Probabilistic fracture mechanics: PTS Screening criteria for RT_{NDT}, application of FAVOR code to a German KONVOI plant

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1 ABSTRACT

In Germany the structural integrity and safety of reactor components, like reactor pressure vessel (RPV) or pipes, is done by deterministic analyses. Deterministic approaches use conservative assumptions (crack geometry, external loadings, material properties, etc.) to maximize the safety margins. Reasons for such conservative assumptions can be missing information (aleatory uncertainties) or missing knowledge of certain mechanisms (epistemic uncertainties).

A probabilistic analysis uses the same methods (e.g. calculation method for stress intensity factor, crack propagation) as a deterministic one, but addresses the uncertainty of required input data or mechanisms. Unlike a deterministic analysis, which criterion is the achievement of a critical or reference value (e.g. stress intensity factor reaches lower bound of fracture toughness), a probabilistic analysis gives a probability of flaw initiation or component failure. Therefore a probabilistic analysis of a reactor component gives an additional classification of the integrity (safety) of such a component under more realistic assumptions and helps quantifying governing parameters for the component failure, which can be useful for lifetime extension.

An example of such a probabilistic safety analysis is the FAVOR (Fracture Analysis of Vessels, Oak Ridge) computer program, which was developed in the US by the Oak Ridge National Laboratory, and is applicable to the core region of a RPV.

This paper will give a short introduction of the FAVOR computer program and its application to the core region of a German KONVOI-type nuclear power plant (NPP) under pressurized thermal shock (PTS) transients. The implicit restrictions and made adjustments, in order to apply FAVOR to a German KONVOI-type NPP, as well as the required input data are presented in this paper. As a result, the correlation between a given RPV failure frequency (failure probability per year) and the increase of the RT_{NDT} according to increase of cumulated neutron fluence (E > 1MeV) will be presented, to define a PTS Screening Criteria for the reference nil ductility transition temperature RT_{NDT}.

2 INTRODUCTION

The main advantage and difference of a probabilistic fracture mechanics analysis compared to a deterministic one is the addressing of potential uncertainties in the required input data or used methods instead of making mostly conservative assumptions. The main result of a probabilistic fracture mechanics analysis is a probability of component failure or flaw initiation.

Usually a deterministic fracture analysis iterates a parameter (e.g. allowable geometry of a single flaw, RT_{NDT}) until a critical criterion is reached (e.g. flaw initiation). With the help of a probabilistic fracture mechanics analysis it is possible to correlate the parameter of interest with a given probability of initiation or failure. In general the procedure of a probabilistic fracture mechanics analysis is applicable to any type of component, like reactor pressure vessel or pipe. A flow chart for a probabilistic fracture mechanics analysis is given in figure 1.
3 A SHORT INTRODUCTION OF FAVOR

FAVOR (Fracture Analysis of Vessels, Oak Ridge) is a probabilistic fracture mechanics tool applicable for reactor pressure vessels in nuclear power plants. The computer program (version v06.1) had been developed by Oak Ridge National Laboratory in 2006. The analysis is done by a Monte-Carlo simulation, where each simulation represents a simulated RPV, i.e. for each simulation flaws in the RPV are gained by the flaw distribution and embrittlement related input data are sampled. For any details about the application of the FAVOR computer program, the reader is referred to Williams et al. (2007).

The main results of FAVOR are initiation and failure frequency of the RPV with regard to the analyzed transients. Initiation and failure frequency are the initiation and failure probability of the RPV per year. Figure 2 shows the data stream flow of FAVOR through three modules:

FAVLoad: Based on the RPV geometry, the material properties for the clad and base material and the thermal hydraulic conditions (i.e. internal pressure, convective heat transfer coefficient and coolant temperature at the vessel inner surface) of each transient a one dimensional finite elements calculation calculates the temperature and stress distribution in the RPV wall for each transient. Additionally stress intensity factors for surface breaking flaws with various depths and aspect ratios (length/depth) are calculated in this module.

FAVPFM: This is the proper probabilistic fracture mechanics analysis. For all input data gained by measurement (e.g. flaw sizes, chemistry, neutron fluence) possible uncertainties can be addressed. The required input data are flaw data (density, size, location) and core region embrittlement data (e.g. chemistry, neutron fluence, unirradiated RT_{NDT}), which describe the embrittlement of the material. Together with the results of the FAVLoad module (stress, temperature) a probability of initiation (CPI) and failure (CPF) for each transient and simulated RPV is calculated.
FAVPost: According to the occurrence frequency of each transient (occurrence per year) and with the results of CPI and CPF initiation and failure frequency (probability per year) for the RPV is calculated.

Figure 2: data stream flow in FAVOR

4 PROBABILISTIC SAFETY CASE OF A KONVOI-TYPE NPP USING FAVOR

The aim of the application will be the defining of a PTS Screening Criteria, i.e. the maximum allowable RTNDT, caused by the embrittlement of the material, according to a given RPV failure frequency. All the required input data, sampled ones and not sampled ones, are presented in this chapter. The representative KONVOI-type power plant used for these calculations is the NPP Emsland.

Another focus lies on the implicit restrictions and assumptions when applying the FAVOR computer program (version v06.1) to a KONVOI-type nuclear power plant. Some of these restrictions had been eliminated with the help of some adjustments. The main implicit restrictions and assumptions as well as made adjustments are also presented in this chapter.

4.1 Implicit restrictions and assumptions

If the FAVOR computer program will be applied for a specific NPP or a specific type of NPP (e.g. KONVOI) some implemented methods will lead to implicit restrictions or implicit assumptions for the application of interest.

4.1.1 Stress calculation

The calculation of the axial and circumferential stress in RPV wall is done in the FAVLoad module by a one dimensional finite elements calculation. Thus only constant boundary conditions are necessary, i.e. no variation of coolant temperature and convective heat transfer coefficient at inner RPV wall in axial or circumferential direction can be taken into account. This restriction prohibits an accurate presentation of the plume effects and will be a first type of implicit restriction.

For the application of FAVOR to NPP Emsland the thermal hydraulic conditions (internal pressure, convective heat transfer coefficient and coolant temperature at inner RPV wall), depending only on elapsed transient time, had been averaged in circumferential and axial direction for the whole core region. To account the plume effects, the thermal hydraulic conditions in circumferential direction had been weighted according to plume width and width of ambient conditions.


4.1.2 Calculation of initiation probability

For the calculation of the initiation probability for a given flaw FAVOR uses a Weibull distribution for $K_{IC}$ over $\Delta T_{RELATIVE} = T - RT_{NDT}$, where $T$ is the current temperature at crack tip. This Weibull model was constructed by the use of the ORNL 99/27 $K_{IC}$ database, where 255 fracture-toughness data points from 18 materials were available.

A comparison of the Weibull model used in FAVOR and available fracture toughness data from the CARISMA project, Gundermann et al. (2008), for German RPV steels is presented in figure 3. It indicates that using the implemented Weibull model for the calculation of initiation probability leads to an overestimation of the initiation probability.

![Figure 3: comparison of FAVOR $K_{IC}$ model and CARISMA database](image)

4.1.3 Consideration of crack arrest

The RPV failure probability is calculated by the use of an internal Monte Carlo simulation. For the current RPV simulation, transient and flaw the RPV failure at current transient time step is simply the number of failure trials divided by the total number of internal Monte Carlo simulations. For each of these simulations the potential crack arrest toughness $K_{IA}$ will be calculated using a lognormal distribution for $K_{IA}$ over $T - RT_{Arrest}$, where $T$ is the temperature at crack tip and $RT_{Arrest}$ is the reference arrest temperature.

In FAVOR there are two $K_{IA}$ models available. The first model was constructed from 112 fracture toughness, $K_{IA}$, data points. These are the existing 50 data points in EPRI NP-719-SR augmented by 62 data points produced by ORNL survey. The second model was gained by adding arrest data for large-specimen experiments to $K_{IA}$ data base of model 1 (183 fracture toughness, $K_{IA}$, data points).

A comparison of the two models with fracture toughness, $K_{IA}$, data points available from CARISMA project, Gundermann et al. (2008), for German RPV steels is presented in figure 4. It indicates that applying FAVOR to the NPP Emsland $K_{IA}$ model 2 should be used, because this model provides a better compliance with the fracture toughness, $K_{IA}$, data points available from CARISMA project. Nevertheless figure 4 indicates that using $K_{IA}$ model 2 will lead to an underestimation of crack arrest.
Figure 4: comparison of FAVOR $K_{Ia}$ model 1 (a) and $K_{Ia}$ model 2 (b) with CARISMA database

4.1.4 Flaw distribution

FAVOR provides three different input files for the classification of the flaw distribution:
- Surface breaking flaws (through clad) for welds and plates/forgings in the core region of the RPV
- Embedded flaws for welds in the core region of the RPV
- Embedded flaws for plates/forgings in the core region of the RPV

For embedded flaws there also exists a restriction on the flaw location. The inner crack tip of an embedded flaw is assumed to lie between clad/base interface and 1/8 of wall thickness or between 1/8 and 3/8 of wall thickness.

The flaw orientation is assumed to be circumferential, if it is a flaw in a circumferential weld (axial, if it is a flaw in an axial weld) and equally circumferential and axial, if it is a flaw in a plate/forging.

As shown in section 4.2.4 one type of the postulated flaws for the NPP Emsland are underclad flaws (see figure 9). Treating these postulated underclad flaws as surface breaking flaws (through clad) or embedded flaws will over- or underestimate the calculated stress intensity factors, $K_i$. Therefore stress intensity factors for underclad flaws according to Marie et al. (2008) with a plastic correction obtained from RSE-M (2000) are implemented. Without changing the code of the computer program this is only possible, if you replace the $K_i$ values calculated by the FAVLoad module for surface breaking flaws with the own calculated $K_i$ values for underclad flaws and adjust the corresponding input file for surface breaking flaw distribution. This procedure leads to the following implicit assumptions:
- Underclad flaws are located in the weld and in the forgings of NPP Emsland
- Underclad flaws are equally divided into axial and circumferential flaws

4.2 Input data for NPP Emsland

The NPP Emsland is a 4 loop PWR. The core region of the RPV contains two forgings (Ring II and Ring III) and one circumferential weld (Corenaht) connecting these two forgings. The analysed transients are PTS transients, in order to define a PTS Screening Criteria.
4.2.1 RPV: Geometry and materials

RPV geometry:
- Inner radius: 2500 mm
- Wall thickness (without cladding): 250 mm
- Cladding thickness: 6 mm
- Height of forging “Ring II”: 2331 mm (mid of upper weld to mid of “Corenaht”)
- Height of forging “Ring III”: 2687 mm (mid of “Corenaht” to mid of lower weld)
- Height of circ. weld “Corenaht”: 87 mm

RPV material:
- Base material: 22 NiMoCr 37
- Cladding material: X10CrNiNb189
- Welding material: NiCrMo1-UP

4.2.2 Analysed PTS transients

For the PTS Screening Criteria 17 transients were analysed. An overview of these transients is given in table 1. The occurrence per year of these transients is assumed to be lognormal distributed with following expectation value $E(x)$ and scattering factor $k_{95}$ (i.e. 95% of all data lie between $E(x)/k_{95}$ and $E(x) \cdot k_{95}$):

<table>
<thead>
<tr>
<th>Size of Leakage [cm²]</th>
<th>No. of transients</th>
<th>$E(x)$</th>
<th>$k_{95}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1 x cold leg break</td>
<td>0.0014</td>
<td>3.9</td>
</tr>
<tr>
<td>10</td>
<td>1 x cold leg break</td>
<td>0.0014</td>
<td>3.9</td>
</tr>
<tr>
<td>15</td>
<td>1 x hot leg break</td>
<td>0.0014</td>
<td>3.9</td>
</tr>
<tr>
<td>20</td>
<td>1 x hot leg break</td>
<td>0.0014</td>
<td>3.9</td>
</tr>
<tr>
<td>25</td>
<td>1 x hot leg break</td>
<td>0.0014</td>
<td>3.9</td>
</tr>
<tr>
<td>40</td>
<td>1 x hot leg break</td>
<td>0.000051</td>
<td>7.8</td>
</tr>
<tr>
<td>50</td>
<td>1 x hot leg break</td>
<td>0.000051</td>
<td>7.8</td>
</tr>
<tr>
<td>100</td>
<td>3 x hot leg break (1)</td>
<td>0.000041</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>2 x cold leg break (1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>3 x hot leg break (1)</td>
<td>0.000041</td>
<td>8.3</td>
</tr>
<tr>
<td>400</td>
<td>2 x hot leg break (1)</td>
<td>0.0000001</td>
<td>10</td>
</tr>
</tbody>
</table>

(1): different safety injections

Table 1: Analysed PTS transients

4.2.3 Embrittlement related parameters

The embrittlement of the material depends among other things on chemistry and cumulated neutron fluence. The chemistry (especially Cu-, Ni-, P- and Mn-content) of the forgings and the circumferential weld is assumed normal distributed and is determined from the measurements through the wall thickness contained in Langer (2002). Chemistry and unirradiated RT$_{NDT}$ are summarized in table 2.
<table>
<thead>
<tr>
<th></th>
<th>Cu [weight %]</th>
<th>Ni [weight %]</th>
<th>P [weight %]</th>
<th>Mn [weight %]</th>
<th>Unirradiated RT_{NDT} [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV'</td>
<td>σ'</td>
<td>MV'</td>
<td>σ'</td>
<td>MV'</td>
<td>σ'</td>
</tr>
<tr>
<td>Ring II</td>
<td>0.05</td>
<td>0</td>
<td>0.913</td>
<td>0.015</td>
<td>0.006</td>
</tr>
<tr>
<td>Ring III</td>
<td>0.05</td>
<td>0</td>
<td>0.91</td>
<td>0.015</td>
<td>0.005</td>
</tr>
<tr>
<td>Corenaht</td>
<td>0.04</td>
<td>0</td>
<td>0.967</td>
<td>0.023</td>
<td>0.007</td>
</tr>
</tbody>
</table>

1) Normal distribution with mean value MV and standard deviation σ
2) Not used in FAVOR

Table 2: embrittlement related parameters

The cumulated neutron fluence (E > 1MeV) at inner surface of the RPV wall is obtained from results of the third embrittlement surveillance program, Langer (2002). The cumulated neutron fluence (E > 1MeV) according to effective full power years of the NPP is linear fitted:

\[ f(x) = 5.48 \cdot 10^{16} \cdot x + 2.74 \cdot 10^{17} \text{ [neutrons/cm}^2\text{]} \] (8)

with \( x \): effective full power years

The axial and circumferential distribution in the core region of the RPV is obtained according to figure 7 (a) and (b) (from Langer (2002)).

Figure 7: Axial (a) and circumferential (b) distribution of neutron fluence in the core region of the RPV

4.2.4 Distribution of postulated flaws

Based on the ultrasonic (UT) examinations a distribution for postulated flaws in the core region of the RPV is generated. For the circumferential weld “Corenaht” (SST 38) all UT indications from weld SST 36, SST 38, SST 39 and SST 30 and for the forgings “Ring II” and “Ring III” AFA 44, AFA 40, AFA 42, AFA 46 and AFA 47 were taken into account. All UT indications are assumed to be flaws.

Figure 8: Location of UT indications

All UT indications used for circumferential weld “Corenaht” lie in the mid of the RPV wall and were treated as fully elliptical embedded flaws in the FAVOR computer program.
As the UT indications used for “Ring II” and “Ring III” all lie near the clad/base interface, they are assumed to be underclad flaws (see figure 9). To address underclad defects in FAVOR, the KI values for surface breaking flaws were replaced by own calculated KI (see section 4.1.4).

![Figure 9: Underclad defect](image)

### 4.2.5 Some other important input data

Beside the input data already described in the previous sections, FAVOR needs much more input data and selections. The more important ones are:

- Unirradiated flow stress $\sigma_f = 510$ MPa
- Maximum value for $K_{Ic}$ and $K_{Ia} = 220$ MPa$\sqrt{m}$ (according to ASME)
- WPS (Warm Prestressing) effect is accounted (see figure 10): A flaw is in state of WPS, if $dK_I/dt \leq 0$ or $K_I < K_{Ic(min)}$ and $K_{Ic(max)} > K_{Ic(min)}$
- For calculation of $\Delta RT_{NDT}$ Eason 2006 correlation is used

![Figure 10: WPS effect](image)

### 4.3 Results for NPP Emsland

The intention for the application of FAVOR to a KONVOI-type NPP was to define a PTS Screening Criteria. Therefore several FAVOR calculations had been made with increasing effective full power years (EFPY), i.e. with increasing cumulated neutron fluence (E $> 1$ MeV). The results of these calculations are summarized in table 3 and were used to define the PTS Screening Criteria (see chapter 5).

<table>
<thead>
<tr>
<th>EFPY</th>
<th>max. neutron fluence [E &gt; 1MeV] [10^19 n/cm^2]</th>
<th>Initiation frequency</th>
<th>Failure frequency</th>
<th>% of flaws, contribute to failure in</th>
<th>Failure frequency according to</th>
<th>Max. irradiated RT_{NDT} [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Corenaht</td>
<td>Corenaht</td>
<td>Corenaht</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ring II</td>
<td>Ring III</td>
<td>Ring II</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ring III</td>
<td>Ring III</td>
<td>Ring III</td>
</tr>
<tr>
<td>8000</td>
<td>44</td>
<td>6.35E-07</td>
<td>1.47E-11</td>
<td>99.89</td>
<td>0.11</td>
<td>1.47E-11</td>
</tr>
<tr>
<td>10000</td>
<td>55</td>
<td>2.37E-06</td>
<td>1.48E-10</td>
<td>99.51</td>
<td>0.49</td>
<td>1.47E-10</td>
</tr>
<tr>
<td>12000</td>
<td>66</td>
<td>6.79E-06</td>
<td>4.06E-10</td>
<td>96.92</td>
<td>3.08</td>
<td>3.93E-10</td>
</tr>
<tr>
<td>15000</td>
<td>82</td>
<td>2.30E-05</td>
<td>1.92E-09</td>
<td>87.63</td>
<td>12.17</td>
<td>1.68E-09</td>
</tr>
<tr>
<td>18000</td>
<td>99</td>
<td>5.75E-05</td>
<td>6.93E-09</td>
<td>73.67</td>
<td>26.33</td>
<td>5.11E-09</td>
</tr>
<tr>
<td>20000</td>
<td>110</td>
<td>9.34E-05</td>
<td>1.31E-08</td>
<td>65.13</td>
<td>34.87</td>
<td>8.54E-09</td>
</tr>
<tr>
<td>25000</td>
<td>137</td>
<td>2.33E-04</td>
<td>4.97E-08</td>
<td>49.53</td>
<td>50.47</td>
<td>2.46E-08</td>
</tr>
<tr>
<td>27000</td>
<td>148</td>
<td>3.06E-04</td>
<td>7.89E-08</td>
<td>48.18</td>
<td>51.82</td>
<td>3.80E-08</td>
</tr>
<tr>
<td>30000</td>
<td>164</td>
<td>4.32E-04</td>
<td>1.39E-07</td>
<td>48.49</td>
<td>51.51</td>
<td>6.76E-08</td>
</tr>
<tr>
<td>35000</td>
<td>192</td>
<td>6.63E-04</td>
<td>3.31E-07</td>
<td>50.28</td>
<td>49.71</td>
<td>1.67E-07</td>
</tr>
</tbody>
</table>

Table 3: Results of FAVOR calculations
5 PTS SCREENING CRITERIA

With the help of the FAVOR results it is possible to define a PTS Screening Criteria, i.e. a correlation between the maximum irradiated RT_{NDT} and a given RPV failure frequency under PTS transients. According to the number of flaws in the circumferential weld “Corenaht” or in the forgings “Ring II” and “Ring III”, which contribute to RPV failure, a failure frequency for the circumferential weld and the forgings can be determined, see table 3. Both, failure frequency according to circumferential weld (“Corenaht”) and to forgings (“Ring II” and “Ring III”) depending on the maximum irradiated RT_{NDT} show a potential trend. Therefore potential fits for the circumferential weld and the forgings are determined by Least-Square method:

- Circumferential weld “Corenaht”: TWCF = 3.268 \cdot 10^{-34} \cdot (RT_{NDT,max})^{11.2} \quad (9)

- Forgings “Ring II” and “Ring III”: TWCF = 1.549 \cdot 10^{-48} \cdot (RT_{NDT,max})^{18.7} \quad (10)

With TWCF as the through wall crack frequency and RT_{NDT,max} in °C.

For a given allowable failure frequency of 1 \cdot 10^{-6} a allowable irradiated RT_{NDT} for the circumferential weld “Corenaht” and the forgings “Ring II” and “Ring III” according to equations (9) and (10) can be calculated. The allowable irradiated RT_{NDT} is given by:

- Circumferential weld “Corenaht”: allowable irradiated RT_{NDT} = 285°C
- Forgings “Ring II” and “Ring III”: allowable irradiated RT_{NDT} = 170°C

![Figure 12: Results of the PTS-Screening-Criteria](image)

With the results of the PTS Screening Criteria it is also possible to qualify deterministic analyses. For example a performed deterministic PTS analysis, Keim et al. (2008), for the NPP Emsland gives an allowable RT_{NDT} of 90°C for the circumferential weld “Corenaht”. The value of 90°C correlates with a failure frequency of 2.5 \cdot 10^{-12}, which is a factor of 4 \cdot 10^6 less than the allowable failure frequency of 1 \cdot 10^{-6} used to define the PTS Screening Criteria.

6 CONCLUSION

Probabilistic fracture mechanics (PFM) analysis tools, like FAVOR, allow the addressing of potential uncertainties in the required input data or used methods, which is also the main difference compared to deterministic analyses. PFM analyses help to define governing parameters for component failure, which can be useful for lifetime extension.
The application of the FAVOR code to a German NPP presented herein shows, that without adapting the computer program or development of an own analysis tool the user has to deal with some possible restrictions or assumptions. Therefore it makes sense to adapt an already existing tool, like FAVOR, or develop an own PFM tool, according to unique boundary conditions of the application of interest. Reasonable adaptations for the application of FAVOR to the NPP Emsland are:

- Implementation of a three dimensional stress field, in order to address plume effects in a realistic way.
- Implementation of own $K_{IC}$ and $K_{IA}$ curves according to the material of interest.
- Implementation of $K_I$ calculation methods for flaw type (underclad flaw) of interest.

Several FAVOR calculations for the NPP Emsland with adapted $K_I$ calculation for underclad flaws (see section 4.1.4) were performed with the aim to define a PTS Screening Criteria for the reference nil ductility transition temperature $RT_{NDT}$, i.e. a maximum allowable $RT_{NDT}$ according to an allowable failure frequency. For an allowable failure frequency of $1 \cdot 10^{-6}$ the maximum allowable $RT_{NDT}$ is given by:

- Circumferential weld “Corenaht”: allowable irradiated $RT_{NDT} = 285°C$
- Forgings “Ring II” and “Ring III”: allowable irradiated $RT_{NDT} = 170°C$

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