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

$\alpha_{th} = 10\times10^{-6}\ 1/K$ $\quad \dot{F} = 6\times10^{13}\ \frac{fiss}{cm^3 \cdot s}$ $\quad T_f : 1600K$ $\quad T_{ref} : 500K$

$\Delta\rho_0 = 0.015$ $\quad B_D : 5\ MWD/kgU$ $\quad \rho = 10.97\ g/cc$ $\quad t = 300\ days$

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

$\epsilon_D = \Delta\rho_0\left[\exp\left(\frac{\beta \ln 0.01}{C_D B_D}\right) - 1\right]$ $\qquad \beta = \frac{\dot{F}t}{N_U}$

$N_U = 10.97 \frac{1}{270} \frac{6.022\times10^{23}}{1\ mol} \frac{1U}{1UO_2}$

$= 2.45\times10^{22}\ U/cc$

$\beta = \frac{(6\times10^{13})(300\times24\times3600)}{2.447\times10^{22}}$

$\beta = 0.064$

$B_D = 5\ MWD/kgU \rightarrow 0.005$ $\qquad \beta > B_D \left(\epsilon_D = -0.015 \right)$

$\epsilon_{SFP} = 5.577\times10^{-2}\rho\beta = (5.577\times10^{-2})(10.97)(0.064) = 0.039$

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

$\rho\beta = 0.697$

$\epsilon_{GFP} = 2.65\times10^{-4}$

$\epsilon_{tot} = 0.011 - 0.015 + 0.039 + 2.65\times10^{-4} = \boxed{0.035}$

$\boxed{3.5\%}$

2) Total creep

$\sigma_m = 85 \text{ MPa} \quad T = 650 \text{ K} \quad LHR = 200 \text{ W/cm} \quad t = 200 \text{ dy}$

$$\dot{\epsilon}_{tot} = \dot{\epsilon}_{ss} + \dot{\epsilon}_{irr}$$

$$\dot{\epsilon}_{ss} = A_0 \left(\frac{\sigma_m}{G}\right)^n \exp\left(\frac{-Q}{RT}\right)$$

$A_0 = 3.14 \times 10^{24} \text{ 1/s}$

$G = 4.2519 \times 10^{10} - 2.2185 \times 10^{7} (650)$

$G = 2.81 \times 10^{10} \text{ Pa} = 28099 \text{ MPa}$

$Q = 2.7 \times 10^5 \quad n = 5$

$$\dot{\epsilon}_{ss} = (3.14 \times 10^{24}) \left(\frac{85}{28099}\right)^5 \exp\left(\frac{-2.7 \times 10^5}{8.3145 (650)}\right) = 1.598 \times 10^{-10} \text{ 1/s}$$

$$\dot{\epsilon}_{irr} = C_0 \Phi^{C_1} \sigma_m^{C_2}$$

$C_0 = 1.054 \times 10^{-24}$

$C_1 = 0.85$

$C_2 = 1$

$\Phi = 3 \times 10^{11} (200)$

$= 600 \times 10^{11}$

$$= (1.054 \times 10^{-24})(600 \times 10^{11})^{0.85} (85)^1$$

$$\dot{\epsilon}_{irr} = 7.234 \times 10^{-11} \text{ 1/s}$$

$$\dot{\epsilon}_{tot} = 2.321 \times 10^{-10} \text{ 1/s}$$

$$\epsilon = \dot{\epsilon}_{tot}\, t = (2.321 \times 10^{-10})(200 \times 24 \times 3600)$$

$$= 0.004 \rightarrow \boxed{0.4\%}$$

3) $T = 1800\ K$ $t = 60\ dy$ $\dot{F} = 3\times10^{13}\ fiss/cm^3\cdot s$

$a_1 = 10\ \mu m$ $a_2 = 25\ \mu m$

$f = ?$

$\tau = \frac{Dt}{a^2}$

$D = D_1 + D_2 + D_3$

$D_1 = 7.6\times10^{-6}\ \exp\left(\frac{-3.03}{kT}\right) = 5.0167\times10^{-14}\ cm^2/s$

$D_2 = 1.41\times10^{-18}\ \exp\left(\frac{-1.19}{kT}\right)\sqrt{3\times10^{13}} = 7.754\times10^{-16}\ cm^2/s$

$D_3 = 2\times10^{-30}\left(3\times10^{13}\right) = 6\times10^{-17}\ cm^2/s$

$D = 1.337\times10^{-15}\ cm^2/s$

$$\tau_1 = \frac{(1.337\times10^{-15})(60\times24\times3600)}{(10\times10^{-4})^2} = 0.0069$$

$$\tau_2 = \frac{(1.337\times10^{-15})(60\times24\times3600)}{(25\times10^{-4})^2} = 0.0011$$

$\tau_2 < \tau_1 < \pi^{-1}$

$$f = 4\sqrt{\frac{\tau}{\pi}} - \frac{3}{2}\tau$$

$$f_1 = 4\sqrt{\frac{0.0069}{\pi}} - \frac{3}{2}(0.0069) = 0.177 \rightarrow \boxed{17.7\%}$$

$$f_2 = 4\sqrt{\frac{0.0011}{\pi}} - \frac{3}{2}(0.0011) = 0.073 \quad \boxed{7.3\%}$$

4) U^{+4}. Oxygen defects or the incorporation of 3+ transition metals into the fluorite structure causes charge state changes.

5) Oxygen concentration goes up versus time/burnup, and the oxygen potential reaches a maximum when the Mo/MoO_2 reaction starts to take place. Thus, Mo acts as a buffer or cap on the oxygen potential in the fuel. The oxygen potential decreases near the periphery of the fuel due to oxygen uptake by the Zr cladding.

6) lattice constant, thermal conductivity, oxygen diffusion

7) soluble oxides: go into fluorite lattice, cause swelling and decrease K_{th}
insoluble oxides: form oxide precipitates, cause swelling, decrease K_{th}
noble metals: form metallic precipitates, increase K_{th}

volatile gases: form gas bubbles, swelling, form corrosive environment for SCC
noble gases: form gas bubbles, swelling, decrease K_{th}

12b) • Initially have high coolant pressure which causes creep down of the cladding. Decrease in cladding radius leads to an increase in the cladding length.

• Partial contact due to creep down. Where contact is made, pellet exerts outward force on cladding, causing radial increase and axial shrinkage. Pellet also exerts axial force, causing local elongation. Where no contact, still have creep down due to coolant pressure.

• Full contact of fuel and cladding. Fuel exerting radial and axial forces, leading to axial shortening and elongation, respectively. Results in a net axial shrinkage of cladding.

9) Permanent deformation due to a stress which is below the yield stress. Occurs over time.

Nabarro-Herring, point defect diffusion.

10) neutron transparent, cheap, good K_{th}

11) Interstitials want to cluster on pyramidal faces of the HCP lattice. This causes an expansion in 'a' and a contraction in 'c'. With enough dose, vacancies cluster preferentially on basal plane, causing further shrinkage in the 'c' axis.

8) 1) Fission gas is produced and diffuses towards the grain boundaries.

2) G.B gas bubbles form and begin to grow and coalesce

3) Interconnected tunnels of gas bubbles form along grain edges, where these tunnels reach a free surface gas is released.

13) Corrosive environment

- volatile fission products diffuse down the temperature gradient and accumulate at the fuel/cladding interface. These FPs can undergo corrosive reactions w/ the Zr cladding

Susceptible material

- all Zr alloys are susceptible to SCC. Slight modifications in alloying species can reduce, but not eliminate, this susceptibility

Sufficient stress

- stress is induced by pellet swelling, exerting an outward push on the cladding leading to large hoop tensile stresses. Pellet cracks or missing surfaces can increase the local stress.

Sufficient time

- SCC requires the buildup of corrosive fission products as well as the breaking of a protective ZrO_2 layer that forms on the inside of the cladding.

14) Iodine can form ZrI_y compounds with the bare cladding. This gaseous species diffuses up the temperature gradient, it is then converted into $ZrO_2 + I_2$. The ZrO_2 deposits on the crack sides, the I_2 is free to interact w/ Zr metal to continue the corrosive reaction.