NE 533

Nuclear Fuel Performance

Spring 2022

Exam 3

7) $T = 625\,K$ $\quad t = 400\,d_y$ $\quad \delta = 500\,\mu m$

a) $$t^*(d) = 6.62\times10^{-7} \exp\left(\frac{11949}{T}\right) = 133\ d_{ys}$$

$$\delta^*(\mu m) = 5.1 \exp\left(\frac{-550}{T}\right) = 2.115\,\mu m$$

$$\delta(\mu m) = \delta^* + K_L\,(t - t^*)$$

$$K_L\,(\mu m/d) = 7.48\times10^{6} \exp\left(\frac{-12500}{T}\right) = 0.0154$$

$$\delta = 2.115 + 0.0154\,(400 - 133) = \underline{6.23\,\mu m}$$

b) $$C_H = \frac{2f\,\delta\,\rho_{ox}\,f^{\circ}_{ZrO_2}\,\frac{M_H}{M_O}}{\left(t - \frac{\delta}{PBR}\right)\rho_{metal}} \times 10^6$$

$$f^{\circ}_{ZrO_2} = \frac{32}{91+32} = 0.26$$

$$= \frac{2(0.18)(6.23)(5.68)(0.26)\,\frac{1}{16}}{\left(500 - \frac{6.23}{1.56}\right)(6.5)} \times 10^6$$

$$C_H = \underline{64\ \text{wt ppm}}$$

d) $\epsilon_{tot} = \epsilon_{th} + \epsilon_{D} + \epsilon_{SFP} + \epsilon_{GFP}$

$\dot{f} = 3.5\times10^{13}\ f/cm^3\text{-}s$ $\quad T = 1200K \quad T_{ref} = 300K \quad t = 85\ d$

$\Delta\rho_0 = 0.01 \quad \beta_D = 5\ MWd/kgU \quad \rho(UO_2) = 10.97\ g/cc \quad \alpha_{th} = 11\times10^{-6}\ 1/K$

$\beta = \frac{\dot{f}t}{N_u} \qquad N_u = 10.97\ g/cc \cdot \frac{1\ mol}{270\ g} \cdot \frac{6.022\times10^{23}\ at}{1\ mol} \cdot \frac{1\ U}{1\ UO_2} = 2.45\times10^{22}\ U/cc$

$\beta = \frac{(3.5\times10^{13})(85\times24\times3600)}{2.45\times10^{22}} = 0.0105\ FIMA$

$\beta_D = 5\ \frac{MWd}{kg} \cdot \frac{1}{950} = 0.0053\ FIMA$

$\epsilon_{th} = \Delta T\alpha = (11\times10^{-6})(1200-300) = 0.0099$

$\epsilon_D: \beta > \beta_D \rightarrow \epsilon_D = \Delta\rho_0 = -0.01$

$\epsilon_{SFP} = 5.577\times10^{-2}\rho\beta = (5.577\times10^{-2})(10.97)(0.0105) = 0.0064$

$\epsilon_{GFP} = (1.96\times10^{-28})\rho\beta(2800-T)^{11.73}\exp(-0.0162(2800-T))\exp(-17.8\rho\beta)$

$\epsilon_{GFP} = (3.63\times10^{7})(5.534\times10^{-12})(0.129)$

$\epsilon_{GFP} = 2.59\times10^{-5}$

$\epsilon_{tot} = 0.0099 - 0.01 + 0.0064 + 2.59\times10^{-5}$

$\boxed{\epsilon_{tot} = 0.0063}$

3) total creep

$$\epsilon = (\dot{\epsilon}_{ss} + \dot{\epsilon}_{ir})t$$

$\sigma_m = 200$ MPa $\quad T = 600K \quad LHR = 150$ W/cm $\quad t = 1.5$ yr

$$\dot{\epsilon}_{ss} = A_o \left(\frac{\sigma_m}{G}\right)^n \exp\left(\frac{-Q}{RT}\right)$$

$A_o = 3.14 \times 10^{24}$ 1/s $\quad G = 4.252 \times 10^{10} - 2.2185 \times 10^7 T$ Pa

$Q = 2.7 \times 10^5$ J/mol $\quad G = 29209$ MPa $\quad n = 5$

$$\dot{\epsilon}_{ss} = (3.14 \times 10^{24})\left(\frac{200}{29209}\right)^5 \exp\left(\frac{-2.7 \times 10^5}{600(8.314)}\right) = 1.47 \times 10^{-10} \text{ s}^{-1}$$

$$\dot{\epsilon}_{ir} = C_o \Phi^{C_1} \sigma_m^{C_2}$$

- assume RXA $\quad C_o = 1.654 \times 10^{-24}$

$C_1 = 0.85$

$C_2 = 1$

$$\Phi = (3 \times 10^{11})(LHR)$$
$$= 4.5 \times 10^{13} \text{ n/cm}^2\text{-s}$$

$$\dot{\epsilon}_{ir} = (1.654 \times 10^{-24})(4.5 \times 10^{13})^{0.85}(200)^1$$

$$\dot{\epsilon}_{ir} = 1.33 \times 10^{-10} \text{ s}^{-1}$$

$$\dot{\epsilon}_{tot} = 1.47 \times 10^{-10} + 1.33 \times 10^{-10} = 2.80 \times 10^{-10} \text{ s}^{-1}$$

$$t = 1.5 \text{ yr} = 4.73 \times 10^7 \text{ s}$$

$$\epsilon_{tot} = \dot{\epsilon}_{tot}\, t = \boxed{0.013} \qquad 1.3\%$$

4) soluble oxides, oxide precipitates, metallic precipitates, volatile gases, noble gases

5) Instead of utilizing burnup-based empirical models, utilize the underlying microstructure, state variable, property relationships to determine behavior/evolution.
Does not depend on the experimental envelope of data. Allows for more descriptive and predictive behavior of nuclear fuel performance.

6) neutron transparent
good compatibility w/ coolant and fuel
cheap and easy to fabricate
etc.

7) Zr has different solubilities in different phases which present under a temperature gradient in metallic fuels, leading to different concentrations radially. Additionally, Zr diffuses up the temperature gradient → Soret diffusion

8) MOX fuel contains Pu, leading to higher fission rates. MOX fuel is operated at higher powers, leading to higher temperatures. MOX fuel is utilized in SFRs with a sodium coolant. MOX undergoes restructuring into four zones with a central void. MOX is fabricated w/ a hypostoichiometric composition. MOX is operated to very high burnup.
etc.

9) Susceptible material - all Zr alloys are susceptible to SCC

Corrosive environment - volatile fission products are generated and diffuse to the fuel/clad interface, participating in corrosion

Sufficient stress - PCMI and the internal pressure of the cladding exert a stress that is lower than σ_y

Sufficient time - cladding in LWRs operates for up to 2 years, providing ample time for diffusion of FPs to fuel/clad interface and stress build up

10) Temperature ramps or transients can increase the pressure of fission gas bubbles, potentially leading to fracture. Phase-field modeling is targeting fracture stresses dependent upon the bubble pressures and morphologies to predict pulverization.

11) RIA occurs very quickly and a LOCA occurs over a longer time. RIA can induce rapid swelling, pulverization, cladding burst and fuel dispersal. LOCA is associated with large plastic deformations and breakaway oxidation.

Control rod ejection accident (CREA) is a type of RIA.

12) - improved oxidation resistance (a)
- improved fuel properties (b)
- improved cladding properties (c)
- improved fission product retention (d)

FeCrAl cladding (a, c)

Cr-doped (b, d) etc.

U_3Si_2 (b)

SiC cladding (a, c)

13) PCMI, cladding elongation / assembly bow, cladding wear, oxidation, power to melt, internal cladding pressure, DNBR, operator limits