ABSTRACT: Structure integrity analysis was performed for the Reactor Pressure Vessel (RPV) of PWR NPP under Pressurized Thermal Shock (PTS) in this paper. Amounts of RPV beltline models with defect were built during analysis. The results from different style and shape factor of defects were compared to obtain the suitable postulated shape in RPV structure integrity analysis. The models with different depth of postulated defects were also calculated and the relationship between depth and stress intensity factor were obtained.

Key words: RPV; PTS; structure integrity; sensitivity analysis;

1 INTRODUCTION

RPV is one of the most important primary components in NPP Reactor Coolant System. It builds the pressure boundary of primary water with the other equipments to prevent the leakage of radiomaterial. So the structure integrity of RPV must be ensured in the whole design lifetime.

The overcooling event happened in USA showed that repressurization may occur at the meantime of rapid temperature dropping during some kinds of overcooling transient (called PTS transient later). Then, high level of tension stress will be generated by the combination of pressure and thermal load. On the other hand, the ductility loss of RPV material will appear for the effect of core irradiation at the end of lifetime. So, fast fracture at the inner surface flaw will happen during serious PTS accident and core meltdown finally.

The research institution of many country have perform amount of related work to ensure the structure integrity of RPV during PTS condition. The deterministic fracture mechanic method advised by International Atomic Energy Agency (IAEA) is applied in this paper to find out the effects of a few important input parameters, such as the postulated flaw, material and welding residual stress.

The shape and size of postulated defect are important parameter in structure integrity analysis and affect the results directly. So, the sensitivity study on the shape of postulated defect is performed in this paper in order to accumulate the method and data for solving engineering problem.

2 INPUT DATA

The beltline of RPV is selected as analysis model for the integrity analysis during PTS because it suffers strongest neutron irradiation leading to a significant nil ductility transition temperature increment and Charpy V upper shelf energy reduction. On the other side, the irradiation embrittlement of welding material is more serious than base metal. So, the beltline with annular weld is modeled in fracture mechanics analysis.

The temperature-dependent thermal and mechanical properties of RPV beltline materials, including base, weld and cladding are applied in analysis. Toughness curve for both base metal and weld is obtained in accordance with Appendix G to ASME B&PV Code XI\[1\] shown in Equation (1).

\[ K_{IC} = 36.5 + 22.783 \exp[0.036(T - RT_{PTS})] \]  

Equation (1)

The safety factor is taken as \( \sqrt{2} \) in accordance with IWB 3600\[1\] for emergency and faulted conditions, then Equation (1) is converted to Equation (2).

\[ K_{IC} = 25.8 + 16.11 \exp[0.036(T - RT_{PTS})] \]  

Equation (2)

Tr3 \[2\] transient is selected as the typical PTS transient, shown in Fig.1.
3 ANALYSIS METHODS

**Thermal analysis:**
The heat convection transfer is applied on the inner surface of the beltline and thermal isolation is considered on the rest of boundaries, including crack face. The results are adopted directly as thermal load in stress analysis.

**Stress analysis:**
The internal pressure and the equivalent tensile are applied on the inner surface, including crack face, and bottom of the beltline respectively. Normal constraints are considered on the bottom and symmetrical planes of beltline, excluding crack face. The thermal loads are obtained from the results of the previous thermal analysis during stress analysis.

**Fracture mechanics Analysis:**
The Virtual Crack Extension method is applied to calculate J-integral which is converted to SIF (Stress Intensity Factor) under plane strain state.

**Structure Integrity Assessment:**
Tangent approach mentioned in IAEA-EBP-08\(^{(3)}\) is applied to obtain the Reference Temperature Limits (PTPTS) which is a very important structure integrity parameter to restrict the embrittlement of RPV material. Typical position A (deepest point) and B (2mm below the interface between base material and cladding) shown in Fig. 2 are evaluated to demonstrate the structure integrity of RPV during PTS.

**FEA models**
The FE models are shown in Fig. 3.

**Boundary Conditions**
The load and constraint boundary condition are shown in Fig. 4 and Fig. 5.
4 SENSITIVITY ANALYSES

4.1 Shape

Traditionally, there are two postulated shapes for surface crack and illustrated in Fig. 6 and Fig.7. The FE models are established for both two shapes and analyzed with linear elastic material behaviors.

The SIF variations along crack front path for both two kinds of shapes at 7200s are showed in Fig.8.

Conclusions:

- The SIF variation for shape 2 is quite flat comparing with shape 1 and it’s more similar to the actual status.
- The SIF at deepest point (point A in Fig.2) is larger than that at point 2mm below interface (point B in Fig.2) for both shapes.
- The SIF at point A for shape 1 is a little lower than that for shape 2 due to the larger pressurized area. But the difference is not so obvious and the results of shape 1 are more conservative. So in the case that just the deepest point is concerned, the crack postulated as shape 1 is also applicable for the facile modeling process.
- The SIF at point B for shape 1 is much lower than that for shape 2 due to the configuration of crack.
4.2 Surface and underclad

The RPV beltline models with surface and underclad axial crack are analyzed with both linear elastic and elastic-plastic material behaviors and the sketch shown in Fig. 9.

![Sketch of surface and underclad crack face](image)

**Fig. 9** Sketch of surface and underclad crack face

The SIF variations along crack front path for surface and underclad cracks at 7200s are obtained and showed in Fig.10.

**Conclusions:**

- Under the same condition, the SIF value obtained from the model with surface crack is much higher and the distribution curve is more flat.

![SIF variations along crack front path for surface and underclad cracks at 7200s](image)

**Fig. 10** SIF variations along crack front path for surface and underclad cracks at 7200s (φ is defined as Fig.7)

### 4.3 Aspect ratio

A series of FE models with surface crack of aspect ratio 0.3, 1/3, 0.5, 0.7 and 1.0 are built and the crack zone of models are shown in Fig.11.

![Crack zone of different aspect ratio](image)

**Fig.11** crack zone of different aspect ratio

The linear elastic and plastic-elastic material mode are applied in the analysis and the SIF variations along crack front path at 7200s are showed in Fig.12 and Fig.13.

![SIF variations of different aspect ratio cracks at 7200s with linear elastic material mode](image)

**Fig.12** SIF variations of different aspect ratio cracks at 7200s with linear elastic material mode

![SIF variations of different aspect ratio cracks at 7200s with elastic-plastic material mode](image)

**Fig.12** SIF variations of different aspect ratio cracks at 7200s with elastic-plastic material mode

**Conclusions:**

- For both linear elastic and plastic-elastic material mode, the SIF distribution curve is very flat when the aspect ratio is between 0.3 and 0.5, especially when aspect ratio is 1/3.

### 4.4 Depth

To obtain the effects of crack depth, the models with the crack of which the depth is 19.5mm, 27.5mm, 37.5mm, 47.5mm and 57.5mm are built and analyzed and crack zone of models are shown in Fig.13.
The SIF variations obtained from calculation are showed in Fig.14 and Fig.15. Fig.16 is the relationship between SIF and depth at 2 typical position showed in Fig.2.

**Fig.13 Models with cracks of different depth (a/c=1/3)**

**Fig.14 SIF variations of different depth cracks at 7200s with linear elastic material mode**

**Fig.15 SIF variations of different depth cracks at 7200s with elastic-plastic material mode**

**Conclusions:**

- When a/c is constant, the area of crack face is increasing with the depth. So the computing values of SIF are increasing with depth at both point A and point B.
- For both point A and point B, the SIF computing values with elastic-plastic material mode are always conservative.
- From Fig.16, the linear relationship between SIF computing values and depth is good.

**5 CLOSING WORDS**

The fracture mechanic analysis and structural integrity assessment of RPV in PWR NPP under Pressurized Thermal Shock (PTS) was performed in this paper. During the process of analysis, amounts of RPV beltline models with cracks were built to obtain the effects of postulated flaws, such as postulated shape, aspect ratio, depth and so on.

Reference:

[3] IAEA-EBP-08, Guidelines on pressurized thermal shock analysis for WWER nuclear power plants, IAEA, 2005