Structural Integrity Assessment of Reactor Pressure Vessel during Pressurized Thermal Shock

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1. Introduction

At present, several different procedures and approaches are used for integrity assessment of reactors pressure vessels (RPVs) [1~3]. This is the case not only between WWER and PWR types of reactors but also within each group. These differences are based, in principle, on different codes and rules used for design, manufacturing and materials used for the various types of reactors on one side, and on the different level of implementation of recent developments in fracture mechanics on the other side. It is also the main reason why results from calculations of pressurized thermal shock (PTS) in different reactors cannot be directly compared.

The purpose of this paper is to introduce a comparative assessment study for the deterministic fracture mechanics approach of the pressurized thermal shock of the reactor pressure vessel. Round robin problems consisting of 10 cases are solved and their results are compared to issue some recommendation of best practices and to assure an understanding of the key parameters of this type of approach, which will be helpful for the benchmark calculations and as a part of the knowledge management for the future generation. Maximum allowable transition temperatures are investigated with respect to the effects of the sensitive parameters like cladding properties, postulated defect shape and size etc.

2. Problem Definition

2.1 Reactor vessel

The reactor vessel considered in this analysis is typical 3-loop PWR, which is made of ASTM A 508 CL. 3 with an inner surface radius of 1994 mm, a base metal thickness of 200 mm, a cladding thickness of 7.5 mm and an outer surface radius of 2201.5 mm. The postulated defect as a base case is surface through clad breaking semi-elliptical crack of 19.5 mm depth and 117 mm length for a/c = 1/3 as shown in Figure 1. The orientation is axial in the weld metal and pressure is assumed to be applied on the crack face.

2.2 Transient

One overcooling transient due to assumed leak is defined as in Figure 2., for which axisymmetric loading conditions are assumed. It is a typical PTS transient with repressurization. The temperature and pressure start to decrease but at a certain time, about 7200 sec after the transient began, the system pressure increases rapidly and it is maintained and slow heating occurs, which shows typical characteristics of the PTS transient. In this case, pressure is assumed to be a dominant factor.

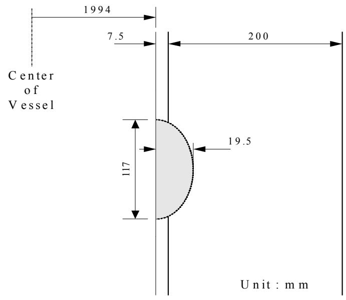


Figure 1. Schematic diagram of postulated defect

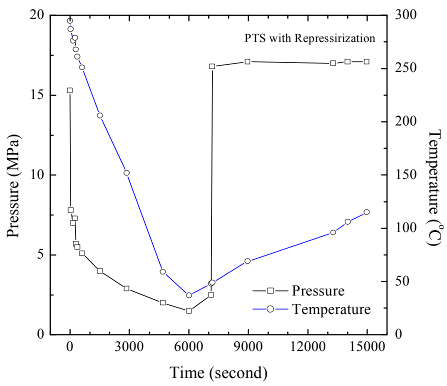


Figure 2. Transient histories

2.3 Sensitivity study

Several parametric studies are proposed to investigate the influence of certain parameters on the results. Of them considered here is postulated defect of those parameters such as orientation, underclad vs. surface crack, defect depth (a = 19.5, 27.5, 47.5) and defect shape (a/c = 0, 1/3, 1/2, 1/1). In addition, the effect of cladding is investigated for three cases as follows:

- C1: No cladding. Cladding properties are assumed as identical to the base metal.
- C2: Cladding thermal conductivity is considered. Additional stress from steep temperature gradient in cladding is evaluated.
- C3: Cladding is fully considered. Additional stresses from steep temperature gradient and differential thermal expansion are evaluated.

3. PTS Analyses

3.1 Analysis method

If a crack with a specific size and shape is given, it is necessary to check whether it is initiated or not during the PTS transient. In this study, the deepest point of a crack was investigated for a possible initiation. The temperature and stress intensity factor histories at crack tip are calculated. Also the fracture toughness K_{IC} is determined using Eq. (1) with $K_{IC\ max} = 220\ \text{MPa}\sqrt{\text{m}}$ for the variations of RT_{NDT} [4] which is assumed arbitrarily.

$$K_{IC} = 36.5 + 22.783 \exp\left[0.036\,(T - RT_{NDT})\right] \qquad (1)$$

The lower bound of allowable RT_{NDT} is determined when K_{IC} curve meets K_I curve tangentially, which is called tangent criteria. In the same way, the upper bound of allowable RT_{NDT} is determined when K_{IC} curve intersects a maximum point of K_I curve, which considers a warm prestressing effect and is called maximum criteria. Even though the RT_{NDT} of the material is higher than the lower bound determined by tangent criteria, the crack will not be initiated due to warm prestressing effect if it is lower than the upper bound. Therefore the range of allowable RT_{NDT} is determined by two criteria depending on the warm prestressing effect.

3.2 FE analyses and results

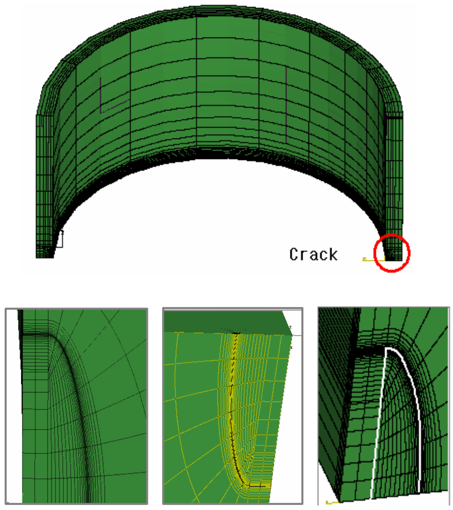
Finite element (FE) analyses were performed by ABAQUS employing FE meshes depicted in Figure 3. to determine the crack tip temperature and K_I values. The material property variation with temperature and pressure load on crack surface were considered. Besides, heat transfer from the outer surface was set to zero and residual stress in weld as well as fluence attenuation were not considered.

Figure 4. compares the effects of cladding, aspect ratio, flaw shape and flaw depth.

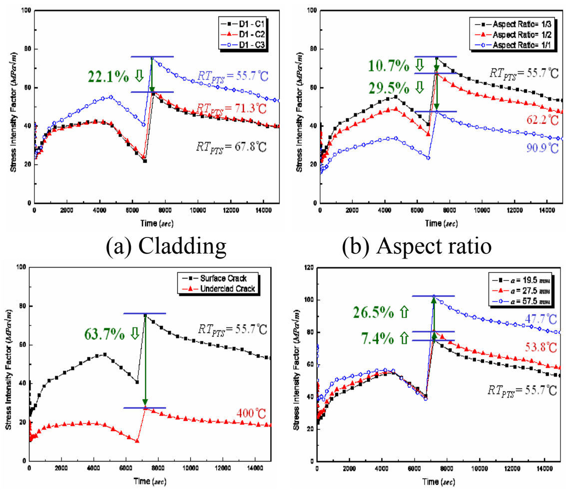
- When the differences in thermal conductivity and thermal expansion coefficients of cladding are fully considered, the stress intensity factor increases, which is greater near the cladding/base interface resulting in the decrease of the maximum allowable RT_{NDT}. Considering cladding thermal conductivity alone produces the most unconservative allowable RT_{NDT}.
- As the aspect ratio increases with the same defect depth, the maximum allowable RT_{NDT} increases.
- The allowable RT_{NDT} for underclad crack is considerably low than that of surface crack with the same defect depth.
- As the crack depth increases, the maximum allowable RT_{NDT} decreases but the difference is almost negligible. Or, the defect depth is not significant for the determination of the allowable RT_{NDT} for a very rapid cooling condition.

4. Concluding Remarks

This study performed a structural integrity assessment of RPV during PTS and analyzed the results from FE analyses with respect to the effects of the sensitive parameters like cladding properties, postulated defect shape and size etc.



(a) Axial surface (b) Circ. Surface (c) Underclad
Figure 3. Typical FE mesh and flaw shapes



(a) Cladding (b) Aspect ratio
(c) Flaw shape (d) Flaw depth
Figure 4. Effects of analysis parameters

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