SMiRT-12 / K. Kussmaul (Editor)

MG10/2

SENSITIVITY OF AND INFLUENCES ON THE RELIABILITY OF AN HTR-MODULE PRIMARY CIRCUIT PRESSURE BOUNDARY

M. Staat

Research Centre Jülich GmbH (KFA), Institute for Safety Research and Reactor Technology, P.O. Box 1913, D-5170 Jülich, Germany

Abstract

The reliability of HTR-Modules for process-heat application and for electricity and steam generation was analysed for normal operation and under accident conditions. The probabilistic fracture mechanics assessment was performed with FORM/SORM /1/ on the basis of the widely used data from /2/, /3/. The calculated failure probabilities may thus be compared with similar investigations. The HTR-Module primary circuit pressure boundary as a unit showed leak-before-break behaviour in a probabilistic sense although not all of its parts did so /4/, /5/.

However, the findings may strongly depend on the stochastic data. Therefore a stochastic reference problem is defined and the results are compared to the Japanese Round Robin on a PWR section /6/. Possible changes of failure probabilities and of the leak-before-break behaviour are discussed for different criteria for the occurance of a leak and for deviations from the stochastic reference problem such as the inclusion of NDE. The results may be used to identify those stochastic variables which have the greatest influence on the computed failure probabilities and to perhaps justify further work to provide more detailed information on them.

1. Stochastic Reference Problem

Two main reasons necessiate a setting of a stochastic reference problem:

- Probabilistic fracture mechanics will hardly yield absolute values for failure probabilities that could be verified by experiments /6/. It is therefore necessary to assess the accuracy of its analytical and numerical methods by comparison to independent analyses.
- Different components, areas of probable failure and failure modes may only be compared if the failure probabilities are obtained from the same stochastic model.

One should therefore agree on a stochastic model that contains the most important parameters of a fracture mechanical problem and yields realistic predictions for the intended class of applications. The following already widely used model is suggested as a basis for further discussions.

The upper shelf fracture toughness K_{Ic} of the steel A533 Grade B Class 1 (comparable to the German 20 MnMoNi 55) is assumed having a Weibull distribution taken from /2/:
mean value: (231-0.096 T) $Nm^{-3/2}$, T in °C.
standard deviation: 49 $Nm^{-3/2}$.

All cracks found in /2/ are converted in a conservative manner to the uniform type of the internal elliptical crack. The depth a of the actually existing cracks caused by manufacture is assumed to be exponentially distributed with the density

$$f_{(a)} = \lambda \; e^{-\lambda a} \tag{1}$$

where $\lambda = 0.161$ mm^{-1}, /2/.

The geometric ratio c/a is assumed in /3/ to have a lognormal distribution with the density

$$f_{(c/a)} = \frac{1}{c/a \;\; \sigma\sqrt{2\pi}} \; e^{-\frac{1}{2}\left(\frac{\ln(c/a)-m}{\sigma}\right)^2}, \tag{2}$$

where m = 1.336 and $\sigma = 0.538$.

The probability of overlooking a crack of depth a (its length c is not considered here) during an inspection prior to operation or of incorrectly determining its size is described by the probability of non-detection PND(a),

$$PND_{(a)} = \epsilon + (1-\epsilon)\; e^{-\mu a} , \tag{3}$$

where $\epsilon = 0.005$ und $\mu = 0.1134$ mm^{-1} /2/. Suppose $\epsilon = 0.0$, then eq. (3) has the form (1) and a parameter variation of λ in eq. (1) may either represent the possible influence of preservice inspection (NDE) or a change of initial crack distribution.

No welding residual stress is considered. All distributions are normalized for finite lower and upper bounds. No correlation between the stochastic variables is assumed.

2. Failure Criteria

The critical stress of a two-dimensional semi-elliptical crack is denoted σ_{2D}. Similarly σ_{1D} is the critical stress of a one-dimensional through-wall crack. The two criteria method (R6) is used to interpolate between crack tip controlled failure (linear elastic fracture mechanics, LEFM) and plastic collpase of the ligament (limit analysis, LA). Any calculation that uses only one of the limiting cases will yield lower bounds of critical stresses and the failure probabilities and thus may be not conservative.

For safety considerations of pressurized components the leak-before-break behaviour (LBB) is of primary concern. In a probabilistic sense it is probable if

$$P_{leak} > P_{break} \; , \tag{4}$$

whereas break-before-leak behaviour (BBL) is more probable if

$$P_{leak} < P_{break} \; . \tag{5}$$

Since the calculated probabilities are uncertain due to unavoidable deficiencies in modelling and in the data base, $P_{leak} \approx P_{break}$ is not decidable.

Two proposed definitions of leak and break probability P_{leak}, P_{break} will be discussed. Since FORM methods assume differentiable limit state functions (failure functions) further implications become necessary.

1. In /6/ a plate (of width 2b and thickness t) is assumed. The definitions actually used are /7/

$$P_{break} = P(\sigma \geq \sigma_{2D} \; or \; b/c \leq 1) \; , \tag{6}$$

$$P_{leak} = P(a \geq 0.8t \; and \; \sigma \leq \sigma_{2D}) \; . \tag{7}$$

Differentiable limit state functions are obtained if

$$P_{break} \approx P_{2D} = P(\sigma \geq \sigma_{2D}) \; , \tag{8}$$

$$P_{leak} \approx P_{80} = P(a \geq 0.8t) \; . \tag{9}$$

LBB is probable at $P_{leak} > P_{break}$. For any other outcome of the calculations BBL is more probable.

2. The definitions in /4/, /5/ are based on the concept of local and global instability of a crack /8/ which formulated probabilistically becomes /1/

$$P_{break} = P(\sigma \geq \max\{\sigma_{1D}, \sigma_{2D}\}) \; , \tag{10}$$

$$P_{leak} = P(\sigma_{2D} \leq \sigma < \max\{\sigma_{1D}, \sigma_{2D}\}) \; . \tag{11}$$

Since the events leading to leak and break are apparently mutually exclusive, the following holds true:

$$P_{failure} = P_{2D} = P(\sigma \geq \sigma_{2D}) = P_{leak} + P_{break} \; . \tag{12}$$

In order to use FORM one may also calculate

$$P_{1D} = P(\sigma \geq \sigma_{1D}) \; . \tag{13}$$

LBB is probable at $P_{2D} > 2P_{1D}$. For any other outcome of the calculations BBL is more probable /4/, /5/. P_{1D} is only used for this decission.

Two different criteria may lead to different assessments of LBB.

3. Japanese Round Robin

The Japanese round-robin test /6/ on a typical beltline portion of a PWR (having one crack) uses LEFM, the first criterion i.e. eqs. (6), (7) and the stochastic reference problem eqs. (1), (2). However only a and c/a are treated as stochastic variables. Fatigue crack propagation is treated deterministically using the Paris rule. Besides other changes a constant K_{Ic} is simulated in the FORM calculations by narrow normal distributions. Fig.1 shows that (after 40 years) the FORM solutions (lines) compare favourable with the Monte Carlo simulation taken from /6/ (markers) (on the basis of 1 crack). In the light of the reported variations shown by the different codes used in /6/ the difference between the Monte Carlo simulation of eqs. (6), (7) and the FORM solution of eqs. (8), (9) is acceptable. Obviously both criteria make BBL more probable than LBB.

If K_{Ic} is treated as a stochastic variable according to the reference problem e.g. P_{2D} changes by at least two orders of magnitude. This is shown in the variation of parameter λ in Fig.2 together with the influence of different distributions (with same mean value and standard deviation) assumed for K_{Ic} at 300°C.. Obviously results obtained with different stochastic models may not be compared.

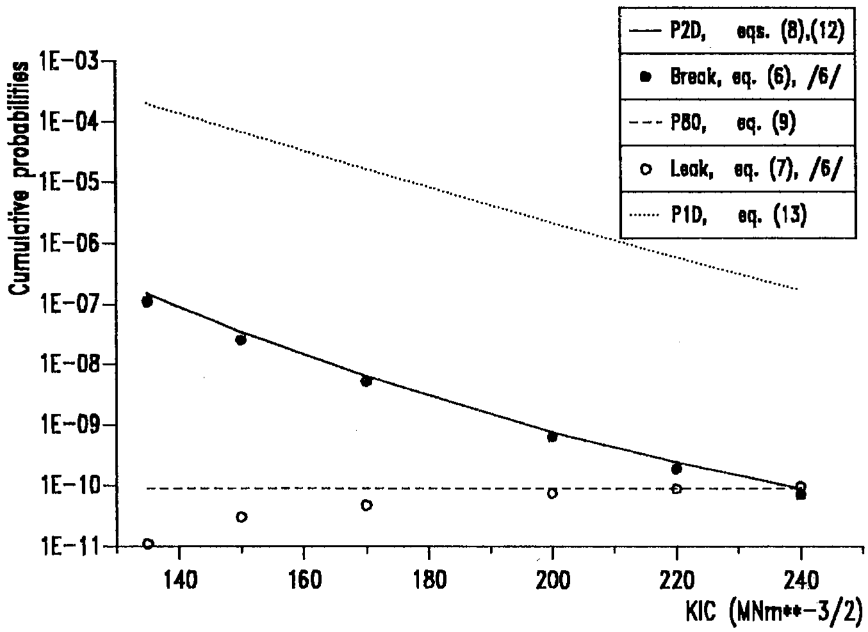

Fig. 1. Cumulative probabilities for the PWR after 40 year operation vs K_{Ic}.

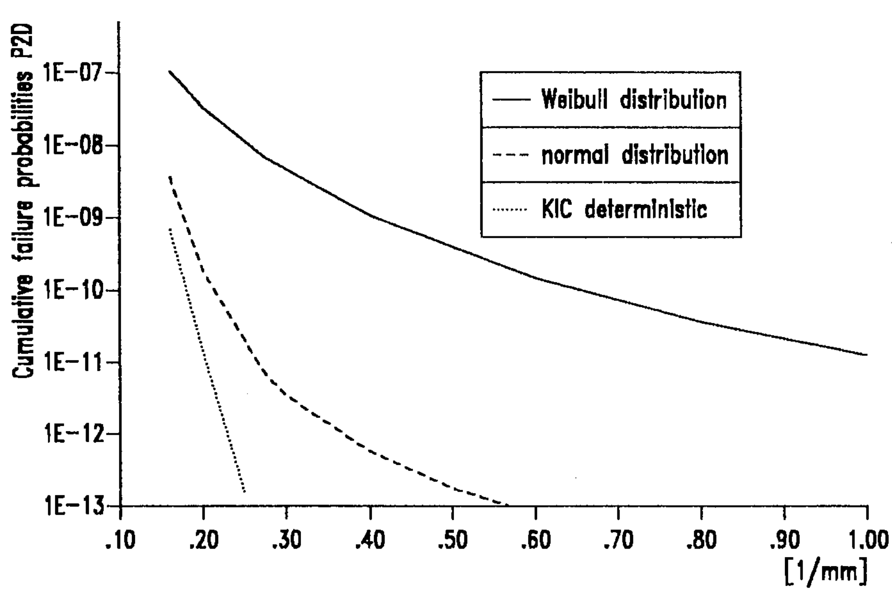

Fig. 2. Cumulative failure probabilities vs parameter λ for different distributions of K_{Ic}.

4. HTR-Module

Defect depth, defect aspect ratio, fracture toughness, flow stress, the constant in the fatigue crack growth law, primary and secondary stresses are considered as the stochastic variables in the analysis of the (Siemens/KWU) HTR-Module reactor pressure vessel (RPV) /4/, /5/. The RPV on core level is considered. The R6 method is used where possible. Nevertheless, the calculated probabilities (after 40 years of normal operation /4/) compare favourable to the above reduced stochastic model for the PWR. Inspection is modeled by eq. (3) only if stated. All cracks are assumed to be oriented circumferentially.

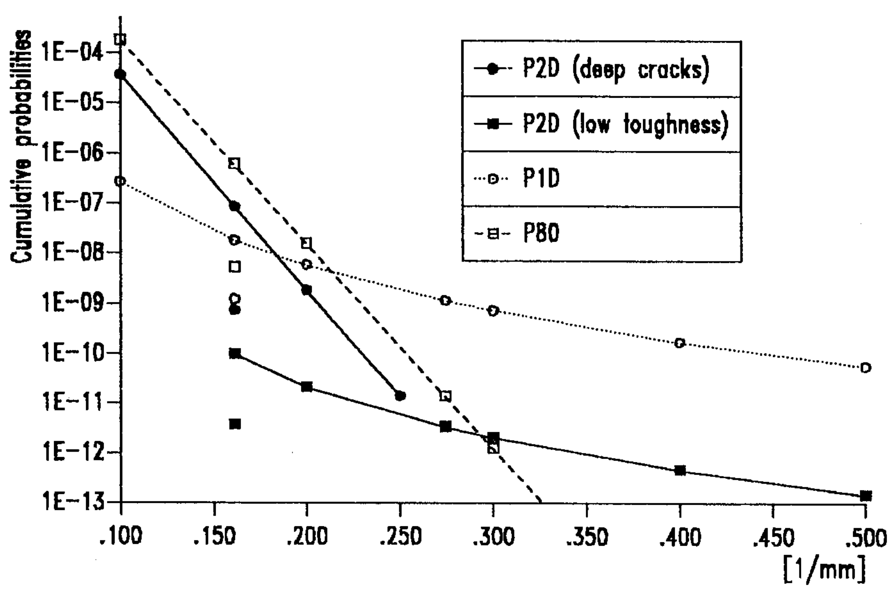

Fig. 3. Cumulative probabilities for the HTR-Module after 40 year operation vs parameter λ.

The influence of a variation of the parameter λ in eq. (1) is shown in Fig.3 (on the basis of 2.53 cracks). It is reasonable to assume that values worse than the reference value (i.e. $\lambda <$ 0.161 mm^{-1}) will not occur. As stated above an increase of λ may also be interpreted as pre-service inspection if cracks are found with some probability 1-PND and repaired. For comparison the markers not positioned on the lines indicate the solution of the reference problem, i.e. eqs. (1), (3) with $\epsilon = 0.005$. The effect of $\epsilon = 0.0$ may be read from the probabilities at $\lambda + \mu$.

Obviously the failure probability P_{2D} is the sum of two contributions. Plastic collapse is most probable for deep cracks (i.e. small λ). Its contribution would have been missed in a LEFM analysis. Low toughness material contributes to P_{2D} and P_{1D} at larger λ. Further note that the chance of BBL increases also with λ.

For comparison with /2/ and others the ratio a/c is varied as a deterministic parameter in Fig.4. Apparently the crack shape has a greater influence than could be expected if modeled as stochastic variable. However, it is not trivial task to interpreted such restricted models.

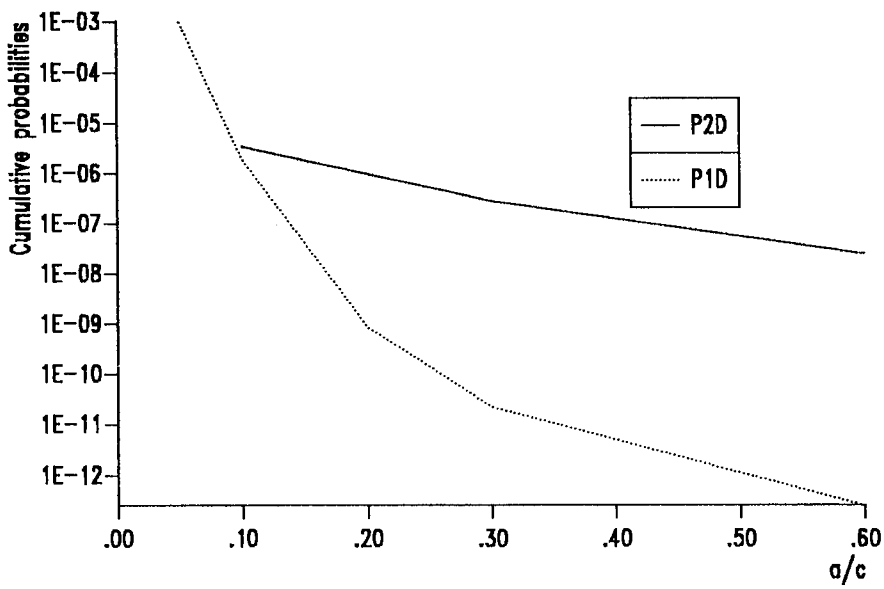

Fig. 4. Cumulative probabilities for the HTR-Module after 40 year operation vs ratio a/c.

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