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LBB Assessment on Ferrite Piping Structure of Large-scale FBR

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Yeon-Sik Yoo[1]

Abstract

These days, the interest on LBB (Leak Before Break) design becomes to be rising in the viewpoint of the cost reduction and structural integrity for the commercialization of FBR plants. LBB design enables plants to be shut down safely before occurring unstable fracture by detecting the leak rates even if a crack initiates and penetrates a wall thickness. It is necessary to assess crack growth and penetration behavior considering in-service conditions under operation temperature, leak rates considering the detector capability and unstable fracture quantitatively for LBB assessment. The governing service loading of FBR can be identified thermal expansion stress and thermal transient stress because the operation temperature is higher than that of LWR and the liquid metals contain higher heat transfer coefficient than water. On that reason, the use of 12Cr type ferrite steel in the primary cooling system is investigated for reducing stress in the design of large-scale FBR. This study deals with LBB assessment when the primary piping components of FBR which consist of 12Cr type ferrite steel are subjected to a series of transients, and the results envisioned the use of 12Cr type ferrite steel for FBR components.

[1] Structural Mechanics Research Group, Advanced Technology Division, Oarai Engineering Center

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大型FBR用フェライト構造物におけるLBB評価

（研究報告）

兪　淵植[1]

要　旨

近年、高速増殖炉（FBR）の実用化を目標に、その健全性と経済性の観点から破断前漏洩（LBB：Leak Before Break）設計法が注目されている。LBB設計法は、万一構造物にき裂が発生し、肉厚を貫通したとしても内容物の漏洩量を検知することによって不安定破壊が起きる前にプラントを安全に止めることを可能にする評価法である。LBB評価のためには、使用温度下での運転条件を考慮した想定荷重からのき裂の進展・貫通挙動、検知器の性能からの漏洩量及び不安定破壊に対する定量的な評価が必要である。高速増殖炉はその使用温度が軽水炉より高いことと冷却材として熱伝達性の高いナトリウムを使用していることから、熱膨張荷重と過渡熱荷重が支配的な運転荷重になると考えられる。そのため、大型FBRの設計では一次冷却系に12Cr系フェライト鋼を用いることで、高温配管系においてより小さい発生応力を図ることが検討されている。本報告書は、高速増殖炉において12Cr系フェライト鋼を用いた大型構造物である一次配管系で、想定される過渡事象を考慮した場合、現状のLBB評価法によりその安全性を評価した結果である。この結果により、高速増殖炉用高温構造物での12Cr系フェライト鋼の有効性を示した。

[1] 大洗工学センター　要素技術開発部　構造信頼性研究グループ

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1. Introduction

These days, the interest on LBB (Leak Before Break) design becomes to be rising for the commercialization of FBR plants. As a result of that, studies on LBB behavior of structural components have mainly performed in the design step in the viewpoint of cost reduction and structural integrity. LBB design enables plants to be shut down safely before occurring unstable fracture by detecting the leak rates even if a crack initiates and penetrates a wall thickness. The present LBB assessment flow and the definition of considerable cracks are represented in Fig.1 and Fig.2 respectively. It is necessary to assess crack growth and penetration behavior considering in-service conditions under operation temperature, leak rates considering the detector capability and unstable fracture quantitatively for LBB assessment. A fracture mode may be justified comparing between the detectable crack length from leak rates assessment and the critical crack length from unstable fracture assessment. The flow suggests that LBB behaviors come into exist and the fracture mode corresponds to a partial penetration if a detectable crack length is smaller than a critical crack length. In addition, the penetrated crack may be an object for LBB assessment in place of a detectable crack if a penetrated crack length is greater than a detectable crack length from the detection capability. After LBB behavior is shown, coolant leakage may be evaluated quantitatively by assuming a detectable crack shape to be a semi-ellipse. According to the above flow, a series of LBB assessments were made on the primary piping components of FBR which consist of 12Cr type ferrite steel in this study, and the results envisioned the use of 12Cr type ferrite steels for high temperature structural components.

2. Theory

2.1 Creep-fatigue crack growth assessment

Creep-fatigue crack growth may be evaluated from the following relations by neglecting the interaction between creep damage and fatigue damage.

$$da/dN = (da/dN)_f + (da/dN)_c \tag{2.1.1}$$

Where,

$$(da/dN)_f = C_f \cdot (\Delta J_f)^{m_f} \tag{2.1.2}$$

$$(da/dN)_c = C_c \cdot (\Delta J_c)^{m_c} \tag{2.1.3}$$

J integral range under a fatigue loading, ΔJ_f, may be dragged by applying an elastic-plastic correction factor, f_{ep}, to elastic J integral range, ΔJ_e. The following relation was adopted as a method to calculate ΔJ_f in this study [1].

$$\Delta J_f = f_{ep} \cdot \Delta J_e \tag{2.1.4}$$

$$f_{ep} = \frac{\sigma_{ref}^{3}}{2\sigma_y^{2} \cdot E \cdot \varepsilon_{ref}} + \frac{E \cdot \varepsilon_{ref}}{\sigma_{ref}} \tag{2.1.5}$$

$$\sigma_{ref} = F_{net} \cdot (p_m \cdot \sigma_m + p_b \cdot \sigma_b) \tag{2.1.6}$$

Where, σ_{ref} is reference stress, and F_{net} is represented by 1 for membrane component and 2/3 for bending component as a net-section shape factor. p_m and p_b are a membrane and a bending stress correction factor respectively and the proposed values of both are 1.

Meanwhile, creep J integral range, ΔJ_c, during a holding time, t_H, may be calculated from following relations in this study [1]:

$$\Delta J_c = \int_0^{t_H} J'(t)dt \tag{2.1.7}$$

Where,

$$J'(t) = f_c(t) \cdot J_e \tag{2.1.8}$$

$f_c(t)$ is a creep correction factor which may be obtained from applying a fully-plastic solution to creep regime.

$$f_c(t) = \frac{E \cdot \dot{\varepsilon}_{c-ref}(t)}{\sigma_{c-ref}} \tag{2.1.9}$$

$\sigma_{c\text{-}ref}$ is creep reference stress at initiation of holding time and may be divided into following cases :

$$\begin{aligned} \sigma_{c-ref} &= \sigma_{ref} \cdot \left(\frac{\sigma_y}{\sigma_{ref}} \right)^p & \sigma_{ref} &< \sigma_y \\ \sigma_{c-ref} &= \sigma_{ref} & \sigma_{ref} &\geq \sigma_y \end{aligned} \tag{2.1.10}$$

Where,

$$p = p_1 + p_2 \cdot \left(\frac{a}{t} \right) \qquad p_1 = p_2 = 0.2 \tag{2.1.11}$$

p_1 and p_2 are correction factors to account for heterogeneous stress distribution under small scale yielding condition.

Stress relaxation for creep-fatigue crack growth assessment may be calculated by considering an elastic follow-up parameter for creep, q_c, of which the value is adopted as 3 and following relations in this study [1]:

$$d\sigma_{relax} = \frac{E \cdot d\varepsilon_c}{q_c} \tag{2.1.12}$$

Where,

$$d\varepsilon_c = \int_t^{t+dt} \dot{\varepsilon}_c(t)dt \tag{2.1.13}$$

The generalized stress relaxation process which may be divided into two-steps during a holding time, as are the first relaxation step from $\sigma_{c\text{-}ref}$ to σ_{ref} and the second relaxation step from σ_{ref} to $\sigma_{1\text{-}ref}$, is illustrated in Fig.3 [1].

2.2 Coolant leakage assessment

Elastic COD for evaluating a detectable crack may be represented as following relation [2]:

$$\delta_e = \frac{4c\sigma_s}{E} V_1(c/b) \tag{2.2.1}$$

Where,

$$\begin{aligned} V_1(c/b) = &-0.0711 - 0.535(c/b) + 0.169(c/b)^2 - 0.090(c/b)^3 \\ &+ 0.020(c/b)^4 - 1.071\frac{1}{c/b}\ln(1-c/b) \end{aligned} \tag{2.2.2}$$

σ_s is nominal stress perpendicular to a crack, c is a half of crack length and b is a half of pipe perimeter.

Coolant leakage considering through-wall crack may be calculated as following relation:

$$Q = \rho \cdot V \cdot S \tag{2.2.3}$$

Where, ρ is coolant density and S is crack opening area which may follow the next relation by assuming that crack opening shape is an ellipse.

$$S = \pi \cdot c \cdot \frac{\delta}{2} \tag{2.2.4}$$

Coolant leak velocity, V, may be obtained from the following relations [3]:

$$V = \sqrt{\frac{2p}{\rho\left\{1.5 + \frac{f_F(1 + rk_C + (1-r)k_B)t}{D_h}\right\}}} \tag{2.2.5}$$

$$\begin{aligned} f_F &= 96/\mathrm{Re} && \mathrm{Re} \le 2000 \\ f_F &= 0.508\,\mathrm{Re}^{-0.3} && \mathrm{Re} > 2000 \end{aligned} \tag{2.2.6}$$

$$\mathrm{Re} = \frac{D_h V}{\mu} \tag{2.2.7}$$

$$D_h = \frac{\pi/2}{\sqrt{1 + 1.464(\delta/2c)^{1.65}}}\delta \tag{2.2.8}$$

$$k_C = \begin{cases} 9 & \delta < 0.0142 \\ 0.0111\delta^{-1.60} - 1 & 0.0142 \le \delta < 0.06 \\ 0 & 0.0600 \le \delta \end{cases} \tag{2.2.9}$$

$$k_B = \begin{cases} 19 & \delta < 0.0534 \\ 0.184\delta^{-1.60} - 1 & 0.0534 \le \delta < 0.347 \\ 0 & 0.347 \le \delta \end{cases} \tag{2.2.10}$$

Where, p is internal pressure, f_F is friction coefficient, μ is dynamic viscosity and t is pipe thickness. D_h is an equivalent diameter, κ_B and κ_C are friction correction factors, Re is Reynolds number and r is stress ratio of membrane stress to entire stress.

2.3 Ductile unstable fracture assessment

A critical crack length may be corresponded to a minimum crack length satisfying the following relation [3].

$$Z\sigma_a \ge \sigma_f \tag{2.3.1}$$

Where, Z is a load multiplier for ductile crack extension and σ_f is a flow stress that may be generally adopted as the average of yield stress and ultimate strength.

Net-section stress, σ_a, was determined considering an elastic follow-up parameter, of which the value was adopted as 3 in this study.

$$\frac{E}{q_p - 1} = \frac{\sigma_{ref}^{E} - \sigma_{ref}^{EP}}{\varepsilon_{ref}^{EP} - \varepsilon_{ref}^{E}}, \quad \sigma_{ref}^{EP} = \sigma_a \tag{2.3.2}$$

Where, σ_{ref}^{E} is an elastic reference stress. The elastic reference stress may be determined from the following relations in the case of a pipe with inner radius, R_i, subjected to a membrane and a gross bending stress [4].

$$\sigma_{ref}^{E} = \frac{\pi \cdot \sigma_{bg}}{2\tilde{S}} \tag{2.3.4}$$

Where,

$$\tilde{S} + \sin\theta = 2\cos\left(\frac{\sigma_m}{\sigma_{bg}} \cdot \tilde{S} + \frac{\theta}{2}\right), \quad \theta = c / R_i \tag{2.3.5}$$

After all, a critical crack length may be evaluated by considering a load-multiplier Z that is affected by a crack size, and the correlation between net-section stress and elastic reference stress from the above equation.

3. Assessment conditions

3.1 Assessment model

The assessment model referred to a design data of large-scale FBR structures. The schematic model is illustrated in Fig.4. Thermal expansion stress and transient stress due to high temperature and thermal transient were calculated elastically by FEM analyses. FEM model in Fig.5 was constructed by 2-dimensinal heat transfer elements with 8-nodes and 3-dimensional thermal conduction elements for thermal conduction analyses and 3-dimensinal solid elements with 20-nodes for structure analyses. The number of degree of freedom was over 65559 and the analysis code was FINAS (Finite Element Nonlinear Structural Analysis System) [5].

In order to analyze the thermal transient stress, the structure analysis referred to the results of thermal transient analysis considering the variation of the heat transfer coefficient per each step.

The materials used in a design of large-scale FBR are HCM12A that is sort of 12Cr-Ferritic steel as piping components and sodium as a liquid metal. The representative materials properties of HCM12A and sodium at 550℃ are shown in Table 1.

Where, E is Young's modulus, υ is Poisson's ratio and κ is thermal conductivity. C is specific heat, α is thermal expansion rate and Pr is Prandtl number.

3.2 Loading condition

As the loading condition, Plant Condition Ⅰ of normal operation and transients such as Plant Condition Ⅱ of Manual Trip (MT) and Power Loss (PL), or Plant Condition Ⅲ of Pump Stick (PS) were treated in this study. The schematic loading condition was illustrated in Fig.6.

The variation of coolant temperature is considered to be one of the most important factors to control loading conditions of the piping structure at transients. Figure 7 shows the variation of coolant temperature and flow rate according to time at each transient. Besides, the referred flow rate was 9.08×10^3 kg/sec. at steady-state in this study [6].

Heat transfer coefficient, h, of coolant was calculated considering the variations of coolant velocity and temperature in each step. The method to calculate heat transfer coefficient is as follows:

$$h = Nu \cdot \kappa / D_i \tag{3.2.1}$$

$$Nu = 0.5 + 0.025 Pe^{0.8} \tag{3.2.2}$$

$$Pe = \Pr \cdot \mathrm{Re} \tag{3.2.3}$$

$$\mathrm{Re} = V \cdot D_i / \mu \tag{3.2.4}$$

Where, Nu is Nusselt number, and Pe is Peclet number.

D_i is inner diameter of a pipe and V is the velocity of coolant. Seban-Shimazaki's equation was used to calculate Nu number in this study. The variations of heat transfer coefficient according to time at transients obtained from the above method were shown in Fig.8.

4. LBB assessment

4.1 Assessment procedure

A penetrated crack length, C_p, may be calculated from creep-fatigue crack growth assessment considering the severest loading condition of Plant Condition Ⅰ ~ Ⅲ. An initial crack size for creep-fatigue crack growth assessment may be concluded by adding the safety margin of 2, to detectable limit of UT (Ultrasonic Testing) at PSI (Pre-Service Inspection), which generally is considered as a semi-elliptical crack of which depth and length correspond to 20% and 100% of a wall thickness respectively. As the piping components of FBR have been operating under the high temperature and low internal pressure, the main loading parameter contributing to the unstable fracture is seemed to be thermal stress to the axis direction, therefore an initial crack was regarded as a circumferential crack in this study.

A detectable crack length, C_d, is usually evaluated conservatively with considering the loading condition of Plant Condition Ⅰ. The detectable crack length refers to an inner (or an outer) surface crack length obtained from the relation between inner crack length and outer crack length after penetration with concluding an outer (or an inner) crack length that corresponds to a leak rate, 200g/h. Where the leak rate, 200g/h, is a value considering the safety margin of 2, to the detection capability, 100g/h. In addition, COD (Crack Opening Displacement) relating to the detectable crack length was calculated elastically in this study. As the result, the evaluated detectable crack length was larger than reality, which meant conservative evaluation. On the contrary, COD for a leak rate is generally evaluated to be small as possible by considering the plastic behavior properly for conservatism. Thermal expansion stress used in the assessment should be an axial component due to thermal expansion moment.

A critical crack length, C_{cr}, may be evaluated considering the severest loading condition of Plant Condition Ⅰ ~ Ⅲ. As margins, 1.5 to the primary stress and 1.1 to the secondary stress were used to the considerable stress components, and the present assessment method is based on the concept of the net-section collapse criteria. Z-factors concerning the effect of a material ductility prior to reaching limit load at the net-section collapse on a large scale piping were extrapolated from the data of JSME [7].

4.2 LBB assessment

As an object of LBB assessment considering a circumferential crack, Y-piece that corresponds to a structural discontinuity and expected to bring about severe stress variation at transients may be chosen. Another object was set to Elbow, which may be treated as an important object of defect assessment. The stress components used in LBB assessment including each transient state were shown in Table 2.

Where, stresses due to thermal expansion moment, Q_{bg}, were concluded to be divided into each transient because the temperature of coolant behaved differently at initiation of each thermal transient. Stresses due to thermal transients, Q_b, corresponded to the maximum increments of bending components obtained from stress distribution through the wall thickness. P_m, $P_{bg\text{-}S}$ and $P_{bg\text{-}W}$ are stresses due to internal pressure, S1 seismic and dead weight respectively, and these values referred to a design data [8]. A plate model was applied for determining the penetrated crack length. The membrane stresses consisted of the stresses due to pressure and each thermal expansion moments, and the bending stresses consisted of the stress variations due to each transient. The holding time was 703 hr corresponding to 427 iterations / 40 years that is based on the design data of FBR plants. Moreover, the stress relaxation was considered during the holding time at 550℃. As coefficients for fatigue crack growth, $C_f = 1\times10^{-3.3}$, $m_f = 1.83$, and for creep crack growth, $C_c = 1\times10^{-1.4}$, $m_c = 1.01$, which are material data of Mod.9Cr-1Mo ferrite steel were adopted. The assessment results may be illustrated in harmony with a master curve as Fig.9 according to a parameter about stress ratio.

Stresses at determining the detectable crack length were composed of stress components due to thermal expansion moment, internal pressure and dead weight. Coolant leakage assessment makes it possible to produce an outer (or an inner) crack length corresponding to detectable leakage. A detectable crack length may be determined by using the above crack length and the characteristics on creep-fatigue crack growth after penetration. In this study, however, the effect of creep on crack growth after penetration was neglected, thus the detectable crack lengths were determined by fatigue crack growth behavior only.

Critical crack length assessments were performed by composing the severest stress states at Plant Condition Ⅰ ~ Ⅲ including each transients. The membrane stress corresponds to stress component due to internal pressure only and the bending stresses correspond to stress components due to thermal expansion moment, dead weight and S1 seismic. The assessment results of penetrated crack length, detectable crack length and critical crack length were summarized in following Table 3.

From results summarized in Table 3, Elbow and Y-piece including a circumferential crack show LBB behavior enough under transients.

5. Discussion and Conclusion

This study dealt with LBB assessment with referring to a design data of large-scale FBR structure and LBB characteristics of large-scale piping structure were well represented. The main results from this study are as following:

- The penetrated cracks and the detectable cracks were evaluated considering creep behavior of ferrite steel and the detection capability according to property of liquid metal respectively.
- The critical cracks obtained from the net-section collapse criteria were compared with the above evaluated cracks, and LBB assessments were done.

Meanwhile, LBB margin which is defined as C_{cr}/C_d or C_{cr}/C_p may be often used as a standard to decide LBB behavior. If LBB margin is over 1, that is to say, it is generally considered that LBB behavior is realized. The following ones may be discussed considering LBB margin.

- Power Loss is seemed to be the severest state of transients from the present results.
- LBB margin on Elbow was close to 31 at each transient. These results means that a circumferential crack growth in Elbow is not so severe if a critical crack length is evaluated from net-section collapse criteria. As Elbow is closely related to buckling modes, buckling assessment under a circumferential or an axial crack may be considered for structural integrity.
- In the case of Y-piece, as the penetrated crack lengths at transients were larger than the detectable crack length, LBB margin may become to be C_{cr}/C_p and its value was 8. Unstable fracture assessment gave a little conservative result in this case, because the critical crack lengths reach to at most 26.5 degree at Power Loss despite LBB behavior.

Z-factor used for unstable fracture assessment which was obtained from the representative data for ferrite steel is considered to be a main reason for conservatism. In order to mitigate the conservatism of present assessment, Z-factor needs to be equipped newly by constructing FAD (Failure Assessment Diagram) about 12Cr type ferrite steel.

The effect of creep time was excluded in present assessment, except for the penetrated crack length assessment. The R5 procedure indicates that large safety margins are required in a non-time-dependent LBB judgment because creep time has a detrimental effect on high temperature LBB behavior [9].

Some margins may be considered to each step in LBB assessment. Margin of 2, which was added to the detection capability, was applied for the penetrated crack and the detectable crack assessment. Moreover, for the critical crack assessment, margins of 1.5 and 1.1 were considered to the primary stress and the secondary stress respectively. Another margin, although not taken into account in this study, may be added to crack length with considering the scattering on crack growth behavior under creep and fatigue tests.

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Table 1 Materials Properties of HCM12A and Sodium at 550℃

Temp. (℃)	HCM12A					
	E (GPa)	υ	κ (W/m·K)	C (J/kg·K)	$\alpha \times 10^{-6}$	ρ (kg/m^3)
550	166	0.306	33.70	910	11.3	7860.0

Temp. (℃)	Sodium			
	κ (W/m·K)	$\mu \times 10^{-7}$ (m^2/sec)	Pr	ρ (kg/m^3)
550	64.6	2.74	0.0044	820.25

Table 2 Stress components used in LBB assessment

	P_m (MPa)	Q_{bg} (MPa)			Q_b (MPa)			P_{bg-S} (MPa)	P_{bg-W} (MPa)
		MT	PS	PL	MT	PS	PL		
Elbow	2.0	12.3	12.63	13.5	2.78	2.87	4.0	1.69	20
Y-piece	3.5	157.0	165.4	176.0	122.4	129.0	154.1	2.44	20

Table 3 Assessment results of penetrated crack length, detectable crack length and critical crack length

	C_p (mm (deg.))			C_d (mm (deg.))	C_{cr} (mm (deg.))		
	MT	PS	PL		MT	PS	PL
Elbow	25.0 (2.3)	24.8 (2.3)	26.7 (2.5)	31.0 (2.87)	974.8 (90.2)	972.4 (90.0)	966.1 (89.4)
Y-piece	33.9 (3.1)	35.5 (3.3)	35.8 (3.3)	25.6 (2.37)	335.1 (31.0)	312.9 (29.0)	286.4 (26.5)

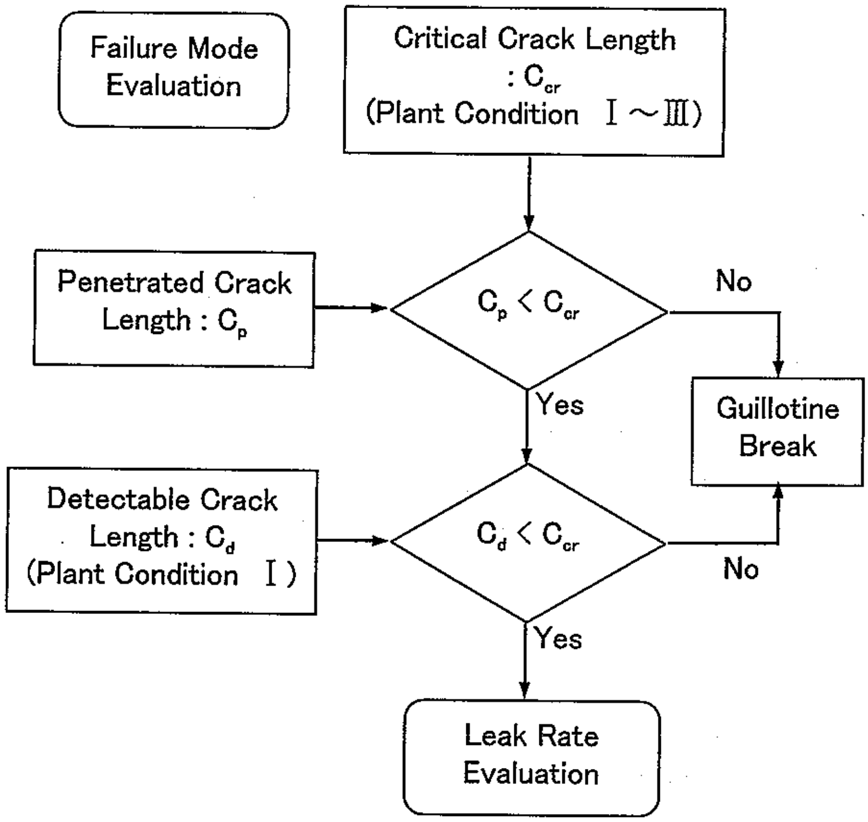

Fig.1 LBB assessment flow

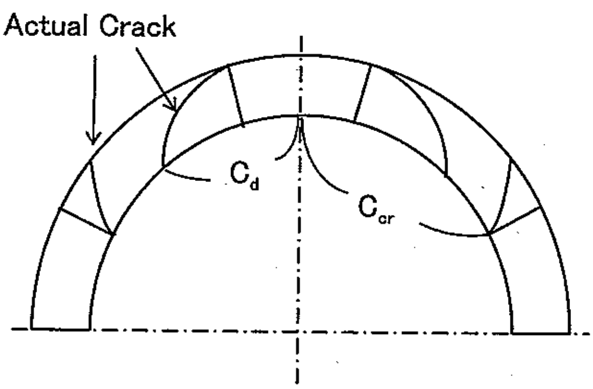

Fig.2 Description of considerable cracks for assessment

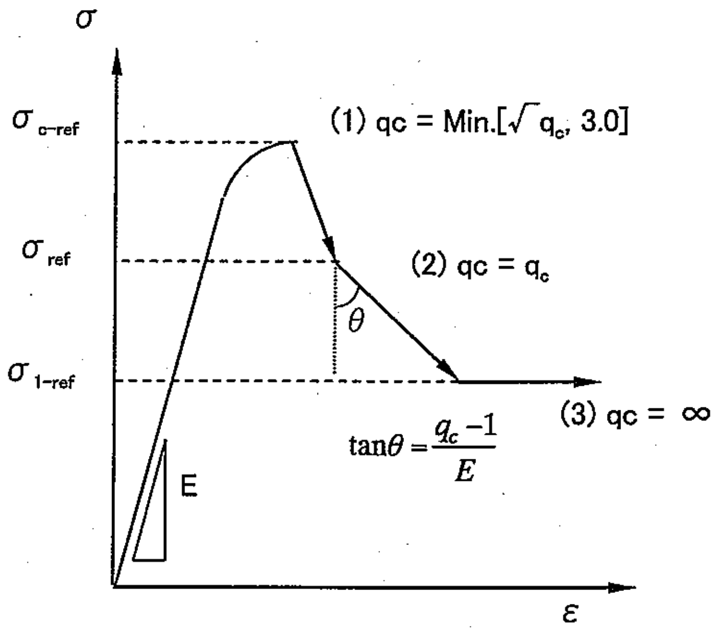

Fig.3 Generalized stress relaxation process

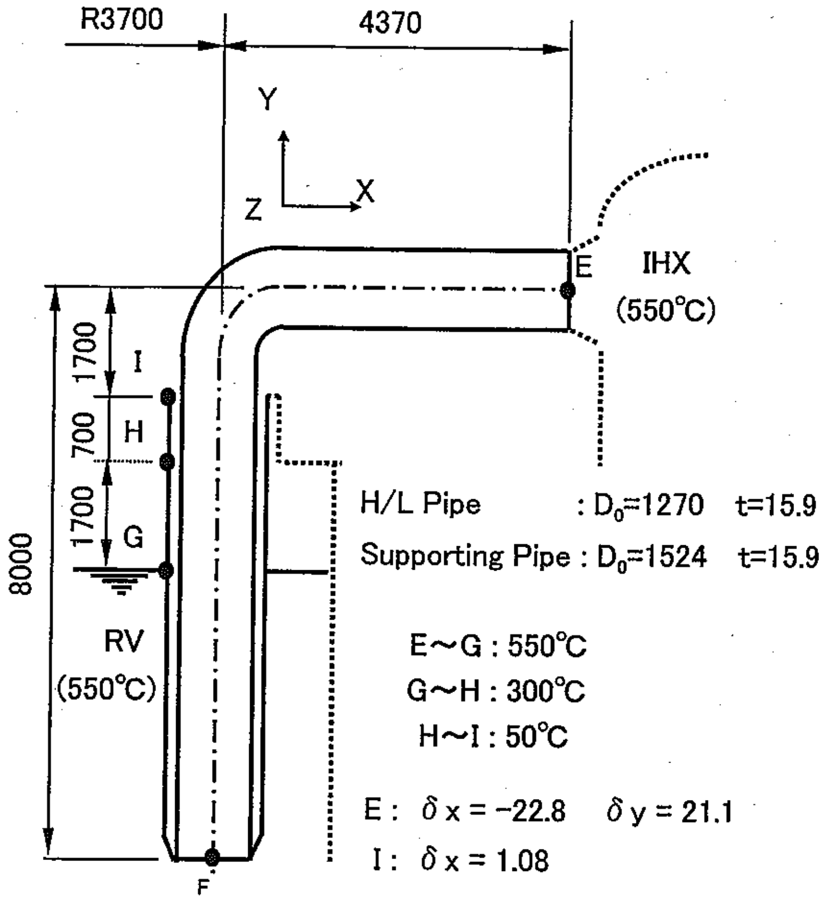

Fig.4 Assessment model

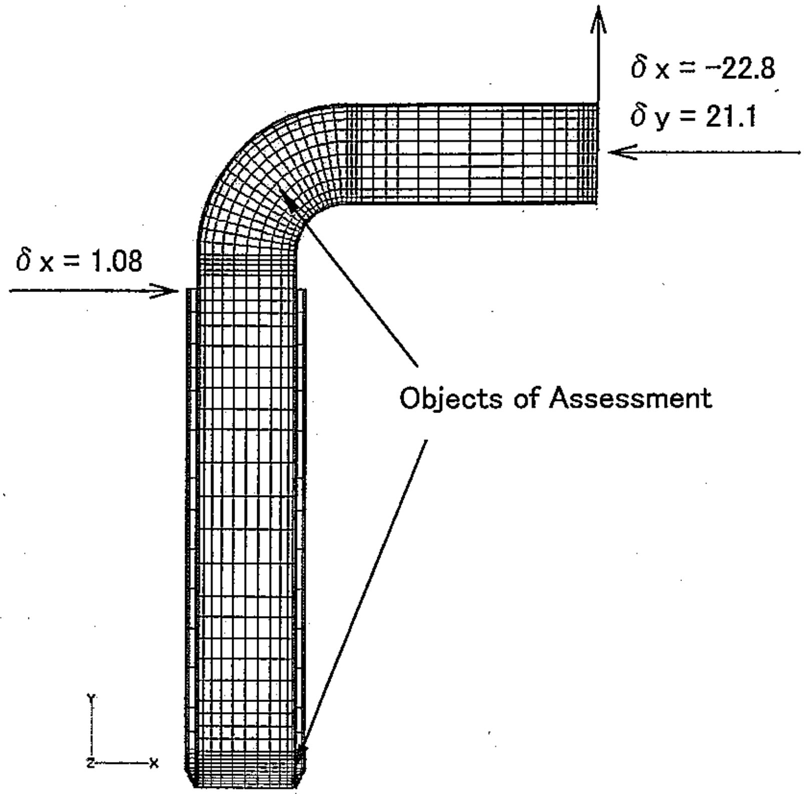

Fig.5 FEM model

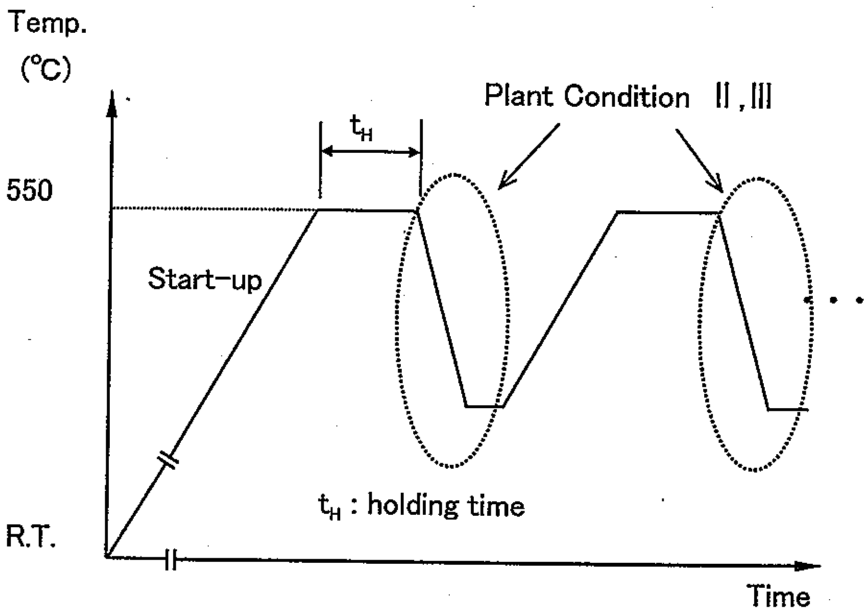

Fig.6 Schematic loading condition

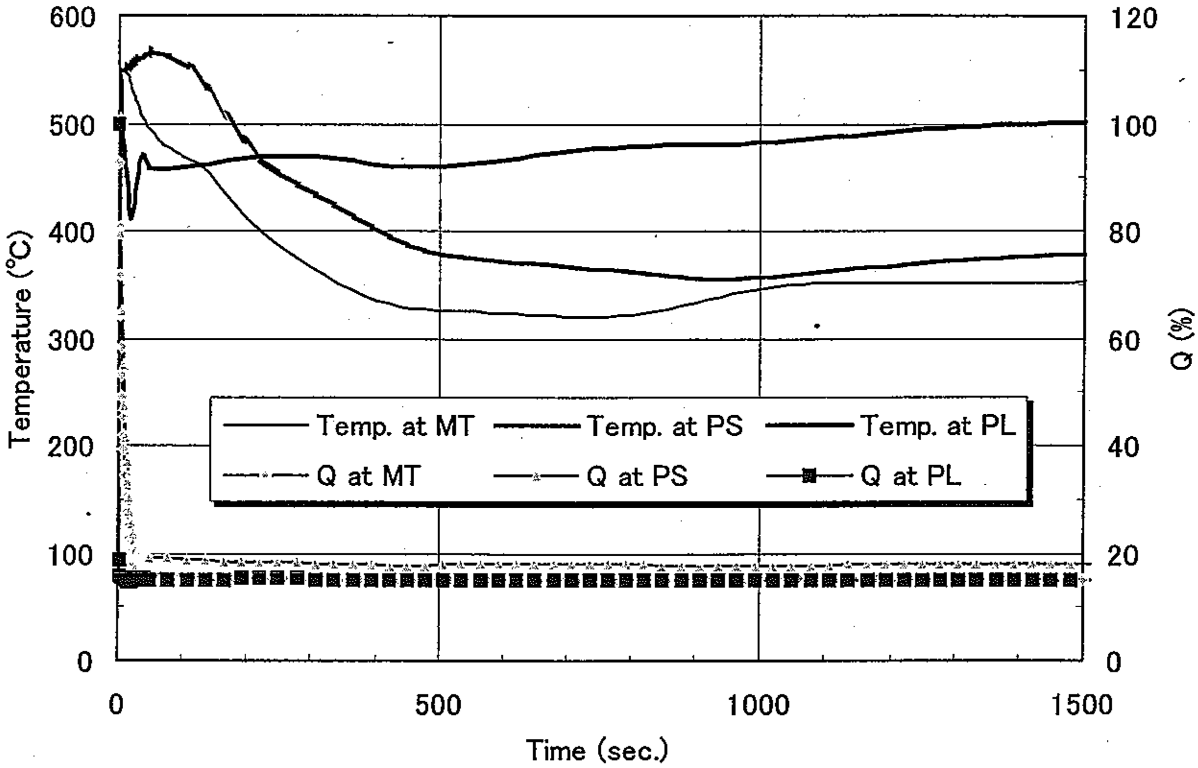

Fig.7 Variation of coolant temperature and flow rate at transients

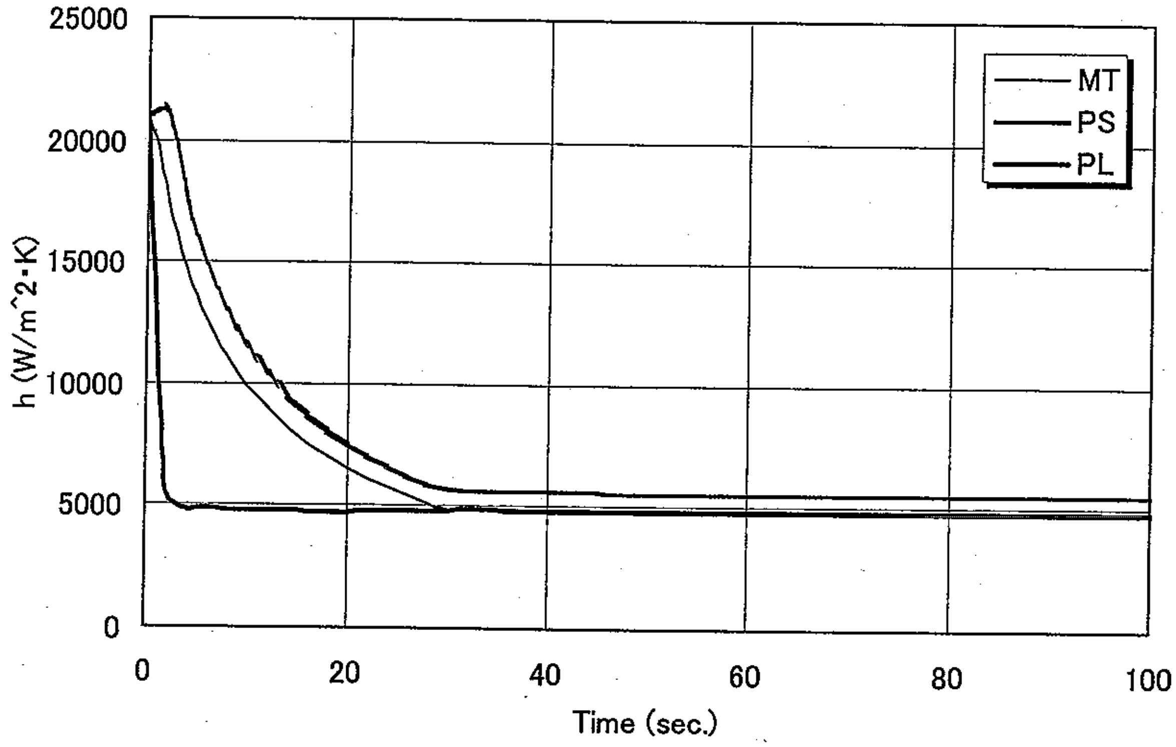

Fig.8 Variation of the heat transfer coefficient at transients

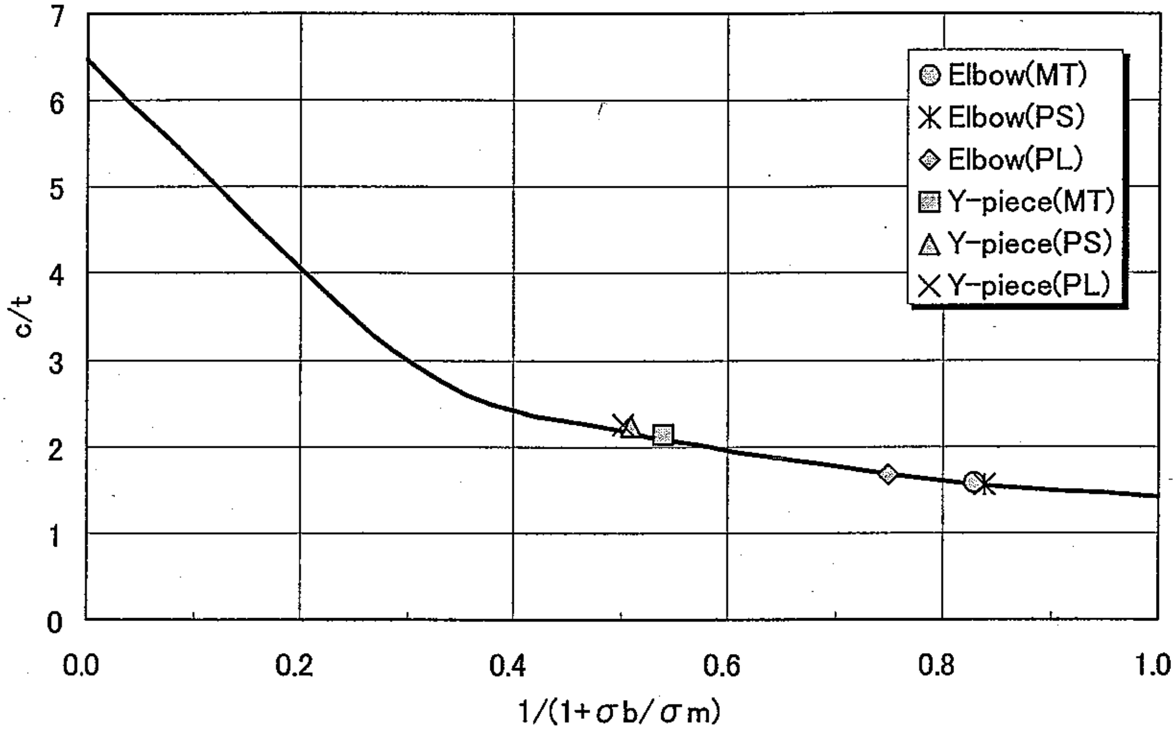

Fig.9 A master curve of creep-fatigue crack growth