Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Crack Initiation Evaluation for RPV Beltline and Nozzle Subjected to Pressurized Thermal Shock

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***Keywords :** pressurized thermal shock, reactor pressure vessel, beltline, nozzle, allowable RT_{NDT}

1. Introduction

Pressurized thermal shock (PTS) refers to an event in which the reactor pressure vessel (RPV) experiences thermal shock due to excessive cooling while the pressure remains high or the system is repressurized. During a PTS event, the RPV undergoes severe loading due to the combined effects of thermal shock-induced stress and pressure-induced stress. In general, the PTS evaluation of the RPV focuses on defects located in the RPV region near the core (i.e., beltline), which is exposed to neutron irradiation, causing a reduction in the fracture toughness of the RPV material. However, there are regions in the RPV where the exposure to neutron irradiation is very low, but stresses are much greater than at the beltline. Therefore, the regions with less reduction in fracture toughness but subjected to high stress, such as the nozzles, should also be included as targets for PTS evaluation.

In this study, crack initiation evaluation for the RPV beltline and nozzle subjected to PTS is performed. To obtain the temperature and stress intensity factor (K_I) at the crack tip, 3-dimensional finite element (FE) analyses are carried out. Finally, the values of allowable RT_{NDT} (reference temperature for nil-ductility transition) for crack initiation in the beltline and nozzle under the PTS event are evaluated based on the tangent and warm pre-stressing (WPS) approaches.

2. PTS Evaluation

2.1 RPV and Postulated Crack

The PWR (pressurized water reactor) type RPV, which is made of SA-508 Grade 3 Class 1, is considered for the PTS evaluation.

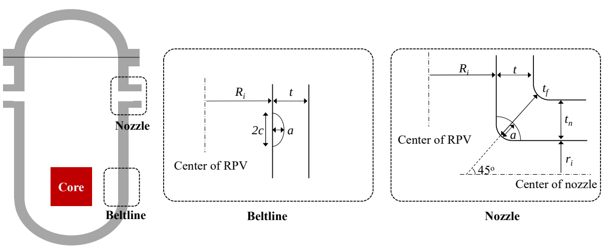


Fig. 1. Postulated crack for RPV beltline and nozzle

Table I: Geometric variables of RPV and postulated crack

RPV			Crack		
R_i/t	r_i/t_n	t_n/t	a/t_f	a/c	a/t
8.22	1.09	0.86	1/4	1/3	1/4

The postulated cracks for the RPV beltline and nozzle with detailed geometric variables are shown in Fig. 1 and Table I. Axial surface cracks with a crack depth equal to one-fourth of the thickness are considered. The crack shapes in the beltline and nozzle are semi-elliptical and quarter-circular, respectively, as presented by the ASME Code Section XI [1] for crack analysis. The cladding is ignored in this evaluation.

2.2 PTS Transient

The selected PTS scenario for the evaluation is shown in Fig. 2, which represents the temperature and pressure histories caused by the main steam line break [2].

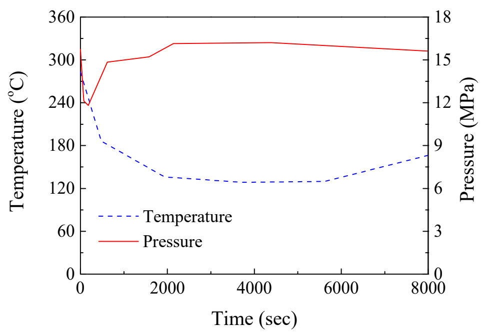
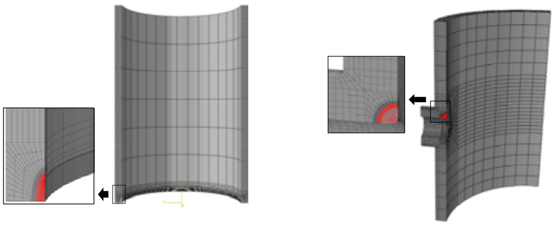


Fig. 2. PTS transient

2.3 Fracture Mechanics Analysis

The linear elastic fracture mechanics (LEFM) analysis is carried out to obtain the temperature and K_I at the crack tip. FE analyses are performed using ABAQUS [3]. The employed FE models are shown in Fig. 3. The quarter model considering the symmetry condition is utilized to reduce computational efforts. The 20-node reduced temperature-displacement element (C3D20RT in ABAQUS library) is used. The crack is modeled to wedge-shaped collapsed elements to consider a singularity near a crack tip. As the loading conditions, the temperature transient is applied on the inner surface of the RPV, and the distributed load corresponding to the pressure transient is applied on the both inner surface of the RPV and the crack face. Temperature-dependent material properties of SA-508 Grade 3 Class 1 are used for the analysis.



(a) Beltline (b) Nozzle

Fig. 3. FE model for LEFM analysis

2.4 Evaluation Methodologies

Under PTS conditions, it was assumed that RPV failure occurred due to cleavage fracture when the crack initiates. In the LEFM regime, crack initiation occurs when the K_I is greater than the initiation fracture toughness (K_{Ic}). K_{Ic} is determined by the equation below, as a function of metal temperature (T) and RT_{NDT}.

$$K_{Ic} = 36.5 + 22.783\exp\left[0.036(T - RT_{NDT})\right]$$

Fig. 4 shows the concept of two approaches used for evaluation, the Tangent approach and the WPS approach. Both approaches aim to determine the allowable RT_{NDT} at which crack initiation occurs. As depicted in Fig. 4, the K_{Ic} curve shifts to the right as RT_{NDT} increases during the service life of RPV. In other words, at the same temperature, K_{Ic} becomes smaller as RT_{NDT} increases.

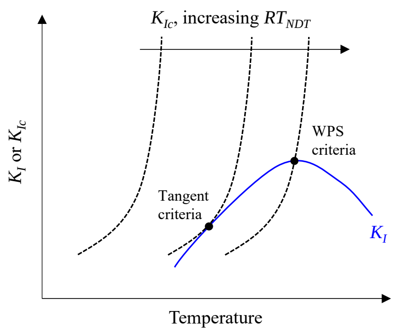
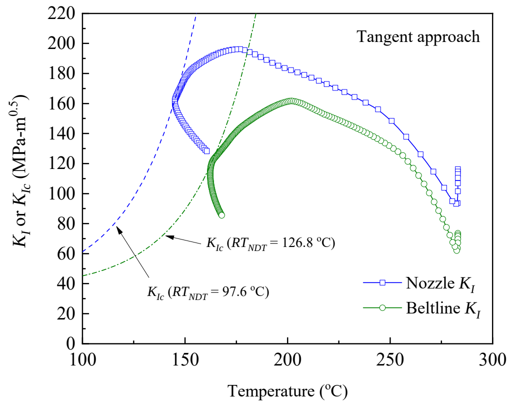


Fig. 4. Methodologies for determination of allowable RT_{NDT}

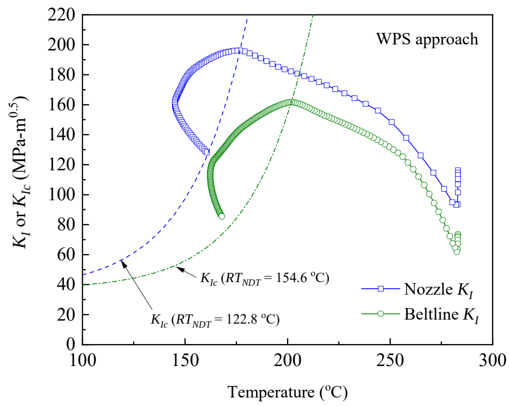
The Tangent approach is a method of determining the RT_{NDT} at the tangent point (first point) where K_I exceeds K_{Ic} as the allowable RT_{NDT} while increasing an arbitrary RT_{NDT}. On the other hand, the WPS approach is a method that takes the warm prestressing effect into account. In this context, crack initiation can be ignored during the transient in which the K_I monotonically decreases after reaching its peak value. As a result, the allowable RT_{NDT} is determined at the point where the peak value of K_I exceeds the K_{Ic} [4].

3. Evaluation Results

Fig. 5 shows the PTS evaluation results of the RPV beltline and nozzle using Tangent and WPS approaches. For the given PTS transient, the allowable RT_{NDT} evaluated using the Tangent approach was lower than that evaluated using the WPS approach since K_I decreases monotonically after the peak. Furthermore, the allowable RT_{NDT} of the nozzle is determined to be lower than that of the beltline for both approaches since the K_I of the nozzle is greater than that of the beltline at all temperatures (i.e., at all times).



(a) Tangent approach



(b) WPS approach

Fig. 5. Determination of allowable RT_{NDT} for beltline and nozzle under PTS

4. Conclusions

In this study, the vales of allowable RT_{NDT} of the beltline and nozzle under PTS events are investigated. Even though the nozzle is exposed to extremely low neutron irradiation compared to the beltline, it could be more vulnerable than the beltline due to its lower permissible RT_{NDT}. Therefore, during PTS evaluation, both the beltline and nozzle should be taken into consideration.

ACKNOWLEDGEMENT

This study was conducted with the support of the National Research Foundation of Korea with the funding of the government (Ministry of Science and ICT). (No.NRF-2020M2D7A1063205)

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