P-T LIMIT CURVE OF REACTOR PRESSURE VESSEL WITH NOZZLE CORNER CRACK

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ABSTRACT

Pressure-Temperature limit curve imposes restriction on the maximum pressure and minimum temperature for several operation conditions, based on the principle of linear elastic fracture mechanics, to prevent a non-ductile fracture during the operation of a reactor coolant system(RCS) with ferritic steel. During the process of establishing a pressure-temperature limit curve, the maximum postulated defect is assumed, and the stress intensity factors from various loads acting on the pressure vessel should be evaluated in terms of fracture toughness representing the material's resistance to fracture. In the present study, an evaluation procedure is developed to establish a pressure-temperature limit curve of the nozzle with a corner circular crack for a SMART(System-integrated Modular Advanced ReacTor) reactor pressure vessel using the finite element method. As a result, an impact assessment of the changes of the reference critical stress intensity factor to be applied as an important criterion to produce a pressure-temperature limit curve is provided. Secondly, the stress intensity factors caused by thermal stress and internal pressure were obtained using 3-D FEM, and the effective methodology for the integrity of RPV was verified through a comparison with reference papers.

INTRODUCTION

The calculated stress intensity factor for a specific temperature and pressure must not exceed the fracture toughness in order to keep the integrity of the reactor pressure vessel with the crack. The fracture toughness obtained from the test, as the material property depending on the temperature, shows the material's resistance to fracture. The resistance to the fracture is weakened by means of the irradiation embrittlement, which increases the strength and hardness of the vessel material, but degrades the ductility. Thus, the reactor pressure vessel needs to be evaluated based on the reference critical stress intensity factor, which is the fracture toughness taking into account neutron fluence and temperature. General requirements of the P-T limit curve concerning pre-service reactors were stipulated in ASME Code Section III, Appendix G, and requirements for in-service reactors were first described in Section XI in 1989. Section XI has been revised, including Code Cases N-588, N-640, and N-641 after that. The reference critical stress intensity factor, K_{IR} was revised to K_{Ic} from ASME Section XI, 1999 Addenda. Also, ASME Section III became the same as Section XI from the 2007 edition [1,2]. On the whole, these revisions are judged to be an intention to reduce the excessive conservativeness and to produce reasonable results.

The assessment must be performed for various regions of the vessel, and the final P-T limit curves are then determined from the dominant region where the stress intensity factors show higher values. The general assessment procedure required for shell and head regions remote from discontinuities is stipulated in detail in the ASME code. However, the general method is not recommended for regions where discontinuities exist, such as nozzles and flanges, because more complicated stress distributions occur. If the general method is applied to the nozzles and flanges, the usefulness of the results should be checked. Alternatively, a complete and detailed analysis method for a nozzle corner crack is not currently available; only an approximate analysis or some limited methods are available [3]. Therefore, an effective method to evaluate the nozzles and flanges is required.

In the present study, the effects of the changes of the reference critical stress intensity factor are provided from the production of the P-T limit curve for a nozzle area. The stress intensity factors caused by thermal stress and internal pressure were obtained using 3-dimensional FEM by ABAQUS, and an effective methodology for the integrity of RPV was suggested.

PRESSURE-TEMPERATURE LIMIT CURVE

Reference Critical Stress Intensity Factor

Based on the reference nil-ductility temperature, RT_{NDT}, determined in Reg. Guide 1.99 [4], and the critical K_I measured as a function of temperature on specimens of SA-533 Grade B Class 1, SA-508-1, SA-508-2, and SA-

508-3 steels, ASME Section XI, Appendix G suggests the reference critical stress intensity factors according to the critical K_I . The reference critical K_{Ic} is an analytical approximation by the lower bound of static critical K_I, and K_{IR} is based on the lower bound of the static, dynamic, and crack arrest critical K_I values.

$$K_{IR} = 26.78 + 1.223 \exp[0.0145(T - RT_{NDT} + 160)] \quad (1)$$

$$K_{Ic} = 32.2 + 20.734 \exp[0.02(T - RT_{NDT})] \quad (2)$$

K_{IR}, K_{Ic} : reference critical stress intensity factor($ksi\sqrt{in}$)

T : crack tip temperature(°F)

RT_{NDT} : adjusted reference temperature(°F)

In the beltline regions, the stress intensity factors calculated from RPV with an axial crack include only K_{Im} and K_{It}, which are produced by membrane stress and thermal gradient in the radial direction, respectively. In order to consider the conservatism, K_{Ic} or K_{IR} is compared with K_{Im} and K_{It} in which safety factors 1 and 2 are applied to as follows:

$$2 \cdot K_{Im} + K_{It} < K_{IR}(or\, K_{Ic}) \quad (3)$$

Adjusted RT_{NDT}

The calculation of ART for the SA508 reactor vessel is based on the procedures of Regulatory Guide 1.99, Rev. 02. The adjusted reference temperature(ART) for each material in the beltline is given by the following expression:

$$ART = Initial\ RT_{NDT} + \Delta RT_{NDT} + \text{Margin} \quad (4)$$

$Initial\ RT_{NDT}$ is the reference temperature for an unirradiated material and ΔRT_{NDT} is the mean value of the adjustment in the reference temperature caused by irradiation. ΔRT_{NDT} is calculated as follows:

$$\Delta RT_{NDT} = CF \cdot f^{(0.28 - 0.1 \cdot \log f)}, \quad (5)$$

where CF is the chemistry factor, which is a function of copper and nickel constant. f is the neutron fluence at any depth in the wall and is determined as follows:

$$f = f_{surf} \cdot e^{(0.24x)} \quad (10^{19} n/cm^2,\ E > 1MeV), \quad (6)$$

where $f_{surf}\,(10^{14} n/cm^2,\ E > 1MeV)$ is the calculated value of the neutron fluence at the inner surface of the vessel, and x is the depth of the postulated crack measured from the surface. "Margin" is the quantity, degrees °F, that is to be added to obtain conservative, upper-bound values of the adjusted reference temperature for the calculations required by Appendix G of 10 CFR Part 50 [5]. In this paper, ART was calculated for the crack location, base, and weld metal as shown in Table 1.

Table 1 Input data for adjusted reference temperature

Metal	Crack locations	f	$Initial\ RT_{NDT}$ (°F)	ΔRT_{NDT} (°F)	Margin (°F)	ART (°F)
Base metal	Inner surface	8.285E-6	-10	0	50	40.0
Weld metal	Inner surface	8.285E-6	-10	0	56	46.0

K_{Im} Determination

K_{Im} corresponding to membrane stress is given as follows by ASME Code Section III.

$$K_{Im} = M_m \cdot \sigma_m = M_m \cdot (pR_i / t), \tag{7}$$

where, M_m is the membrane correction factor, σ_m is the membrane stresses, p is the internal pressure, R_i is a vessel inner radius, and t is a vessel wall thickness. K_{Im} from the nozzle corner zone applied to equation (7) may include uncertainty because M_m from the ASME Code is applicable only for conditions with the specified shape and size of the crack. Reference [3] suggests calculating K_{Im} for the nozzle as follows:

$$K_{Im} = F(a / r_n) \cdot \sigma_{vm} \sqrt{\pi a}, \tag{8}$$

where, a is the crack length in Fig. 1, R_n is the nozzle radius in Fig. 1, $F(a/r_n)$ are factors defined in reference [4], and σ_{vm} is the membrane stress in the reactor vessel shell. Equation 8 can be adopted by assuming a nozzle for the hole in the flat plate with a large radius. The values of $F(a/r_n)$ are halfway between the values for one crack under uniaxial tension and equivalent biaxial tension. Gilman and Rashid[6] provided the approximate $F(a/r_n)$ by using FEM to calculate K_{Im} for a specific nozzle configuration[6]. To evaluate more accurate integrity at the nozzle corner, K_{Im} need to be calculated according to the location of the crack tip. Mohamend and Schroeder[7] published K_{Im} according to the location of the crack tip as follows[7]:

$$K_{Im}(\theta) = M_f \frac{\sigma_a \sqrt{\pi a}}{\pi / a}, \tag{9}$$

where, θ are the angles defined in Fig. 1, M_f is the magnification factor for the front free surfaces, and σ_a is the hoop stress at the same point when the crack is absent. In this paper, $K_{Im}^{FEM}(\theta)$ depending on the angles and an average stress intensity factor, $K_{Im,avg}^{FEM}$ are calculated by using the 3-D finite element model with a 1/4 elliptical crack. These results are compared to those in the references mentioned above.

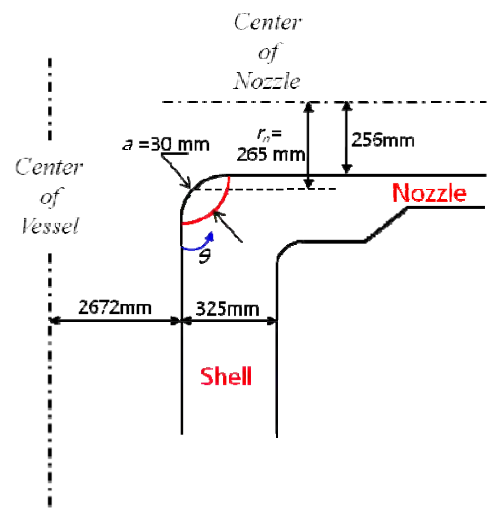

Fig. 1 Schematic illustration of nozzle corner crack

K_{It} Determination

The ASME suggests equations that can calculate K_{It} as a function of temperature change rates and section thickness regardless of the specified time. However, this method may be quite conservative since it does not consider the effect of the thermal gradient due to time transient but rather the maximum thermal gradient. Also, this method is valid only as long as the thermal gradient meets the figure depicted in ASME. For a nozzle corner, this condition is not met since the stress distribution is very complicated. ASME Code Section III, 2004 recommends an alternative method to use the maximum bending stress produced by the radial thermal gradient. The maximum bending stress method is as follows:

$$K_{It} = M_{tb} \times \sigma_{tb} \; (MPa\sqrt{m}), \tag{10}$$

where M_{tb} is a bending correction factor defined as $2/3M_m$ and σ_{tb} is the maximum bending stress by the thermal gradient. In this study, K_{It} are calculated using 3D-FEM and the maximum bending stress method and the results of the two methods are compared to each other. The 3-D FEM method requires more complex tasks but has an advantage in that it considers the time transient.

From the results of K_{Im}, K_{It}, and the evaluation in Eq. (3), the allowable pressure for any specified temperature at the depth of the postulated defect during service conditions is determined. The allowable pressure-temperature relationship for the inside surface crack under a heat-up condition is determined from following equation($K_{It} = 0$) as membrane stresses are compressive at the inner surface.

$$P = \frac{K_{IR}(or\, K_{Ic})}{2M_m}\left(\frac{t}{R_i}\right) \tag{11}$$

On the other hand, K_{It} of the outer surface crack for a heat-up condition, and the inner surface crack for a cool-down condition are calculated, and the minimum pressure at any specified temperature is determined as follows:

$$P = \frac{K_{IR}(or\, K_{Ic}) - K_{It}}{2M_m}\left(\frac{t}{R_i}\right), \tag{12}$$

K_{Ic} or K_{IR} is calculated from Eq. (1, 2) using the temperatures at the crack tip, and RT_{NDT} values at the corresponding locations of interest.

FINITE ELIMENT ANALYSIS

All stress intensity factors produced by external loads are analyzed using a 3-D FEM with crack models, and the pressure-temperature limit curve is then determined according to the reference critical stress intensity factors. The postulated cracks are located at the nozzle corner showing the highest stress distributions and have a depth of one-tenth of the section thickness with a 1/4 circular shape, as in Fig. 1. The postulated defect at the 300 mm section is assumed since the sections of the nozzle corner are greater than 300 mm in thickness. The inner radius of the reactor vessel is 2,672 mm, and the section thickness is 325 mm. According to previous studies for the beltline, the P-T limit curve is dominated by a cool-down condition rather than a heat-up condition. Thus, only cool-down conditions are evaluated in this paper. Although there are various temperature rates during the cool-down process, rates of 5.6℃/hr, 22.2℃/hr, 33.3℃/hr, 45℃/hr, and 55.6℃/hr were considered for the analyses.

Elastic analysis is performed using a commercial program ABAQUS v.6.9, which can consider the strain singularity. Figure 2 shows the typical 3-dimensional finite element model used in this paper. 20-node iso-parametric brick elements with reduced Gauss integration are used, and quarter point crack tip singular elements are considered for the crack tip region. Due to the symmetry, only 1/16 of the pressure vessel was modeled. Each stress intensity factor is calculated at all crack points from the vessel surface. For a cool-down condition, thermal stress intensity factors for inner corner cracks are calculated in the transient analysis. K_{Im} corresponding to the internal pressure is then calculated. Finally, M_m is obtained from Eq. (10) and K_{Im}. Table 2 shows the analysis matrix for the P-T limit curve calculation performed in this paper.

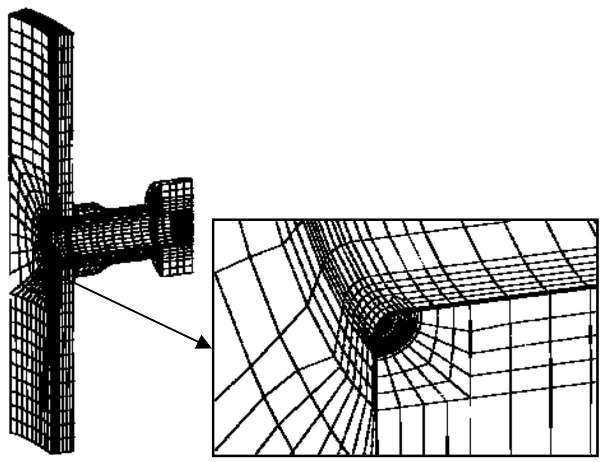

Fig. 2 3-dimensional FE model

Table 2 Analyses matrix for P-T limit curve

Operation condition	Heat up (℃/hr)					Cool-down (℃/hr)				
Temp. rate / Analysis location	5.6	22.2	33.3	45	55.6	5.6	22.2	33.3	45	55.6
Nozzle inner corner zone ($t/10$)	x	x	x	x	x	○	○	○	○	○

RESULTS

K_{Im} by Internal Pressure

Figure 3 shows the results of K_{Im} according to the circular angle from the vessel inner surface to the nozzle inner surface when the internal pressure of $17\,MPa$ is applied. The maximum K_{Im} is shown at the nozzle's inner surface. The K_{Im} curve for the circular angles is close to a quadratic function except the values at the vessel inner surface and nozzle inner surface. This tendency agrees well with the results obtained by Mohamed's [7] equation. The K_{Im} curve for the circular angles is fitted as a 2nd order polynomial curve, which is not valid where θ is 0 and 90 degrees.

$$K_{Im} = 97.017 - 0.719\theta + 0.009\theta^2 , \tag{13}$$

where, θ is the circular angle from the vessel's inner surface as shown in Fig. 1. The averaged stress intensity factor, $K_{Im,avg}$ and $F(a/r_n)$, obtained using finite element analysis at each crack tip are compared with the reference results, as shown in Table 3. The results show good agreement with those of Rashid [6] and Mohamed [7]. However the results of a flat plate model give 17% higher $F(a/r_n)$ and $K_{Im,avg}$ values than the finite element method. The results of the ASME method are derived by substituting the membrane stress at 45degrees, which is calculated from the finite element model without a crack, into Eq. (7). These results imply that the flat plate model and ASME method may be inaccurate due to many assumptions such as geometrical nonconformance. To evaluate conservatively the P-T limit curve, substituting the maximum K_{Im}, 113.8 $MPa\sqrt{m}$, obtained from the finite element analysis into Eq. (7) gives correction factor, $M_m^{FEM} = 0.81\sqrt{m}$.

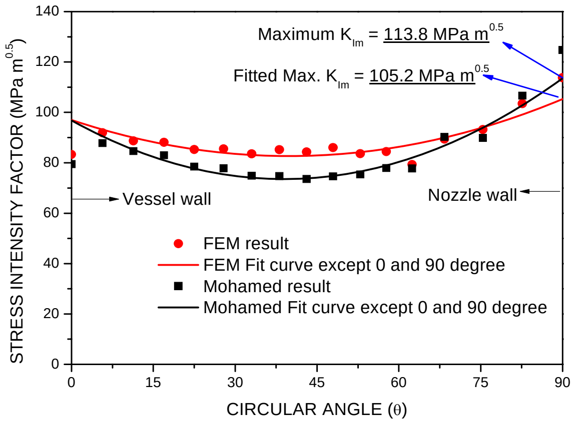

Fig. 3 Comparison of K_{Im} with reference.

Table 3 Comparison of $F(a/r_n)$ and $K_{Im,avg}$ with the reference

	FEM results	Ref.[3] WRC Bullutin 175	Ref.[6] Rashid	Ref.[7] Mohamed	ASME
$F(a/r_n)$	1.96	2.3	1.95	1.86	×
$K_{Im,avg}$ ($MPa\sqrt{m}$)	88.8	104.3	88.4	84.2	121.3

K_{It} by Thermal Stress

According to the cool-down rate, Fig. 4 shows the K_{It} results of the ASME and finite element analysis at the crack tip of the 45 degrees from the vessel inner surface.

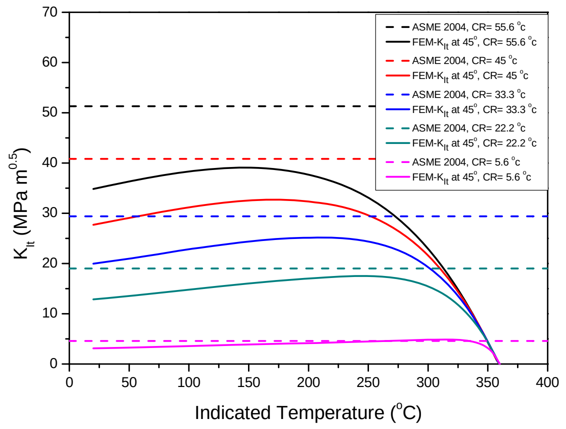

Fig. 4 K_{It} results obtained from the ASME and FEM.

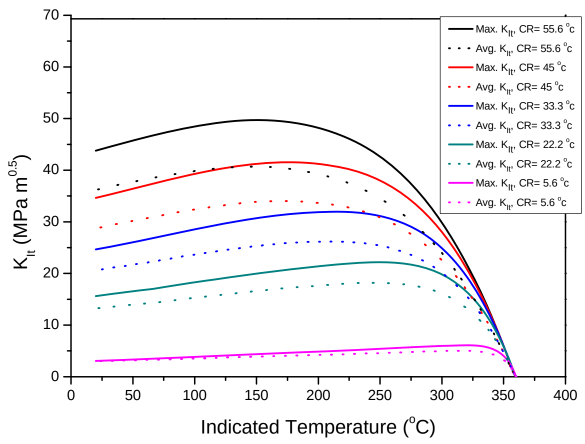

Fig. 5 Maximum and averaged K_{It} by FEM.

Among all the cool-down rates, 55.6 ℃/h gives the most severe K_{It} according to the indicated temperature, and the ASME method provides 31% higher number of K_{It} than FEM under a cool-down of 55.6 ℃/h. These differences come from the limitation of the ASME Code based on the continuity vessel wall with a crack depth of t /4. Therefore, it may not be reasonable to apply K_{It} obtained by the ASME method to the P-T limit curve. Figure 5 shows the maximum and averaged K_{It} obtained by the finite element method. As with K_{Im}, a maximum K_{It} curve is used to conservatively evaluate the P-T limit curve.

Figure 6 illustrates the effects of the reference critical stress intensity factors derived by substituting K_{Im}, K_{It} and adjusted RT_{NDT} into Eq. (12). The cool-down curve moves to the right and restricts the operating range as the cool-down rate increases. According to the revised reference critical stress intensity factor, K_{Ic} leads to 46℃ more alleviated operating condition than K_{IR} for the design pressure. Figure 7 and 8 show the final P-T limit curves for K_{IR} and K_{Ic}, respectively. The minimum bolt-up temperature, lowest service temperature (LST) and maximum pressure below LST out of the P-T limit curves are evaluated by the ASME Code.

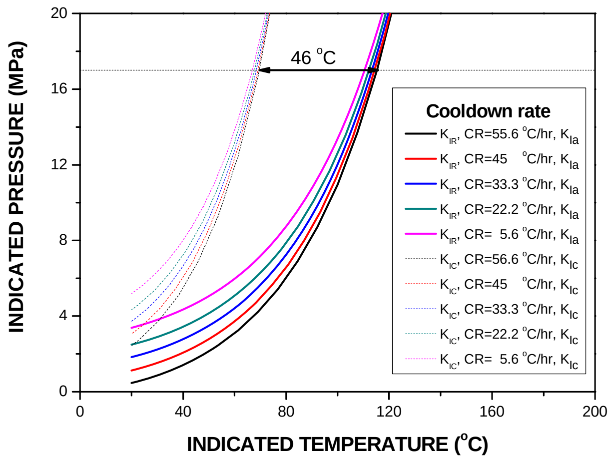

Fig. 6 P-T limit curve for cool-down.

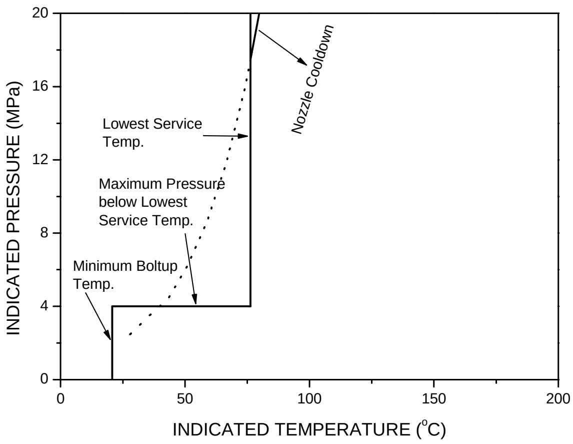

Fig. 7 P-T limit curve applied from K_{IR}.

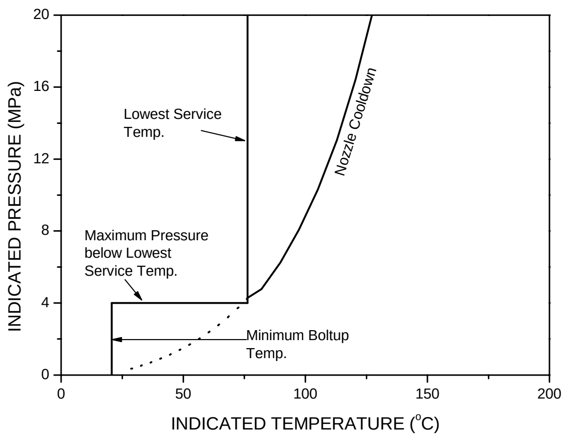

Fig. 8 P-T limit curve applied from K_{Ic}.

CONCLUSION

The results of this study are as follows. First, the impact assessment for the changes of the reference critical stress intensity factor, to be applied as important criteria to produce a pressure-temperature limit curve, is provided. Second, the stress intensity factors caused by thermal stress and internal pressure were obtained using a 3-D FE analysis by ABAQUS, and the validity of the suggested methodology was verified, as the results through FEM show good agreement with the reference results. K_{Im}, obtained by the flat plate model and ASME method were over 17% higher than the finite element method, and K_{It} was 31% higher than the finite element method. Therefore, applying the flat plate model and general ASME method to the P-T limit curve is more likely to result in a conservative evaluation.

ACKNOWLEDGEMENTS

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