A Systematic Evaluation of the Coverage of Pressure Vessel Inspections

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Abstract
Research efforts are made in order to evaluate the coverage and balance of various pressure vessel inspections. The first phase of the work, the development of a fault-tree of reasons contributing to a pressure vessel failure, is briefly quoted.

The second phase, a probabilistic fracture model in its early stage and the application to the main welds of a pressurizer is discussed. The residual stresses are found to have a great impact on the fracture probability.

1. Introduction
The evaluation of the importance of various pressure vessel inspections has been initiated by the Finnish Centre for Radiation and Nuclear Safety (STUK), which is responsible for both nuclear power plant regulation and inspections in a broad area including reactor safety, pressure vessels and radiological protection. The preliminary part of the work, sponsored by the STUK, was carried out by the Technical Research Centre of Finland in 1982–83. Its present stage is a qualitative model (a fault tree) for pressure vessel failures, a brief presentation of which is in Section 2.

For the quantitative evaluation of the role of various parameters a probabilistic fracture analysis is needed. Because of different characteristics involved in each individual pressure vessel (material, manufacturing, loading, design and circumstances), the distinct fracture analysis is required for each one.

As the first quantitative exercise, a computer program was developed which takes the following effects into account: the initial flaw size distribution, the crack growth due to thermal fatigue, NDE-inspections, stresses and fracture toughness. The rest of this paper considers some details of this computer program and the first results of its application.

A complete quantitative model which would consider explicitly all important factors from fabrication to operational errors is the target we are able to approach only gradually.
2. The fault tree of a pressure vessel failure

A scheme of reasons which contribute to the fracture and appear in the design and fabrication of a pressure vessel or in planning, construction and operation of a power plant was the objective of the qualitative study.

All the detailed material collected in preceding studies was reduced to one basic fault tree, which is partly illustrated in Fig. 1. The construction of the tree was initiated by dividing the top event into two main contributors: stress state and material parameters (level 2 in Fig. 1). Essential material parameters are yield strength and fracture toughness. Stress state is divided into primary and secondary stresses. The most essential contributor to fracture, i.e. crack size, was included as the third factor in the stress state (level 3).

On the fourth level, the division in the material train continues according to the phase of operation and in the stress state train according to stress causes.

On the fifth level, there are 47 contributors altogether. The subfactors to these are categorized into three groups: failure in system operation, mistake in mechanical design or fault in manufacture. These factors, about 150 altogether were studied separately concerning fault, reason, probability, inspections and mutual dependencies.

3. The computer program for the pressure vessel failure probability

The applied fracture criterion is the initiation of crack growth when \( K_I \) exceeds \( K_{IC} \) -value or an overall yielding at the crack vicinity. For \( K_I \) -computation the analytical formulae of Newman and Raju /1/ are adopted.

The solution developed by Harrison et al has been applied to the plastic collapse criterion of the remaining ligament of an semi-elliptical surface crack, as referred in eq. (3) of ref /2/.

The program considers uniform primary stresses and linearly changing secondary stresses. The residual stresses in weldments are superimposed on secondary stresses and thus assumed to have the same linear distribution in the case of cracks shallower than 20 % of wall thickness. In the case of deeper cracks the residual stresses are not supposed to have any effect on fracture. The positive effects of residual stresses, as well as the crack arrest in general, are omitted.

The probabilistic fracture analysis procedure is based on discrete probability distribution method (DPD) /4/; the discrete distributions of loads, residual stresses, and crack depth are applied to resolve the probability distribution of \( K_I \). The fracture toughness and secondary stress distributions are given separately for normal operating temperatures and accidental conditions at the lowest credible temperature.

The crack size distribution after fabrication is supposed to be lognormal, and can thus be characterized by two parameters: median and standard deviation. The effect of non-destructive examinations is taken into account by giving a discretized nondetection probability dependent on flaw size for
preservice and inservice inspections. The crack shape is constant in all considerations and has a depth-to-length ratio 1:10. The due time of fracture analysis is optionally before or after the first inservice inspection.

The thermal fatigue is so far the only crack growth mechanism which has been adopted. The method is semi-deterministic, with the probabilistic feature that we can give alternative combinations of stress variation/number of cycles, together with their respective probabilities of occurrence. The crack growth curves given by ASME Code are used with a 0.5 probability for both wet and dry condition.

The probabilistic fracture analysis program is made for a microcomputer. When having 9 locations in a pressure vessel to be analyzed, the crack depth being discretized in 20 nominal sizes, 4-13 discrete values for nondetection probability, 2-5 discrete values for various stresses, strength and toughness, the CPU time of a microcomputer totals 2-3 minutes.

4. An example: pressurizer
4.1 Initial values

As the first exercise, the pressurizer of a PWR was analyzed by the probabilistic fracture program. The most important distributions for the basic case were selected as follows

- The crack depth of main welds has a median of 8 mm and a standard deviation of 0.542. The number of defects in this example is 10/m^2 weld material, which gives a total of about one defect for longitudinal and bottom head welds.
- Two different NDE procedures and related nondetection probabilities have been considered: NDE1 is close to "alternative procedures" and NDE2 to "PISC procedure" in the PISC reports /3/.
- The fatigue loading period considered for the bottom head weld is \( \Delta t = 150 \text{ MPa, } n = 2000 \).
- The primary, secondary and residual stress distributions, maximum annual values, are given in Table 1.
- The distribution of \( K_{IC} \) is given in Table 2. Higher values than \( K_{IC} = 220 \text{ MPa} \sqrt{m} \) have not been considered by LEFM, but the ligament yielding is the only fracture criterion for those cases. The low values of \( K_{IC} \) down to 100 MPa/\( \sqrt{m} \) refer to the possibility of an improper manufacturing practice.

4.2 Results

The annual fracture probabilities of the two main welds (1: bottom head weld, 2: longitudinal weld in cylinder) are illustrated in Figure 2. The fatigue loading cycle applied to the bottom head weld is quite moderate: one "PISC-procedure" inspection is needed to eliminate its effect. In Figure 2 the fracture probability is also shown for alternative initial defect distributions after one preservice inspection, fatigue cycle and inservice inspection. All these cases with lognormal crack size distributions seem to
result in a fracture probability within one decade. The number of cracks has a linear influence on the fracture probability.

4.3 Sensitivity studies

Instead of having a probability distribution of residual stresses as shown in Table 1, two deterministic values were used: 50 and 300 MPa. With other variables having their basic statistical distributions, the difference in residual stresses contributes by a factor of $10^3$ at normal temperatures when having the larger fracture probability at the level of $10^{-4}$/a. When more inspections are taken into consideration and the probability of fracture is lower ($10^{-7} - 10^{-6}$ with 300 MPa), the impact of the difference in residual stresses is still larger. For LOCA-conditions the factor between the two cases varies from 20 to 2000.

Another sensitivity exercise was made in the variation of the primary and secondary stresses. Values in Table 1 were replaced by deterministic maximum allowable values ($S_m, 3S_m$). This did increase the fracture probability by a factor of 30 (bottom head weld) and 200-300 (longitudinal weld in cylinder). A change of 10% in the maximum allowable deterministic stresses would change the fracture probability by a factor of 2.

Fracture toughness was also varied by using two deterministic values, $K_{IC} = 160$ and 220 MPa√m, the other variables having a statistical character. $K_{IC} = 220$ MPa√m was higher than any $K_I$ resulting from loads. Accordingly, the only fracture cases were related to the ligament yielding of a nearly through-wall crack. The numerical values amounted to $10^{-9}$ or less. For normal operating conditions, $K_{IC} = 160$ MPa√m guarantees the reliability of a pressure vessel equally well, but for LOCA-conditions with higher thermal stresses we end up with fracture probabilities ranging from $10^{-8}$ to $10^{-7}$.

For comparison, the corresponding fracture probabilities with the $K_{IC}$-distribution of Table 2 are around $10^{-6}$ for normal temperatures and around $10^{-7}$ for LOCA-conditions.

5. Discussion

An attempt is made to use such statistical distributions for material properties and loads that would include the effect of some errors and mistakes in the design, manufacturing and operational stages. The distributions chosen are not based on any serious research results of our own. Partly they are based on our engineering judgement, partly they are more like guess. The results indicate that the probabilities of unusually low $K_{IC}$, high stresses exceeding design values and of large flaws are the most sensitive and important points of the model.

6. Conclusions

In this stage of the study it can be concluded that the avoidance of the following factors is of primary importance when assuring the structural integrity of pressure retaining components:
- high tensile residual stresses
- low fracture toughness such as $K_{IC} < 150$ MPa $\sqrt{m}$
- large flaws which might cause the gross yielding of the remaining liga-
mament, and mechanisms which could make cracks grow to the large size.

References


Table I  Discrete distributions of primary ($\sigma_I$), secondary ($\sigma_{II}$), and residual ($\sigma_R$) stresses [MPa]

<table>
<thead>
<tr>
<th>Weld</th>
<th>$\sigma_I$</th>
<th>$\sigma_{II}$ Normal</th>
<th>$\sigma_{II}$ LOCA</th>
<th>$\sigma_R$</th>
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<tbody>
<tr>
<td>1</td>
<td>86</td>
<td>160</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>111</td>
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<td>200</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>99</td>
<td>200</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>127</td>
<td>100</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>109</td>
<td>$10^{-3}$</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td></td>
<td></td>
<td>300</td>
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</tbody>
</table>

Table II  Discrete distributions of $K_{IC}$. Values for LOCA-temperatures in parenthesis if different from normal conditions.

<table>
<thead>
<tr>
<th>$K_{IC}$ (MPa $\sqrt{m}$)</th>
<th>100</th>
<th>130</th>
<th>160</th>
<th>190</th>
<th>220</th>
<th>N.A.</th>
</tr>
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<tbody>
<tr>
<td>Probability</td>
<td>0.001</td>
<td>0.01</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Fig. 1 A part of the fault tree for pressure vessel failure.

Fig. 2 Fracture probabilities of welds 1 and 2 at normal conditions. A = as welded, B = after one preservice inspection, C = after a fatigue loading cycle (only weld 1), D = after an in-service inspection. For weld 1 a less efficient inspection procedure (NDE2) is illustrated than for weld 2 (NDE1). The effect of different parameters in the lognormal distribution of initial defect (median in mm/deviation) is illustrated in column D.