1.) a.) oxide thickness?

Givens

$T = 625\,K$

$t = 400$ days

$x = 500\,\mu m$

$PBR = 1.56$

$\rho_{ZrO_2} = 5.68\,g/cc$

$\rho_{Zr} = 6.5\,g/cc$

$$t^{*}(d) = 6.62e\text{-}7 \exp\left(\frac{11949}{625}\right)$$

$$t^{*} = 133.15 \text{ days}$$

$$\approx 133 \text{ days}$$

$$t > t^{*}$$

$$\Rightarrow \delta^{*}(\mu m) = 5.1 \exp\left(\frac{-550}{625}\right)$$

$$\delta^{*} = 2.12$$

$$\Rightarrow \delta(\mu m) = \delta^{*} + K_L (t - t^{*})$$

$$K_L = 7.48e\text{-}6 \exp\left(\frac{-12500}{625}\right)$$

$$K_L = 1.54e\text{-}14$$

$$\delta = 2.12 + 1.54e\text{-}14(400 - 133)$$

$$\boxed{\delta = 2.12}$$

b.) H PPM after 1 year?

$$C_H = \frac{2 f \delta \rho_{ZrO_2} \left(\frac{M_H}{M_O}\right)}{\left(x - \frac{\delta}{PBR}\right) \rho_{Zr}}$$

$$C_H = \frac{2(0.18)(2.12)(5.68)\left(\frac{1}{16}\right)}{\left(500 - \frac{2.12}{1.56}\right)(6.5)} \times 10^{6}$$

$$\boxed{C_H = 83.6 \text{ wt. PPM}}$$

2.) Total fuel vol change?

Givens

$\alpha_{th} = 11e\text{-}6$

$\dot{f} = 3.5e13 \ \frac{\text{fission}}{cm^3 s}$

$T = 1200\ K$

$T_{ref} = 300\ K$

$D\rho_0 = 0.01$

$\beta_D = 5 \ \frac{MWD}{KgU}$

$\rho_{UO_2} = 10.97 \ g/cc$

$t = 85$ days

$$\Rightarrow \beta = \frac{\dot{f} t}{N_U}$$

$$N_U = 2.45e22 \ U/cc$$

$$\beta = \frac{(3.5e13)(7.34e6)}{2.45e22}$$

$$\beta = 0.0105 \ \text{FIMA}$$

$$\Rightarrow \epsilon_{th} = \alpha_{th} \Delta T$$

$$\epsilon_{th} = 11e\text{-}6(1200-300)$$

$$\epsilon_{th} = 0.0099$$

$$\Rightarrow \epsilon_D = \Delta\rho_0 \left[\exp \frac{\beta \ln(0.01)}{C_D \beta_0} - 1 \right]$$

$$\beta_0 = 5 \frac{MWD}{KgU} \cdot \frac{1}{950} = 0.0053 \ \text{FIMA}$$

$$\epsilon_D = 0.01 \left[\exp \frac{0.0105 \ln(0.01)}{1(0.0053)} - 1 \right]$$

$$\epsilon_D = -0.0099$$

$$\Rightarrow \epsilon_{SFP} = 5.577e\text{-}2 \rho \beta$$

$$= (5.577e\text{-}2)(10.97)(0.0105)$$

$$\epsilon_{SFP} = 0.0064$$

$$\Rightarrow \epsilon_{GFP} = 1.96e\text{-}28 \rho \beta (2800-T)^{11.3} \exp(-0.0162(2800-T)) \exp(-17.8 \rho \beta)$$

$$= (1.96e\text{-}28)(10.97)(0.0105)(2800-1300)^{11.3} \exp(-0.0162(2800-1300)) \exp(-17.8 \cdot 10.97 \cdot 0.0105)$$

$$\epsilon_{GFP} = 6.107e\text{-}13$$

$$\Rightarrow \epsilon_{tot} = \epsilon_{th} + \epsilon_D + \epsilon_{SFP} + \epsilon_{GFP}$$

$$\epsilon_{tot} = 0.0099 - 0.0099 + 0.0064 + 6.107e\text{-}13$$

$$\boxed{\epsilon_{tot} = 0.0064}$$

3.) Zr Creep?

Givens

$\sigma_m = 200\,MPa$

$T = 600\,K$

$LHR = 150\ W/cm$

$t = 1.5\ yrs$

$n = 5$

$A_0 = 4e\text{-}24\ s^{-1}$

$Q = 2.7e5\ J/mol$

$$\Rightarrow G = (4.1e10) - (2.3e7)\,T \quad (Pa)$$

$$G = 2.72e4$$

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

$$\dot{\epsilon}_{ss} = (4e\text{-}24)\left(\frac{200}{2.72e4}\right)^5 \exp\left(\frac{-2.7e5}{8.314 \cdot 600}\right)$$

$$\dot{\epsilon}_{ss} = 2.68e\text{-}58\ s^{-1}$$

$$\Rightarrow \dot{\epsilon}_{ir} = C_0\, \Phi^{C_1}\, \sigma_m^{C_2}$$

$$\Phi = 3e11\ LHR = 4.5e13$$

$$\dot{\epsilon}_{ir} = (2.714e\text{-}24)(4.5e13)^{0.85}(200)^1$$

$$\dot{\epsilon}_{ir} = 2.19e\text{-}10\ s^{-1}$$

$$\Rightarrow \dot{\epsilon}_{tot} = \dot{\epsilon}_{ss} + \dot{\epsilon}_{ir}$$

$$\dot{\epsilon}_{tot} = 2.68e\text{-}58 + 2.19e\text{-}10$$

$$\dot{\epsilon}_{tot} = 2.19e\text{-}10$$

$$\epsilon_{tot} = \dot{\epsilon}_{tot}\, t$$

$$\epsilon_{tot} = (2.19e\text{-}10)(4.73e7)$$

$$\boxed{\epsilon_{tot} = 0.0104 = 1.04\%}$$

4.) 1. Soluble Oxides
2. Insoluble Oxides
3. Metals
4. Volatiles
5. Noble Gases

5.) Microstructure modeling:
Utilizes material microstructure relationships that are functions of state variables and fuel conditions to determine material properties of fuel and cladding

Has the potential to provide a more predictive fuel performance capability

6.) 1. Low neutron x-section
2. Good thermal conductivity
3. Affordable Cost

7.) Zr diffuses via Soret diffusion up the temperature gradient, and Zr also has different solubilities in U phases, leading to distinct zones of Zr content in radial rings

8.) MOX has different neutronics, fission gas release, thermal conductivity, etc.
Designed to operate at much higher LHR

9.) 1. Corrosive environment
2. Susceptible material
3. Sufficient stress
4. Sufficient time

Process of PCI involves combination of high internal mechanical stress in the cladding and a corrosive environment resulting from volatile fission products accumulating in fuel-clad gap

10.) Can occur during LOCA transients
Phase-field modeling being used to account for effects of surface tension and gas bubble pressure

11.) RIA - dependent upon control rod insertion/ejection
LOCA - coolant flow reduced or lost altogether
RIA example - Chernobyl

12.) 1. Improved Fuel properties
2. Improved Cladding Properties
Cladding coating/liner

13.) 1. PCMI
2. Cladding Oxidation and Hydrogen Pickup