1. INTRODUCTION

For assuring the structural integrity of PWR plants, it is important to estimate the fracture strength of nuclear pressure vessels under pressurized thermal shock (PTS). From this point of view, a number of researches have been conducted for old pressure vessels which were embrittled by neutron irradiation [1]. On the other hand, there have been few works for unirradiated pressure vessels whose fracture would happen on upper shelf toughness region, since it is quite difficult in applying non-linear fracture mechanics to treat thermal strain and load history which is caused by the independent transients of internal pressure and coolant temperature.

In this paper, J-values of an axially cracked pressure vessel under thermal shock, internal pressure, and several PTS conditions are evaluated over the full range of crack depth using a simple estimation scheme which we proposed in our earlier works. Then, several parameter studies are performed, and some characteristic features of the fracture strength under PTS are discussed. Furthermore, a simple procedure is developed to judge whether J-controlled crack growth condition is satisfied or not during present analyses.

2. ANALYTICAL METHOD

2.1 ANALYTICAL MODEL, METHOD, AND MATERIAL PROPERTIES

In this study, an axially cracked pressure vessel with mean radius $R_m=2.1$ [m] and wall thickness $W=0.2$ [m] as shown in Fig.1 is considered. Material is assumed to be A533B steel whose uniaxial stress-strain law and fracture toughness (93 ~ 290 °C) [2, 3] are given in following equations.

\[
\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_0} + 1.4 \left( \frac{\sigma}{\sigma_0} \right)^{8.71}, \quad J_{JC} \approx 0.2 \ [\text{MPa}\cdot\text{m}], \quad \frac{dJ}{ds} = 50 \sim 100 \ [\text{MPa}]
\]  

(1)

where $\sigma_0$ is yield stress (=460 MPa) and $\epsilon_0$ is yield strain (= $\sigma_0/E$, $E$ is Young's modulus =207000 MPa). The influences of the temperature and load history on these material properties are not considered.

Strictly speaking, it is not proper to use the deformation theory of plasticity (J2D-theory) for the evaluation of J-values under PTS, since the influence on J-values of load history caused by SMiRT 11 Transactions Vol. G (August 1991) Tokyo, Japan, © 1991

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the independent transient of internal pressure and thermal stress may not be negligible, though it may be small [4]. From the viewpoint of engineering approach, however, the J2D-theory is quite convenient for numerical analysis, so J-values in this paper are calculated by using a simple method which we developed based on J2D-theory [5, 6].

2.2 SIMPLIFICATION OF PTS CONDITIONS

As shown in Fig.1, forces acting on cracked member can be separated into tension (P), bending moment (M), and local stress (σL). Among them, σL is negligible in the evaluation of J-values [7]. And, internal pressure acting on crack face is not considered in this study.

Then, internal pressure and thermal shock conditions can be represented by only \( \bar{P}_0 \) and \( \bar{M}_0 \) defined as follows respectively:

\[
\bar{P}_0 = \frac{P_0}{\sigma_0 W}, \quad \bar{M}_0 = \frac{6M_0}{\sigma_0 W^2}
\]

(2)

where \( P_0 \) and \( M_0 \) are \( P \) and \( M \) in the absence of crack. \( \bar{P}_0 = 0.34 \) corresponds to internal pressure of 15.7 [MPa] (160 atm) which is an operating pressure of PWR pressure vessel, and \( \bar{M}_0 = 0.9 \) may happen in the most severe thermal shock accident of LBLOCA [7]. Therefore, following calculations are performed in the region of \( 0 \leq \bar{P}_0 \leq 0.34 \) and \( 0 \leq \bar{M}_0 \leq 0.8 \). For example, in the case of typical MSLB accident, \( \bar{P}_0 \) and \( \bar{M}_0 \) are approximately 0.17 (i.e., 80 atm) and 0.6 respectively.

3. NUMERICAL RESULTS AND DISCUSSION

In this section, J-values under several PTS conditions are calculated over the full range of crack depth (a/W), and both stable and unstable crack growth are discussed based on the tearing instability theory [8]. On the other hand, it is important to make clear whether J-controlled crack growth condition [9] is satisfied or not, for assuring that J-integral represent near-tip deformation during such tearing crack growth analyses. Though it has been quite difficult for real structures even to discuss it qualitatively, in this section, simple method and quantitative results for this problem is presented, which is one of the useful products of our simple procedure [5].

3.1 UNDER THERMAL SHOCK AND INTERNAL PRESSURE

At first, J-values are calculated under both thermal shock (TS) and internal pressure (IP) conditions for clarifying each feature (see Figs.2). Under both realistic TS and IP conditions mentioned earlier in section 2.2, when crack is short as \( a/W \leq 0.37 \), J-values are always smaller than \( J_{IC} \)-value (see eq.(1)), which means that structural integrity in these cases are assured. Whereas comparing with Fig.2 (a) and Fig.2 (b) from the viewpoint of tearing instability estimation, \( dJ/da \) under IP is shown to become larger than that under TS, so the IP is likely to become the cause of unstable crack growth.

On the other hand, Figs.3 show the influence of wall thickness ratio (i.e., the compliance of cylindrical shell) on J-values. In any case with finite compliance, J-value seems to reach its maximum at a certain crack depth and drops to zero, and this maximum value is strongly influenced by the compliance of cylindrical shell. The fact that J-value drops to zero, which is similarly shown in following calculations under PTS, may be concerned with crack closure.
Therefore this fact may explain the phenomena of crack arrest of pressure vessel qualitatively, though the effect of inertia should be taken into account for quantitative discussion.

3.2 UNDER PRESSURIZED THERMAL SHOCK

Next, J-values of typical cases of TS, IP, and PTS are compared as shown in Fig.4. This figure shows following two characteristic features of J-value under PTS. One is that J-values become considerably large due to the mixture of TS and IP, the other is that the variation of J-value shows two phases at about $a/W \simeq 0.6$ and 0.8 which seem to reflect the features under TS and IP respectively.

Then, for researching above features quantitatively, J-values and $J/a$ under several PTS conditions are calculated by changing $M_0$ and $T_0$ as shown in Figs.5 and 6. Under any PTS condition, as mentioned earlier, it is confirmed that J-values drops to zero at about $a/W \simeq 0.9$, and that variations of J-value show two phases. The latter feature can be well explained by two maximum values of $dJ/da$ shown in Figs.6. Furthermore, the influences of $M_0$ and $T_0$ may roughly speaking that the increasing of $M_0$ causes the decreasing of critical crack depth (in the sense of both stable and unstable crack growth), and that the increasing of $T_0$ accelerates the increasing of both J-value and $dJ/da$.

Comparing these results with the fracture toughness data of eq.(1), under realistic PTS conditions (i.e. $T_0 \leq 0.34$, $M_0 \leq 0.6$) stable and unstable crack growth will not happen for $a/W \leq 0.28$ and $a/W \leq 0.44$ respectively. Considering the fact that $M_0$ never become greater than 0.9 when $W=0.2$ [m] [7], and $T_0$ can easily become greater than 0.34 in the case of re-pressureurized transient, it is concluded to be quite important to grasp the transient of internal pressure under any imaginable accident from the viewpoint of structural integrity.

As mentioned earlier, the main object of this study is the parametrical survey for clarifying the influences on J-value and $dJ/da$ of TS and IP conditions, so there are some assumptions which cause both overestimate and underestimate. In particular, J-value may be effected by the assumption of no crack face loading. We will leave these problems in the further research.

3.3 J-CONTROLLED CRACK GROWTH CONDITIONS

The size of the region at the crack tip dominated by Hutchinson-Rice-Rosengren singularity is known to be large in the case of bending type loading [9]. And this condition is quantitatively given by Shih [10] in terms of $c/b$ (see eq.(3)) which means the ratio between bending moment and tension defined on the rotational axis of ligament. On the other hand, proposed method enables us to know easily the variation of $T$ and $M$ during above crack growth analyses, and the condition satisfying bending type loading can be calculated by them using following equation [5],

$$\frac{M/eP}{1-a/W} - 0.566 = \frac{c}{b} > 0.7$$

When eq.(3) is satisfied, valid length for tearing crack growth analysis is large, for example it can be estimated approximately 23 mm when initial crack depth ($a_0/W$) is 0.4 [5].

Figures 7 show $c/b$ of present analyses. From the results shown in Figs.5 and 6, it follows that crack growth may happen in the region of $a/W \simeq 0.4 \sim 0.6$. In this region, except for the case that $M_0$ is very small (A and B in Fig.7(a)) and $T_0$ is very large (D in Fig.7(b)), eq.(3) is well satisfied and bending type loading is acting on cracked section. Consequently, under typical PTS conditions, the region at the crack tip dominated by the Hutchinson-Rice-Rosengren singularity is substantially large enough to apply the J-based criterion to predict unstable ductile fracture.

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4. CONCLUSIONS

In this paper, the $J$-value of an axially cracked cylinder under several PTS conditions are evaluated using a simple estimation scheme which we proposed. Results obtained are summarized as follows:

(1) Under any PTS conditions, the effect of internal pressure is so predominant upon the $J$-value and $dJ/da$ that it is very important to grasp the transient of internal pressure under any imaginable accident from the viewpoint of structural integrity.

(2) Under any IP, TS, and PTS conditions, $J - a/W$ relation shows that the $J$-value reaches its maximum at a certain crack depth, then drops to zero at $a/W \approx 0.9$. Though the effect of inertia is not taken into account, this fact may explain the phenomena of crack arrest qualitatively.

(3) The compliance of a cylindrical shell plays an important role in the fracture prediction of a pressure vessel.

(4) Under typical PTS conditions, the region at the crack tip dominated by the Hutchinson-Rice-Rosengren singularity is substantially large enough to apply the $J$-based criterion to predict unstable ductile fracture.

REFERENCES


Fig. 1 Analytical model for Axially cracked cylinder

Fig. 2 J-values under several thermal shock and internal pressure conditions

Fig. 3 Influence of the compliance of cylindrical shell on J-values

Fig. 4 Comparison of J-value under TS, IP and PTS conditions
Fig. 5  $J$-values under several PTS conditions

Fig. 6  $dJ/da$ under several PTS conditions

Fig. 7  Loading type of present analyses  \((\varepsilon/b>0.7 \text{ indicates bending type loading})\)