The Design Study of Fuel Cladding for Ultra long Cycle Fast Reactor

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1. Introduction

As a part of a Basic Atomic Energy Research Institute (BAERI) research program, we at UNIST are investigating the feasibility of key technical issues for the development of Ultra long Cycle Fast Reactor (UCFR). The refueling time of this type of reactor is at least 30 years, peak cladding temperature of this reactor is about 700℃, and the maximum dose of this reactor is about 200dpa (displacement per atom). The concept for UCFR is designed to be operating at higher temperature and neutron dose than other liquid metal-cooled fast reactors, so the requirement for the fuel cladding such as creep rupture and swelling will be also more challenging.

In this paper, several key design parameters for UCFR fuel cladding 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.

2. Design parameters for UCFR fuel cladding

2.1 Fission gas release

As a result of longer refueling time which is about 30 years, a large amount of fission gas is expected to be built up inside of the cladding. Therefore, internal pressure is increasing because of produced fission gas. This gives problem on the safety of the cladding. There are many equations to formulate and model fission gas release in various type of nuclear fuels. Among these, only MASSIH [1] have been assessed critically against detailed high burn-up experiments and irradiations. For this reason, one of them, MASSIH is the suitable for this reactor. The original MASSIH model begins by solving the gas-diffusion equation for constant production and properties in a spherical grain:

$$dC/dt = D(t)_{\Delta_r} C(r,t) + \beta(t) \quad [2]$$

with boundary conditions

$$C(r,0) = 0$$
$$C(a,t) = 0$$

where
C = gas concentration
β = gas production
$\triangle_r = d^2/dr^2 + 2/r \cdot d/dr$
D = diffusion constant
a = outside radius

2.2 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. [3] And thermal creep is severe in materials that are subjected to heat for long periods, and near melting point. [4] This paper briefly summarizes especially with respect to their possible intercorrelation 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 200dpa, 700℃, 200MPa) 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:

$$\varepsilon_{irr} = B\sigma^n{}_e \phi t + DS_0\sigma_e \quad [5]$$

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(%)

The thermal creep strain can be expressed as follows:

$$\dot{\varepsilon}_t(\%/hr) = \frac{A}{kT}(\sigma - \sigma_0)^3 \exp\left(-\frac{Q}{kT}\right) \quad [6]$$

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

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

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:

2.3 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 200dpa). 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, i.e.,

$$\left(\frac{\Delta V}{V}\right)_{swelling} \propto [\phi t]^n \quad [7]$$

where n is greater than unity. (In early correlations, the exponent n tended to increase from unity at 400℃ to nearly 2 at higher temperatures.)

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

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

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)

3. Life prediction

3.1 Larson Miller Parameter

The Larson-Miller parameter [8] 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.

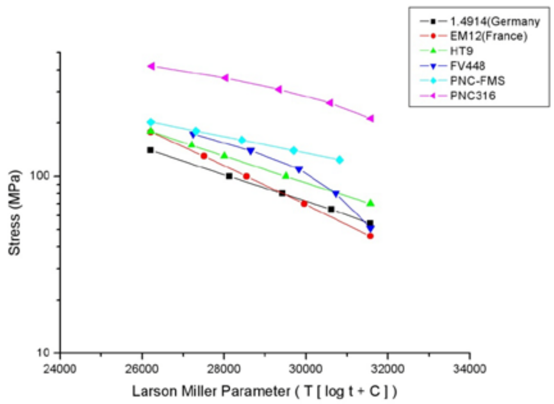

Fig. 1. The LMP of SFR cladding materials at 650℃, 150dpa. [9]

This Larson-Miller parameter is about several UCFR cladding candidate materials at 650℃, 150dpa. As a result, PNC316 shows the best performance at the environment in this graph.

3.2 Life prediction

Table I: 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

Table 1 about life prediction has been derived based on the result shown in Figure 1. 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 Figure 1.

4. Conclusions

In this study, key design parameters for the design of UCFR fuel cladding have been reviewed. Currently available models for internal pressure from fission gas release, irradiation creep and swelling are discussed. Also, the life prediction model based on Larson-miller parameter is applied to get the estimation for creep rupture time of candidate materials for fast reactor cladding materials

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