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Recent Progress in Research on Structural Integrity of Reactor Pressure Vessel – Focusing on PVP Conference Papers

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1. Introduction

Reactor pressure vessel (RPV) in nuclear power plant is one of the most important components because it is not replaceable and the materials under irradiation. Section XI of the ASME code provides models of the fracture toughness of ferritic steel used for RPV materials. Recent efforts have been made to apply newly developed model and extend applicable range based on enhanced database and model[1-7] along with structural integrity evaluation of RPV using advanced FE modeling technique[8-9] by the number of researchers. In this paper, recent progress in research on structural integrity of RPV is analyzed with a focus on latest PVP conference papers. Issues on fracture toughness curve, nozzles in the beltline region, PTS evaluation and eXtended Finite Element Method (XFEM) are dealt with and discussed for the future work.

2. Issues on RPV Integrity

In this section newer toughness models that are based on considerably more data, effect of nozzles in the beltline region to P-T limits evaluation and crack evaluation techniques using XFEM are described.

2.1 Fracture Toughness Model

Section XI of the ASME code provides models of the fracture toughness of ferritic steel. The K_{IC} and K_{IA} curves were developed in 1972. The code has recently been expanded to include procedures to estimate RT_{NDT} using Master Curve (MC) index temperature T_0. In 2010, based on newly reported large amounts of data, index temperature screening limits are established by the NRC's PTS re-evaluation effort. This result was adopted in 10CFR50.61a of the alternative index temperature screening limits. Therefore, the ASME code might be improved throughout this historical background and following limitations[1-4].

· On the lower shelf, the low-temperature asymptote of the K_{IC} curve does not represent a lower bound to all available data.

· On the upper shelf, the de facto K_{IC} limit of applicability of 220 MPa√m exceeds available data, especially after consideration of irradiation effects.

· The separation between the K_{IC} and K_{IA} curves depends on the amount of irradiation embrittlement, a functionality not captured by the ASME Section XI equations.

Researches on this area, models were proposed by reflecting both the temperature dependence and scatter in a number of fracture toughness metrics (i.e K_{JC}, K_{IA}, J_{IC}, and $J_{0.1}$). These models and interrelationships are linked via a single parameter: the MC index temperature, T_0. ASME code could be revised by using these models and analyses results of existing ample data for more accurate toughness models to overcome conservatism of the current RT_{NDT}-based approach.

Additionally, modified Advance MC (AMC_m) approach for the Ultra High Strength Steel (UHSS) with yield strength in excess of 900 MPa was proposed by Kim Wallin[5].

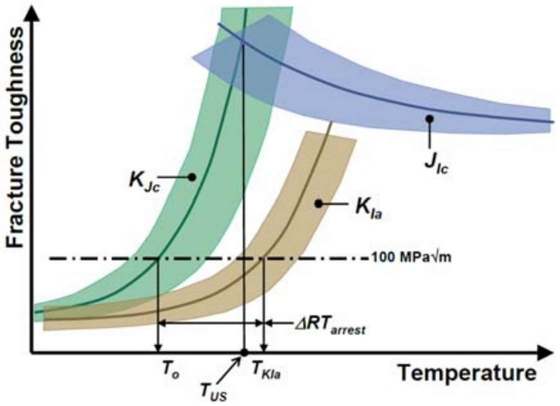

Fig. 1. Fracture toughness based on enhanced database and model[3].

2.2 Evaluation of Extended Beltline Region

Considering extended beltline region has become an issue due to the long-term operation of NPP. Interested area is the P-T limit evaluation. The highest RT_{NDT} material does not always produce the most restrictive P-T limits because the highest stress locations is occurred at RPV discontinuities, such as nozzles, under severe thermal transient. In 2013, the nozzle corner solution was adopted into ASME code, Section XI, Nonmandatory Appendix G[6]. NRC performed DFM/PFM analysis to quantify the effect of the stress concentration characteristic of the nozzle in 2015[7]. It was reported that nozzles produce controlling P-T limits for low embrittlement PWR plants by DFM analysis, and for the larger (1/4T) postulated flaw size on the inner diameter (ID) subjected to a normal heat up condition by PFM analysis as shown in Fig. 2-3. It means that assessment of the impact of nozzle discontinuities is necessary to evaluate P-T limit curve along with operating condition of NPP in the future.

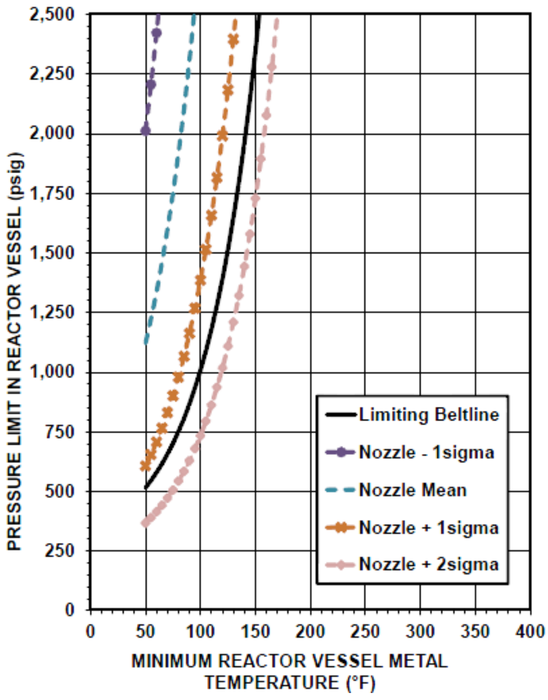

Fig. 2. Calculated P-T limits for low embrittlement plant[7].

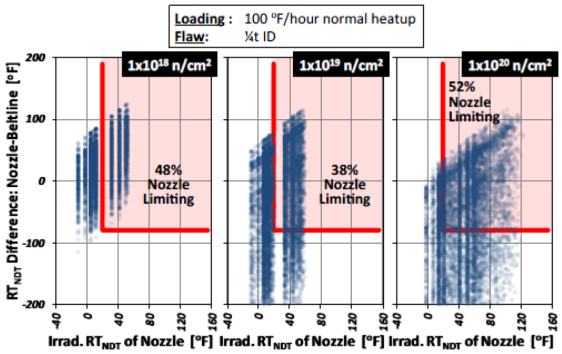

Fig. 3. Comparison of critical RT_{NDT} conditions (red box) with range of material RT_{NDT} possible at three different fluence levels for the case of a $\frac{1}{4}$t flaw on the ID subjected to a normal heat-up at 100 °F/hour[7].

2.3 Application of XFEM

The extended finite element method is an extension of the conventional finite element method based on the concept of partition of unity. Advantages of this method are both simple simulation of crack growth behavior and simple crack modeling. Applicability of XFEM was proven by research results[8], and it is widely used in recent years. In structural assessment of RPV, XFEM is useful to simulate initiation, propagation and arrest of postulated crack. According to the research results performed by AREVA, XFEM analyses show a good agreement with the standard PTS analyses as summarized in Table 1(the first and second column) without crack growth)[9]. The third column shows the resulting allowable reference temperatures and corresponding safety margins when limited crack propagation (3 or 4 mm) is tolerated. The XFEM analyses show that, even if the postulated crack initiation occurs under significant PTS transient, only relatively small amount of crack propagation can be expected.

This methodology will be useful if the plume effect is evaluated by CFD analysis, and analysis of fluid-structure interaction are performed using CFD results in one FE program. If this unified analysis is possible, more accurate analysis is expected.

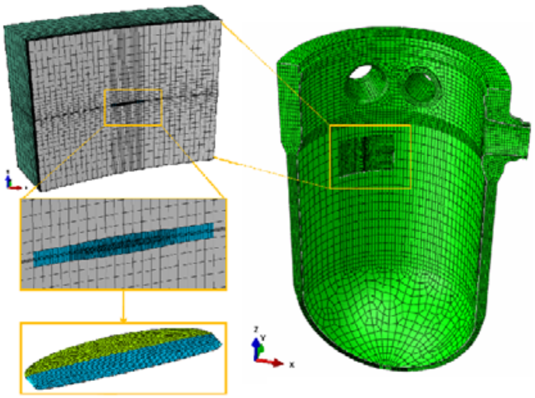

Fig. 4. FE model used in the XFEM analyses[8].

Table I: Safety assessment : standard PTS vs. XFEM[8]

Assessed region	RT_{NDT} allowable [°C] Standard PTS Tan / Max	RT_{NDT} allowable [°C] XFEM Activaton of crack front without CG	RT_{NDT} allowable [°C] XFEM limited crack growth 3 / 4 mm	$RT_{ref,ART}$° [°C]	
Base metal in vicinity of core weld	62 / 84	64 - 81	109 / 131	33*	-16**
Leading TH trasient surface breaking crack a = 10 mm. a/2c = 1/6, Point A					
Safety marigin in [K] according to B01 Method I	29 / 51	31 - 48	76 / 98		
Safety marigin in [K] according to B01 Method II, Option A	78 / 100	80 - 97	125 / 147		
Base metal in vicinity of core weld	61 / 81	61 - 80	101 / 123	33*	-16**
Leading TH trasient surface breaking crack a = 10 mm. a/2c = 1/6, Point B					
Safety marigin in [K] according to B01 Method I	28 / 48	28 - 47	68 / 90		
Safety marigin in [K] according to B01 Method II, Option A	77 / 97	77 - 96	117 / 139		

3. Conclusions

In this paper, recent issues on RPV integrity researches, such as fracture toughness model, effect of the beltline region to the P-T limit curve and XFEM technique are reviewed. Considering the increase of operating years of domestic NPPs, intensive and extensive researches should be carefully prepared to overcome a threat of material aging degradation.

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