Prediction of Fuel Cladding Performance for Ultra-long Cycle Fast Reactor Application

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INTRODUCTION

As a part of R&D activities for the development of advanced fast reactors, feasibility of the development of ultra-long cycle fast reactor (UCFR) based on the assessment of key technical issues is investigated. The concept for UCFR is designed to be operating without refueling during the total operation period, so the requirement for the fuel cladding such as creep rupture and swelling will be also more challenging. The total operation period of UCFRs is varied from 30 to 60 years, peak cladding temperature is 650℃ or higher, and the maximum neutron damage is 400dpa (displacement per atom) or higher depending on the specific design.

In this paper, several key design parameters for UCFR fuel cladding design including the internal pressure from fission gas release, irradiation creep and swelling are technically reviewed. In the later part of this paper, life prediction based on creep rupture is also discussed.

DESIGN PARAMETERS FOR UCFR FUEL CLADDING

Fission Gas Release

Considering the total operation period of UCFR which is 30 to 60 years, a large amount of fission gas is expected to be built up inside of fuel cladding. This may raise a several technical issues on the safety of the cladding. There are various equations to formulate and model the fission gas release (FGR) in various type of nuclear metallic fuels. Among them, GRSIS (Gas Release and Swelling in Isotropic fuel matrix) model [1] has been thoroughly assessed based on the detail high burn-up irradiation experiments. For this reason, GRSIS code is used for the analysis of FGR of metallic fuel in UCFR in this study. The formulation of FGR is given as follows:

$$\begin{aligned} FGR &= 0,\ S_t < S_{th} \\ &= f_{th}(C_{gb1}+C_{gb2}+C_{gb3}),\ S_t = S_{th} \\ &= C_{gb4},\ S_t < S_{th} \end{aligned} \qquad (1)$$

where S_t = total swelling
S_{th} = threshold swelling
f_{th} = fraction of closed bubbles to be open at the threshold closed bubble swelling
C_{gbi} = gas atom concentration as the bubble-i in the matrix (atoms/m^3)

Irradiation creep

The definition of irradiation creep is the difference in dimensional changes between a stressed and an unstressed sample irradiated under identical conditions. Also irradiation creep occurs when external non hydrostatic stresses are applied during irradiation. [2] And thermal creep is severe in materials that are subjected to heat for long periods, and near melting point. [3] This paper briefly summarizes especially with respect to their possible inter-correlation between irradiation creep and thermal creep. When applied to UCFR, high neutron dose by long refueling time, 30 years, and high temperature and pressure (near 400dpa, 600℃, 470MPa) can produce high irradiation creep as well as thermal creep. Therefore this part should be thoroughly examined and tested. The equation regarding irradiation creep strain is expressed as follows [4]:

$$\varepsilon_{irr} = B\sigma^{n}{}_{e}\phi t + DS_0\sigma_e \qquad (2)$$

where ε_{irr} = irradiation effective creep strain
Φt = fast neutron fluence (10^{22} n/cm^2)
σ_e = effective stress (MPa)
n = stress exponent(1.3)
B = irradiation creep coefficient($-2.9+9.5\times10^{-3}T(10^{-26}MPa^{-1.3}cm^2/n)$)
D = swelling enhanced creep coefficient($6.1(10^{-6}MPa^{-1})$)
S_0 = initial swelling(%)

Thermal creep

The thermal creep strain can be expressed as follows [5]:

$$\dot{\varepsilon}_t(\%/hr) = \frac{A}{kT}(\sigma-\sigma_0)^3 \exp\left(-\frac{Q}{kT}\right) \qquad (3)$$

where A = 7.385×10^{-3}, Q = 1.23eV
σ_0= -0.2185T+198.178 ksi
k = 8.63×10^{-5}eV/K

The total creep strain can be expressed as the sum of thermal creep strain and irradiation creep strain. In conclusion, the total creep equation is as follows:

$$\varepsilon_{tot} = B\sigma^{n}{}_{e}\phi t + DS_0\sigma_e + \int_0^t \frac{A}{kT}(\sigma-\sigma_0)^3 \exp\left(-\frac{Q}{kT}\right)dt \qquad (4)$$

Swelling

Swelling is mainly caused by the increase of volume and decrease of density of materials subjected to intense neutron radiation. UCFR's operation environment is high neutron dose (near 400dpa). It causes too serious problem in cladding material because of swelling. After the fluence threshold of 10^{22}n/cm^2 is attained, early experience characterized the increase in terms of an exponential rise [6]:

$$\left(\frac{\Delta V}{V}\right)_{swelling} \propto [\phi t]^n \quad (5)$$

where n is greater than unity.

A form of the stress-free void swelling relationship that has received widespread usage is as follows:

$$\left(\frac{\Delta V}{V}\right) = \frac{V_f - V_0}{V_0} \cong (0.01) R \left[\phi t + \frac{1}{\alpha} \ln\left(\frac{1+\exp\left[\alpha(\tau - \phi t)\right]}{1+\exp(\alpha\tau)} \right) \right] \quad (6)$$

where V_f = final specimen volume
V_0 = initial specimen volume
R = swelling rate parameter in units of % per 10^{22} n/cm^2 (E>0.1MeV)
Φt = neutron fluence in units of 10^{22} n/cm^2 (E>0.1MeV)
α = curvature parameter in units of (10^{22} n/cm^2)$^{-1}$
τ = incubation parameter in units of 10^{22} n/cm^2 (E>0.1MeV)

LIFE PREDICTION

Larson Miller Parameter

The Larson-Miller parameter [7] is a means of predicting the lifetime of material vs. time and temperature using a correlative approach based on the Arrhenius rate equation. The value of the parameter is usually expressed as *LMP=T(C + log t)* where *C* is a material specific constant often approximated as 20, *t* is the time in hours and *T* is the temperature in Kelvin.

Life prediction using LMP

Table 1 about life prediction has been derived based on ref. [8]. This experiment is taken effect at 700℃, 150MPa, 150dpa. In this environment, the best performance material is the PNC316. The PNC316 can endure over 30 years according to Table 1.

Table 1. Life prediction at 700℃, 150Mpa, 150dpa

Materials	Estimated stress rupture time (hour)
HT9	949.2694775
1.4914	36.57687327
EM12	463.4271789
FV448	9248.776303
PNC-FMS	57478.66602
PNC316	63095734.45

Life prediction using design parameters

Table 2 summarizes what design parameters calculate. Table 2 shows strength and deformation of the cladding on UCFR.

Table 2. Life prediction at 600℃, 30years, average fluence

	EBR-II FM Steel	UCFR FM Steel	UCFR ODS Steel	UCFR SiC/SiC$_f$ composite
Fraction of Fission Gas Release (%)	73%	73%	73%	73%
Internal Pressure (MPa)	19.48	37.58	37.58	37.58
Effective Stress (MPa)	169.87	468.84	468.84	468.84
Displacement Per Atom (dpa)	31	394.84	394.84	394.84
Thermal creep (%)	2.03	465.03	367.95	0.0077
Irradiation Creep (%)	1.07	101.85	14.80	4.15
Swelling (%)	3.43	81.03	5.20	< 0.36

CONCLUSIONS

In this study, key design parameters for the design of UCFR fuel cladding have been reviewed. Currently Table 2 shows reasonable value at 600℃, 30years, average fluence. As can be seen in Table 2, the SiC/SiC$_f$ composite is a material that meet the cladding design criteria. The more extreme environments, such as UCFR, SiC/SiC$_f$ composite is able to endure a lot better than the FM steels, ODS steels.

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