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Study on the failure criteria of cladding in MECURY code

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1. Introduction

In the present situation where the stability of nuclear power plant is important, it is necessary to construct a simulation code for design based accident such as Loss of Coolant Accident (LOCA) to maintain the integrity of nuclear fuel cladding. KAERI is developing a **M**ulti-dimensional **E**ntire **R**od **C**ode for sim**U**lation of fuel behavio**R** developed b**Y** KAERI (MERCURY) to simulate detail deformation of the cladding tube. The MERCURY code based on finite element method (FEM) has been described. The MERCURY incorporates transient thermal analysis model, nonlinear mechanical model, thermos-mechanical model, multi-dimensional gap conductance model, burnup dependent material properties. During LOCA, the resulting substantial blockage of sub-channel would restrict emergency core cooling. It requires establishing a reasonable understanding of the factors that control the ballooning and fracture of cladding. Therefore, the failure model was also applied to MERCURY code.

In this paper, we analyze the simulation results according to various existing failure criteria. In order to analyze the effect by failure criteria in MERCURY code, we used the results of PUZRY test [1] (from KFKI AEKI). Alpha-version of MERCURY, which is an axisymmetric FEM code, has been used clad ballooning behavior under isothermal condition.

2. Mechanical model of MERCURY code

2.1 Creep Model

To simulate large deformation of clad which occurs during LOCA, creep model is employed instead of elasto-plastic deformation model. The creep equation (1) is the Norton's power-law creep model and the coefficients of the creep model were taken from Erbacher's paper [2]

$$\dot{\varepsilon}^{cr} = A \cdot \exp\left(\frac{-Q}{RT}\right) \cdot \bar{\sigma}^{n} \tag{1}$$

2.2 Cladding burst failure model

The TRANSURANUS [3] code defined various failure criteria. The failure criteria were plastic instability condition, overstress, overstrain, combination of the plastic instability and overstress criteria, and the combination of the overstress and overstrain. In the FRAPTRAN [4] code, as shown in Fig. 1, the failure criteria were defined in combination of burst strain and burst stress.

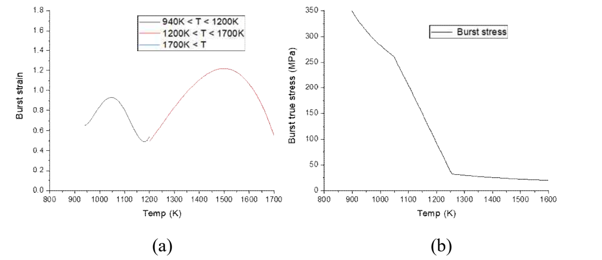


Fig. 1. Failure criteria at FRAPTRAN [4]: (a) Burst strain, (b) Burst stress

In the BISON [5] code, the combination of the plastic instability and overstress criteria was applied on the failure criteria. The plastic instability criteria were defined as the strain rate variable in Eq. (2) at the TRANSURANUS [3] code. As in Eq. (3), the over stress criteria of Erbacher's paper [2] was used.

$$\dot{\varepsilon}_{failure} = 100 \; [/hr] \tag{2}$$

$$\sigma_{Over} = a\exp(-b \cdot T) \cdot \exp\left[-\left(\frac{100 \cdot O_x - 0.12}{0.095}\right)^2\right] \tag{3}$$

We applied the criteria of the two codes, which are typical fuel performance code, to the MERCURY code.

3. Ballooning simulation with various failure criteria

3.1 PUZRY test

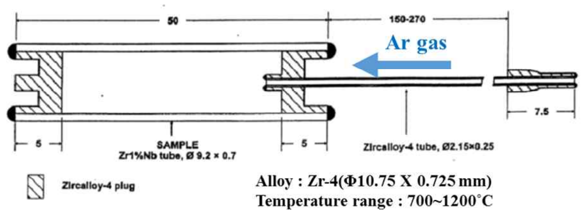


Fig. 2. Schematic drawing of the Zry-4 specimen for ballooning test at high temperature condition. [1]

As shown in Fig. 2, PUZRY test were performed in the same test facility with 31 irradiated and unoxidized Zircaloy-4 tube specimens to provide comparative data by linearly increasing the pressure under isothermal conditions in the 700-1200 °C. The pressure rise rate during a large break LOCA is generally 2 to 4 bar/s, but the maximum pressure rise rate in the test is one digit lower. It is recommended to simulate with the test at the highest pressure rise rate to avoid the effects of long-term exposure to high levels of stress. Since anisotropic properties have not yet been applied to the analysis code, experiments were selected to be evaluated based on the isotropic properties of the Zr β-phase. In general, Zr β-phase is transformed at temperatures above 1000°C. Therefore, three cases of the highest pressure rate in the temperature range with beta phase are selected as shown in Table 1.

Table 1: Selected PUZRY tests

	Temperature [˚C]	Pressure rate [bar/s]
PUZRY-08	1000	0.076
PUZRY-10	1100	0.071
PUZRY-12	1200	0.072

3.2 Burst Simulation of the PUZRY test

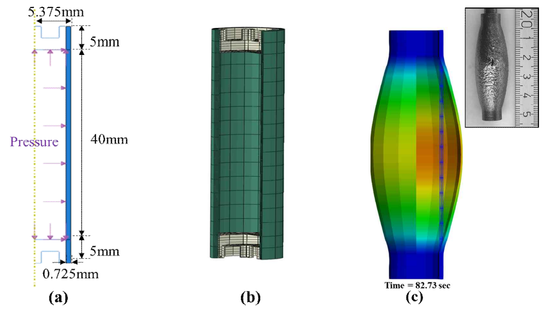
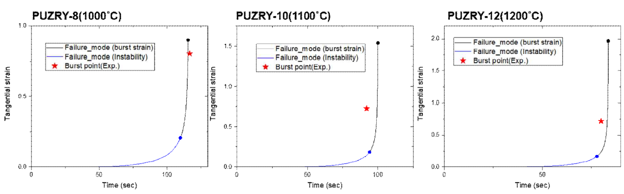


Fig. 3. Analysis model for PUZRY test; (a) axisymmetric model, (b) model rotated 270˚ in the axial direction, and (c) simulation results

The PUZRY experiment was modeled as an axisymmetric shape, as shown in Figure 3. Since both ends are fixed with plugs, the analysis result shows the center of the cladding is swollen, as in the experiment result. Therefore, the maximum strain is measured at the center of cladding. The three representative PUZRY tests were simulated using MERCURY code with different failure criteria. The results obtained from analysis are shown in Fig. 4.



(a) (b) (c)

Fig. 4. Simulation results considering failure criteria; (a) PUZRY-8, (b) PUZRY-10, and (c) PUZRY-12.

As shown in Fig. 4, the deformation of the clad accelerates and the ballooning rapidly occurs. The experiment results were found to be near the deformation path resulting from the analysis. The burst strain of experiment lies between the two failure criteria. The first point in the simulation model that satisfies the two failure criteria was equally the inner wall at the center of the cladding. In the case of failure criteria of FRAPTRAN, the burst strain increases as the temperature conditions increase in the temperature range of 1000 ˚C to 1200 ˚C, as in Fig. 1(a). On the contrary, in case of failure criteria of BISON code, the burst strain decreases as the temperature increases because the creep strain rate is a function of the temperature like Eq. (1). The experimental results show that the burst strain decreases with increasing temperature, similar to the BISON criteria. In addition, when looking at the analysis results, the failure occurred due to the strain criterion among the FRAPTRAN failure criteria, and due to the instability criterion among the BISON failure criteria

4. Conclusions

MERCURY code has been developed to take into account large deformation of cladding under LOCA condition. Creep model is used to describe the large deformation of cladding tube. According to the failure criteria, the burst point obtained from the analysis is different. It is appreciate to use the plastic instability criterion conservatively because failure occurs first when the BISON criteria is applied rather than the FRAPTRAN criteria. However, since the gap between the results of the experiment and the simulation is large, a new failure criterion definition is required to improve the code reliability.

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