Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999 G04/3

Development of Flaw Evaluation Guideline for FBR Components

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ABSTRACT

Central Research Institute of Electric Power Industry (CRIEPI) has been conducting a research project on the verification of evaluation method for structural integrity of high-temperature components of Fast Breeder Reactor (FBR) plants, in which applicability of inelastic fracture mechanics to austenitic stainless steels used in these components has been studied. A flaw evaluation guideline was generated based on the research results. The guideline provides evaluation procedures for creep-fatigue crack propagation, ductile fracture, and sodium leak rate together with related materiel properties. This paper presents the evaluation procedures recommended in the guideline.

1. INTRODUCTION

In the formal design assessment for Fast Breeder Reactor (FBR) components, no initial defects are assumed and prevention of crack initiation from defect-free structures is a main concern. However, the existence of initial defects such as weld defects can not be totally excluded and initiated cracks do not lead to component failure instantly. Therefore, evaluation of structure integrity under the presence of crack-like defects is also important to complement the "formal" design assessment.

Since main components of FBR plants are made of austenitic stainless steels which exhibit high ductility and inelastic response due to high temperature, inelastic fracture mechanics, rather than linear elastic fracture mechanics, needs to be applied to assess the strength of the FBR components with an assumed flaw. Creep-fatigue is considered to be an essential driving force for crack propagation during operation. Consideration of ductile fracture is needed to evaluate the possibility of instantaneous component failure under monotonic loading. Sodium leakage from a penetrated flaw is also an important phenomenon to be assessed from the viewpoint of structural integrity of components installed to cope with possible sodium leakage.

Central Research Institute of Electric Power Industry (CRIEPI) has been conducting a research project on the verification of the evaluation method for structural integrity of high-temperature components of FBR plants under the sponsorship of the Ministry of International Trade and Industry. During the course of the study, a flaw assessment guideline for FBR components was first presented in 1993FY [1-4]. After that, continuous efforts have been made to improve the applicability and the reliability of the evaluation method. Based on their results, an advanced guideline was generated in 1998FY. This paper presents the outline of the guideline.

2. OUTLINE OF THE GUIDELINE

2.1 Organization

Table 1 shows the contents of the guideline. The main body provides the scope, application, and concept of the evaluation methods. Details of the evaluation procedures and material properties are given in the appendices.

2.2 Scope

The objective of the guideline is to present a method for the evaluation of the structural integrity of flawed FBR components. A postulated flaw can be regarded as an equivalent crack in the guideline. The assumption of initial flaw size, applied loading, or safety factor is not included in the guideline because they should be determined according to a specific purpose of the evaluation. It can be leak-before-break evaluation, rationalization of crack opening area, rationalization of safety-concerned equipment, rationalization of in-service inspection, assessment of synthetic margin against fracture, and so on.

2.3 Application

The materials considered in the guideline are SUS304 and 316FR stainless steels. SUS304 is a main high-temperature structural material of the Japanese prototype FBR. 316FR was developed by restricting chemical compositions of conventional Type 316 stainless steel to improve the long term creep strength, and is nominated for the Japanese demonstration FBR. The maximum applicable temperature in the guideline is 650 °C. Welded joints are to be made by a tungsten inert gas (TIG) welding.

2.4 Evaluation Methods

The guideline deals with evaluation methods for creep-fatigue crack propagation, ductile fracture, and crack opening area and leak rate. The evaluation flows are shown in Figures 1 to 3. The outline of the evaluation methods is presented in the following sections.

Table 1 Contents of the Guideline

Main Body	Appendices	
1. Scope	Appendix A	Evaluation of Fatigue J-Integral Range and Creep J-Integral
1.1 Objective	Appendix B	Evaluation of Stress Intensity Factor
1.2 Fracture Modes to Be Considered	Appendix C	Evaluation of Reference Stress
2. Application	Appendix D	Crack Propagation Rate Law
2.1 Materials	Appendix E	Evaluation of Net-Section Stress
2.2 Temperature	Appendix F	Flow Stress
2.3 Welding	Appendix G	Evaluation of Crack Opening Displacement
3. Evaluation Methods	Appendix H	Evaluation of Velocity of Leakage
3.1 Creep-Fatigue Crack Propagation	Appendix I	Monotonic Stress-Strain Relation
3.2 Ductile Fracture	Appendix J	Cyclic Stress-Strain Relation
3.3 Crack Opening Area and Leak Rate	Appendix K	Creep Strain
Table 1 Stress Classification	Appendix L	Sodium Properties
Table 2 Classified Stresses and Fracture Modes	Appendix M	Fracture Ductility Correction Factor

3. CREEP-FATIGUE CRACK PROPAGATION

3.1 Evaluation Method of Creep-Fatigue Crack Propagation

Crack propagation law due to cyclic loading, $(da/dN)_f$, is given by,

$$(da/dN)_f = C_1 \cdot \Delta J_f^{m_1} \tag{1}$$

where ΔJ_f is the fatigue J-integral range [5] and m_1 is the material constant. C_1 is given as a function of the rise time (tension process time) so that the effect of the rise time on the crack propagation can be included [6]. This effect might be regarded as a part of creep crack propagation, however, it is practically difficult to separate its contribution.

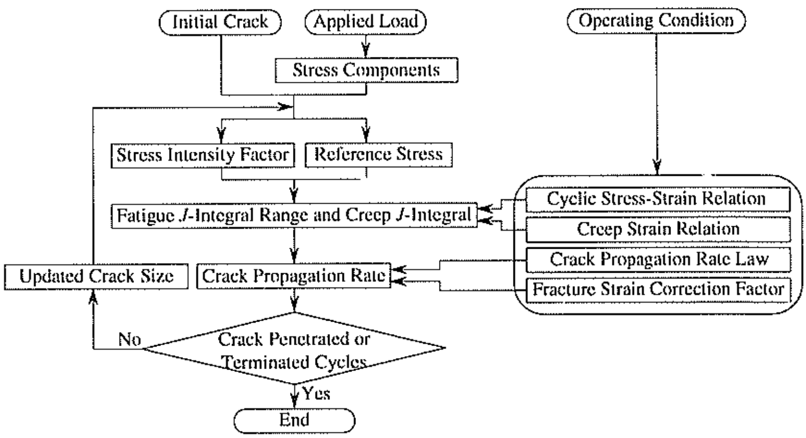


Figure 1 Evaluation Flow of Creep-Fatigue Crack Propagation

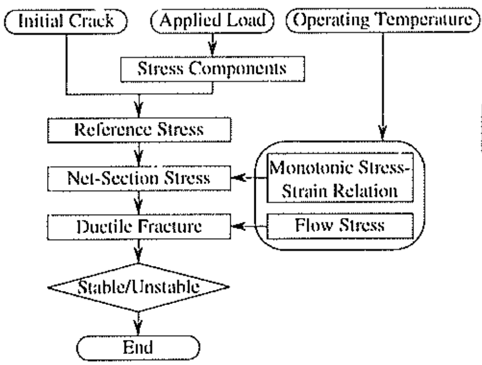


Figure 2 Evaluation Flow of Ductile Fracture

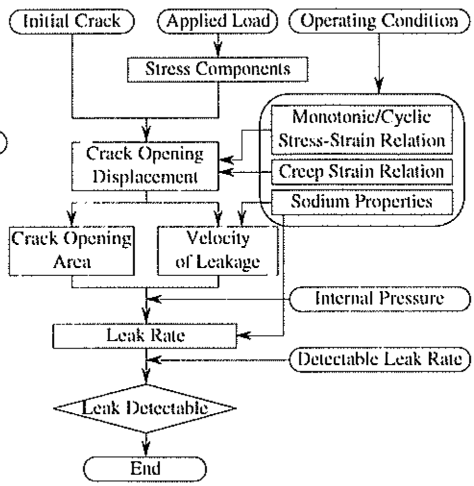


Figure 3 Evaluation Flow of Crack Opening Area and Leak Rate

Crack propagation law during hold time, $(da/dN)_c$, is given by,

$$(da/dN)_c = \int_{\tau_0}^{\tau_1} \left[C_2 \cdot \left(\frac{J'}{\tilde{\varepsilon}_f}\right)^{m_2} \right] dt \tag{2}$$

where τ_0 and τ_1 are times of the start and the end of holding, respectively, J' is the creep J-integral [7], C_2 and m_2 are the material constants, and $\tilde{\varepsilon}_f$ is the true fracture strain introduced to describe the effect of the applied stress level on the crack propagation rate [6]. Crack propagation rate at the same value of J' is accelerated with decreasing applied stress, and it can be explained by the reduction of ductility during cumulative holding. Since the crack propagation rate was found to be inversely proportional to the fracture strain under a constant strain rate [8], $J'/\tilde{\varepsilon}_f$ is expected as a possible parameter to describe the crack propagation under constant loading. $\tilde{\varepsilon}_f$ is formulated as a function of the temperature and the cumulative holding time.

Creep-fatigue crack propagation rate, da/dN, is considered to be simply evaluated using a linear summation rule give by,

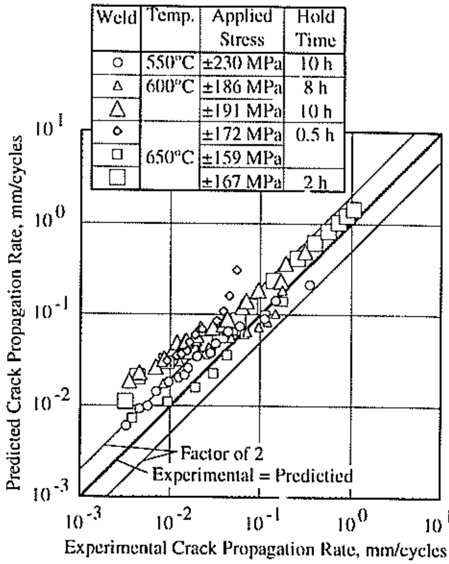


Figure 4 Comparison of Experimental and Predicted Creep-Fatigue Crack Propagation Rate for 316FR Weld Metal

$$da/dN = (da/dN)_f + (da/dN)_c \tag{3}$$

Figure 4 shows the comparison between experimental and predicted creep-fatigue crack propagation rate for 316FR weld metal. It can be seen that the Eq. (3) is applicable with an acceptable accuracy.

3.2 J-Estimation Scheme

The evaluation methods of ΔJ_f and J' are based on the concept of the reference stress method [9]. ΔJ_f used to predict the fatigue crack propagation rate is evaluated by,

$$\Delta J_f = 4 \cdot U^2 \cdot F \cdot J_e$$
$$F = E\, \varepsilon_{ref} / \sigma_{ref} \tag{4}$$

where U is the crack opening ratio assumed to be unity, tentatively. F is the plastic correction factor calculated using the Young's modulus, E, the reference stress, σ_{ref}, and the corresponding reference strain, ε_{ref}. J_e is the elastic J-integral directly obtained from the stress intensity factor, K_I. The solutions of σ_{ref} as well as K_I are given in the appendices for various cracked configurations.

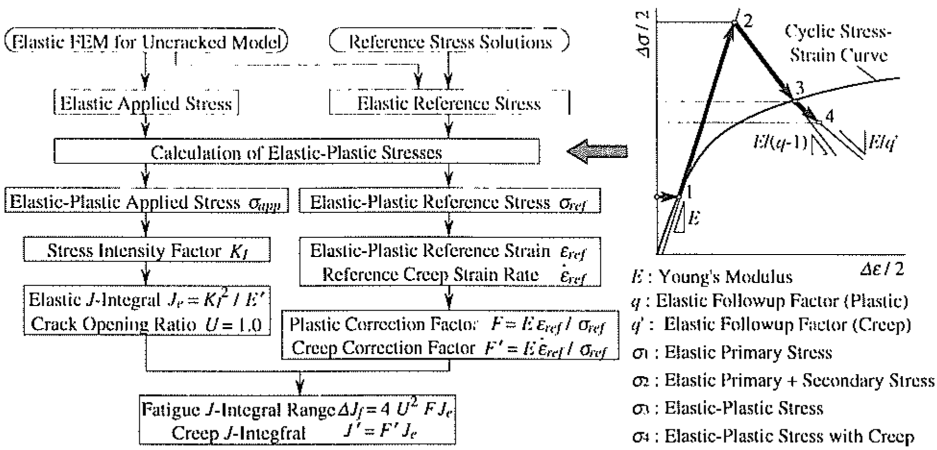


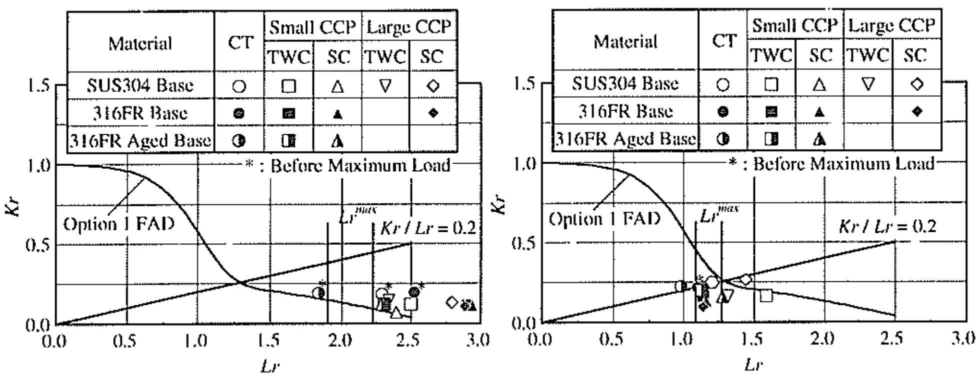
Figure 5 Evaluation Procedure of Fatigue *J*-Integral Range and Creep *J*-Integral

J' for the prediction of the creep crack propagation rate is evaluated by,

$$
\begin{aligned}
J' &= F' \cdot J_e \\
F' &= E\,\dot{\varepsilon}_{ref} / \sigma'_{ref}
\end{aligned}
\tag{5}
$$

where F' is the creep correction factor obtained from the reference stress, σ'_{ref}, and the corresponding reference strain rate , $\dot{\varepsilon}_{ref}$. Stress relaxation is taken into account in the evaluation of σ'_{ref} and $\dot{\varepsilon}_{ref}$.

The definition of the stresses needed to calculate ΔJ_f and J' is strictly provided in the guideline. Figure 5 shows an outline of the evaluation procedure of ΔJ_f and J'.



(a) Base Metal **(b) Welded Joint**

Figure 6 Screening of Criterion Using Two-Parameter Approach for SUS304 and 316FR at 550°C

4. DUCTILE FRACTURE

The occurrence of ductile fracture is evaluated by the following equation.

$$\sigma_n < \sigma_f, \quad \text{Ductile fracture does not occur}$$
$$\sigma_n \geq \sigma_f, \quad \text{Ductile fracture occurs} \tag{6}$$

where σ_n is the net-section stress and σ_f is the flow stress defined as an average of design yield stress and design tensile strength. Eq. (6) means that the ductile fracture is controlled by the Net-Section Collapse criterion rather than the *J/T* criterion. The propriety of the Net-Section Collapse criterion is verified by the screening using two-parameter approach [2]. The screening results of the experimental maximum loads for SUS304 and 316FR at 550°C obtained from CT and CCP tests are shown in Figures 6(a) and (b). The maximum load points are located in the plastic-collapse region prescribed by the Net-Section Collapse criterion in the Failure Assessment Diagrams regardless of the difference between base metal and welded joint, specimen size, loading type or crack geometry.

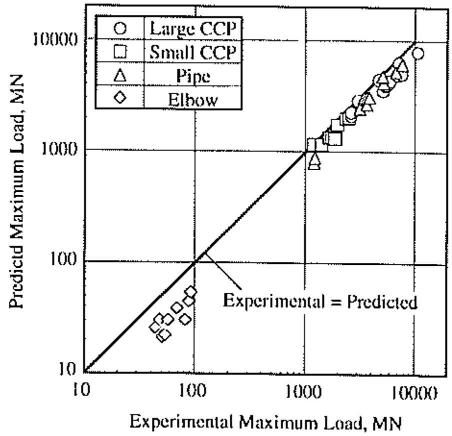


Figure 7 Comparison of Experimental and Predicted Maximum Load

It is also ascertained that the Net-Section Collapse criterion is favorably appropriate to predict the load-carrying capacity for cracked straight pipes [10] and cracked elbows [11]. Figure 7 shows the comparison between experimental and predicted maximum loads for cracked plates, pipes, and elbows.

5. CRACK OPENING AREA AND LEAK RATE

5.1 Evaluation method of Crack Opening Area

Crack opening area, S, is evaluated as,

$$S = \pi \cdot c \cdot \delta / 2 \tag{7}$$

where c is the half crack length and δ is the crack opening displacement. The fully plastic solution in the GE/EPRI estimation scheme [12] is extended to apply to three-dimensional crack problem including elastic-plastic and creep condition. Eq. (7) involves the assumption that the crack opening geometry is approximated by an ellipse. The propriety of the assumption was verified using 3D FEM analyses. The applicability to complex crack configuration such as different crack length or different crack opening displacement on both surfaces was also confirmed.

5.2 Evaluation method of Leak Rate

Leak rate under Light Water Reactor condition can be evaluated based on the Moody's critical flow model. A simpler model can be used for FBR condition because sodium behaves as a single-phase incompressible fluid.

Leak rate, Q, is given by,

$$Q = \rho \cdot V \cdot S \tag{8}$$

where ρ is the density of sodium, V is the velocity of leakage, and S is given by Eq. (7). The equation to calculate V is derived from the Bernoulli's formula as,

$$V = \sqrt{\frac{2p}{\rho\left(1.5 + f_F\left(1 + k_C + k_B + k_E\right)\dfrac{L}{D_h}\right)}} \tag{9}$$

where p is the internal pressure, f_F is the friction factor, k_C, k_B and k_E are the correction factors, L is the length of flow path (equivalent to thickness), and D_h is the hydraulic diameter. The capability of Eq. (9) was validated from water leak tests using artificially slit acrylic plates with various dimensions. Considering actual crack configurations, some difficulties arise from three-dimensional shape of internal flow path or roughness of crack surface. These effects are considered through the correction factors. k_C, k_B and k_E are the factors to account for the effect of roughness of crack surface, the effect of shape of internal flow path (reduction, step or turning of flow path) due to bending, and the effect of out-of-plane deformation for cracked elbows, respectively. These factors are formulated as functions of the components of δ in the appendix based on water leak tests using plates, pipes and elbows with creep-fatigue cracks.

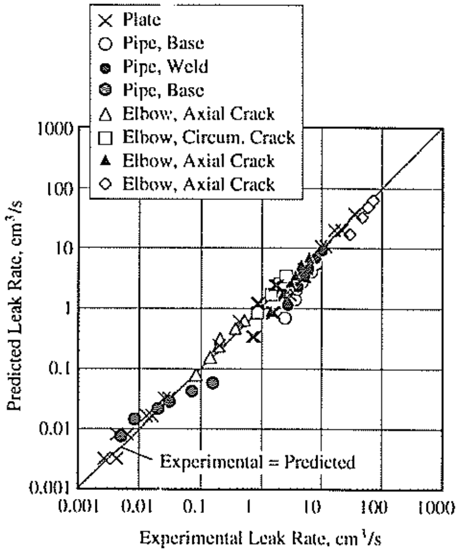


Figure 8 Comparison of Experimental and Predicted Leak Rate

Figure 8 shows the comparison between experimental and predicted leak rates for cracked plates, pipes, and elbows. The present method gives good prediction for different cracked models.

6. CONCLUSIONS

In this paper, the outline of the guideline for the flaw evaluation applied to FBR components was presented. The guideline provided the flaw evaluation methods for creep-fatigue crack propagation, ductile fracture, and crack opening area and leak rate.

Creep-fatigue crack propagation law was identified in consideration of both the effect of rise time on crack propagation for cyclic loading and the effect of cumulative time on creep crack propagation. The procedure to estimate the dominant parameters of crack propagation law, fatigue J-integral range and creep J-integral was also given.

The Net-Section Collapse criterion was employed to evaluate the occurrence of ductile fracture. The criterion was appropriate to apply to cracked plates, pipes and elbows.

The evaluation methods to predict crack opening area and leak rate were prepared. The fully plastic solution was used to calculate crack opening area. The equation to calculate leak rate was derived form the Bernoulli's formula together with the consideration of the effect of actual crack configurations.

ACKNOWLEDGMENT

This study was carried out as a part of the project of the Ministry of International Trade and Industry entitled "Verification Tests of Fast Breeder Reactor Technology", which has been conducted since 1987. The authors would like to express their sincere gratitude to all members of an advisory committee chaired by Professor Genki Yagawa of the University of Tokyo.

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