Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October, 25-26, 2012

The Prediction of Cladding Performance in Ultra-long Cycle Fast Reactors

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1. Introduction

As a part of R&D activities for the development of advanced fast reactors, HT9 cladding performance of Ultra-long Cycle Fast Reactor (UCFR) is evaluated in various cladding peak temperatures and design power levels (1000MWe and 100MWe). The key design concept of UCFR is a non-refueling during 30 to 60 years operation, and this concept may require the maximum cladding temperature of ~ 650°C peak cladding temperature and cladding radiation damage of over 200 dpa (displacements per atom). Therefore, for the design of UCFR, challenges such as thermal creep, irradiation creep and swelling must be quantitatively evaluated.

As a cladding material, HT9 shows distinguishably favorable properties for UCFR. In this study, therefore, key design parameters for the cladding performance will be evaluated for UCFR cladding design and resulted the prediction of life time of cladding in UCFR.

2. Design parameters for UCFR fuel cladding

2.1 Design criteria for UCFR 1000 and 100

The design criteria for UCFR cladding is that thermal strain is lower than 1%, total strain is lower than 3%, and swelling is lower than 5%. Maximum cladding temperature is set as 650℃ [1, 2, 3]. The calculated cladding temperature of UCFR-100 is set as 601℃ and that of UCFR-1000 is over 650℃

2.2 Fission gas release (FGR)

Fraction of fission gas release is analyzed by GRSIS (Gas Release and Swelling in ISotropic fuel Matrix) model [4]. GRSIS is based on 3-dimensional, high burnup and metallic fuel analysis. The simulation process is based on the nucleation, growth and interconnection between different size bubbles. Therefore, FGR of UCRF is analyzed by GRSIS model as below. Its flow chat is shown in Fig. 1.

$$\mathrm{FGR} = 0$$

$$= f_{th}\,(C_{gb1} + C_{gb2} + C_{gb3}),\ S_t = S_{th} \qquad (1)$$

$$= C_{gb},\ S_t < S_{th}$$

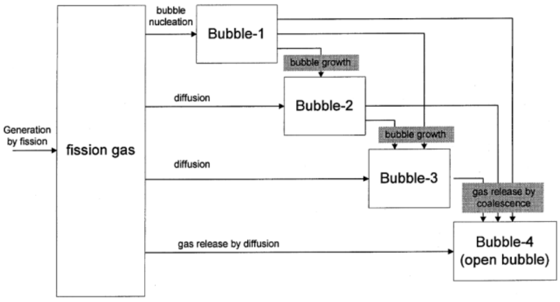

Fig. 1. GRSIS code overview [4]

2.3 Thermal creep

Thermal creep strain of HT9 in UCFR is evaluated by Garofal's Model [5] which enables to calculate the primary creep strain and linearly time-dependent steady state creep strain

Creep correlation for primary and steady-state regimes as follows [5]:

$$\epsilon_{\mathrm{ps}} = \epsilon_{\mathrm{p}}[1 - \exp(-\mathrm{m}t)] + \dot{\epsilon}t \qquad (2)$$

Where ε_p is primary (transient) creep strain, m is material constant (≒ $2.11*10^{-6}$ [sec^{-1}]), ε_s is steady-state creep rate and t is time, respectively. Primary creep strain as follows:

$$\log\epsilon_{\mathrm{p}}(\%) = \mathrm{P}_0(\mathrm{T}) + \mathrm{P}_1(\mathrm{T})\log\sigma_{\mathrm{eff}}(\mathrm{MPa}) \qquad (3)$$

where σ_{eff} is effective stress which is produced by internal pressure from fission gas and which is calculated by stress through axial, radial and hoop stresses as below.

$$\sigma_{\mathrm{eff}} = \sqrt{\left(\frac{1}{2}\right)[(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + (\sigma_a - \sigma_\theta)^2]} \qquad (4)$$

where σ_θ is hoop stress, σ_r is radial stress and σ_a is axial stress, respectively.

Also, steady-state creep rate (at higher stress exponent regime) as follows:

$$\log\dot{\varepsilon}_s(sec^{-1}) = S_h(T) + 19.7\log\sigma_{\mathrm{eff}}(\mathrm{MPa}) \qquad (5)$$

2.4 Irradiation creep

The external non-hydrostatic stress during irradiation condition is adopted as the mechanism of irradiation creep. In the case of UCFR, high neutron dose for long period (30~60 years), high temperature and high internal pressure is applied on the cladding material. Therefore irradiation creep strain is calculated based on paper of A. Boltax et al.[6].

$$\varepsilon_{\mathrm{irr}} = \mathrm{B}\sigma_{eff}^{n}\phi_{\mathrm{t}} + \mathrm{DS}_0\sigma_{\mathrm{e}} \qquad (6)$$

$$\mathrm{B} = (-2.9 + 9.5 * 10^{-3} * T) * 10^{-26}$$

Where $\varepsilon_{\mathrm{irr}}$ is irradiation effective creep strain, Φ_t is fast neutron fluence, σ_{eff} is effective stress, n is stress exponent (≒ 1.3), B is irradiation creep coefficient, D is swelling enhanced creep coefficient (= $6.1*10^{-6}$ MPa^{-1}) and S_0 is initial swelling (%), respectively.

2.5 Swelling

Swelling occurs when materials are subjected to neutron radiation. Because UCFR has high neutron dose (over 200dpa), cladding materials are subjected to severe swelling behavior.

In this paper, only swelling ratio of HT9 is evaluated. A form of the stress-free void swelling relationship that has received widespread usage is as follows:

$$\left(\frac{\Delta \mathrm{V}}{\mathrm{V}}\right) = \frac{V_f - V_0}{V_0} \cong (0.01R)[\phi_t + \frac{1}{\alpha}\ln(\frac{1+\exp[\alpha(\tau-\phi_t)]}{1+\exp(\alpha\tau)})] \qquad (7)$$

Where V_f is final specimen volume, V_0 is initial specimen volume, R is swelling rate parameter in units of % per 10^{22} n/cm^2 (E>0.1MeV), Φ_t is neutron fluence in units of 10^{22} n/cm^2 (E>0.1MeV), α is curvature parameter in units of (10^{22} n/cm^2)$^{-1}$and τ is incubation parameter in units of 10^{22} n/cm^2 (E>0.1MeV), respectively.

3. Parameters evaluation

Table. 1. Parameters of UCFR-1000 and UCFR-100 (*cladding temperature is 600°C and ** cladding temperature is 650°C)

	Thermal Strain (%)	Total Strain (%)	Swelling (%)
Design Criteria	< 1	< 3	< 5
UCFR-1000*	0.144	413	327
UCFR-1000**	0.347	482	280
UCFR-100	0.0708	126	225

4. Conclusion

Among the cases of UCFR-1000 (600℃ and 650°C) and UCFR-100 (600℃), thermal strains due to thermal creep meet the design criteria, 0.144, 0.347 and 0.0708, respectively. However, total strain which is sum of thermal strain and irradiation strain is far more than design criteria because of irradiation creep. Also, swelling of HT9 for each UCFR shows high swelling ratio.

5. References

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