ASSESSMENT OF THE RELIABILITY OF PRIMARY COMPONENTS OF A PRESSURIZED WATER REACTOR BY PROBABILISTIC FRACTURE MECHANICS

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ABSTRACT

The reliability of structural components estimated by probabilistic fracture mechanics is governed by three parameters: the loads, the material properties and the number and size of defects in the structure. It is calculated by the well-known convolution-integral assuming all input variables as distributed values. This integral is evaluated by using the Monte Carlo technique with importance-sampling.
Two failure modes of two different primary components of a PWR are considered:
- brittle fracture of the reactor pressure vessel
- leakage of the main coolant pipe.

The most important parameter will be the defect distribution. There are considered several ways of coming up with such a distribution. Additionally different actions are taken into account, e. g. pre-service and in-service ultrasonic inspections and/or hydro-tests. Taking into account the short intervals between the in-service inspections (e. g. four years) the reliability of the components referred to can be shown to be extremely high.

KEYWORDS

Probabilistic fracture mechanics; reliability; primary components; Monte Carlo technique; brittle fracture; leakage.

INTRODUCTION

Since many controls during fabrication and operation of structural components safely prevent unfavourable combinations of loads, material properties and defect sizes, an estimation of reliability-numbers other than 1 is very difficult and depends on the probabilistic model.
The load L as well as the resistance R of the structure may be a function of several variables. All these variables are considered as distributed values. Then the reliability $P(L < R)$ of the

structure is calculated by the following well-known convolution-integral:

$$P\ (L < R) = 1 - \int_{-\infty}^{+\infty} f^L(x)\ .\ F^R(x)\ dx \qquad (1)$$

with f^L being the probability density function of the load and F^R being the cumulative distribution function of the resistance. This integral is evaluated by using the Monte Carlo technique with importance-sampling.

The dependence of the reliability on time is achieved by taking into account the crack growth by normal, upset and test conditions or by operational vibrations. This is evaluated by using the Paris law:

$$\frac{dx}{dN} = C\ .\ (\Delta K)^n \qquad (2)$$

with dx/dN	crack growth rate
ΔK	change of stress intensity factor
C, n	material constants

BRITTLE FRACTURE OF THE REACTOR PRESSURE VESSEL

Failure criterion: $K_I \geq K_{IC}$

with $$K_I = \frac{M_m}{\sqrt{Q}} \cdot \sqrt{\pi\ .\ x}\ .\ \sigma \qquad (3)$$

x	crack depth
σ	stress
K_{IC}	fracture toughness
M_m, Q	factors according to ASME XI, App. A

Only circumferential defects in the cylindrical part of the pressure vessel (wall-thickness t = 250 mm, inner radius r_i = 2500 mm) are considered, because there are no longitudinal welds. The stresses are caused by internal pressure (normal operation: p = 158 bar, hydro-test: p = 228 bar); also residual stresses are taken into account. The material is 20 MnMoNi 55: the fracture toughness is that for the upper shelf. The loads for the assessment of the crack growth according to eq. (2) are taken from specifications. Only the changes of internal pressure are considered.

LEAKAGE OF THE MAIN COOLANT PIPE

Failure criterion: $x \geq t$

with x	crack depth
t	wall-thickness

Only circumferential surface flaws in the straight part of the pipe (t = 45 mm, r_i = 400 mm) are considered. Starting with the initial defect distribution the crack growth is determined according to eq. (2): the loads are taken from specifications and a parameter study on operational vibrations is done.

DEFECT DISTRIBUTION

The most important parameter in the assessment of the reliability of primary components will be the defect distribution, this means the number and size of defects in the structure. There are considered three ways of coming up with the initial distribution function:

- a survey in the literature
- an interpretation of the indications during the pre-service ultrasonic inspection
- a model about generating defects during the welding process

For the reactor pressure vessel some work has already been done: Harrop (1979) reviewed it and a comparison of all these results is given in Fig. 1. The most important defect distribution is that developed by Marshall (1976), see curve F in Fig. 1:

$$f\ (x) = 14{,}8\ .\ \exp\ (-\ 0{,}16\ .\ x) \qquad (4)$$

with x	crack depth in mm
$f(x)$	absolute number of cracks with depth x

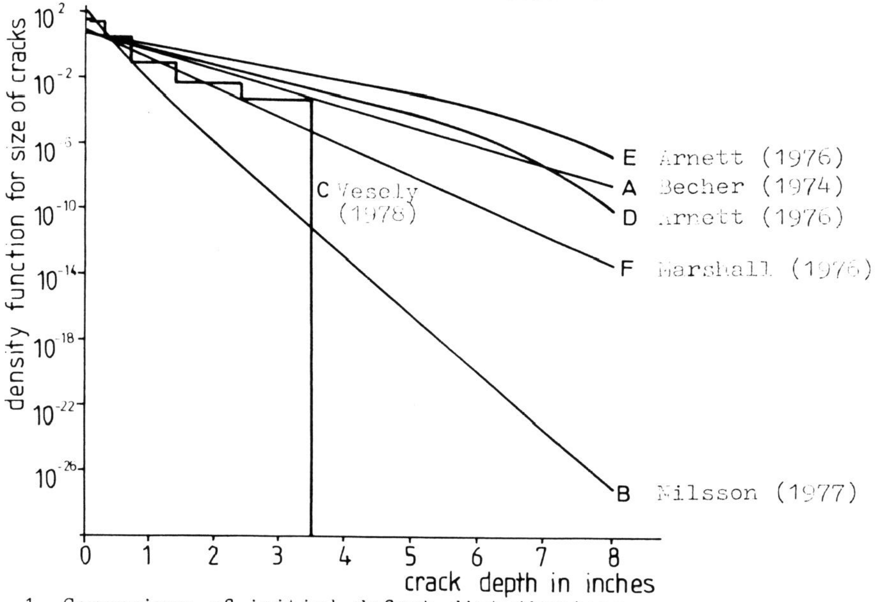

Fig. 1. Comparison of initial defect distributions.

To come up with a defect distribution by using the ultrasonic indications the detection probability of the ultrasonic inspection has to be known. Again Harrop (1979) made a review of the literature: His results are presented in Fig. 2.

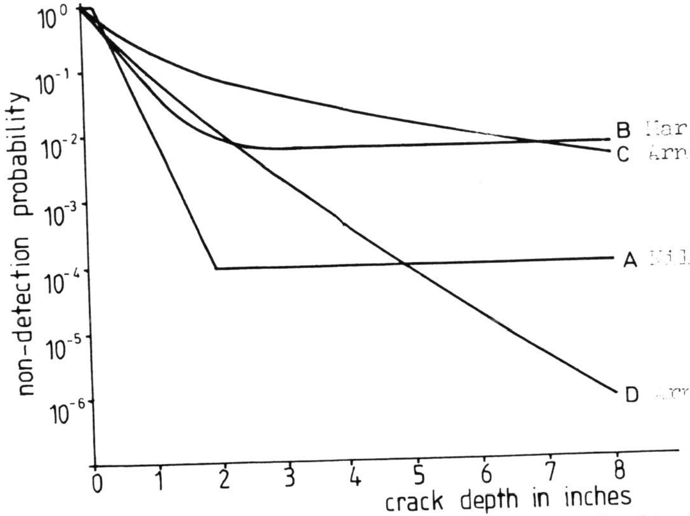

Fig. 2. Comparison of detection probabilities of ultrasonic inspections.

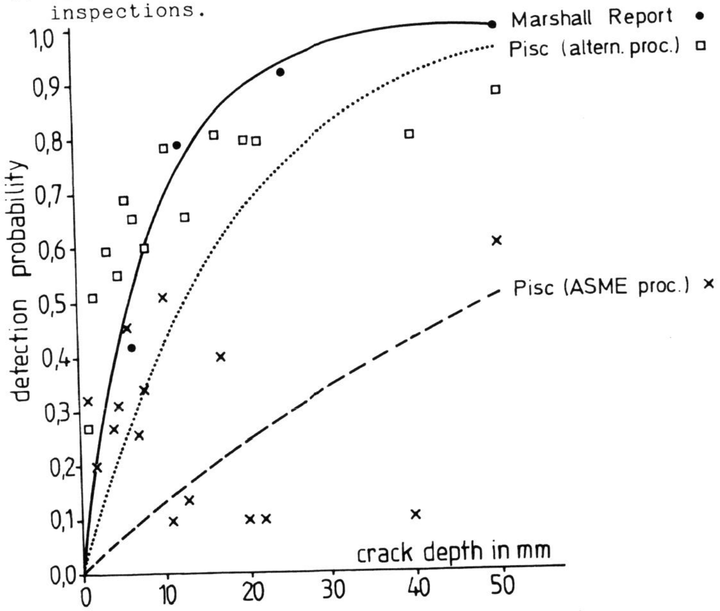

Fig. 3. Detection probability by Marshall (1976) and the results by the PISC Programme (1979).

The detection probability given by Marshall (1976) is based on an interpretation of questionnaires sent out to experienced ultrasonic operators (see curve B in Fig. 2):

$$DP\ (x) = 0{,}995 \cdot \left[1 - \exp\ (-\ 0{,}1134 \cdot x) \right] \qquad (5)$$

with x crack depth in mm
$DP(x)$ detection probability of a crack with depth x

A comparison with the results gained by the PISC Programme (1979) shows that it is not too pessimistic as argued by many people at publication of the Marshall Report (see Fig. 3).

Using the indications during the pre-service ultrasonic inspection of the reactor pressure vessel of the KWU-plant Biblis B and the detection probability given by eq. (5) the following defect distribution will be obtained (for the welds in the cylindrical part):

$$f\ (x) = 17710 \cdot \exp\ (-\ 0{,}9142 \cdot x) \qquad (6)$$

Another way to come up with the initial defect distribution will be a model about generating defects during the welding process. Such a proceeding will yield to a defect distribution being somewhat between those given by eqs. (4) and (6), as can be seen in Fig. 4 (also for the welds in the cylindrical part of the vessel).

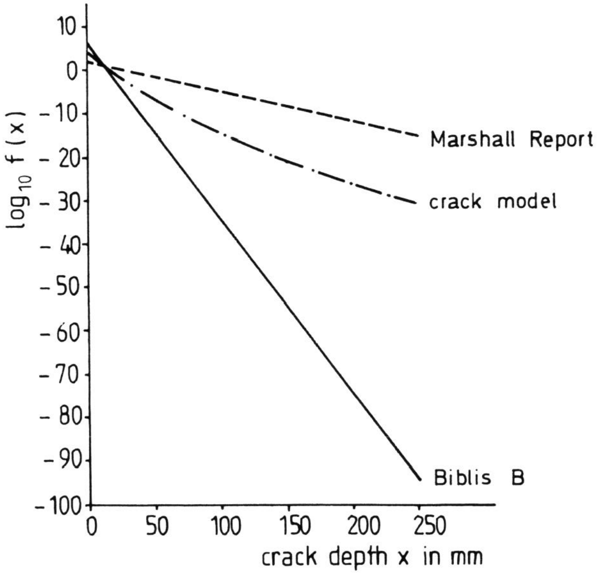

Fig. 4. Comparison of initial defect distributions for the reactor pressure vessel used by KWU.

The initial defect distribution for the main coolant pipe will be found by application of the mentioned crack model. In Fig. 5 the used defect distributions are shown (per circumferential weld).

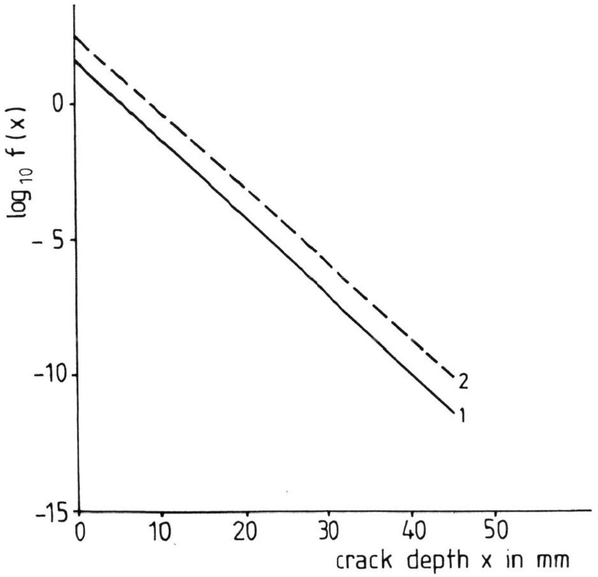

Fig. 5. Initial defect distributions for the main coolant pipe.

INFLUENCE OF INSPECTIONS AND TESTS

The influence of the following actions on the reliability of the primary components will be studied:

- pre-service/in-service ultrasonic inspections
- pre-service/in-service hydro-tests

These effects can be shown by variation of the initial defect distribution after having passed one of these actions sucessfully (see Fig. 6), i. e. :

- All defects found during the inspection are repaired totally.
- The component survived the hydro-test.

RESULTS AND CONCLUSIONS

All results concerning the brittle fracture of the reactor pressure vessel are compared with those of the Marshall Report (1976) being:

Failure Probability FP = 10^{-7} up to 10^{-6} per plant and year (taking into account one pre-service ultrasonic inspection and hydro-test).
Using the defect distribution for the KWU-plant Biblis B given by eq. (6) this failure probability is decreased by a factor of 10^{10} up to 10^{12}. Each in-service ultrasonic inspection with a detection

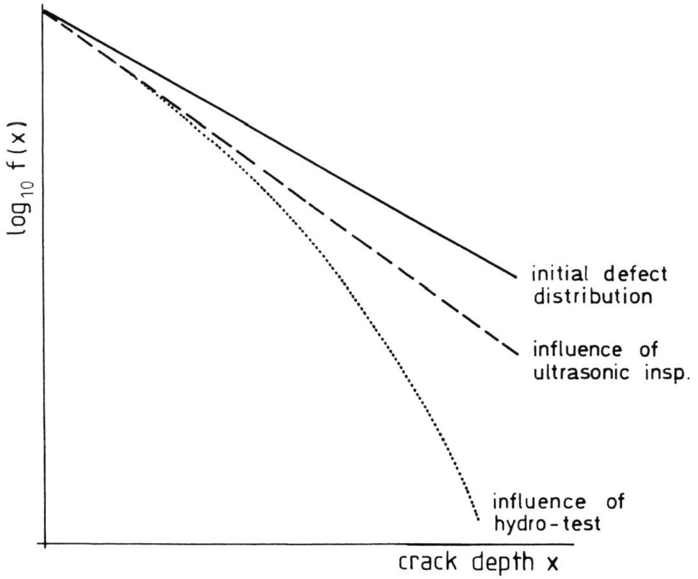

Fig. 6. Influence of ultrasonic inspections and hydro-tests on the defect distribution (schematic).

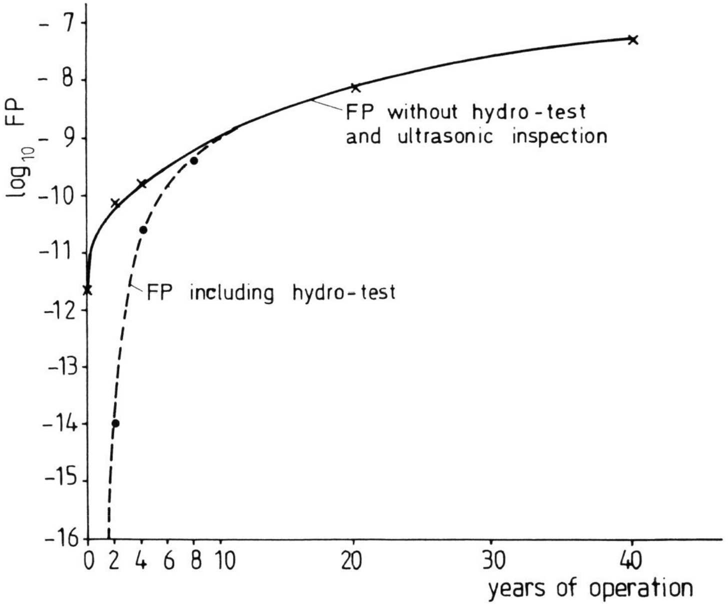

Fig. 7. Influence of a hydro-test on the failure probability FP.

probability given by eq. (5) will diminish FP by a factor of 100 supposing all inspections as independent. The influence of a survived hydro-test is very dependent on the pressure during the test: A hydro-test with the pressure of normal operation or design has no positive effect on the failure probability after the first four years of operation. Taking a pressure of 1,3 times design pressure Fig. 7 shows the influence on the failure probability (defect distribution given by eq. (4)):

- The positive effect is very dependent on the time passed since the hydro-test: After 8 to 10 years of operation there is no influence, whereas in the first years it is very considerable.
- The positive effect diminishes when the probability for large cracks becomes higher.

In principle each in-service hydro-test and ultrasonic inspection shows the same effects on the failure probabilities. Therefore the failure probability can be shown to be sufficiently small if the intervals for the in-service inspections are chosen in a suitable way (e. g. four years).

The results concerning the leakage of the main coolant pipe are shown in Fig. 8. As the loads taken from the specifications have almost no influence on the crack growth, a parameter study on operational vibrations is done. In this context the term "load" is defined as follows:

$$\text{load} = N \cdot (\Delta\sigma)^n \qquad (7)$$

with	N	number of vibrations
	$\Delta\sigma$	change in stress during one vibration
	n	exponent in the Paris-law eq. (2)

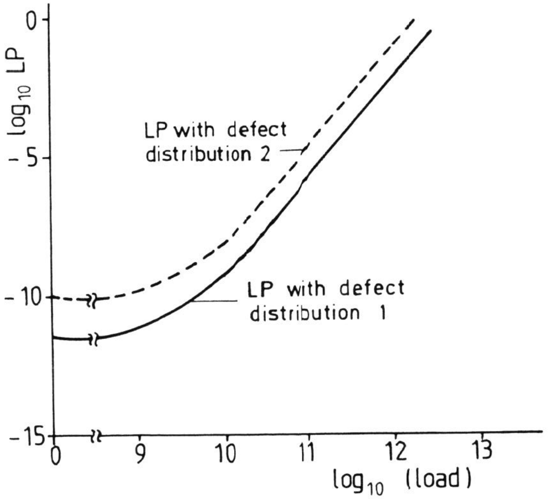

Fig. 8. Dependence between leakage probability LP and load.

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