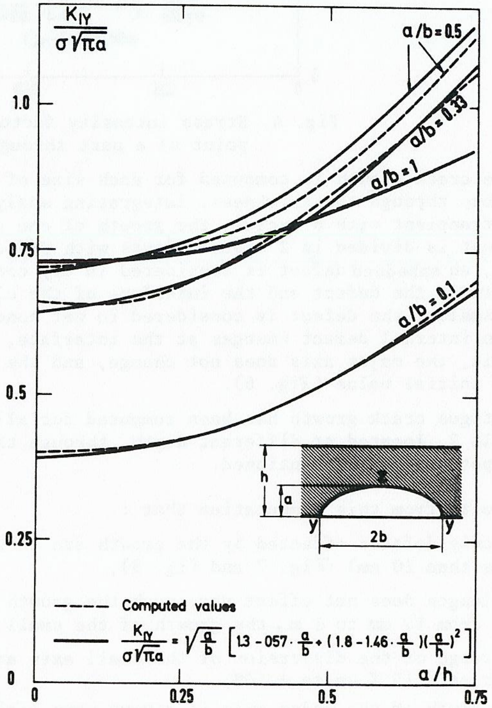

Fig. 3 Stress intensity factor at the emergence point of a part through crack

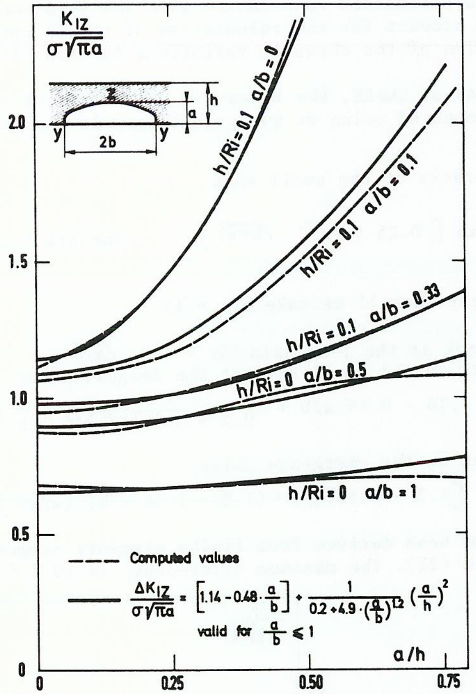

Fig. 4 Stress intensity factor at the deepest point of a part through crack

Fatigue crack growth is computed for each size of defects (Table 2) and for five positions through the thickness, integrating analytically the Paris' law. Where, for a transient with N cycles, the growth of one axis is higher than 10 %, the transient is divided in 2 subtransients with N/2 cycles each. During fatigue crack growth, an embedded defect is considered in dry condition when the ligament remaining between the defect and the interface of the cladding is larger than 8 mm ; when it is smaller the defect is considered in wet condition (Fig. 5). On the other hand, when an internal defect emerges at the interface, we assume that it becomes semi-elliptic, the major axis does not change, and the small axis doubles with respect to its initial value (Fig. 6).

The fatigue crack growth has been computed for all sizes of the defects presented in Table 2, located at different depth through the thickness, and according to the the hypothesis above mentioned.

It results from this computation that :

- the only defects affected by the growth are those close to the internal surface (less than 20 mm) (Fig. 7 and Fig. 8),
- the length does not affect very much the growth of the defect, when the length goes from 16 mm to 1 m, the growth of the small axis increases by 7 %,
- the range of the dispersion of the small axis around the medium value is of the order of - 15 % up to + 40%,
- the growth of the major axis is always very limited.

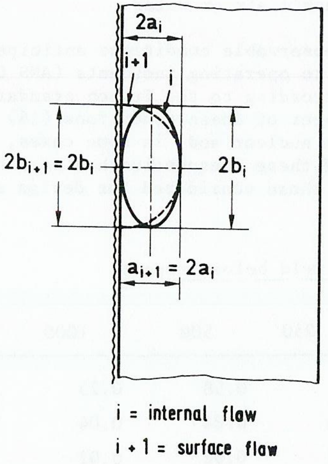

Fig.5 Transition between internal and surface flaw

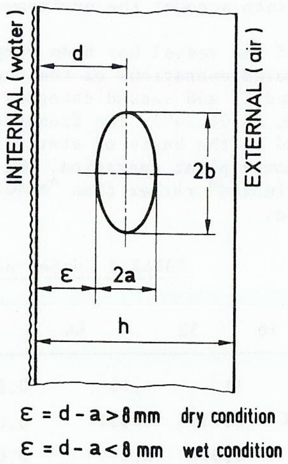

Fig.6 Transition between dry and wet conditions

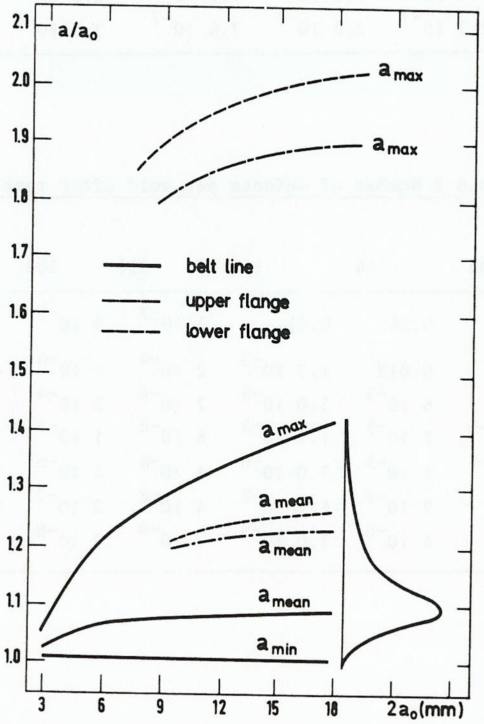

Fig. 7 Fatigue crack growth at the 40 th year of an initial emerging defect, at different positions in the vessel

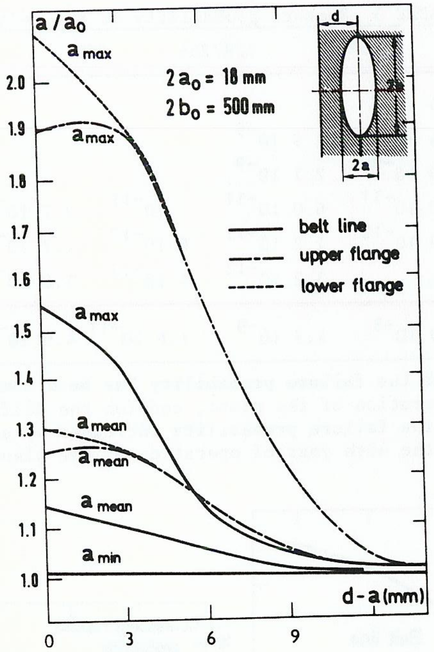

Fig. 8 Fatigue crack growth at the 40 th year of a defect (18 mm x 500 mm) located at different depth in the wall

FAILURE OR LEAKAGE PROBABILITY

Failure can occur in different situations : either under normal and upset conditions, or under emergency and faulty conditions. In the first case, it can be due to a through-crack propagated by fatigue or to an instability when the stress intensity factor becom larger than the toughness. Evaluation of both phenomena has shown that, for crack size distribution computed at the end of life of the plant, the probability of occurrence was negligible. The second category encompasses Faulted conditions (ANS Conditions III and IV, and Third and Fourth Category Conditions according to the French "Arrêté du 26.2.74"). The probability of occurrence of these latter conditions during the life of the power plant is very low, and they are therefore not taken into consideration for crack propagation. However, these conditions are involved in the probability of fast fracture calculated at any given moment in the plant operating life.

Identification and quantification of these conditions have been performed using event tree analysis, followed by grouping in few envelopes faulty conditions to which is assigned a probability of occurrence. Faulty conditions so defined concern :

- LOCA with different breach sizes, different temperatures of the ECCS water storage tank, and different time to operate the core cooling recirculation system,
- Steam break, with different breach sizes, with and without electrical power, and different times to depressurise the primary circuit.

For all the situations thus defined a transient thermoelastic analysis is made at different depths. Temperature and the three main stresses are computed at different

times during the transient, and the stress intensity factor is computed using formula (1)(2)(3)(4) with plastic zone correction. Different approaches for rupture criteria have been considered : LEFM-EPFM and plastic instability. After comparison of various criteria with 141 experimental data it has been concluded that the criterion proposed by Dowling and Townley (23) gives a good approximation in plasticity and brittleness conditions by computing stress intensity factor as determined by formulae (1)(2)(3)(4) and using the Merkle (24) formula to evaluate the upper-shelf plastic instability pressure.

The toughness of the carbon steel has been determined according to copper and phosphorus content, fluence, temperature, position through the thickness and around the weldment (16).

The modelling of the crack evolution during a transient has been performed according to the simplified hypothesis presented on fig. 9. It is assumed that when an internal defect becomes unstable, it is transformed in a semi-elliptical surface crack having the same excentricity and keeping its inner front at the same position as the initial crack. This modelling does not consider all the possibilities ; this is due to the fact that the inner side of the vessel is always more brittle than the rest of the material. On the other hand, when a defect becomes unstable through the thickness, the code does not preclude the possibility of subsequent arrest in a warmer and less irradiated zone through the wall.

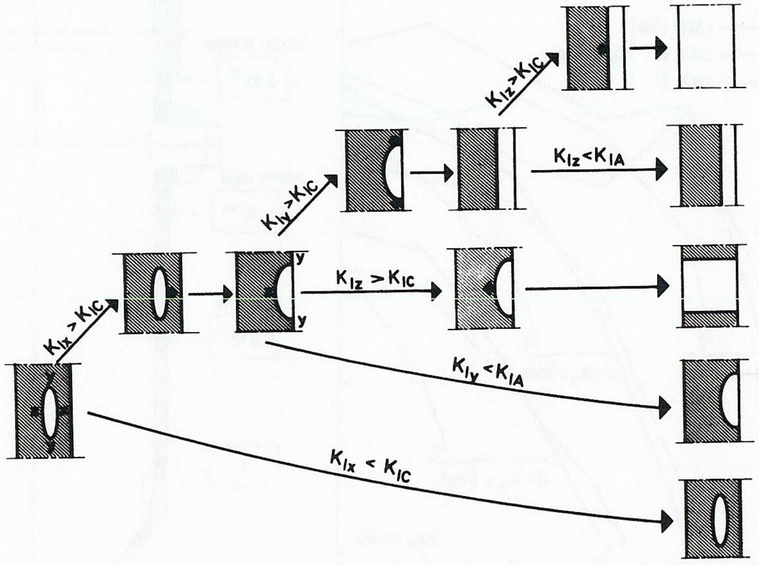

Fig. 9 Modelling of a crack evolution during fast propagation

RESULTS

The computer code COVASTOL has been used to evaluate the rupture probability of a three-loop PWR pressure vessel in its 40th year of operation. The distribution of initial defects has been taken from Table 2, and all the above mentioned situations have been applied. Conditional probability has been computed for a given defect at a given position. Fig. 10 shows that the rupture probability is roughly the same for large and intermediate LOCAs and is three times lower for a small LOCA. Rupture probability is stabilized at a given depth, when the width reaches a certain value ; this is due probably to the fact that toughness and stress intensity factor increase in the same manner. As it has been shown for the fatigue crack propagation, the position through the thickness is an important factor.

An overall probability computation has been performed for all situations above-mentioned with the following probabilities : large LOCA 10^{-4}, intermediate and small LOCA 5 10^{-4} and 10^{-2}, large steam break 10^{-3}. Results for the belt line are presented Table 3 as a function of the defect size. The contribution of faulted conditions are : 2.5 10^{-9} for a large LOCA, 9 10^{-9} and 2.2 10^{-8} for intermediate and small LOCAs; no probability has been found for steam break accident.

For all accidents concerned, the contribution of the different welds of the vessel is represented fig. 11. Computation has been performed for different temperatures of the Emergency Core Cooling Water, the rupture probability becomes 10 times larger when the temperature goes from 20 to 3 °C and is 3 times larger when the temperature varies from 20 °C to 10 °C.

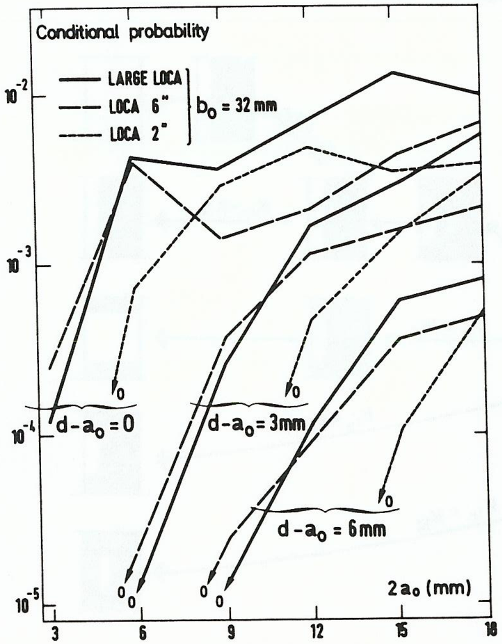

Fig. 10 Conditional rupture probability versus initial width for one defect, during various LOCAs occuring at the 40th year.

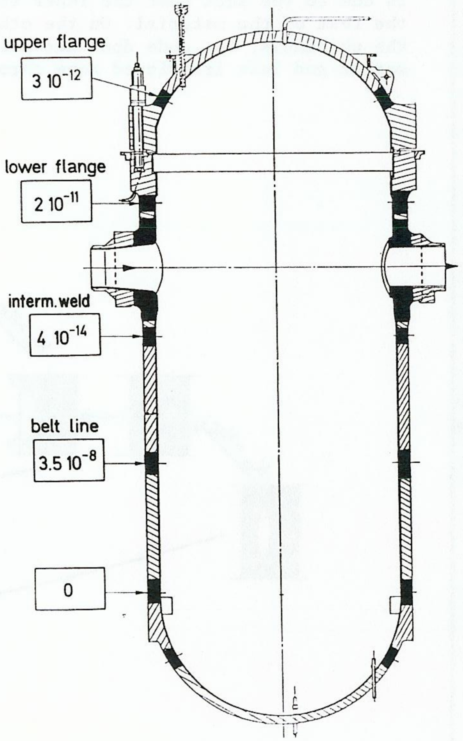

Fig. 11 Rupture probability of different welds at the 40th year.

TABLE 3 Rupture probability of the belt line

2a \ 2b	16	32	64	128/256	500	1000	2000	Σ
3	$8.1\ 10^{-9}$	$1.4\ 10^{-8}$						$2.3\ 10^{-8}$
6	$1.5\ 10^{-11}$	$1.4\ 10^{-9}$	$1.9\ 10^{-9}$					$3.3\ 10^{-9}$
9	$4.3\ 10^{-10}$	$3.9\ 10^{-9}$	$2.7\ 10^{-9}$					$7.0\ 10^{-9}$
12	$2.7\ 10^{-12}$	$2.0\ 10^{-11}$	$6.0\ 10^{-11}$	10^{-11}	$2.7\ 10^{-11}$	10^{-10}		$2.0\ 10^{-10}$
15		$1.9\ 10^{-12}$	$1.2\ 10^{-11}$	$6\ 10^{-12}$	$1.7\ 10^{-11}$	$4.3\ 10^{-12}$		$4.2\ 10^{-11}$
18			$3.2\ 10^{-13}$	$4\ 10^{-13}$	$1.8\ 10^{-12}$	$5.8\ 10^{-13}$		$3.0\ 10^{-12}$
Σ	$8.6\ 10^{-9}$	$1.9\ 10^{-8}$	$4.7\ 10^{-9}$	$1.6\ 10^{-11}$	$4.6\ 10^{-11}$	$1.2\ 10^{-10}$		$3.4\ 10^{-8}$

The time-dependence of the failure probability has been computed for a time between 20 and 40 years of operation of the plant, and for the different welds of the vessel. Figure 12 shows that the failure probability increases by a factor larger than 100 between the 20th and the 40th year of operation of the plant.

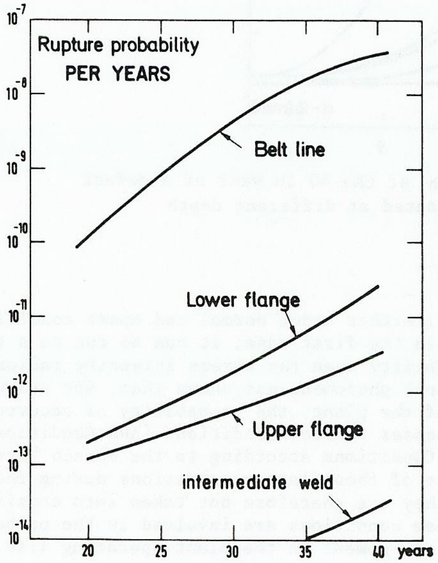

Fig. 12 Evolution of the rupture probability versus operation time for different welds.

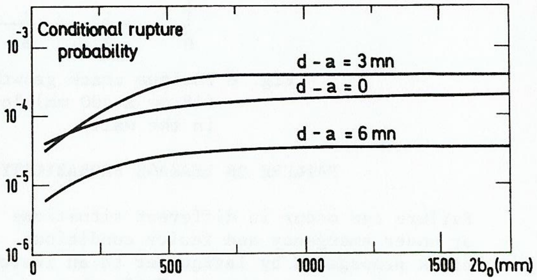

Fig. 13 Influence of the length of the defect on the conditional rupture probability at the 40th year for one defect of 18 mm width situated at different depths through the belt line.

The influence of the position of the defects has been investigated. Figure 13 shows that, for the belt line, the conditional rupture probability decreases by a factor 10 when a defect goes from the internal surface to a depth of 6 mm, the same figure shows that the failure probability is relatively insensitive to the length of the defect when the latter is longer than 0.5 metre.

To evaluate the weight of the main parameters used in the code, a sensitivity study has been performed varying K_{1c}, K_{1a} and the size distribution of the defects. The results are presented Table 4. This Table indicates that the more sensitive parameter is the toughness ; however, its influence seems lower than it has been found by H. Kitagawa (25) who attributed an increase of the rupture probability from 100 % to 500 %, according to the time, to a decrease of 10 % on the K_{1c}.

The influence of the transition criterion between dry and wet condition has been also investigated, the criterion used in the code is a 8 mm thick ligament between the defect and the interface of the cladding. A computation has been performed, for defects size givenby Table 2, assuming that the environment becomes wet when the defect becomes tangent to the interface of the cladding. Results show that the rupture probability decreases by a factor less than 2.

TABLE 4 - Sensitivity Study

PARAMETE	VARIATION	INFLUENCE ON THE RUPTURE PROBABILITY
Ki_c	+ 10%	- 40%
Ki_a	+ 10%	- 10%
Width of all defects	+ 10%	+ 20%
length	+ 10%	+ 2%

CONCLUSION

In this paper, we have formulated the failure probability of a pressure vessel so as to follow as closely as possible the physical processes involved during all the life of the plant and we have made detailed assumptions for several parameters. In particular, the distribution of actual defect sizes in a vessel has been evaluated according to NDE performed on 12 nuclear pressure vessels by 3 manufacturers, taking into account the reliability of the NDE presently available. Following as closely as possible the physical process of crack growth and onset of unstable propagation, it is possible to give some conclusions : crack growth in the belt line is lower than in head weld, but the failure probability is higher due to radiation embrittlement. Thermal shocks are the most critical loading. Therefore LOCAs with any size of breach are the more critical situations and low temperature of injected water can increase the failure probability by 10.

All phenomena considered in this study proceed from normal manufacturing and operating conditions ;in particular it has been assumed that there has been no serious error during quality control and quality assurance operations. But due to the low failure probability so obtained, it will be necessary to investigate all types of errors, the occurrence of which is unlikely, and which might result in failures having a much higher probability. In any case, the conclusions of this study ought to result in some fall-out on the manufacturing, NDE process, and on the operating specifications.

ACKNOWLEDGMENT

The author would like to express his gratitude to people and organisations who have participated to this work : Framatome - Breda and Rotterdam Nuclear for the collection of defects, Mrs Lanore (CEA/DSN) for the processing of the so obtained data, Mr Lucia, Elbaz and Brunhuber (Euratom/Ispra) for the development of the COVASTOL program. MM. Quero, Grandemange, Pelissier-Tanon from Framatome, for their efficient participation to the management of the general program and Mr. P.E. Becher, Danish Atomic Energy Commission for his valid contribution.

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