Creep Model for PWR Spent Nuclear Fuel

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1. Introduction

After reactor operation spent nuclear fuel (SNF) has been stored in wet storage. The coolant temperature of wet storage is below 55℃. Due to low temperatures, cladding creep is not activated. However, after wet storage, SNF transferred to dry storage. Initial peak cladding temperature in dry storage is known around 400oC. Therefore, cladding creep in dry storage has been considered as a main degradation mechanism which can bring a gross rupture of the cladding. In general, cladding creep in dry storage is recognized as a thermal creep because the fast neutron fluence is very low compare to in-reactor condition. In this work, we reviewed the creep model of PWR cladding material.

2. Post-irradiated creep models

CSFM model

Creep deformation map of zirconium alloys was proposed for the first time [1, 2]. Creep deformation mechanisms has general five categories: high stress deformation, diffusion controlled dislocation creep, grain boundary sliding, diffusional creep and athermal creep. The proposed model follows in the form of the power law creep.

$$\dot{\epsilon} = ADexp\left(\frac{-Q}{RT}\right)\left(\frac{Eb}{kT}\right)\left(\frac{b}{d}\right)^p\left(\frac{\sigma}{E}\right)^n \quad (1)$$

Where A is the constant, D is the diffusion coefficient, Q is the activation energy, E is the elastic modulus, b is the burgers vector, d is the grain size, k is the Boltzmann's constant, is the stress, p and n are the model constant stress exponent dependent upon the each mechanism, respectively.

JNES model

Ito et al. [3] and Kamimura et al. [4] performed creep experiment with irradiated cladding materials. The cladding material is low tin Zircaloy-4 with burnup range of 44-46 Gwd/tU. They formulated creep phenomenon based on the CSFM methodology. Creep equation consists of saturated primary creep strain and steady state creep rate.

$$\epsilon = \epsilon_p^s + \dot{\epsilon} t \quad (2)$$

where, $\dot{\epsilon}$ is the steady state creep rate and t is the time(hr) and ϵ_p^s is saturated primary creep strain as shown below

$$\epsilon_p^s = A_p\left(\frac{E}{T}\right)\left(\frac{\sigma}{E}\right)^{n_p}\exp\left(-\frac{Q_p}{RT}\right) \quad (3)$$

where, A^p is the constant (K/MPa), n_p is primary stress exponent, Q_p is the primary creep activation energy and R is the gas constant. Steady state creep rate is convolution of high stress creep and low stress creep model.

$$\dot{\epsilon} = \dot{\epsilon}_L + \dot{\epsilon}_H \quad (4)$$

Where $\dot{\epsilon}_L$ is for the low stress regime, and $\dot{\epsilon}_H$is for the high stress regime.

EDF-CEA model

EDF-CEA [5]established Zircaloy creep model which has different form comparison with previous model. Assuming that the creep kinetics is governed by dislocation glide, creep is dependent on a static recovery and strain hardening. On the other hand, Herranz and Feria [6, 7] modified EDF-CEA model with their irradiated creep results. This creep model, so called CIEMAT model, covers a quite large range of stresses, temperatures and fast neutron fluences: Stress: 55-225 MPa, temperature: 350-420℃, Fluence:9E21 n/m^2.

$$\dot{\varepsilon}_\theta = f_1(\sigma_\theta) f_2(T) f_3(\phi t) t^{-0.5} \quad (5)$$

where, $f_1(\sigma_\theta) = \frac{a}{2}\sigma_\theta^b$, $f_2(T) = \exp(\frac{-c}{T+273})$, $f_3(\phi t) = \exp(-d\phi t)$, and other parameters are given in Table 1.

Table 1. Parameters of CIEMAT creep law

Parameters	T<380℃ or $T \geq 380^oC, \sigma_\theta$	$T > 380^oC,$ $\sigma_\theta > 187\,MPa$
a	6E4	300
b	1.84	2.95
c	15000	
c	2.8E-22	

3. Results and discussion

The characteristics of the each creep model were summarized in Table 2. CSFM model provides a wide range of creep map. This model covers wide temperature range of room temperature to melting temperature. However, the data base used in the modelling consists of the data of irradiated and un-irradiated zirconium alloys: Zircaloy-2, Zircaloy-4, and Zr-1Nb. In other words, this model cannot identity the creep dependency of material and irradiation effect.

Table 2. Characteristics of the creep models

model	Temp (℃)	Stress (MPa)	Fluence (n/m2)	Hydrogen effect
CSFM	25-1850	5-500	NA	NA
JNES	330-420	40-310	6.1-8.2E21	NA
EDF-CEA	350-420	50-220	1.8-9E21	NA
CIEMAT	350-420	55-225	9E21	NA

JNES, CEA, and CIEMAT models are appropriate for the spent nuclear fuel creep during dry storage. Creep model of JNES is a function of stress and temperature. The model contains irradiation effects but not a function of neutron fluence. In addition, JNES model consists of low stress regime and high stress regime but only can be applicable to low burn-up spent nuclear fuel. On the other hand, CEA and CIEMAT models can be applicable to low to high burn-up SNF. These models contain the irradiation hardening effect; however, they cannot distinguish the hydrogen effects on the material.

After vacuum drying followed by dry storage, cladding temperature increase abruptly but the temperature decrease slowly with increase in time. The following equation is the proposed temperature history during dry storage based on the decay heat of fuel assembly and cask system [8].

$$T_k = 517.48 + 155.52\exp(-0.0877t) - 0.6922575t \quad (6)$$

where, t is time in year, and T is temperature in kelvin. To evaluate the creep behavior of the maximum low burnup fuel of 45 Gwd/tU during dry storage, CEA-EDF model and JNES model was used and the cladding temperature is presumed to follow the above temperature history. It was assumed that hoop stress of cladding is proportional to the temperature history based on the idal gas law and the model covers the temperature below 330℃. This assumption is conservative because stress decreasing with decreasing temperature and creep is hard to activate at low temperatures. Figure 1 shows the creep strain during dry storage when the fast neutron flux was 4.5E21. The behavior of cladding strain is far different. However, the models showed that creep strain is far below 1% creep strain, which is a previous criterion to determine creep failure.

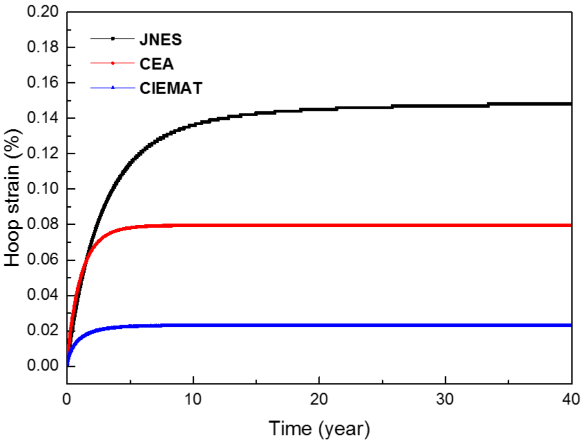

Fig. 1. Hoop strain during 40-year dry storage.

4. Conclusions

EDF-CEA and JNES creep model showed that creep strain of 45 Gwd/tU during dry storage is far below 1% creep criterion. However, these creep models have some limitation in evaluating creep during long-term dry storage: low temperature creep and hydrogen effect on creep. Therefore, hydride effect on cladding creep is required for evaluating the post irradiation creep behaviors. Post-irradiation creep model for PWR SNF is required for the dry storage operation for the safe storage of SNF.

5. Acknowledgement

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