Cole Manfred, NE 533 Exam 3

1. Total change in fuel volume

$\alpha_{th} = 10\times10^{-6}$ 1/K, $\dot{F} = 6\times10^{13}$ fiz/cm$^3\cdot$s, $T_F = 1600K$

$T_{ref} = 500K$, $\Delta P_0 = 0.015$, $B_D = 5$ MWD/kgU $= 0.005$ FIMA

$\rho_{UO_2} = 10.97$ g/cm^3, $t = 300$ days

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_D + \varepsilon_{sfp} + \varepsilon_{gfp}$$

$$\varepsilon_{th} = \alpha\Delta T = 10\times10^{-6}(1600-500) = \boxed{0.011}$$

$$\varepsilon_D = \Delta P_0\left(\exp\left[\frac{B\ln(0.01)}{C_D\, B_D}\right]-1\right)$$

$$B = \frac{\dot{F}t}{N_U}, \quad N_U = \frac{10.97\,g}{cm^3}\times\frac{1\,mol}{270\,g}\times\frac{6.022\times10^{23}\,atoms}{1\,mol}\times\frac{1U}{1UO_2}$$

$$N_U = 2.45\times10^{22}\ U/cm^3$$

$$B = \frac{(6\times10^{13})(300\times24\times3600)}{2.45\times10^{22}} = 0.0636\ FIMA$$

$C_D = 1.0$

$$\varepsilon_D = 0.015\left(\exp\left[\frac{0.0636\ln(0.01)}{0.005\,(1.0)}\right]-1\right)$$

$$\boxed{\varepsilon_D = -0.015}$$

$$\varepsilon_{sfp} = 5.577\times10^{-2}\rho B = 5.577\times10^{-2}(10.97)(0.0636)$$

$$\varepsilon_{sfp} = 0.039$$

$$\varepsilon_{gfp} = 1.96\times10^{-28}\rho B(2800-T)^{11.73}\exp[-0.0162(2800-T)]\exp[-17.8\rho B]$$

$$\varepsilon_{gfp} = 2.64\times10^{-6}$$

$$\boxed{\varepsilon_{tot} = +0.035}$$

2. Total creep, RXA, $\sigma_m = 85$ MPa, $T = 650$ K, LHR $= 200$ W/cm, $t = 200$ days

$A_0 = 3.14 \times 10^{24}$, $n = 5$, $Q = 2.7 \times 10^5$, $C_0 = 1.654 \times 10^{-24}$

$C_1 = 0.85$, $C_2 = 1$

Thermal: $\dot{\varepsilon}_{ss} = A_0 (\sigma_m / G)^n \exp[-Q/RT]$

$G = 4.2519 \times 10^{10} - 2.2185 \times 10^7 T \rightarrow 2.81 \times 10^{10}$ Pa

$$\dot{\varepsilon}_{ss} = (3.14 \times 10^{24}) \left(85 / 2.81 \times 10^4 \right)^5 \exp\left[\frac{-(2.7 \times 10^5)}{8.3144 \times 650}\right]$$

$$\boxed{\dot{\varepsilon}_{ss} = 1.597 \times 10^{-10}}$$

Irradiation: $\dot{\varepsilon}_{ir} = C_0 \phi^{C_1} \sigma_m^{C_2}$

$\phi = 3 \times 10^{11} \times \text{LHR} \rightarrow 6 \times 10^{13}$ n/cm$^2 \cdot$s

$$\dot{\varepsilon}_{ir} = (1.654 \times 10^{-24})(6 \times 10^{13})^{0.85} (85)^1 = 7.234 \times 10^{-11}$$

$$\varepsilon_{tot} = (\dot{\varepsilon}_{ss} + \dot{\varepsilon}_{ir})\, t = (2.32 \times 10^{-10})(200 \times 24 \times 3600)$$

$$\boxed{\varepsilon_{tot} = 0.004}$$

3. $t = 60$ days, $T = 1500K$, $\dot{F} = 3\times10^{13}$ fiz/cm^3·s

$a_1 = 10$ um, $a_2 = 25$ um, In-Pile

$\tau = Dt/a^2 \qquad D = D_1 + D_2 + D_3$

$D_1 = 7.6\times10^{-6} \exp[-3.03/k_bT] \rightarrow 5.017\times10^{-16}$

$D_2 = 1.41\times10^{-18} \exp\left[\frac{-1.19}{k_bT}\right]\sqrt{\dot{F}} \rightarrow 7.754\times10^{-16}$

$D_3 = 2.0\times10^{-30}\ \dot{F} \rightarrow 6\times10^{-17}$

$D = 1.337\times10^{-15}$

$\tau_1 = \frac{Dt}{a_1^2} = 0.007 < \pi^{-2}$ / 0.101

$\tau_2 = \frac{Dt}{a_2^2} = 0.0011 < \pi^{-2}$

$f_1 = 4\sqrt{\frac{Dt}{\pi a_1^2}} - \frac{3}{2}\frac{Dt}{a_1^2}$ / $a_1 = 10\times10^{-4}$ cm

$f_1 = 0.177 \rightarrow$ 17.7% FGR

$f_2 = 4\sqrt{\frac{Dt}{\pi a_2^2}} - \frac{3}{2}\frac{Dt}{a_2^2}$ / $a_2 = 25\times10^{-4}$ cm

$f_2 = 0.073 \rightarrow$ 7.3% FGR

4. Typical charge state of U in UO_2 is +4. Liberation of oxygen from fission and the production of fuel products can cause the valence state of uranium to change to preserve localized charge
5. Oxygen concentration changes across pellet as the free energy of oxygen changes w/ burnup, composition, temperature, etc. The concentration increases toward the rim. Mo/MoO_2 reaction is a limiting reaction that holds the oxygen potential constant, serves as a bound on oxidation
6. Properties that change with stochiometry in UO_2 include thermal conductivity, melting point, and lattice parameter
7. 5 types of fission products
   - Soluble oxide - decrease thermal conductivity
   - Insoluble oxides - can increase or decrease thermal conductivity
   - Metals - usually slightly increase conductivity
   - Volatile gases - degrade gap conductance, increase plenum pressure, corrode cladding
   - Noble gases - degrade gap conductance

8. Stages of fission gas release

a) Gas diffuses to grain boundaries

b) Gas bubbles nucleate at grain boundaries

c) Bubbles form interconnected network for gas transport

9. Creep is the time-dependent relaxation of residual stress in the form of plastic deformation.

A mechanism of creep is Nabarro-Herring, otherwise known as bulk diffusion creep. Noticeable at high temperatures.

10. Benefits of Zr cladding

- Low neutron cross-section
- Cheap
- Good thermal conductivity

11. Irradiation growth of Zr from point defects

- Interstitial loops form on prismatic planes, increasing a-parameter and reducing c-parameter
- Vacancy loops form later on basal planes, further reducing c-parameter.
- Result is anisotropic irradiation growth

12. Creep starts off strong before going to a constant rate (channel cleaning), last stage is breakaway creep where vacancy loops form

13. 4 conditions of SCC

- Corrosive environment - composition of gas in rod changes w/ fission over time, ZrI_4 type species
- Sufficient stress - PCI begins w/ pellet cladding contact, creates stress in cladding especially at stress concentraters.
- Susceptible material - all Zircaloy is susceptible
- Time - there is an incubation period required for all SCC conditions to be met

14. Iodine is formed as a fission product. Once released, it wants to pair with Zr cladding. However, oxygen has a higher affinity for Zr, and forms ZrO_2 instead. This releases the iodine to form more gaseous Zr - I species that degrade the cladding.