Exam 2: NE33: Nuclear Fuel Performance

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1. Consider a fuel rod with a pellet radius of 4.5 mm that is experiencing a linear heat rate of 250 W/cm.
    a. What is the maximum stress experienced by the pellet, assuming that the fuel has k = 0.1 W/cm-K, E = 290 GPa, ν = 0.3, and α = 8.2e-6 1/K? (10 pts)
    b. Given $\sigma_{fracture}$=120 MPa, how far do cracks extend into the fuel? (4 pts)

(1)

$$\Delta T = \frac{QR_f^2}{4k} = \frac{250 \frac{W}{cm} (0.45cm)^2}{4 \cdot 0.1 \frac{W}{cmK}} = 121.5°K$$

$$\sigma^* = \frac{\alpha E \Delta T}{4(1-\nu)} = \frac{8.2 \cdot 10^{-6} \frac{1}{K} \cdot 2.9 \cdot 10^5 MPa \cdot 121.5 K}{4\ (1-0.3)}$$

$$\sigma^* = 103.2\ MPa$$

$$\text{for } r=1\ \sigma_\theta = -\sigma^* (1-3) = \boxed{206.4\ MPa}$$

(b) $$r = \left(\left(1+\frac{\sigma_{fr}}{\sigma^*}\right)/3\right)^{1/2} = \left(\left(1+\frac{120}{103.2}\right)/3\right)^{1/2} = 0.849$$

$$r_{fracture} = 0.849 \cdot R_F = 0.38 cm$$

2. Consider the stress state in a zircaloy-clad fuel rod pressurized to 50 MPa with an average radius of 5.4 mm and a cladding thickness of 1.2 mm.
    a. Calculate all three components of the stress using the thin-walled cylinder approximation. (4 pts)
    b. Calculate all three components of the stress at r=5.6 mm assuming a thick-walled cylinder. (6 pts)
    c. Calculate the maximum strain, with the stress components from (b) and with E=180 GPa and ν=0.28. (4 pts)

(2)

(a) Thin walled

$\bar{\sigma}_\theta = \frac{PR}{\delta}$ $\bar{\theta}_z = \frac{PR}{2\delta}$ $\bar{\sigma}_r = -\frac{1}{2}P$

$\bar{\sigma}_\theta = \frac{50\text{ MPa}\cdot 0.54\text{cm}}{0.12\text{cm}} = 225\text{ MPa}$

$\bar{\sigma}_z = \frac{50\cdot 0.54}{2\cdot 0.12} = 450\text{ MPa}$

$\bar{\sigma}_r = \frac{-50}{2} = -25\text{ MPa}$

(b)

$\sigma_{rr} = -P\frac{(R_o/r)^2-1}{(R_o/R_i)^2-1} = -50\frac{(6/5.6)^2-1}{(6/4.8)^2-1} = -13.15\text{ MPa}$

$\sigma_{\theta\theta} = P\frac{(R_o/r)^2+1}{(R_o/R_i)^2-1} = 6.58\text{ MPa}$

$\sigma_{zz} = \frac{P}{(R_o/R_i)^2-1} = 337\text{ MPa}$

(c)

[redacted]

2 c $\varepsilon = \frac{E}{\sigma} = \frac{180}{0.337} = \boxed{540}$

3. Calculate the change in the gap thickness due to thermal expansion. Only perform one adjustment to the gap thickness. $R_f = 0.52$ cm. $t_{gap} = 0.005$ cm, $T_{CO} = 550$ K, $t_{clad} = 0.08$ cm, $k_{fuel} = 0.05$ W/cm-K, $k_{gap} = 0.003$ W/cm-K, $k_{clad} = 0.15$ W/cm-K, LHR = 225 W/cm, $\alpha_c = 4.5\times10^{-6}$ 1/K, $\alpha_f = 15\times10^{-6}$ 1/K, T_{ref}(fuel=clad) = 300 K. (16 pts)

(3)

$$\Delta T_{ci} = \frac{LHR\, t_{clad}}{2\pi R_f\, k_{clad}} = \frac{225\cdot 0.08}{2\pi\cdot 0.52\cdot 0.15} = 36.73°K$$

$$T_{ci} = 586.73°K$$

$$T_s = T_{ci} + \frac{LHR\cdot t_g}{2\pi R_F\cdot k_g} = 586.73 + \frac{225\cdot t_g}{2\cdot\pi\cdot 0.52\cdot 0.003} = 701.51$$

$$T_o = \frac{LHR}{4\pi k_f} + T_s = \frac{225}{4\pi\cdot 0.05} + 701.51 = 1059°K$$

$$R_c = R_F + t_g + t_c/2 = 0.565\,cm$$

$$\Delta t_c = 0.565\cdot(4.5\cdot10^{-6})(550-300) = 6.35\cdot10^{-4}\,cm$$

$$\Delta t_f = 0.52\cdot(15\cdot10^{-6})\cdot(701.51-300) = 3.128\cdot10^{-3}\,cm$$

$$t_{gap} = 0.005 + 6.35\cdot10^{-4} - 3.128\cdot10^{-3} = \boxed{0.00251\ cm}$$

4. A fuel pellet with an average grain size of 8 microns is irradiated with a volumetric neutron flux of 2.0e13 fissions/(cm^3-s). Assume the diffusion coefficient is $2x10^{-15}$ cm^2/s. How many gas atoms/cm^3 are released from the fuel after 2 years of irradiation? Assume the yield = 0.3017. (12 pts)

4.)

$t = 365 \cdot 24 \cdot 3600 = 31536000$ s/yr $\quad D = 2 \cdot 10^{-15}$ cm^2/s

$a = 8 \cdot 10^{-4}$ cm $\quad \phi = 2 \cdot 10^{13}$ $Y = 0.3017$

$$\tau = \frac{D \cdot t}{a^2} = 7.10 \cdot 10^{-32} > \pi^{-2}$$

$$f = 1 - \frac{0.0662}{\tau}\left(1 - 0.93 e^{-\pi^2 \tau}\right) \simeq 1$$

$$\dot{F} = N^{235} \cdot \phi \cdot \sigma_F V$$

$$V = \frac{\pi}{6}(a)^3 = 2.68 \cdot 10^{-10} cm^3$$

$$\dot{F} = 2.5 \cdot 10^{22} \#/cm^3 \cdot 2 \cdot 10^{13} \cdot 550 \cdot 10^{-24} \cdot 2.68 \cdot 10^{-10} = 73722 f/s$$

$$G = Y \cdot \dot{F} \cdot t = 5.05 \cdot 10^{15}$$

$$g_{released} = G \cdot f = \boxed{5.05 \cdot 10^{15}}$$

5. Define strain hardening. What causes strain hardening? (8 pts)

   A change in the yield stress caused by an applied stress that exceeds the previous yield stress.

6. Name three properties that vary as a function of stoichiometry in UO2. (6 pts)

   The density, thermal conductivity, and melting point.

7. What three things must all fuel performance codes be able to do? (6 pts)

   Numerically model the temperature in the fuel, model the stress in the cladding, consider gap pressure, closure, and heat transfer in some way

8. List the three stages of fission gas release. (9 pts)

   1 Gas production and diffusion to the grain boundaries.
   2 Gas bubbles nucleate on grain boundaries, growing and interconnecting.
   3 Gas travels through interconnected bubbles to a free surface.

9. What performance effects result from the High Burnup Structure? (6 pts)
   instability of the crystalline structure, increased porosity.

10. Provide an example of a 0-D defect. Provide an example of a 3-D defect. (4 pts)
    0D: – Interstitial impurity atoms 3D: Pores.

11. What is the driving force for fuel densification? What is the driving force for grain growth (6 pts)
    Fuel Densification: The change in free energy from the decrease in surface area of pores and lowering of the surface free energy
    Grain Growth: The reduction of the grain boundary energy

12. What is the valence state of U in UO2? What are the possible valence states of U? (4 pts)
    UO_2: U^{4+}
    Possible: U^{4+} U^{5+} U^{6+}