# Verification and Validation of MECURY code

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## 1. Introduction

In order to describe the deformed shape of the actual cladding tube, multi-dimensional FE-based fuel performance codes have been developed in various organizations [1, 2]. KAERI is also developing a Multi-dimensional Entire Rod Code for simUlation of fuel behavioR developed bY KAERI (MERCURY) to simulate the deformation of the cladding tube in the event of a designed-based accident.

In this paper, the MERCURY code based on finite element method (FEM) has been described and the verification of the code was carried out. The MERCURY incorporates transient thermal analysis model, nonlinear mechanical model, thermos-mechanical model, multi-dimensional gap conductance model, burnup dependent material properties, cathcart-pawel model for high temperature oxidation, and transient creep model for clad ballooning. The MERCURY can be used as stand-alone code or as a module of system code to couple fuel behavior with thermal-hydraulic code. In order to verify the developed FE-based fuel performance code, we used the results of PUZRY test [3] (from KFKI AEKI).

## 2. Verification of MERCURY code

### *2.1 Creep Model*

To simulate clad ballooning which occurs during LOCA, creep model at high temperature can be employed instead of elasto-plastic deformation model. In the creep model, the nonlinear equation for stress and creep strain at current step is given by Eq. (1) and Eq. (2), respectively.

$$\bar{\sigma}_{n+1} = \bar{\sigma}_n + C:\left(\Delta\varepsilon_{n+1} - \Delta\varepsilon^{cr}_{n+1}\right) \tag{1}$$

$$\Delta\varepsilon^{cr}_{n+1} = f\left(\bar{\sigma}_{n+1}, \varepsilon^{cr}_{n+1}, T\right) \tag{2}$$

Two unknowns (current stress and creep strain) are related to each other and must be calculated as an implicit nonlinear simultaneous equation. Equation (3) and (4) are the nonlinear simultaneous equations. As shown in Fig. 3, the stress locus satisfying all of these formulas should be calculated.

$$g_1 = \bar{\sigma}_{n+1} - \bar{\sigma}^T + \Delta\varepsilon^{cr}_{n+1}\frac{\partial\bar{\sigma}}{\partial\boldsymbol{\sigma}}:C:\frac{\partial\bar{\sigma}}{\partial\boldsymbol{\sigma}} \tag{3}$$

$$g_2 = \Delta\varepsilon^{cr}_{n+1} - \dot{\bar{\varepsilon}}^{cr}\left(\bar{\sigma}_{n+1}, \varepsilon^{cr}_{n+1}, T\right)\Delta t \tag{4}$$

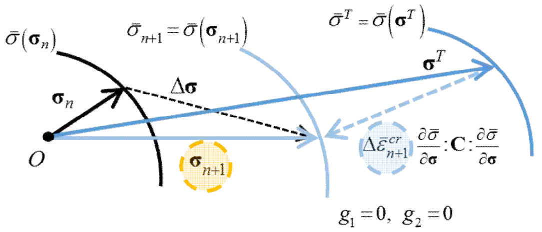
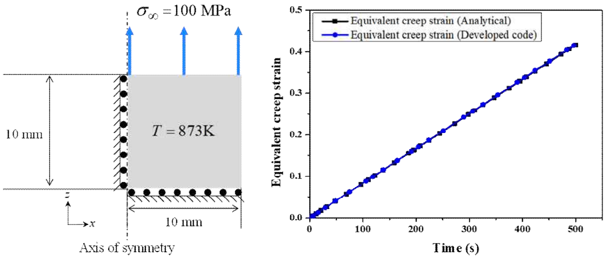


Fig. 1. Effective stress locus for creep model.

### *2.2 Verification with creep strain of uni-axial tension*



(a) (b)

Fig. 2. A cylindrical disk with a constant stress: (a) Simulation model, (b) Creep strain histories

In order to verify the implementation of the creep model, the steady-state creep deformation of a uni-axially loaded disk was analyzed. Figure 2 (a) shows uniaxial loading of a cylindrical disk which has a diameter of 20 mm and a length of 10 mm. It was assumed that there is no heat transfer and the temperature of the disk is constant as 873K. The Young's modulus and the Poisson's ratio of this disk were assumed to be 99.3 GPa and 0.37, respectively.

$$\dot{\varepsilon}^{cr} = A\cdot\exp\left(-Q/_{RT}\right)\cdot\bar{\sigma}^n \tag{6}$$

The creep equation (6) used in this analysis was the Norton's power-law creep model and the coefficients of the creep model were taken from Rosinger [4]. Second order quadrilateral elements with reduced integration were used. As shown in Figure 2 (b), the equivalent creep strain increases linearly with the time since the creep strain rate is a function of the temperature and the stress, and these are constant. Also note that the numerical result did not deviate from the analytical solution.

## 3. Validation of MERCURY code

### *3.1 PUZRY test*

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 cladding specimens had an inner diameter of 9.3 mm and an outer diameter of 10.75 mm, depicting the PWR fuel cladding geometry. The deformed shapes of Zircaloy-4 cladding were measured when the burst of cladding occurred.

### *3.2 Simulation of the PUZRY test*

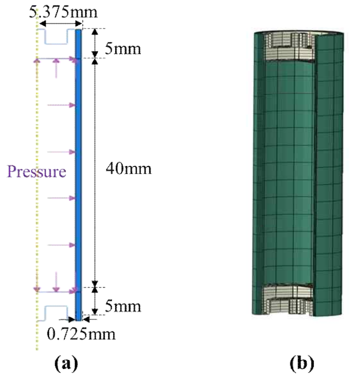


Fig. 3. Analysis model for clad ballooning test; (a) axisymmetric model and (b) model rotated 270˚ in the axial direction.

The PUZRY experiment was modeled as an axisymmetric shape, as shown in Figure 3. The three representative PUZRY test were simulated using MERCURY and commercial FE code, ABAQUS. The results obtained from analysis are shown in Fig. 4.

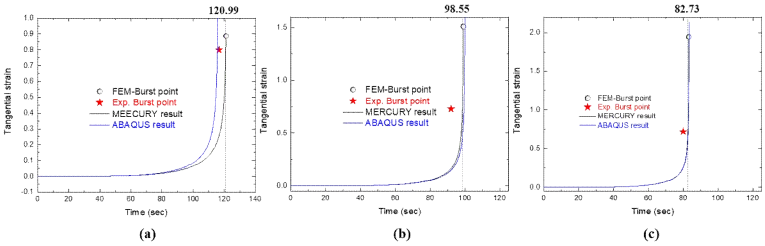


Fig. 4. Maximum circumferential strain over time (a) PUZRY-8(1000°C), (b) PUZRY-10(1100°C), and (c) PUZRY-12(1200°C)

As the ambient temperature increase, the deformation of the clad accelerates and the ballooning rapidly occurs. The results of ABAQUS and MERCURY code are similar except for one case. The difference from the ABAQUS is in the modeling of the plugs at both ends. The discrete rigid element is used at ABAQUS, while 8-node element with high modulus is designed at the developed code. The experiment results were found to be near the deformation path resulting from the analysis. In the case of testing, the burst strain decreases as the temperature increases, while in the case of analysis, the burst strain increases as the temperature conditions increase. This is considered to be due to the fact that the burst criteria of FRAPTRAN. Since the failure criteria of FRAPTRAN is considering high-temperature oxidation, it is necessary to analyze the different failure criteria to evaluate the PUZRY test, which is to assess the behavior of the fresh material under non-oxidation condition.

## 4. Conclusions

MERCURY code has been developed to take into account multidimensional fuel behavior for evaluation of reactor safety analysis. Alpha-version of MERCURY, which is an axisymmetric FEM code, has been simulated clad ballooning behavior under isothermal condition. Cladding deformation model, which is creep model, was verified against the result of analytical solution. Although the burst strain obtained from the experiment and analysis is different, the experiment results are found near the strain path according to the time from the analysis. The difference of burst strain between the experiment and simulation could be due to the failure criteria for the material, so that this could be further improved if the proper coefficients are obtained through other experiments.

For the future, fuel specified models in MERCURY will be validated against various experimental data. Code-to-code benchmark will also be carried out. Based on the V&V results, the fuel specified models will be improved. MERCURY module will be coupled with thermal hydraulic codes (MARS-KS, CUPID etc.).

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