Probabilistic Fracture Mechanics Analyses of Reactor Pressure Vessel under PTS Transients

Kunio ONIZAWA**, Katsuyuki SHIBATA**, Daisuke KATO*** and Yinsheng LI***

The probabilistic fracture mechanics (PFM) analysis code PASCAL has been developed in JAERI. This code can evaluate the conditional probabilities of crack initiation and fracture of a reactor pressure vessel (RPV) under transient conditions such as pressurized thermal shock (PTS). Based on the temperature and stress distributions in the vessel wall for four cases of PTS transients in a typical 3-loop PWR, parametric PFM analyses were performed using PASCAL on the variables such as pre-service inspection method, crack geometry, fracture toughness curve and irradiation embrittlement prediction equation. The results showed that the Arakawa’s model for a pre-service inspection had a significant effect on the fracture probability and reduced it by more than 3 orders of magnitude compared with no inspection case. The fracture probability calculated by the fracture toughness estimation method in Japan was about 2 orders of magnitude lower than that by the USA method. It was found that the treatment of a semi-elliptical crack after its initiation in PASCAL reduced the conservatism in a conventional method where it is transformed into an infinite length crack.

Key Words: Reactor Pressure Vessel, Probabilistic Fracture Mechanics, Pressurized Thermal Shock, Non-Destructive Examination, Irradiation Embrittlement, Fracture Toughness

1. Introduction

Prevention of non-ductile fracture of a reactor pressure vessel (RPV) is one of the most important items to assure the integrity of primary loop pressure boundary of a light water reactor. Therefore, stringent design criteria are prescribed in the codes and standards, such as fracture toughness requirements and surveillance program method.

One of the major aging degradation mechanisms of an RPV is the fracture toughness degradation due to neutron irradiation, that is, the irradiation embrittlement of RPV steel around the beltline region. For pressurized water reactors, pressurized thermal shock (PTS) events are a major safety concern considering the irradiation embrittlement. Regarding the integrity assessment of the RPV for PTS events, a specific rule and a regulatory guide were established in the U.S.A.(1),(2) and afterwards in some countries. The PTS rule prescribes the screening criterion for the reference temperature of fracture toughness curve. When the reference temperature is predicted to reach the criterion, additional analysis by means of probabilistic fracture mechanics (PFM) is required according to the regulatory guide to assess the risk due to PTS events for the operation of the plant with the reference temperature above the criterion. The OCA-P(3) and VISA-II(4) codes are referred to in the regulatory guide as the representative PFM analysis codes.

Since the PTS rule was established, there have been advancements in relevant technologies associated with the physical phenomena involved in PTS events that may impact the RPV integrity assessment. Based on the advancements, the level of conservatism in the screening criterion may be reduced without affecting the level of safety(5). The PTS re-evaluation project was therefore initiated to revisit the technical basis for the current PTS rule and to possibly propose to revise the rule that would reduce any unnecessary level of conservatism in the current rule within the framework established by modern probabilistic risk assessment (PRA) techniques(6). The improved models have been implemented into the FAVOR code(7). Some
PFM analysis codes have also been developed in the other countries, such as PROFMAC-II\(^8\) and OPERA\(^9\) codes.

In JAERI, the PFM analysis code PASCAL (PFM Analysis of Structural Components in Aging LWR) has been developed\(^{10,11}\). This code can evaluate the conditional probabilities of crack initiation and failure of a RPV under transient conditions such as PTS events. The probabilistic simulation methods used in this code are the importance sampling Monte Carlo and stratified sampling Monte Carlo methods. PASCAL has some methods proposed in Japan, such as the crack detection capability formula on a pre-service inspection method, fracture toughness \(K_{IC}\) curve and irradiation embrittlement prediction equation as well as those in the USA. The initial crack size, chemical composition, neutron fluence, fracture toughness and ductile to brittle transition temperature are treated as probabilistic variables.

The PTS transients analyzed in the study were three cases of loss of coolant accident (LOCA) and one case of main steam line break for a typical 3-loop PWR. These were selected from many transients considering the severity on the crack initiation and fracture. Based on the results of thermal hydraulic analyses of the transients, the stress distributions in the vessel wall were calculated with the finite element analysis tool in PASCAL.

The objective of this study is to confirm the effect of variables important to the integrity assessment of a RPV. In the study, we performed parametric PFM analyses on some important models and parameters including pre-service inspection models, fracture toughness curves and irradiation embrittlement prediction equations. A RPV having a semi-elliptical surface crack or an infinite length surface crack in the axial direction was analyzed. The Marshall exponential model\(^{12}\) was used to simulate the distribution of an initial crack depth. This paper summarizes the description of the PTS transients selected for this study and the results of PFM analyses on several important methods and parameters. Since the overall PTS impacts on the RPV integrity are to be evaluated with all possible transients through PRA procedure taking into account their respective occurrence frequencies, this study is considered as a scoping analysis on the important features in conditional fracture probability. The comprehensive PTS analyses are to be performed in the next step.

2. Analysis

2.1 Thermal hydraulics analysis

PTS analyses are performed for an RPV of 3-loop PWR. Referring to the analysis results performed for the H. B. Robinson reactor\(^{13}\), four out of more than 20 sequences were selected, considering the frequency of the event and likelihood of crack initiation during each event. The selected four PTS sequences are as follows:

1) Small break LOCA at hot 0% power condition (SEQ 1)
2) Small break LOCA at hot 0% power condition (Auxiliary feed water not stopped) (SEQ 2)
3) Main steam line break at hot 0% power condition (SEQ 3)
4) Medium break LOCA at full power (SEQ 4)

For SEQ 1 to SEQ 3, thermal hydraulics analyses in the primary loop were performed by using the TRAC-PF1 code for approximately one hour after the event occurrence\(^{14}\). The temperature of the coolant at the downcomer region inside the RPV shell, primary loop pressure, and heat transfer coefficient obtained from the thermal hydraulics analyses are plotted as a function of time in Figs. 1 to 3. The SEQ 4 corresponds to the sequence 2.1 in the PTS analysis report for the H. B. Robinson\(^{15}\). The temperature, pressure and heat transfer coefficient for SEQ 4 are those shown in the report. The time histories of these parameters were extrapolated until two hours in order to confirm the termination of the thermal stress during the sequence.

2.2 Stress analysis

A RPV was modeled by a cylindrical shell with the inside radius of 1 994 mm and the thickness of the vessel wall of 197 mm including 5 mm of overlay cladding at the inner surface. Physical and mechanical properties of the weld metal and cladding used in the thermal stress anal-
Fig. 3 Heat transfer coefficients (HTC) during PTS transients.

Table 1 Physical and mechanical properties used in the analyses

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Thermal conductivity (W/m/K)</td>
<td>37.7</td>
<td>39.9</td>
</tr>
<tr>
<td>Density x specific heat (x10^3 J/m^3·K)</td>
<td>3.488</td>
<td>3.775</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>204</td>
<td>200</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Thermal expansion (x10^-6/K)</td>
<td>12.62</td>
<td>13.47</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>460</td>
<td>440</td>
</tr>
</tbody>
</table>

as an example. At 40 minutes after the transient initiation, the circumferential stress at the inside region of weld metal becomes highest during the transient. At that time, the stress at the inside region reached the yield strength of weld metal as seen in Fig. 4. When the level of stress is compared among the sequences, SEQ 2 results in the highest, while SEQ 4 is the lowest.

2.3 Probabilistic fracture mechanics analysis

A single crack in the weld metal was modeled in axial direction of the RPV and assumed to be an infinite length crack or a semi-elliptical crack at the inner surface. No combination of multiple cracks was considered. A distribution of the size of crack is a major factor for fracture mechanics analysis. The distribution was simulated using the Marshall distribution that was expressed as an exponential type equation. For the semi-elliptical crack, the aspect ratio (depth / length: a/c) was assumed to follow a log-normal distribution where the probability of aspect ratio less than 0.2 was approximately 1%.

Non-destructive examination (NDE) was considered only for a pre-service inspection (PSI). To study the effect of the NDE, the ultrasonic testing model proposed by Arakawa and the NDE model developed at LLNL were applied in the present study. The Arakawa model was developed for advanced ultrasonic testing methods based on theoretical considerations and laboratory experi-
ments. The LLNL model was developed for the ultrasonic testing of nuclear piping and applied to a PFM analysis code, PRAISE.

Neutron fluence at the vessel inner surface was varied up to $10 \times 10^{19}$ n/cm$^2$ ($E > 1$ MeV) by considering an extended operation beyond the design basis plant lifetime. The decrease in fracture toughness due to neutron irradiation was evaluated by the shift of transition temperature in the fracture toughness curve according to either the method prescribed in the JEAC 4206(18) or the method used in the USA. For the JEAC method, the transition temperature shift of RPV steel is estimated by the Japanese embrittlement prediction equation in the JEAC. The chemical compositions, such as Cu, Ni, P and Si in the material important to the irradiation embrittlement were set to correspond to those in a typical old-type RPV weld metal. Fracture toughness was evaluated by means of the Japanese $K_{IC}$ curve established for the generic PTS analysis prescribed in the JEAC 4206. On the other hand, Regulatory Guide (R. G.) 1.99 revision 2(19) and the $K_{IC}$ and $K_{Ia}$ curves based on the ASME code(20) were used for the USA’s method. Since the $K_{IC}$ and $K_{Ia}$ curves in the code are defined as a lower bound ones for a deterministic analysis, the stochastic models developed for the IPTS study(3) was applied in the PASCAL code. In the JEAC 4206, the $K_{Ia}$ curve is not prescribed. Therefore, the $K_{Ia}$ curve for the JEAC method was defined by using the JEAC $K_{IC}$ curve and the temperature difference between the stochastic models for the $K_{IC}$ and $K_{Ia}$ curves. The attenuation of neutron fluence and the degree of embrittlement were estimated by using the exponential type equation provided by R. G. 1.99 rev.2. The initial condition of the fracture toughness of the RPV steel is defined by the reference temperature, $R_{T0}$NDT. Therefore, the initial $R_{T0}$NDT value was set to $-50^\circ$C for a relatively new material and $-17.8^\circ$C for an old one, respectively.

For PFM analyses, several parameters are considered as probabilistic variables with a normal distribution. Table 2 lists the variables with their respective mean, standard deviation, and limits used in this study. In this study, a total of eight cases of the combinations of parameters mentioned above were analyzed for each sequence as indicated in Table 3.

Using the PASCAL code, the conditional probabilities of crack initiation and fracture were calculated assuming a crack subjected to the transient for all cases. A stratified Monte Carlo simulation is applied to the cases with a semi-elliptic crack while a Monte Carlo simulation is applied to the cases with an infinite length crack. The maximum number of sampling in the simulations was $2.7 \times 10^8$ times for the cases of a semi-elliptical crack and $1 \times 10^8$ times for the cases of an infinite length crack. The warm pre-stress effect was not considered in this study. The deviation from the mean of the fracture toughness was calculated only once before crack initiation in the Monte Carlo simulation based on the benchmark exercises for PFM analyses(21),(22). The detail information on the other functions for fracture mechanics analysis is described elsewhere(23). In this study, the fracture is defined as the propagation of a crack through 100% of the wall thickness.

### 3. Results and Discussion

#### 3.1 Comparison of fracture probability on transients

The conditional fracture probabilities for base cases 1-0 and 2-0 are summarized in Table 4. These results were obtained from the analyses with applying the Arakawa’s NDE method to PSI. When the probabilities are compared among the transients, those of SEQ 1 and SEQ 2 are almost the same values each other and larger than the other transients. The transient of SEQ 3 was the least severe, and no fracture was calculated for case 1-0 in the simulations. These results can be understood from the coolant temperature of the transients as was shown in Fig. 1. Since the final coolant temperature for SEQ 3 is highest, al-
though the initial cooling is rather rapid and there is repressurization, thermal stress could be very low for a crack to propagate through the wall. Since the results of SEQ 1 transient are almost similar to those of SEQ 2 transient and the results of SEQ 3 is less important, the following discussion, the transients of SEQ 2 and SEQ 4 are used for the comparison of the results.

### 3.2 Effect of NDE

The conditional fracture probabilities obtained here are very low as indicated in Table 4. This can be due to high capability of crack detection in the PSI based on the Arakawa model. In Fig. 5, the conditional fracture probability by applying the Arakawa model and LLNL model as the PSI are compared with no PSI case. When the effects of NDE are compared, it is obvious that the fracture probability by the Arakawa model is lower than the others by more than 3 orders of magnitude as shown in Fig. 5. The difference between the Arakawa and LLNL models is ~2 orders for a semi-elliptical crack and ~3 orders for an infinite length crack. This result is similar to the result of the literature. The probabilities for no crack detection for the Arakawa model, LLNL model and VISA-II model are plotted in Fig. 6. The curves for the LLNL and VISA-II methods are plotted in two patterns varying the parameter. Clearly the Arakawa model results in the lowest probability of no crack detection. When the fracture probabilities as a function of crack size are concerned, the results may be explained by practically the good NDE performance by the Arakawa model. Figure 7 shows the results of case 1-d for SEQ 2 transient at the neutron fluence of $10 \times 10^{19}$ n/cm² ($E > 1$ MeV) when the Arakawa model was applied. From Fig. 7, it is found that a crack larger than 9% of the wall thickness does not contribute the fracture in this case. The crack size of the highest probability of fracture in this case was 3% of the wall thickness, that

### Table 4 Comparison of conditional fracture probability as a function of neutron fluence

<table>
<thead>
<tr>
<th>Fluence (n/cm²)</th>
<th>SEQ 1</th>
<th>SEQ 2</th>
<th>SEQ 3</th>
<th>SEQ 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 10^{19}$</td>
<td>1.29E-06</td>
<td>1.64E-06</td>
<td>&lt;4E-09</td>
<td>2.23E-08</td>
</tr>
<tr>
<td>$3 \times 10^{19}$</td>
<td>2.72E-06</td>
<td>3.01E-06</td>
<td>&lt;4E-09</td>
<td>2.74E-08</td>
</tr>
<tr>
<td>$5 \times 10^{19}$</td>
<td>4.42E-06</td>
<td>4.75E-06</td>
<td>&lt;4E-09</td>
<td>7.51E-08</td>
</tr>
<tr>
<td>$7 \times 10^{19}$</td>
<td>5.58E-06</td>
<td>5.77E-06</td>
<td>&lt;4E-09</td>
<td>1.26E-07</td>
</tr>
<tr>
<td>$10 \times 10^{19}$</td>
<td>6.63E-06</td>
<td>6.80E-06</td>
<td>&lt;4E-09</td>
<td>1.65E-07</td>
</tr>
</tbody>
</table>

### Fig. 5 Effect of NDE for SEQ 2 transient

### Fig. 6 Comparison of NDE models on the probability of no crack detection

### Fig. 7 Fracture probability as a function of crack size for Case 1-d at neutron fluence of $10 \times 10^{19}$ n/cm² ($E > 1$ MeV)
value of the reference temperature, $RT_{NDT}$. As mentioned in section 2.3, two cases of initial $RT_{NDT}$ values, $-17.8^\circ$C and $-50^\circ$C, were used in this study. Figure 8 shows the comparison of fracture probabilities for SEQ 2 and SEQ 4 transients. The difference of $32^\circ$C in initial $RT_{NDT}$ value results in 3 to 20 times of difference depending on the amount of neutron fluence and the transient condition. The difference tends to decrease as the neutron fluence increases.

When the fracture toughness curve is changed from the curve corresponding to the ASME code to that of the JEAC, the fracture probability is significantly decreased as indicated in Fig. 9. The $K_{IC}$ curve corresponding to the JEAC used in the PASCAL code was defined by the similar method to the ASME curve with an assumption of a normal distribution. For SEQ 2 transient, the difference in the probability is more than one order of magnitude, indicating very low value for JEAC curve. This is because the fracture toughness $K_{IC}$ in the JEAC is higher than that in the ASME code.

### 3.4 Effect of embrittlement prediction equation

Neutron irradiation embrittlement is predicted as a transition temperature shift using an equation established through a statistical analysis of surveillance database. The equations applied in this study are those used in the USA and Japan. For the chemical composition of the weld, the R. G. 1.99 rev.2 gives higher shift of transition temperature of $188^\circ$C at neutron fluence of $10 \times 10^{19}$ n/cm$^2$ ($E > 1$ MeV), while the JEAC equation gives $134^\circ$C at the same fluence. The difference of these shift values directly leads to the difference in the fracture probability as shown in Fig. 10. For SEQ 2 and SEQ 4 transients, the differences in the probabilities are factors of 2.5 and 4.5, respectively. The differences are not so large as compared to the effect of NDE mentioned above. There exists the difference in the database used to establish the prediction equations between in the USA and in Japan. The level of copper content of material studied here is slightly higher than the range of Japanese RPV welds, while the nickel content is higher than the range of the USA RPV welds. It is also noted that the equation in R. G. 1.99 rev.2 is based on the analysis of the surveillance data in the USA available in 1984. Since then, a large number of surveillance data have become available, and the understanding of embrittlement mechanisms has advanced. The improved correlations have recently been developed in the USA. Further comparisons using the improved equations are necessary.

### 3.5 Effect of fracture toughness estimation method

In the previous two subsections, the differences in fracture toughness curves and embrittlement prediction equations were separately compared. However, the estimation of fracture toughness after neutron irradiation is practically performed in the combination of these methods. Figure 11 shows the results of the comparisons for a semi-elliptical crack and an infinite length crack for SEQ 2 and SEQ 4 transients. It is found from the figure that the fracture probability by the USA method is two orders of magnitude higher than that by the JEAC method, indicating the significant conservativeness of the USA method in the analyzed case. This trend is clearer from the comparison of the results in the case of infinite length crack as shown in Fig. 11 (b). The difference of the probabilities by the two methods becomes three orders of magnitude. As mentioned in 3.3 subsection, the difference in fracture toughness curve affects the fracture probability by two or-
ders of magnitude. Therefore it can be concluded that the large part of the difference in Fig. 11 comes from the difference in fracture toughness curve.

3.6 Effect of crack geometry

When a semi-elliptic crack is subjected to higher stress at the surface point than the deepest point, the crack initiates towards the length direction. In the VISA-II code\(^4\) and the FAVOR code\(^7\), the crack geometry is transformed to an infinite length crack in such case. However, in the PASCAL code, the function to simulate the increment of crack length at the surface has been incorporated in the same manner as the deepest point of the crack. Using the function, the effect of crack geometry between a semi-elliptic crack and an infinite length crack on the fracture probability was studied. Figure 12 compares the fracture probabilities for a semi-elliptical crack and an infinite length crack. The probability for an infinite length crack is 7 to 20 times, approximately one order, higher than that for a semi-elliptical crack for both the JEAC and USA methods. The method to calculate the initiation and subsequent propagation of a crack at the surface as well as the deepest point may be more realistic than the method that transforms a semi-elliptical surface crack into an infinite length surface crack. Therefore, this calculation performed in PASCAL reduces the conservatism due to the use of an infinite length crack in PFM analysis.

4. Conclusion

The PFM analysis code PASCAL has been developed in JAERI to analyze the failure probability of the RPV during PTS transients for a typical 3-loop PWR. Parametric PFM analyses under PTS transients were performed mainly focusing on the difference in the methodologies between Japan and the USA using the PASCAL code. The results showed the following conclusions:

- When the good performance NDE model proposed by Arakawa for pre-service inspection is applied, the fracture probability is reduced by more than 3 orders of magnitude.
- Due to the difference in the equations, the fracture toughness estimation method in Japan gives about 2 orders of magnitude lower values of fracture probability than those of the USA’s method for the cases studied.
- The calculation method for a semi-elliptical surface crack used in PASCAL reduces the conservatism in the method assuming an infinite surface crack transformed from an elliptical crack.

Acknowledgements

The authors thank to Drs. M. Suzuki and M. Hirano, JAERI for their helpful discussion and supports. They also appreciate the help and comments by Dr. M. Hirano, JAERI who kindly supplied the information on the PTS transients.
References