PROBLEMS AND CHANCES FOR PROBABILISTIC FRACTURE MECHANICS IN THE ANALYSIS OF STEEL PRESSURE BOUNDARY RELIABILITY

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Abstract

It is shown that the difficulty for probabilistic fracture mechanics (PFM) is the general problem of the high reliability of a small population. There is no way around the problem as yet. Therefore what PFM can contribute to the reliability of steel pressure boundaries is demonstrated with the example of a typical reactor pressure vessel and critically discussed. Although no method is distinguishable that could give exact failure probabilities, PFM has several additional chances. Upper limits for failure probability may be obtained together with trends for design and operating conditions. Further, PFM can identify the most sensitive parameters, improved control of which would increase reliability. Thus PFM should play a vital rôle in the analysis of steel pressure boundaries despite all shortcomings.

1. Introduction: The Problem for Probabilistic Fracture Mechanics

In predicting the failure pressure for 134 longitudinally flawed pipes and vessels with four engineering methods the 'best' method was within ±10% (±20%) in only 40% (60%) of all cases /1/. This poor result can only partly be attributed to the concepts used and their mathematical formulations. The other reason is the large uncertainty introduced by insufficient material characterisation and a lack of control over the many influences. Since most of these uncertainties are of a stochastic nature one could expect probabilistic fracture mechanics (PFM) to resolve the problem. Unfortunately this is only possible in a narrow sense to be explained in the present paper. In terms of failure probability P_f any computation must be poor in principle if P_f is small as is best understood from Fig.1.

In probabilistic structural or fracture mechanics a generalised reliability index β_E may be computed with an accuracy similar to that expected for the deterministic prediction of a safety factor. Transforming β_E to failure probability $P_f = \Phi(-\beta_E)$, where Φ is the standard normal distribution function, is very sensitive and strongly amplifies any error if the reliability is high. Predicting $\beta_E = 5$ within ±10% yields $P_f = 1.9 \cdot 10^{-8} ... 3.4 \cdot 10^{-6}$. Thus for close bounds of β_E even the order of magnitude of P_f remains questionable. Moreover, actual failure often results from gross errors in design, production or operation and may not be adequately treated probabilistically. However, problems are small for small reliability because $\beta_E = 2$ within ±10% yields $P_f = 1.4 \cdot 10^{-2} ... 3.6 \cdot 10^{-2}$.

Assuming that β_E is in any way more precise than P_f would be a complete misunderstanding. Both are mathematically equivalent since the transformation is one-to-one and thus $\beta_E = -\Phi^{-1}(P_f)$. The deterministic safety factor as a reliability measure gives no quantitative answer and is sometimes even qualitatively wrong. It is not generally order-preserving i.e. a component with a lower deterministic safety factor may be more reliable. This is because the deterministic safety margin does not contain the uncertainty and the different behaviour of different failure modes. A convincing and easy-to-follow textbook example of the limit analysis of a portal frame is given in /2/ on pp.139-141.

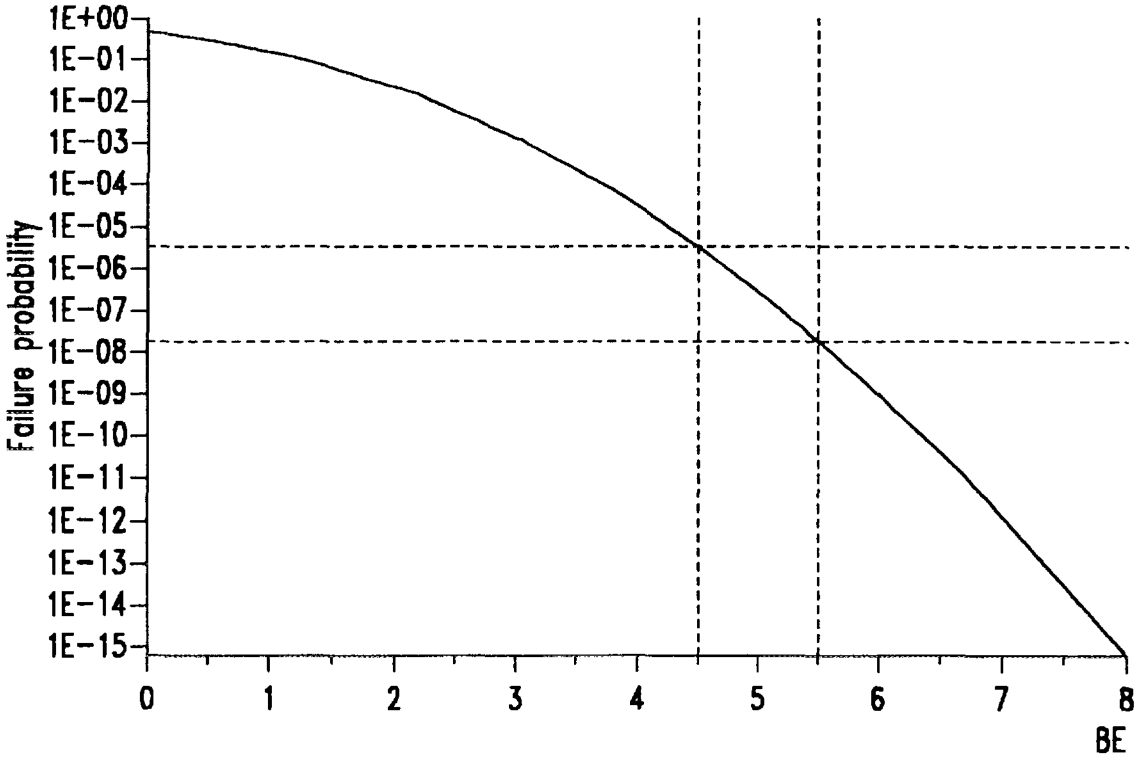

Fig. 1. Failure probability vs generalised reliability index.

Only under the conditions of mass production or an otherwise huge population of sufficient homogeneity may reliability be evaluated by the statistical treatment of direct observation. The direct observation of failure probabilities of non-nuclear pressure vessels and the transfer to nuclear ones poses further questions. But a few conclusions have been drawn /3/. Note as additional comment that the population is necessarily small and of older design and production with little knowledge of properties, operation history, and homogeneity of population. The sensitivity observed in parameter variations in PFM calculations indicates that homogeneity is highly questionable and that failure statistics hardly apply to just similar components. The decrease of P_f with improved design and quality control or its increase with particular service conditions such as stress corrosion cracking or neutron irradiation cannot be assessed by direct observation. Experimental verification of low P_f must be excluded by comparison with the effort of numerical experiments known as Monte Carlo Simulation (MCS). Even these numerical experiments are hardly feasible without limiting their number by some variance reduction, by Importance Sampling (IS) or Stratified Sampling /2/. The basic problem of small P_f of a small population persists. If P_f is assumed to be in the order of P^* and no variance reduction can be employed the number of (numerical or real) experiments may be estimated to be $N=(1-P^*)/(\epsilon^2 P^*)$ where ϵ is the desired relative error /2/. Therefore 10^6 experiments (or simulations) are needed to prove $P^* = 10^{-6}$ within $\pm 100\%$ (i.e. $\epsilon = 1$ just to check the order of magnitude). The formula says that one failure is expected in 10^6 experiments which may or may not occur. It also says that a prediction within $\pm 10\%$ needs 10^8 simulations.

It therefore becomes necessary to investigate the possible contribution of computational probabilistic fracture mechanics (PFM) to the assessment of the reliability of passive components which are not mass products in a positive manner. Despite the provoking section title there is no particular problem for PFM but rather a problem of high reliability of a small population. It is a vicious circle: collecting strength data is equivalent to observing the reliability of the tension specimen. If the population is too small it is too small for both activities.

2. Numerical Method

The failure function (limit state function) g(x) of all variables (basic variables) $\mathbf{x} = (a, a/c, K_{Ic}, R_F, C, \sigma_p, \sigma_s)^T$ used in the fracture mechanics model is defined such that $g(\mathbf{x})<0$ in case of failure, and $g(\mathbf{x})\geq 0$ otherwise. Since all basic variables **x** are uncertain they may be treated as stochastic variables **X** with the joint cumulative distribution function $F_{\mathbf{X}}(\mathbf{x})$. Then the failure probability P_f is the probability that $g(\mathbf{x})<0$, i.e. $P_f = P(g(\mathbf{x}) < 0)$. It is computed with a code which was developed starting from the ZERBERUS code using FORM/SORM /4/,/5/.

If $\mathbf{X} = (X_1, X_2, ...)^T$ is independent but not normally distributed, the reliability problem is transformed into the space of independent standard normally distributed variables $\mathbf{U} = (U_1, U_2, ...)^T$. The point $\mathbf{u}^*$ on the failure surface $g(\mathbf{x}) = h(\mathbf{u}) = 0$ closest to the origin is called design point. The transformation is derived from the condition $F_i(x_i) = \Phi(u_i)$ on the marginal distribution $F_i(x_i)$. Assuming the failure surface is smooth, $\mathbf{u}^*$ is computed iteratively with the Rackwitz-Fiessler algorithm. The design point $\mathbf{u}^*$ in standard normal space is $\mathbf{u}^* = -\beta\ \boldsymbol{\alpha}$, where the absolute value of the reliability index β is the local minimum distance from $h(\mathbf{u}) = 0$ to the origin, and $\boldsymbol{\alpha}$ is the unit normal to the failure surface in $\mathbf{u}^*$. Then:

- the failure probability $P_f = \Phi(-\beta)$ is obtained using a linear approximation of $h(\mathbf{u}) = 0$ in FORM (a quadratic approximation in SORM).
- the design point $\mathbf{x}^*$ is obtained from $\mathbf{u}^*$ by inverse transformation. Its components are the values assumed by the stochastic variables at the most probable point of failure.
- the sensitivity factors are the components of $\boldsymbol{\alpha}$, and are a measure of the influence produced by the individual stochastic variables on failure probability.
- P_f may be improved by MCS with IS around the design point, its numerical error estimated, and the design point checked.

The latest major structural changes of the code, which are relevant for the present calculations, are the completed implementation of pre-service and in-service inspection (PSI and ISI). The variables of crack depth and shape may become dependent after inspection and a Rosenblatt transformation /2/ is used to transform these variables into standard normal space.

3. Analysis Conditions for a Reactor Pressure Vessel

The Japanese round robin /6/,/7/ may serve as an appropriate starting point since it already gives some flavour of the problems and chances for PFM. However, it becomes necessary to extend its limited stochastic approach at least gradually to some material data. Similarly, its linear elastic fracture mechanics (LEFM) approach must be extended to an elastic plastic analysis. The beltline portion of a typical reactor pressure vessel is analysed as a plate of thickness t = 200mm and width 2b = 12.6m using the design data taken from /8/. All necessary data is also given in /6/,/7/ and will not be repeated here.

3.1 Failure Criteria

The fracture and leak criteria given in /6/,/7/ must be completed and modified from /9/ yielding a 'break' probability which could be more appropriately called failure probability

$$P_f = P_{break} = P(\sigma \geq \sigma_{2D}) \ . \tag{1}$$

It is the probability that the crack opening stress σ exceeds the critical stress σ_{2D} of a semi-elliptical surface crack. Instead of the simple leak criterion yielding

$$P_{leak} = P(a \geq 0.8t \; and \; \sigma < \sigma_{2D} \; and \; b/c > 1) \tag{2}$$

an upper bound is used

$$P_{80} = P(a \geq 0.8t) \geq P_{leak} \; . \tag{3}$$

This is the probability that the crack will penetrate 80% of the wall. In /6/,/7/ eq. (2) was used but only the reduced condition in eq. (3) was given /9/.

With these definitions the RPV shows leak-before-break behaviour (LBB) in a probabilistic sense if $P_{break} < P_{leak}$ i.e. if

$$P_f < P_{leak} \; . \tag{4}$$

Here the less demanding condition

$$P_f < P_{80} \; , \tag{5}$$

is used although it should be noted that other definitions may be more rational but also more critical /9/. For $P_{leak} \approx P_{break}$, no definite conclusion can be drawn since the calculated probabilities are uncertain due to unavoidable deficiencies in both the modelling and data base.

3.2 Material Data

Fatigue crack growth and fracture toughness K_{IC} at 300°C is treated deterministically in /6/,/7/ but gradual decrease due to thermal ageing

$$K_{IC} = \begin{cases} 135 \; MNm^{-3/2} & for \;\; t \leq 14.5 \, years \\ 145.95 - 9.43 \log_{10} t & for \;\; t > 14.5 \, years \end{cases} \tag{6}$$

and neutron irradiation

$$K_{IC} = \begin{cases} 135 \; MNm^{-3/2} & for \;\; F(t) \leq 0.361 \\ 3.29 - 118.71 \, F^{-0.102} & for \;\; F(t) > 0.361 \end{cases} , \tag{7}$$

where F is neutron fluence ($10^{19} ncm^{-2}$), is taken into account. "It should be noted here that the chemical contents of the material tested were slightly modified for an acceleration study of thermal ageing phenomena, and that the above K_{IC} values seem somewhat lower than actual values of operating power plants..." /7/. Therefore the given decrease is unlikely to hold for standard A533 Grade B Class 1 (Germany: 20MnMoNi55, France: 16MND5) material and cannot be transferred to the stochastic treatment of data.

At 300°C the mean values ± standard deviation for K_{IC} are taken from /8/

$$K_{IC} = 202 \pm 49 MNm^{-3/2} \; , \tag{8}$$

and for the flow stress $\sigma = 0.5(R_{p02} + R_m)$ from /5/

$$\sigma_F = 485 \pm 23 Nmm^{-2} \; . \tag{8}$$

The standard deviation of K_{IC} seems conservative for modern steel production. That of σ_F is perhaps a little optimistic. A Weibull and a normal distribution are used for both in turn.

3.3 Crack Size and Shape

All cracks found in /8/ are converted in a conservative manner to the uniform type of internal semi-elliptical surface crack. The depth a of cracks caused by manufacture was derived from experience with non-nuclear vessels to be exponentially distributed with the density

$$f_{(a)} = \lambda\ e^{-\lambda a}\ , \tag{9}$$

where $\lambda = 0.161\ mm^{-1}$, /3/,/8/.

The crack length 2c is introduced through the geometric ratio c/a as a shape variable. A lognormal distribution with the density

$$f_{(c/a)} = \frac{1}{c/a\ \sigma\sqrt{2\pi}}\ e^{-\frac{1}{2}\left(\frac{\ln(c/a) - m}{\sigma}\right)^2}\ , \tag{10}$$

where m = 1.336 and $\sigma = 0.538$, is assumed in /10/.

Crack size and shape are modified if all cracks found by PSI are repaired (introducing no new cracks). The probability of non-detection $P_{ND(a)}$ given in /6/,/7/ is completed from /10/ yielding

$$P_{ND(a,c)} = \varepsilon + (1 - \varepsilon)\ erfc(v \ln \frac{A}{A^*})\ , \tag{11}$$

where erfc is the complementary error function and

$$A = a \min\{2c, D_B\}\ , \qquad A^* = a^* D_B\ .$$

Here $D_B = 25.4$mm is the diameter of the ultrasonic beam, $\varepsilon = 0.005$ a residual chance of overlooking deep cracks, and a^* is the crack depth at which $P_{ND} = 0.5$. This equation poses some problems for FORM/SORM since a and c/a are dependent after inspection. Alternatively

$$P_{ND(a)} = \varepsilon + (1 - \varepsilon)\ e^{-\mu a}\ , \tag{12}$$

from /8/ is used with $\mu = 0.1134\ mm^{-1}$ (corresponding to $a^* = 6.11$mm) and the same ε. This widely used function has the disadvantage that the chance to detect a crack becomes independent of its length 2c.

Clearly e.g. crack depth is defined only up to wall thickness t, thus $0 \leq a \leq t$. Therefore all densities are truncated and normalised for finite lower and upper bounds of their arguments, resulting in the densities given in /6/,/7/ for the above equations. Further truncation may become necessary since limit load solutions are given in closer ranges in the literature. No correlation between the above stochastic variables is assumed before inspection.

4. Computations for a Reactor Pressure Vessel

The comparison with /6/,/7/ is also a comparison of methods. FORM/SORM gives more insights by providing design points and sensitivity factors as additional information about the problem. All probabilities refer to one crack, and no residual stress due to welding is considered in the calculations.

Crack growth is the only reason for P_f increasing with time if K_{IC} is constant in an LEFM analysis. Fig. 2 shows the FORM and SORM results together with the seven different MCS (with IS or mostly Stratified Sampling) in /6/,/7/ for years of operation under design conditions. Both FORM and SORM are sufficiently accurate; the SORM solution seems to be closer to the majority of the computations. It should be pointed out that the FORM/SORM solutions may change slightly with starting point and with convergence of the optimisation whereas the MCS results may improve with the number of samples. Similarly FORM/SORM solutions may be improved by IS around the design point. In practice, one is content if P_f is found within a factor of two and P_{leak} within a factor of five /6/. If K_{IC} is varied as a deterministic parameter it is found that P_{leak} is about one order of magnitude less than P_{80} at $K_{IC} = 135 MNm^{-3/2}$ and $P_{leak} \approx P_{80}$ at $K_{IC} = 200 MNm^{-3/2}$ /9/. It has become clear by now that one is interested only in orders of magnitude. Thus FORM results are sufficiently accurate for all computations to follow.

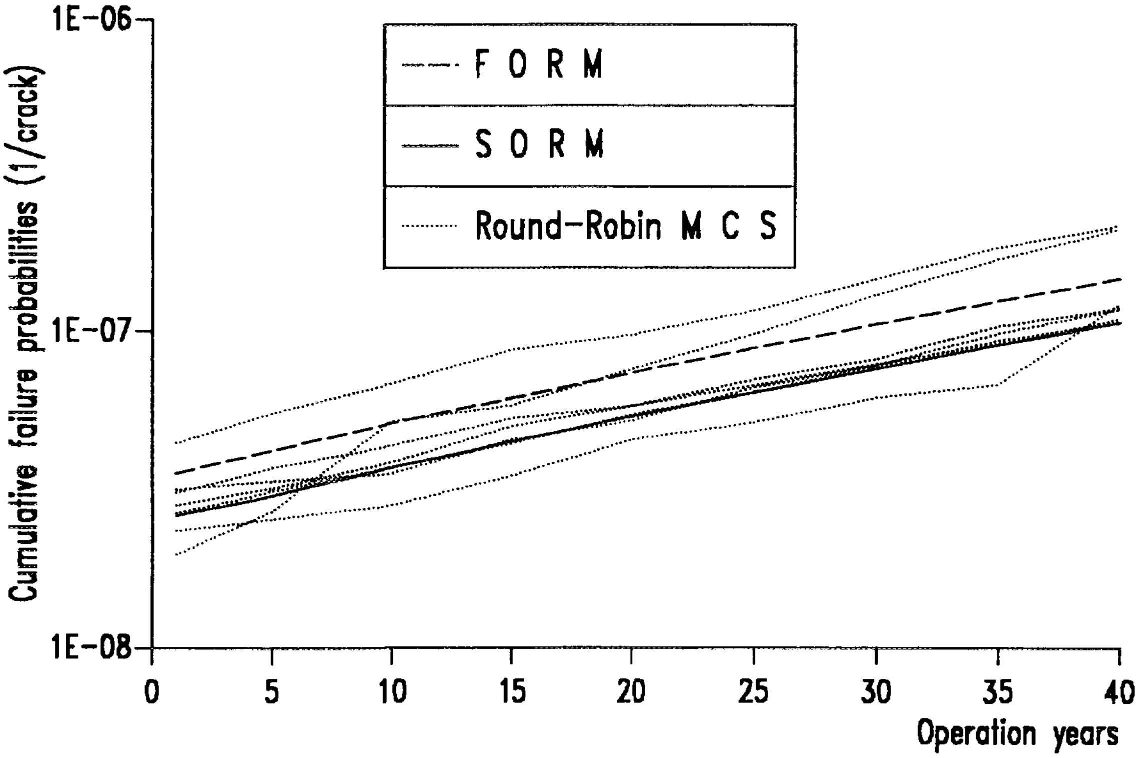

Fig. 2. Time histories for Pf of the RPV for different methods of computation.

The idea in /7/ of using PFM in a criterion for life-extension judgement is as follows:

- First, compute P_f at design life from the design loads, operating conditions and material data. Define this $P_{f_{design}}$ as design criterion.
- Second, compute the time from start of operation until the designed $P_{f_{design}}$ is reached under the actually measured loads, operation conditions and material data. This gives a new time until end-of-life (EOL).

This idea is used to discuss the effects of reduced neutron fluence F (by measurement or by leakage reducing fuel-charging schemes) and of different intervals for ISI. ISI may change P_f

only if followed by repair. This is possible for the RPV in principle as recently demonstrated by the FENIX project for the twenty-year-old Unit 1 at Oskarshamn, Sweden /11/ (actually the RPV itself was found to be free of cracks). For obvious reasons the frequency of such repairs cannot be high.

Here an 'old design' with F(40years) = $3 \cdot 10^{19} ncm^{-2}$ is compared with an 'evolutionary design' with F(60years) = $1 \cdot 10^{19} ncm^{-2}$ according to the limits set in /12/. The decrease of K_{IC} and increase of P_f is shown in Fig.3 and Fig.4 for the two designs together with the effect of thermal ageing. Note, that the time scale is lost and the two effects cannot be compared if one does not specify a designed lifetime. The above comparison may be used with any kind of ageing passive component. From the flat slope, the lack of data, and the sensitivity of the prediction it should be clear that no sharp time may be given but necessary actions may be indicated. The situation is not very different in deterministic lifetime predictions.

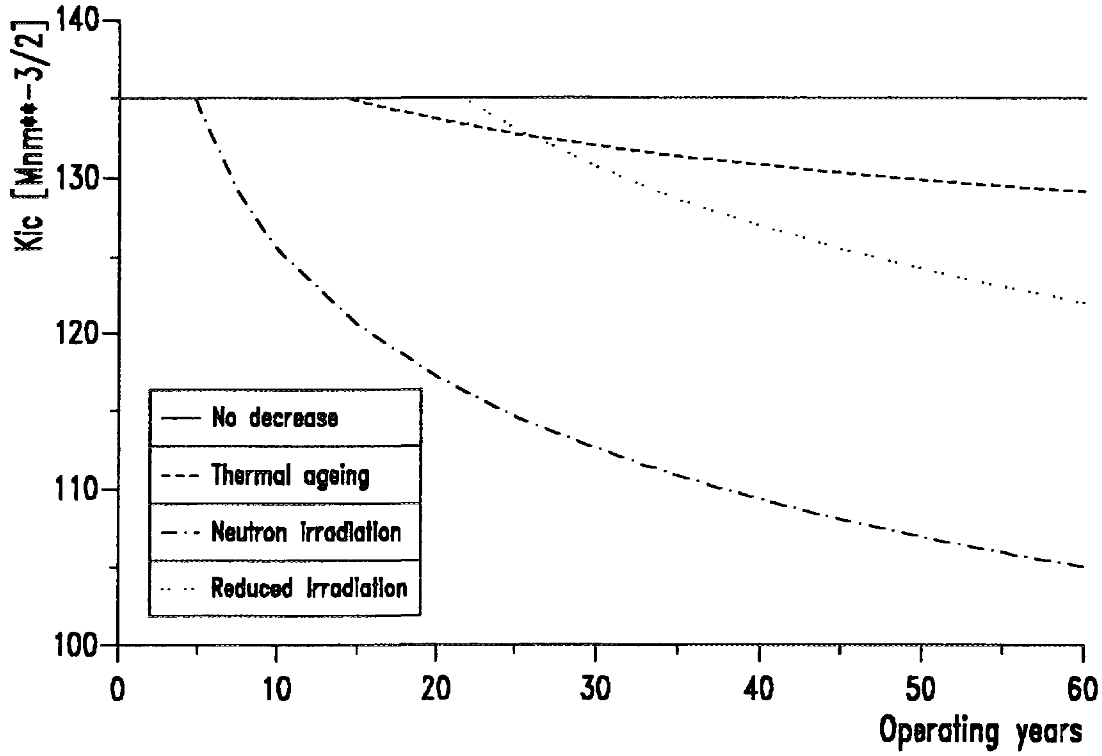

Fig. 3. Decrease of Kic with ageing and different irradiation conditions.

Results of PFM similar to those in Fig.4 may be interpreted differently if one is not primarily interested in lifetime predictions. They actually show the possible loss or gain in reliability for different scenarios. Since both interpretations use only relative changes the absolute values of P_f may be in error. Parameter variations and different stochastic assumptions should be used to discover whether these relative changes are stable.

4.2 Material Data as Additional Stochastic Variables

Assuming a Weibull distribution, but compensating by lifting K_{IC} to the usual values, changes P_f only slightly in an LEFM analysis, see Fig.5. Modelling effective PSI can reduce P_f by one or two orders of magnitude. The optimistic PSI model in eq. (12) may compensate the pessimistic distribution $f_{(a)}$, eq.(9) leading to an overall realistic statistical modelling according to

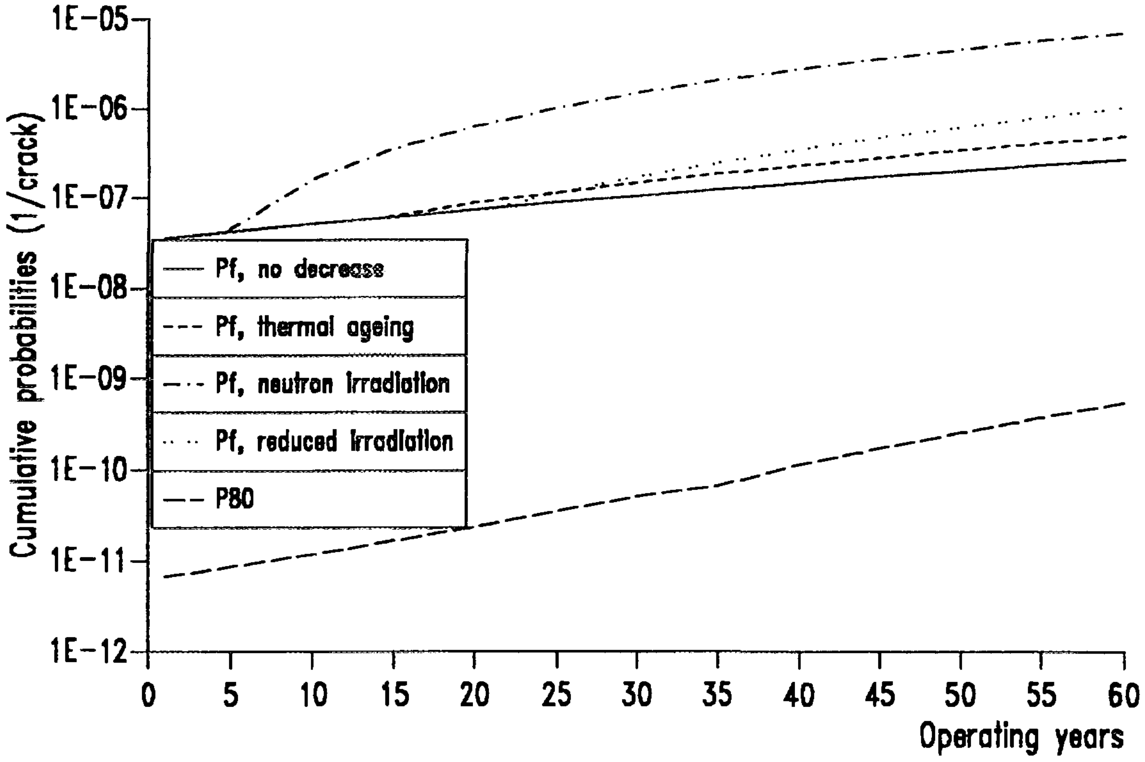

Fig. 4. Increase of Pf with ageing and different irradiation conditions.

/13/. With the μ used there is a 50% chance of finding 6.11mm deep cracks. Obviously the function used for modelling P_{ND} has a great influence since $a^* = 6.35$mm taken from /10/ reduces P_f further by one order of magnitude. /6/,/7/ are more pessimistic about PSI and ISI using $a^* = 31.75$mm for PSI, which was given in /10/ for austenitic steels.

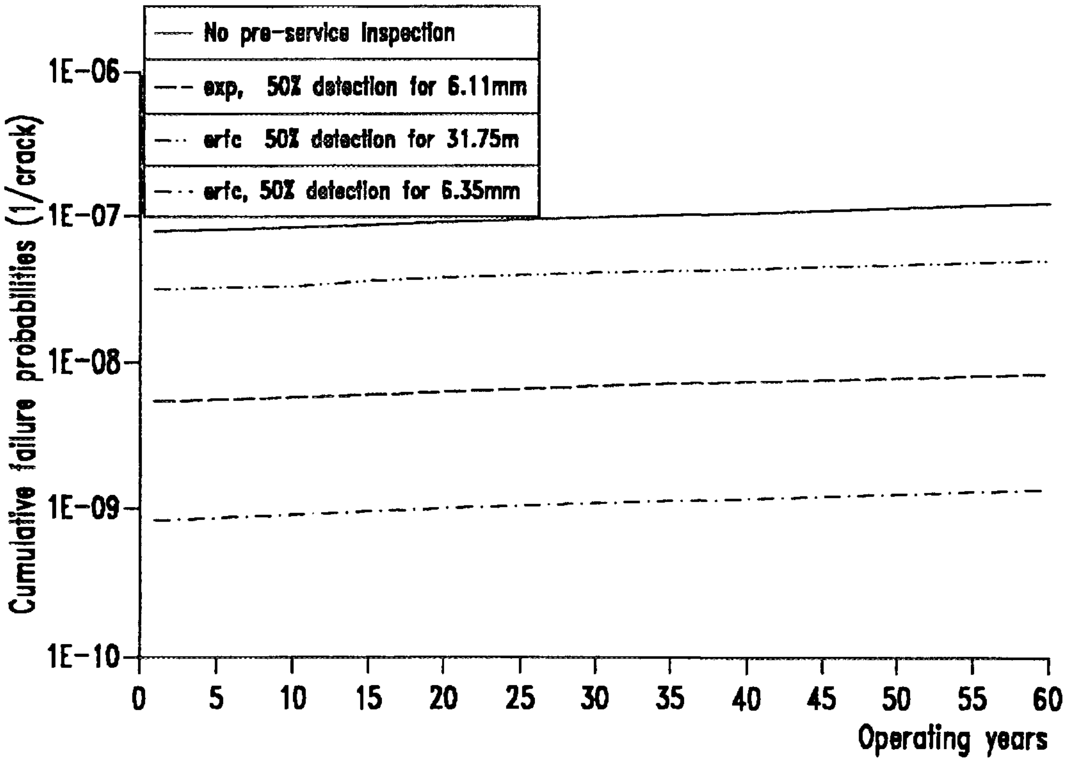

Fig. 5. Time histories for Pf of the RPV for different effectiveness of PSI.

It is important to notice that despite the uncertainty about P_f its relative increase in 60 years is between 53% and 61% for all four curves in Fig.5. This is quite stable but about one order of magnitude lower than the relative increase found in Sec.4.1 with deterministic K_{IC}. In this simplified modelling a has the greatest influence with a sensitivity factor of about -0.9. Tab.1 shows that this rôle is taken over by K_{IC} in the completed modelling (but with positive sign since P_f increases if the design point of K_{IC} decreases. This is opposite for a). Obviously the uncertainty about a stochastic variable of medium sensitivity results in moderate uncertainties about P_f and allows for stable predictions of relative changes i.e. the trends for P_f. Better control of K_{IC} reducing its standard deviation would reduce its sensitivity.

TABLE 1. INFLUENCE OF PSI FOR 40 YEARS OF DESIGN OPERATION
(Design points, sensitivity factors and failure probabilities, see Fig. 5.)

Case	a [mm]		c/a		K_{IC} [$MNm^{-3/2}$]		P_f	
	designp.	sensit.	designp.	sensit.	designp.	sensit.	FORM	SORM
No PSI	35.7	-0.52	2.73	-0.26	66.6	0.81	$1.1 \cdot 10^{-7}$	$8.9 \cdot 10^{-8}$
exp, $a^* = 6.11$mm	20.3	-0.47	2.67	-0.22	49.0	0.86	$7.4 \cdot 10^{-9}$	$3.9 \cdot 10^{-9}$
erfc, $a^* = 31.75$mm	26.0	-0.45	2.61	-0.24	55.4	0.86	$4.5 \cdot 10^{-8}$	-
erfc, $a^* = 6.35$mm	10.4	-0.34	3.06	-0.26	36.0	0.91	$1.2 \cdot 10^{-9}$	-

Suppose now $\varepsilon = 0.0$. Then increasing λ in a parameter variation may be interpreted as either representing the possible influence of PSI (in the sense of eq. (12)) or a shift of initial crack distribution towards shallow cracks (in the sense of eq. (9)) by extracting some deep cracks from the population with improved production /9/. The left line for $\lambda = 0.161 mm^{-1}$ in Fig.6 represents the non-nuclear vessels with no PSI. It is reasonable to assume that nuclear vessels are not worse than that but can be improved by controlled production and PSI up to the right line for $\lambda = 0.161 mm^{-1} + \mu = 0.2744 mm^{-1}$. Thus the optimistic PSI model in eq. (12) may compensate the pessimistic distribution $f_{(a)}$, eq.(9) leading to an overall realistic stochastic modelling according to /13/.

If one uses the R6 method /14/ for interpolation between LEFM and limit analysis (LA) there are two contributions to P_f shown in Fig.6 (at 40 years of operation with design loads) and identified by inspection of the design points in Fig.7. The first failure mode caused by low toughness is not missed by LEFM. The second new one is the plastic collapse of deep half-through cracks. Since both failure modes are weakly correlated P_f is the sum of both contributions /15/. It is impossible to combine two deterministic safety factors in a similar way. The large scatter in K_{IC} data leads to a high sensitivity and slow reduction of P_f with improved vessel (i.e. increasing λ). Changing the distributions of K_{IC} and σ_F from Weibull to normal distribution with the same mean values and standard deviations reduces the low toughness contribution by about three orders of magnitude. The plastic collapse contribution is not affected because of the low sensitivity factor of 0.1 (or less) for σ_F. This is not surprising since a fairly narrow distribution was assumed for σ_F. Conservatively secondary stress was not excluded in LA.

On the basis of the simple criterion in Sec.3.1 no LBB behaviour could be demonstrated probabilistically. The situation becomes 'worse' for improved vessels because PSI followed by repair removes the large cracks thus further reducing P_{80}. The reliability is increased, however,

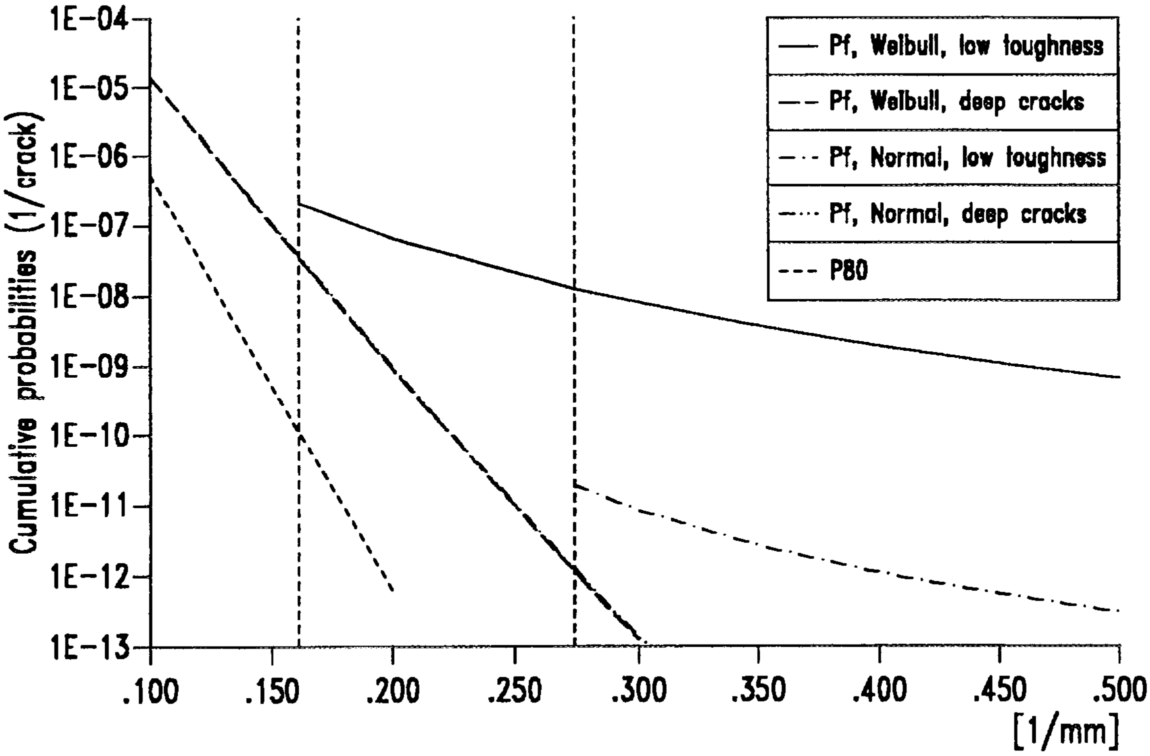

Fig. 6. **Pf vs parameter λ for different distributions** (40 years design operation).

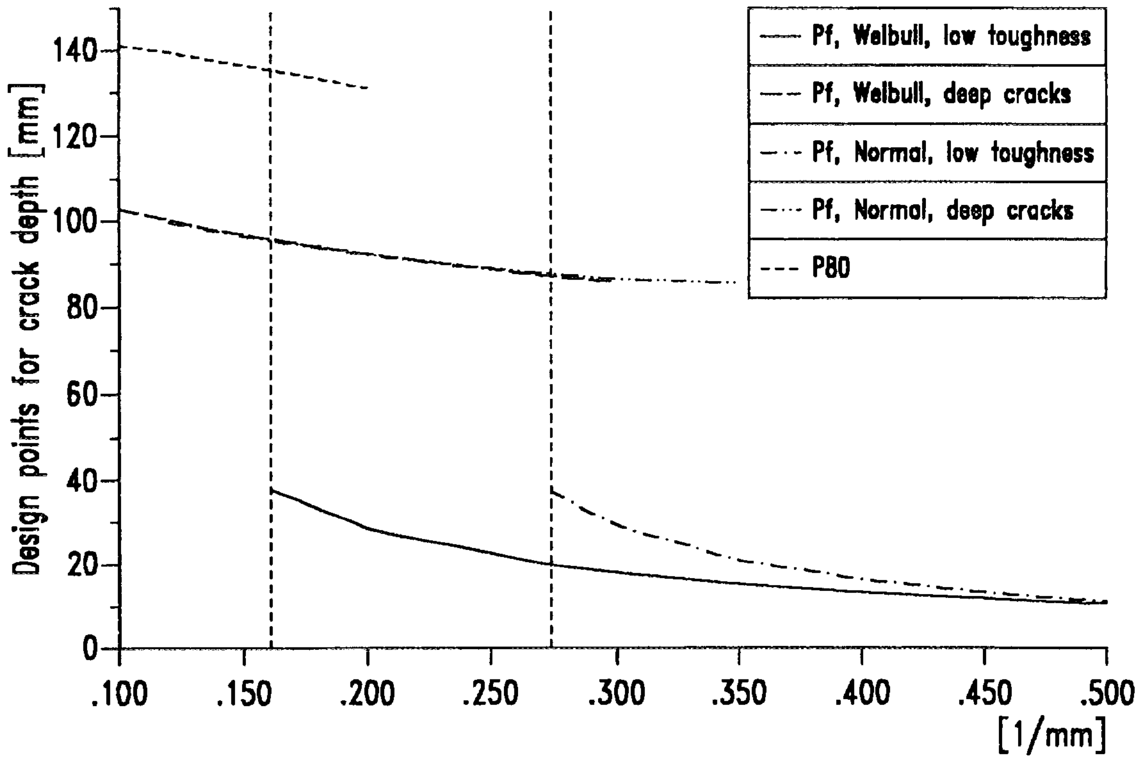

Fig. 7. **Design points for a vs parameter λ for different distributions** (40 years design operation).

for all probabilities are reduced by PSI. The RPV of the Siemens/KWU HTR-Module reactor is thinner at core level than the design point for a in Fig.7 for the P_{80} calculations. Thus the simple criterion makes LBB more probable for this RPV /9/ (in these calculations primary stress was correctly excluded in LA). But the questions should be postponed for refined criteria. Comparing the results in /5/,/15/ for the whole primary circuit pressure boundary of the HTR-Module helps identify the part and mode of most probable failure. It is found that normal operation contributes to risk more than the accident conditions in /15/. Finally, note that all probabilities come closer together as they increase with reduced quality of the RPV.

5. Conclusions: The Chances for Probabilistic Fracture Mechanics

If the population is small failure statistics, experimental and numerical predictions of safety face the same problem of high reliability. There is a particular chance for the numerical approach because it breaks failure down into all possible contributions, for which, stochastic models of the physical process can be made. Thus extrapolation from a small data base is supported by a model of the distribution functions of the stochastic variables. Although not mentioned this was done for most distributions used in the text (e.g. an exponential distribution of crack-depth may be derived from certain possible reasons for the existence of defects in welds /16/). However, it was shown that the choice of distribution for a sensitive variable has a great influence on failure probability. By the very nature of the problems identified in Sec.2 there is no optimal solution. Asking for the value of very low failure probabilities of a small population is asking too much. However, there is a clear sub-optimal solution.

Summarising, one can conclude that with all the different stochastic models and even with the more conservative assumptions about the distributions the reliability of the RPV proves to be high and P_f may even be much lower than this. For the safety of the whole plant it is not so relevant to know exactly how small P_f might be. But it is of prime concern to know an upper bound for its value and its change during operating years. Therefore target values for P_f and for its increase in time may be generated for critical passive components by probabilistic safety analyses (PSA) and it remains the objective of PFM to demonstrate that these single passive components are not worse than the demands under realistic but still conservative assumptions. If P_f is too high for a component PFM may be used to guide its improvement by changing design, improving production and quality control, or by modified operation. For existing plants there are several means to move the material back towards its original conditions (including crack distribution). PFM may demonstrate their effectiveness. Low P_f should be regarded as an operative value and should not be taken as an absolute value for the reliability properties of a component /5/,/16/.

There is a similarity and a fundamental difference between deterministic and probabilistic fracture mechanics. In deterministic analysis a crack size and shape is conservatively postulated and material data and loading are handled in the same pessimistic spirit. Then the answer 'yes' or 'no' is given with no quality of the confidence in this answer. In PFM distributions for the above data are conservatively selected and the answer 'no' is chosen. Then the confidence in this answer is quantified. Of course, both kinds of analyses can be done in a best-estimate sense as well. Besides giving the more complete answer PFM has the chance to monitor all possible realisations of data, conditions, and all possible failure modes together with all their possible interactions at one time. Finally, since P_f (and the generalised reliability index β_E) are the only rational reliability measures, PFM has the chance to help identify components, conditions, locations and modes of the most probable failure together with the possible influences of different conditions and possible actions.

What remains to be done? For the RPV stochastic models for fatigue crack-growth should be used or developed for ageing and neutron irradiation. Existing models for all variables may be checked for possible improvement. The methodology should be applied to other pressurized passive components. Other ageing phenomena may come into play for other passive components such as stress corrosion cracking /17/ or creep crack-growth /18/. Sensitivity factors as computed by FORM/SORM methods may be of some help in identifying the most influential data and in guiding research into the most productive areas. Reducing the scatter in sensitive data will reduce both failure probability and uncertainty of its prediction. The invention of some variance reduction for real experiments, thus reducing the number necessary, would be the major breakthrough. Finally the reader may consult /19/ for "The meaning of probability in probabilistic safety analysis".

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