Exam 3: NE591-10: Nuclear Fuel Performance

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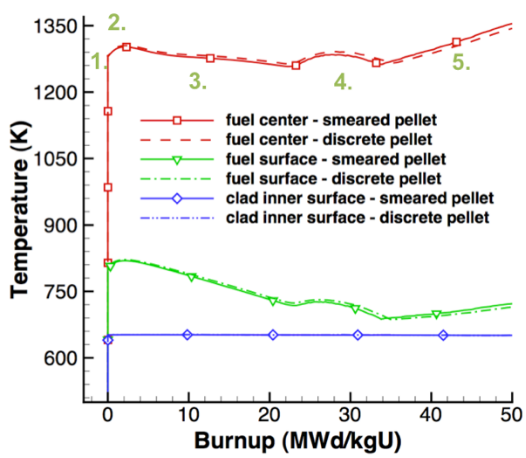
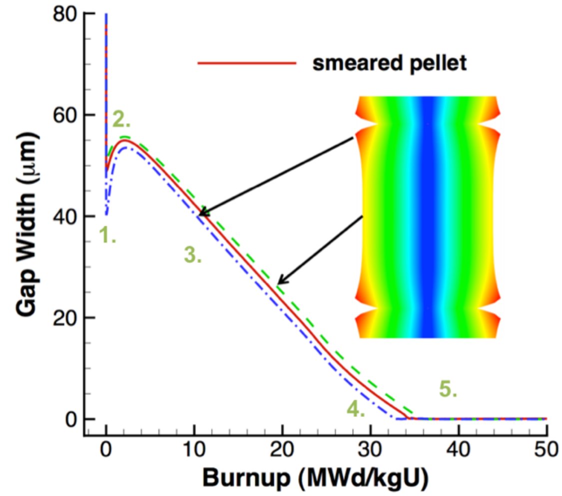
1. The temperature and gap width of a fuel pellet, as predicted by a fuel performance code, is shown below. Using the plots as your guide, determine what is currently occurring within the cladding, gap and/or pellet at each number. Note that the numbers are at the same burnups on the two plots. (15 pts)





For each number (1-5), describe what is occurring in the cladding, gap, and pellet. Also, describe what features in the plots indicated these behaviors.

1: In the pellet, the heat generated in the pellet. Denification of the pellet happening, fission product product and fission gas produced, which will cause the fuel swelling that is why Temperature increase and gap decrease

2. After certain burn and usage of the fuel, the heat generated decrease. Also since the fission gas release from fuel, which cause the gap width increase. Also fracture may be happen in the fuel it also will accelerat fission gas release

3. As the useage of fuel increase, and fission product produce and interact with Zr, which cause the producing a low thermal conductivity material, which cause the temperature a little bit decrease solid fission product cause the sweelig

5. clad and fuel fully connect with each other, ⇒ large T increase

2. 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 pellet is at a uniform temperature of 900°C.

a) What is the fission gas diffusion coefficient at this temperature? (5 pts)

$a = 8\mu m = 8\times10^{-4}$ um $\quad \phi = 2.0\times10^{13}$ fission /(cm^3-s) $\quad T = (900+273.15)\,K = 1173.15$

$N_u = N_{UO_2} = \frac{N_a \delta_u}{(238+2\times16)} = \frac{10.97\times6.022\times10^{23}}{270}$ atom/cm^3 $= 2.4467\times10^{22}$ atom/cm^3

$\dot{F} = q N_u \sigma_{f\text{-}235}\,\phi = 5\% \times 2.4467\times10^{22}$ atom/cm^3 $\times 5.5\times10^{-22}\,cm^2 \times 2.0\times10^{13}$ fission /(cm^3-s) $= 1.35\times10^{13}$ fission/(cm^3-s)

$D_1 = 7.6\times10^{-6}\,e^{-3.03eV/k_BT} = 7.3706\times10^{-19}$

$D_2 = 1.41\times10^{-18}\,e^{-1.19eV/k_BT} = 4.0137\times10^{-17}$

$D_3 = 2.0\times10^{-30}\dot{F} = 2.7\times10^{-17}$

$D = D_1 + D_2 + D_3 = 6.7874\times10^{-17}$

b) How many gas atoms/cm^3 are released from the fuel after 2 years of irradiation? Assume the yield y = 0.3017. (5 pts)

$\tau = Dt/a^2 = \frac{6.7874\times10^{-17}}{(8\times10^{-4})^2} = 0.0067 \qquad \tau < \pi^{-2}. \qquad t = 63072000\,s$

$f = 4\sqrt{\frac{Dt}{\pi a^2}} - \frac{3}{2}\frac{Dt}{a^2} = 0.1745 \qquad V = \frac{4}{3}\pi\left(\frac{a}{2}\right)^3 = 2.6808\times10^{-10}\,cm^3$

$GR = f\cdot N_{FG} = f\cdot y\cdot\dot{F}\cdot t\cdot V = 0.1745\times0.3017\times1.35\times10^{13}\times63072000\times2.68808\times10^{-10}$ atoms

$= 1.1982\times10^{10}$ atoms

c) The pellet is removed from the reactor and from its cladding, venting all released gas. It is then moved to a furnace and annealed at 2000 °C. Estimate how long before 60% of the gas trapped in the pellet is released. Assume $\tau > \pi^{-2}$. (10 pts)

$$f = 1 - \frac{6}{\pi^2}e^{-\pi^2 Dt/a^2} = 0.6$$

$$e^{-\pi^2 Dt/a^2} = \frac{0.4\pi^2}{6}.$$

$$-\pi^2\frac{Dt}{a^2} = \ln\left(\frac{0.4}{6}\pi^2\right)$$

$$t = -\frac{a^2}{\pi^2 D}\ln\left(\frac{0.4}{6}\pi^2\right) = 4.0\times10^8\,s$$

3. A ZIRLO cladding tube is in reactor at 600 K for one year. The initial wall thickness is 600 μm.

a) Estimate the oxide thickness after this time? (8 pts)

$T = 600\,K \qquad t = 365\text{ days}$

$t^*(d) = 6.62\times10^{-7}\exp\left(\frac{11949}{T}\right) = 295.0072\text{ days} < 365\text{ days}$

$\delta^*(\mu m) = 5.1\exp\left(-\frac{550}{T}\right) = 2.0392\,\mu m$

$K_L(\mu m/d) = 7.48\times10^{6}\exp\left(-\frac{12500}{T}\right) = 0.0067\,\mu m/d$

$\delta(\mu m) = \delta^*(\mu m) + K_L(t-t^*) = (2.0392 + 0.0067\times(365-295.0072))\,\mu m = 2.5082\,\mu m$

b) Assuming the hydrogen pickup fraction is 15%, what is the weight PPM of hydrogen in the cladding after one year? Assume PBR = 1.56, ρ_{Zr} = 6.5 g/cc, ρ_{ZrO2} = 5.68 g/cc. (8 pts)

$\rho_{O_2} = \frac{32}{(91+32)}\times5.68\,g/cc = 1.47\,g/cc. \qquad$ weight gain $= 1.47\,g/cm^3 \times 2.5082\times10^{-4}\,cm$

$= 3.69\times10^{-4}\,g/cm^3$

$d = 600 - 2.5082/PBR = 598.39\,\mu m$

$N_O = \frac{3.69\times10^{-4}\,g/cm^2\times N_A}{16} = \frac{3.69\times10^{-4}\,g/cm^2\times6.022\times10^{23}\,atom/mol}{16\,g/mol} = 1.39\times10^{19}\,atom/cm^2$

$dm^2 \Rightarrow 10^2$

$N_H = f\cdot N_O = 0.15\times1.39\times10^{19}\,g/cm^3 = 2.085\times10^{18}\,atoms/cm^2 \Rightarrow m_H = \frac{2.085\times10^{18}\,atom/cm^2}{N_A} = 3.46\times10^{-6}\,g/cm^2$

$V_{Zr} = 598.39\times10^{-4}\,cm\times10\,cm\times10\,cm = 5.98\,cm^3 \qquad m_{Zr} = \rho_{Zr}V = 5.98\,cm^3\times6.5\,g/cm^3 = 38.87\,g$

$C_H^{clad} = \frac{3.46\times10^{-6}\times10^2\times10^6}{38.87}\,wt.ppm = 8.901\,wt\,ppm$

4. Determine the total change in the fuel volume given: $\alpha_{th}=11\times10^{-6}$, fission rate = 3.5×10^{13} fiss/cm^3-s, T=1600 K, T_{ref}=300 K, $\Delta\rho_0$=0.01, B_D=5 MWD/kgU, ρ(UO2)=10.97 g/cc, t=85 days. (15 pts)

$\alpha_{th} = 11\times10^{-6} \qquad \dot{F} = 3.5\times10^{13}\,fiss/cm^3\text{-}s \qquad T = 1600K \quad T_f = 300\,K$

$B_D = 5\,MWD/kgU \qquad \rho(UO_2) = 10.97\,g/cm^3 \qquad t = 85\text{ day} \qquad B_D = \frac{5}{950}\,FIMA$

$N_U = \frac{N_A\,\rho(UO_2)}{m_{UO_2}} = \frac{6.022\times10^{23}\times10.97}{238+16\times2}\,atoms/cm^3 = 2.4467\times10^{22}\,atoms/cm^3$

$B = \dot{F}*t/N_u = 0.0105 \qquad T > 750 \quad C_D = 1 \qquad \Delta\rho_0 = 0.01$

$\epsilon_D = \Delta\rho_0\left(e^{\frac{B\ln 0.01}{C_D B_D}} - 1\right) = -0.01$

$\epsilon_{sfg} = 5.577\times10^{-2}\times\rho_{UO_2}*B = 0.0064$

$\epsilon_{gfg} = 1.96\times10^{-28}\rho_{UO_2}\cdot B\,(2800-T)^{11.73}\,e^{-0.0162(2800-T)}\,e^{-17.8\rho(UO_2)B}$

$= 0.0138 \qquad \epsilon_{th} = \alpha(T-T_{ref}) = 0.0143$

$\epsilon_{tot} = \epsilon_{th} + \epsilon_{sfg} + \epsilon_{gfg} + \epsilon_D = 0.0245$

5. What are the five types of fission products that form in the fuel? (5 pts)
   Soluble oxides, Insoluble oxides; Metals; Volatiles; Noble gases

6. List the three stages of fission gas release. (6 pts)
   Stage1: Gas atoms are produced throughout the fuel due to fission and diffuse towards grain boundaries; Small intragranular bubbles form within the grains; Gas atoms that don't get trapped within the intragranular bubbles migrate to grain boundaries. Stage2. Gas bubbles nucleate on grain boundaries, growing and interconnecting. Stage3. Gas travels through interconnected bubbles to a free surface

7. Name two types of creep. Which type of creep is based on bulk diffusion? (5 pts)
   thermal creep and irradiation creep. Thermal creep is based on bulk diffusion

8. What performance effects result from the High Burnup Structure? (6 pts)
   Efficiently retain fission gas; increased toughness and softness and increased thermal conductivity

9. Describe the concept of microstructure-based fuel performance modeling. (6 pts)

Structure/property relationships connect the microstructure variables to the property values

10. List three benefits of using Zr cladding. (5 pts)
    Low neutron cross section; Resistance to void swelling; good thermal conductivity

11. Why does metallic fuel undergo constituent redistribution? (5 pts)
    Zr diffuses via Soret diffusion up to the temperature gradient and Zr possesses different solubilities in each phase of U

12. Why is the microstructure of U-Zr based fuels so varied and complex? (6 pts)
    The temperature range in the U-Zr is 800 ~1100K. From the phase diagram, we can see that it is in the multiphase region which include bcc, beta, alpha U, delta UZr2 and alternate bcc phases and because of fuel redistribution, it also has variable composition of Zr.