THE EFFECT OF POSTULATED FLAWS ON THE STRUCTURAL INTEGRITY OF RPV DURING PTS

MYUNG JO JHUNG*, YOUNG HWAN CHOI, YOON SUK CHANG[1] and JONG WOOK KIM[2]
Korea Institute of Nuclear Safety
19 Guseong-dong, Yuseong-gu, Daejeon 305-338, Korea
[1]Sungkyunkwan University
300 Cheoncheon-dong, Jangan-gu, Suwon, 440-746 Korea
[2]Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea
*Corresponding author. E-mail : mjj@kins.re.kr

Received May 22, 2007
Accepted for Publication August 25, 2007

Postulation of flaws, one of the most important areas in RPV integrity assessment, significantly affects the results. In the present work, several parameters, such as orientation, underclad vs. surface cracking, crack depth and shape, etc., are postulated and parametric studies are performed to investigate the influence of the flaw parameters on the structural integrity assessment of the reactor pressure vessel during pressurized thermal shock. The influence of individual parameters describing the crack is evaluated based on sensitivity study results.

KEYWORDS : Pressurized Thermal Shock, Reactor Pressure Vessel, Structural Integrity, Stress Intensity Factor, Warm Prestressing

1. INTRODUCTION

At present, several different procedures and approaches are used for integrity assessments of reactors pressure vessels (RPVs). This is the case not only between Eastern and Western types of reactors but also within each group. In principle, these differences are based, on different codes and rules used for design, manufacturing, and the materials used for the various types of reactors. Furthermore, different levels of implementation of recent developments in fracture mechanics also account for the differences in assessment procedures Accordingly, results from calculations of pressurized thermal shock (PTS) in different reactors cannot be directly compared [1, 2].

There are several parameters that are important in the RPV integrity evaluation during PTS. However, they are defined and implemented in individual codes in different ways and to varying degrees depending on the overall approach used in the procedure. The approach is basically connected with the principal material fracture toughness approach as well as the implementation of further detailed inputs for the calculations.

Postulation of defects used in reactor pressure vessel integrity assessments is one of the most important aspects of the assessment, and significantly affects the results. Postulated defects are usually exactly defined in the applied standard, in some cases in relation to the status of non-destructive testing used in the assessed RPV.

The aim of the present study is not to define the parameters of a postulated crack, as has been done in the standard, but to explain the influence of individual parameters describing the crack, largely based on sensitivity study results.

Several parameters are postulated such as orientation, underclad vs. surface cracking, defect depth and shape, etc. Parametric studies were performed to investigate the influence of flaw parameters on the structural integrity assessment of the reactor pressure vessel during pressurized thermal shock.

2. ANALYSIS

2.1 Reactor Vessel and Postulated Defect

The reactor vessel considered in the analysis is from a typical 3-loop PWR, and 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.

As a base case, the postulated defect is a through-clad surface-breaking semi-elliptical crack of 19.5 mm depth $\times$117 mm length for a'/c = 1/3, as shown in Fig. 1. The orientation is axial in the weld metal and pressure is assumed to be applied on the crack face. An analysis matrix for the sensitivity of the postulated defect is given in Table 1[3].

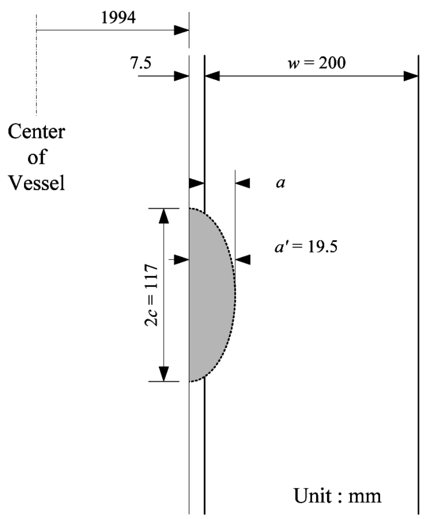


Fig. 1. Postulated Defect

Table 1. Analysis Matrix for Sensitivity Study of Postulated Defect

Location	Orientation	Shape	Aspect ratio*	Depth	
				a	a/w
surface	axial	semi-elliptical	1/3	12	0.06
surface	circum.	semi-elliptical	1/3	12	0.06
underclad	axial	semi-elliptical	1/3	12	0.06
underclad	axial	semi-elliptical	1/3	15	0.075
surface	axial	semi-elliptical	1/2	12	0.06
surface	axial	semi-elliptical	1/1	12	0.06
surface	axial	infinite	0	12	0.06
surface	axial	semi-elliptical	1/3	20	0.10
surface	axial	semi-elliptical	1/3	50	0.25
underclad	axial	elliptical	1/3	12	0.06

* a'/c for surface, a/c for underclad.

2.2 Transient

One overcooling transient due to an assumed leak is defined as presented in Fig. 2, for which axisymmetric loading conditions are assumed. It is a typical PTS transient with repressurization. At the beginning of the transient, temperature and pressure decrease, but at a certain time, i.e., roughly 7200 s after the transient begins, the system pressure increases rapidly and slow heating occurs; temperature and pressure are thereafter maintained at nearly constant values. In this case, pressure may be the dominant factor.

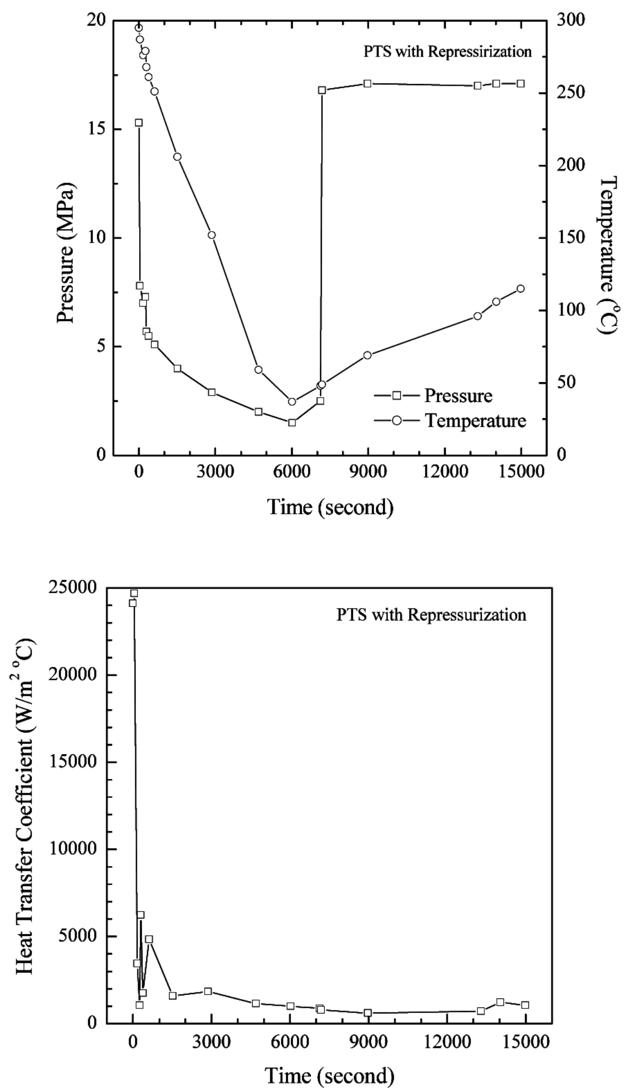


Fig. 2. Transient Histories of PTS with Repressurization

2.3 Analysis Method

If a crack with a specific size and shape is given, it is necessary to check whether it is initiated during the PTS transient. In this study, the deepest point of the crack and 2 mm below the interface were investigated for possible initiation. The temperature and stress intensity factor histories at the crack tip are calculated. The fracture toughness K_{IC} is determined using Eq. (1) for various

RT_{NDT} [4], which is assumed arbitrarily.

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

The upper bound of allowable RT_{NDT} is determined when the K_{IC} curve meets the K_I curve tangentially; this is called a tangent criterion (Fig. 3). In the same manner, the upper bound of the allowable RT_{NDT} is determined when the K_{IC} curve intersects the maximum point of the K_I curve considering the warm prestressing effect and is called the maximum criterion. Even though the RT_{NDT} of the material is higher than the upper bound determined by the tangent criterion, the crack will not be initiated due to the warm prestressing effect if it is lower than the upper bound determined by the maximum criterion. Therefore, the range of allowable RT_{NDT} is determined by two criteria, the tangent criterion and the maximum criterion, depending on the warm prestressing effect [5].

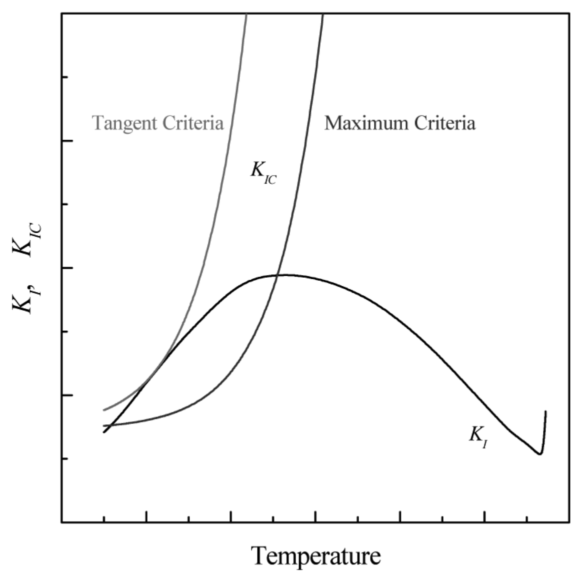


Fig. 3. Determination of Maximum Allowable RT_{NDT}

2.4 Fracture Mechanics Analysis

3-D finite element analyses were performed for the investigation of the cladding effect, defect aspect ratio, and defect geometries. The I-DEAS program was used for the finite element modeling. ABAQUS, a general purpose finite element analysis program, was also used for the analysis.

Due to the symmetry of the geometric configuration and load condition, only a quarter of the whole reactor pressure vessel was modeled, as shown in Fig. 4. The model was designed with 20-node isoparametric quadratic brick elements with reduced Gaussian integration points and 20-node quarter point brick element for the crack front point. The stress intensity factor was calculated from the value of J-integral with the following equation representing the plane strain condition:

$$K_I = \sqrt{\frac{JE}{1-\nu^2}} \qquad (2)$$

2.5 Determination of Allowable RT_{NDT}

The stress intensity factor and temperature histories at the deepest point are shown in Figs. 5 and 6, respectively. From these figures, the maximum allowable RT_{NDT} is obtained, as shown in Fig. 7.

3. RESULTS AND DISCUSSION

3.1 Underclad vs. Surface

The crack position through the wall thickness is usually postulated as a surface or underclad crack. The surface position is more conservative than the underclad, but no known flaws in the base or weld metal extended up to the inner surface of the RPV (i.e. penetrating the cladding) have been found in real cladded RPVs. Moreover, for

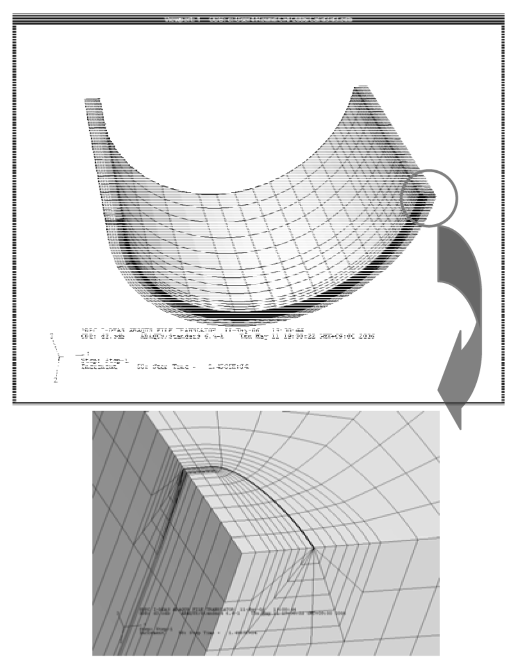


Fig. 4. 3-D Finite Element Mesh for Semielliptical Surface Crack

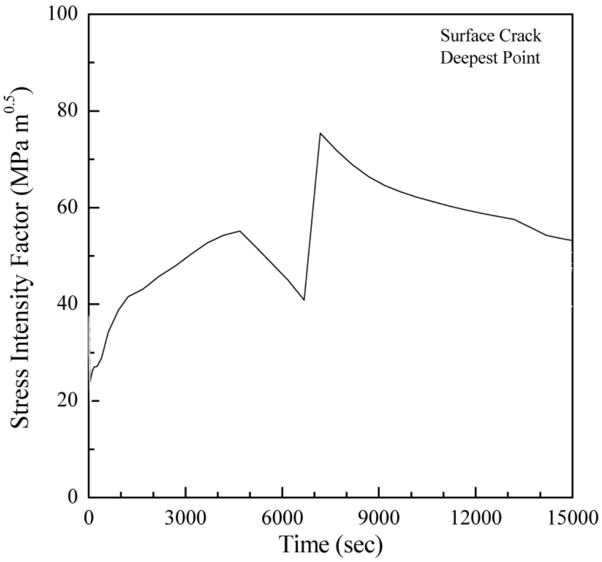


Fig. 5. Stress Intensity Factor at the Deepest Point

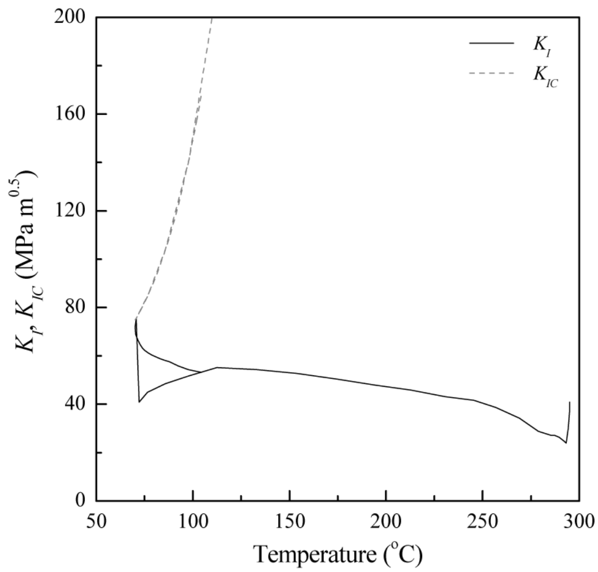


Fig. 7. Determination of Allowable RT_{NDT}

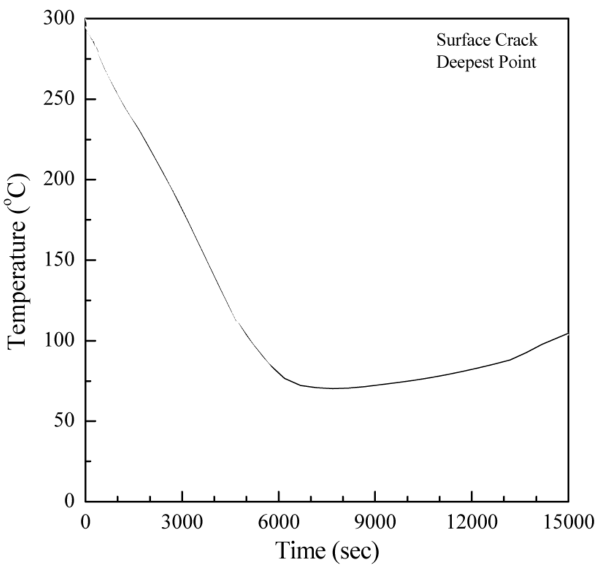


Fig. 6. Temperature at the Deepest Point

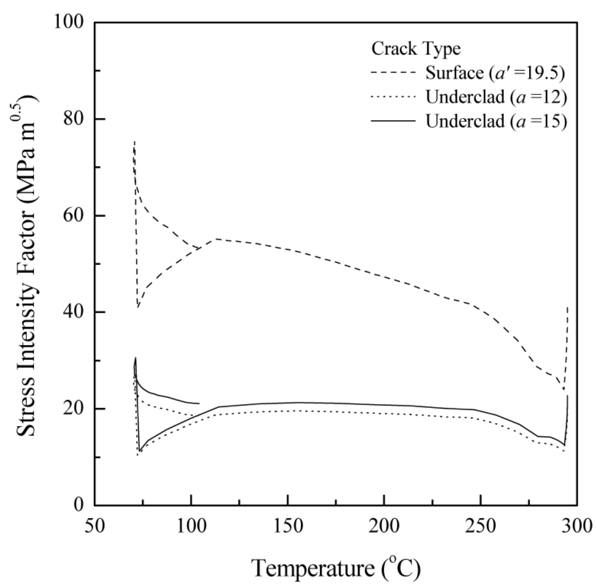


Fig. 8. Comparison of Stress Intensity Factors between Defect Types

multi-layer claddings, the probability of surface cracking is still lower. The bands of multi-layer cladding are usually welded such that they are overlapped.

The position of the postulated defect should be based on the standard used. It is well known that underclad defects exhibit much smaller K_I values and, as consequence, much higher allowable index temperatures (i.e. less conservative solution) than surface breaking defects exhibit. In the performed benchmark, postulation of an underclad defect brings a benefit reduction of more than 50% in terms of K_I (Fig. 8) and significant benefit in terms of RT_{NDT}.

3.2 Defect Depth

The maximum depth of the postulated crack is a very important parameter of the RPV integrity assessment. It should be prescribed by the applied standard and is generally prescribed directly in the standard (e.g. as $^1/_4$ of the wall thickness). According to some recent standards, the original (large) prescribed maximum depth of the postulated crack can be significantly reduced on the basis of qualified non-destructive testing results. The crack depth is in this case connected to the plant specific non-destructive testing qualification criteria, along with application of some safety margins.

With respect to the effect of the postulated crack depth on the results of PTS analyses, it might be assumed that with postulation of a deeper crack, an accordingly more conservative solution would be obtained. In reality, however, the situation is not this simple. When assessing the deepest point of the crack only (which is sufficient according to some older standards), the K_I values increase in most cases with increasing crack depth. However, at the same time, the temperature at the deepest point of the crack also increases with increasing crack depth (and, consequently, the fracture toughness of the material also increases). Before the calculation, it is not clear which effect prevails. Moreover, if attenuation of the fluence is taken into account, the deeper points may not be as dangerous as points closer to the inner surface. As such, the standards generally prescribe that a set of postulated defects be analyzed with varying depths.

In the case of assessment of the (near) interface point of the crack, the situation is somewhat different. The temperature at this point does not change with increasing crack depth; while the K_I values increase, postulation of a deeper crack is conservative (from the point of view of assessment of the (near) interface point).

Figures 9 and 10 show the stress intensity factor and allowable RT_{NDT} with respect to the defect depth, respectively. From these figures, it is evident that in the cases with increasing crack depth, the assessment of the deepest point provides less conservative results: the deepest point is not the worst point on the crack front and some point closer to the interface is worst. The assessment at this point gives more conservative results for a deeper crack. Thus, when the assessment is performed for the whole crack front (rather than for the deepest point only), consideration of a deeper crack always yields a more conservative solution.

3.3 Defect Shape

Another important parameter entering the assessment is the shape of the postulated defect. The most representative shape is a semi-elliptical one. Some standards prescribe elliptical defects (underclad or partially penetrating the cladding). It should be noted that modelling elliptical underclad defects in finite element models is a difficult task compared to assessing them using simplified codes.

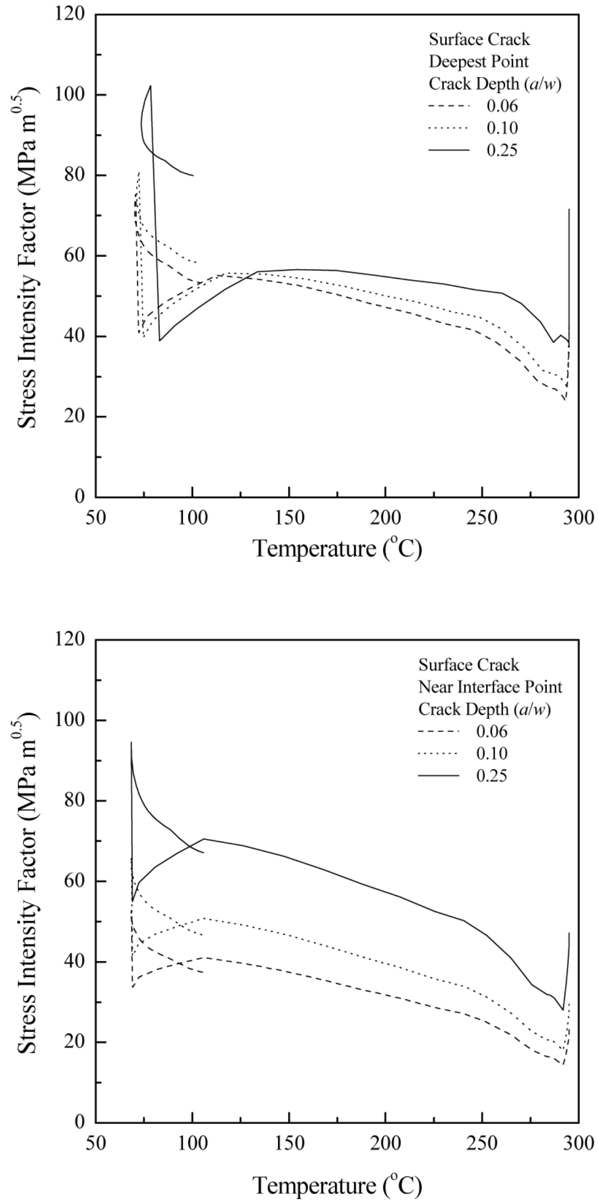


Fig. 9. Comparison of Stress Intensity Factors between Defect Depths

3.3.1 Aspect Ratio

The exact shape of the crack is expressed by the aspect ratio parameter, a/c, which means the ratio of the minor semi-axis of the (semi)ellipse, denoted by a, to the crack half length (the major semi-axis of the (semi)ellipse), denoted by c. It has to be noted that semi-elliptical and elliptical cracks with the same depths and aspect ratios have different lengths.

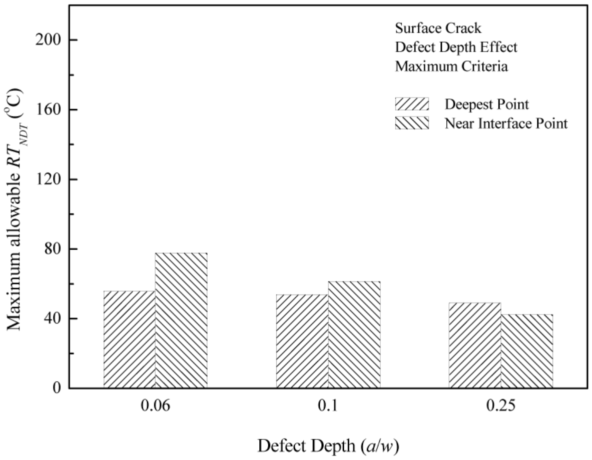
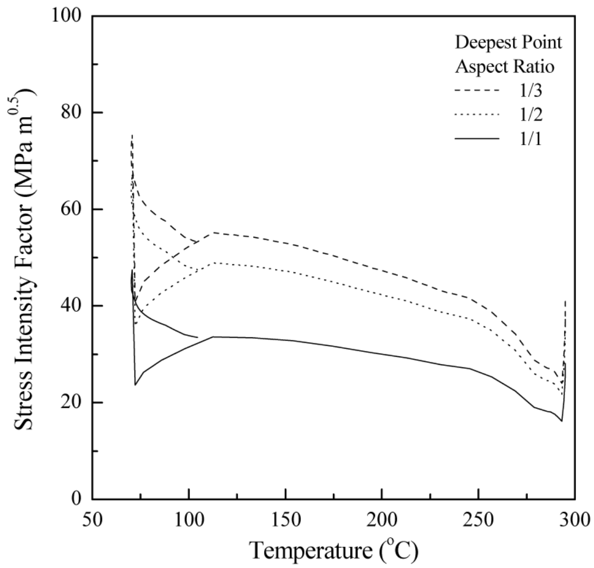


Fig. 10. Effect of Defect Depth on Allowable RT_{NDT}



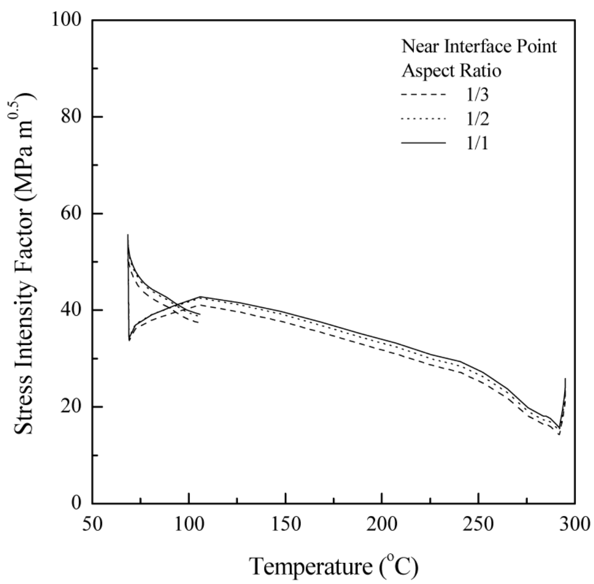


Fig. 11. Comparison of Stress Intensity Factors between Aspect Ratio

Figure 11 shows the stress intensity factor at the deepest and near interface points. These results indicate that for the deepest point of the semi-elliptical crack (both surface and underclad), smaller aspect ratios (i.e. the longer crack) produce higher K_I values and, consequently, more conservative solutions (lower maximum allowable transition temperature) (Fig. 12). For the near interface point, the situation is not as clear and generally smaller aspect ratios produce smaller K_I values. Since in most cases it is not clear (before performing the analyses) which aspect ratio is more conservative, some standards require assessment of several postulated cracks with different aspect ratios selected from the prescribed range.

3.3.2 Elliptical vs. Semi-elliptical Underclad Crack

Sensitivity studies revealed that elliptical and semi-elliptical underclad cracks of the same depths and lengths give similar K_I values at the deepest point (Fig. 13). On the other hand, the K_I values at the near interface point differ significantly and more conservative results are obtained for elliptical cracks.

3.3.3 Orientation and Position

Orientation of the postulated defect (axial or circumferential) is a very important parameter in terms of its effect on the results of the assessment. The degree of conservativeness of the orientation is strongly dependent on the transient assessed. For transients with no cold plume (axisymmetric cooling), an axial crack is always more conservative as a result of having twice larger circumferential stresses due to pressure (while the thermal stresses are of the same magnitude in both orientations). On the other hand, cold plumes (or other types of non-axisymmetric cooling) give additional axial thermal stresses below the cold plume that may cause a circumferential crack to become the most conservative case. The ratio between higher circumferential stresses due to pressure and higher axial stresses due to non-axisymmetric cooling are (generally) not known before performing the analyses.

Also, the position close to a large geometry change of the RPV (e.g. change of thickness of the RPV wall between the beltline and nozzle rings) can affect the behaviour of axial and circumferential cracks. For an axial crack

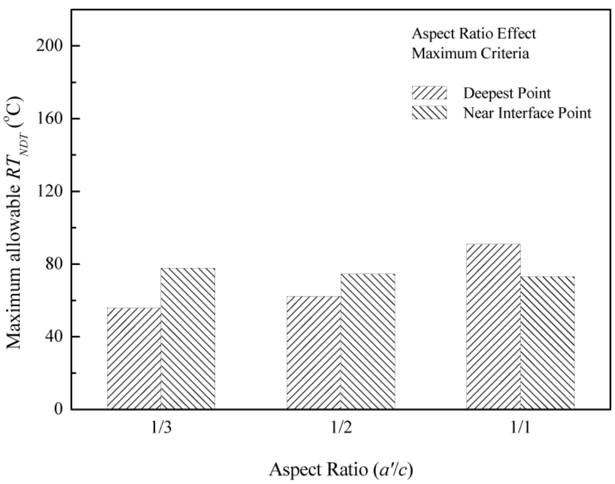


Fig. 12. Effect of Aspect Ratio on Allowable RT_{NDT}

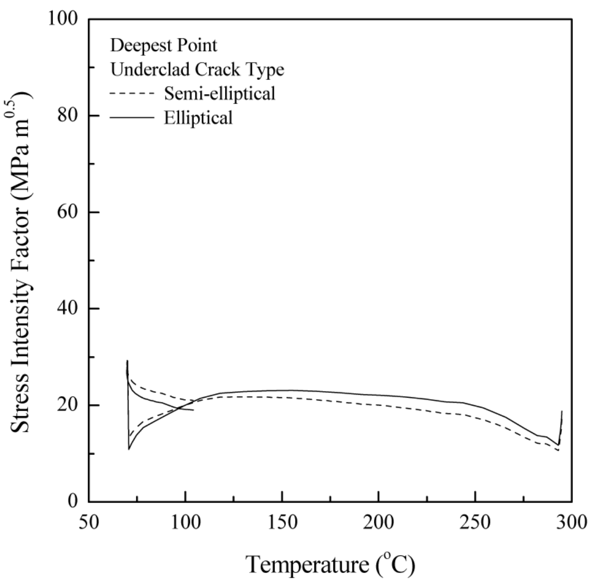


Fig. 13. Comparison of Stress Intensity Factors between Underclad Crack Shapes

postulated in the thinner part of the RPV in the vicinity of its thicker part, the K_I values due to the inner pressure are reduced in comparison to a crack postulated far from the thickness change. The effect of geometry change on K_I due to thermal shock is not very significant for an axial crack. For a circumferential crack postulated in the thinner part of the RPV in the vicinity of its thicker part, the K_I values due to thermal shock are increased. The effect of geometry change on K_I due to inner pressure is not very significant for a circumferential crack.

For the reasons given above, most standards require assessment of both crack orientations.

4. CONCLUSIONS

Several parametric analyses were performed to investigate the effects of postulated flaws in a structural integrity assessment of the reactor pressure vessel during pressurized thermal shock. The following conclusions were thereupon obtained:

- As the aspect ratio increases with the same defect depth, the maximum allowable RT_{NDT} increases for the deepest point and vice versa for the near interface point.
- As the crack depth increases, the maximum allowable RT_{NDT} decreases but the difference is almost negligible for the deepest point. The defect depth is not significant for the determination of the allowable RT_{NDT} for a very rapid cooling condition at the deepest point.
- The maximum allowable RT_{NDT} for a circumferential crack is much higher than that for an axial crack.
- The maximum allowable RT_{NDT} for an underclad crack is much higher than that for a surface crack without consideration of the plume effect.
- The effect of underclad crack shape on the stress intensity factor is almost negligible for elliptical and semi-elliptical shapes for the deepest point, even though the stress intensity factor for the semi-elliptical shape is slightly higher than that of the elliptical shape beyond the time when cooling stops and repressurization occurs.

These conclusions can be used to suggest some recommendations of best practices. Furthermore, they should provide insight into the key parameters of this type of approach and will be helpful for benchmark calculations and comparisons of results. Finally, the work presented here is expected to contribute to knowledge management for the future generation of young operators, scientists, computer analysts, and regulatory bodies.

REFERENCES

[1] OECD, Comparison report of RPV pressurized thermal shock international comparative assessment study (PTS ICAS), NEA/CSNI/R(99)3, Organization for Economic Cooperation and Development (1999).

[2] Jhung, M.J., Jang, C., Kim, S.H., Choi, Y.H., Kim, H.J., Jung, S.G., Kim, J.M., Sohn, G.H., Jin, T.E., Choi, T.S., Kim, J.H., Kim, J.W. and Park, K.B., "Round robin analysis for probabilistic structural integrity of reactor pressure vessel under pressurized thermal shock," *Journal of Mechanical Science and Technology*, Vol.19, No.2, pp.642-656 (2005).

[3] KINS, Benchmark calculations of structural integrity assessment for reactor pressure vessels during pressurized

thermal shock, KINS/RR-453, Rev.1, Korea Institute of Nuclear Safety (2007).
[4] ASME, ASME Boiler and Pressure Vessel Code, Section XI Rules for Inspection of Nuclear Power Plant Components, Appendix A Analysis of Flaws, The American Society of Mechanical Engineers (2004).
[5] Jhung, M.J., Kim, S.H., Lee, J.H. and Park, Y.W., "Round robin analysis of pressurized thermal shock for reactor pressure vessel," *Nuclear Engineering and Design*, Vol.226, pp.141-154 (2003).