NE 533

Nuclear Fuel Performance

Spring 2022

Exam #2

1) $R_F = 4.5$ mm $LHR = 250$ W/cm

a) max stress? $\rightarrow \sigma_\theta$ $K_f = 0.1$ W/cm-K $E = 290$ GPa $\nu = 0.3$

$\alpha = 8.2 \times 10^{-6}$ 1/K

$$\sigma_\theta = -\sigma^* (1 - 3\eta^2)$$

$$\sigma^* = \frac{\alpha E (T_0 - T_s)}{4(1-\nu)}$$ $$T_0 - T_s = \frac{LHR}{4\pi K_F} = 199 \text{ K}$$

$$\sigma^* = \frac{(8.2 \times 10^{-6})(290 \times 10^3)(199)}{4(1-0.3)} = 169 \text{ MPa}$$

σ_θ max @ $r = R_F \rightarrow \eta = 1$ $\sigma_\theta = -\sigma^* (1 - 3(1)^2)$

$$\sigma_\theta = 2\sigma^* = \boxed{338 \text{ GPa}}$$

b) $\sigma_{fr} = 120$ MPa

$$\sigma_{fr} = -\sigma^* (1 - 3\eta^2)$$ $$120 = -169 (1 - 3\eta^2)$$

$$\eta = 0.75$$

25% into the fuel

2) $p = 50$ MPa $\bar{r}_c = 5.4$ mm $t_c = 1.2$ mm

$r_i = 4.8$ mm $r_o = 6$ mm

a) thin-walled

$$\sigma_\theta = \frac{pR}{\delta} \qquad \sigma_z = \frac{pR}{2\delta} \qquad \sigma_r = \frac{-p}{2}$$

$$\sigma_\theta = \frac{50\,(5.4)}{1.2} = \underline{225 \text{ MPa}} \qquad \sigma_z = \frac{\sigma_\theta}{2} = \underline{112.5 \text{ MPa}}$$

$$\sigma_r = -\frac{50}{2} = \underline{-25 \text{ MPa}}$$

b) $r = 5.6$ mm $\frac{R_o}{R_i} = \frac{6}{4.8} = 1.25$ $\frac{R_o}{r} = \frac{6}{5.6} = 1.07$

$$\sigma_r = -p\,\frac{\left(\left(\frac{R_o}{r}\right)^2 - 1\right)}{\left(\frac{R_o}{R_i}\right)^2 - 1} \qquad \sigma_\theta = \frac{p\left[\left(\frac{R_o}{r}\right)^2 + 1\right]}{\left(\frac{R_o}{R_i}\right)^2 - 1} \qquad \sigma_z = \frac{p}{\left(\frac{R_o}{R_i}\right)^2 - 1}$$

$$\sigma_r = \frac{-50\left((1.07)^2 - 1\right)}{1.25^2 - 1} = \underline{-12.9 \text{ MPa}} \qquad \sigma_\theta = \frac{50\,(1.07^2 + 1)}{1.25^2 - 1} = \underline{190.6 \text{ MPa}}$$

$$\sigma_z = \frac{50}{1.25^2 - 1} = \underline{89 \text{ MPa}}$$

c) $$\epsilon_\theta = \frac{1}{E}\left(\sigma_\theta - \nu\,(\sigma_r + \sigma_z)\right)$$

$$\epsilon_\theta = \frac{1}{190\times10^3}\left(190.6 - 0.28\,(-12.9 + 89)\right) = \underline{9.4\times10^{-4}}$$

3) Δt_g $R_f = 0.52$ cm $t_g = 0.005$ cm $T_{co} = 550K$ $t_c = 0.08$ cm

$K_f = 0.05$ W/cm-K $k_g = 0.003$ W/cm-K $k_c = 0.15$ W/cm-K

$LHR = 225$ W/cm $\alpha_c = 4.5\times10^{-6}$ 1/K $\alpha_f = 15\times10^{-6}$ 1/K $T_{ref} = 300K$

$$\frac{LHR}{2\pi R_f} = \frac{225}{2\pi(0.52)} = 68.9 \text{ W/cm}^2$$

$$\Delta T_{clad} = \frac{LHR}{2\pi R_f}\frac{t_c}{K_c} = 68.9\frac{0.08}{0.15} = \underline{37\text{ K}}$$ $T_{ci} = \underline{587\text{ K}}$

$$\Delta T_g = \frac{LHR}{2\pi R_f}\frac{t_g}{K_g} = 68.9\frac{0.005}{0.003} = \underline{114\text{ K}}$$ $T_s = \underline{701\text{ K}}$

$$\Delta T_F = \frac{LHR}{4\pi K_F} = \frac{225}{4\pi(0.05)} = \underline{358\text{ K}}$$ $T_o = \underline{1059\text{ K}}$

$$\bar{T}_c = \frac{T_{co}+T_{ci}}{2} = \frac{550+587}{2} = \underline{568.5\text{ K}}$$

$$\bar{T}_F = \frac{T_o+T_s}{2} = \frac{1059+701}{2} = \underline{880\text{ K}}$$

$$\Delta t_c = \bar{R}_c\alpha_c(\bar{T}_c - T_{ref}) \qquad \Delta t_F = R_F\alpha_F(\bar{T}_F - T_{ref})$$

$$\bar{R}_c = 0.52 + 0.005 + \frac{0.08}{2} = 0.565$$

$$\Delta t_c = 0.565(4.5\times10^{-6})(568.5-300) = 6.83\times10^{-4}$$

$$\Delta t_F = 0.52(15\times10^{-6})(880-300) = 4.52\times10^{-3}$$

$$t_g = 0.005 + (6.83\times10^{-4} - 4.52\times10^{-3}) = \boxed{0.0012\text{ cm}}$$

4) $A = 8\ \mu m$ $\dot{\phi} = 2\times10^{13}\ \text{fiss}/\text{cm}^3\text{-s}$ $D_{Xe} = 2\times10^{-15}\ \text{cm}^2/\text{s}$

$t = 2\ \text{yrs} = 6.307\times10^{7}\ \text{s}$

$$\tau = \frac{Dt}{a^2} = \frac{(2\times10^{-15})(6.307\times10^{7})}{(8\times10^{-4})^2} = 0.1971 > \pi^{-2}$$

long time

in-pile release

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

$$\underline{f = 0.709}$$

total gas $= y\dot{F}t$

$\dot{F} = 2\times10^{13}\ \text{fiss}/\text{cm}^3\text{-s}$

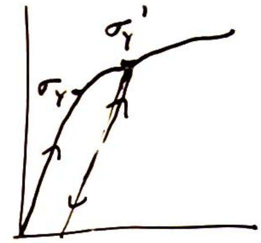
$$G = 0.3017\,(2\times10^{13})(6.307\times10^{7}) = 3.81\times10^{20}\ \frac{Xe}{cm^3}$$

gas $\frac{\text{atoms}}{\text{cc}}$ released $= 0.709 \times 3.81\times10^{20}$

$$= \underline{2.70\times10^{20}\ \frac{Xe}{cm^3}}$$

5) Increase in the yield strength after permanent/plastic deformation.

Dislocations allow for plastic deformation. Dislocations diffuse and can encounter barriers to their motion. When dislocations pile-up, they repel each other, and create an increase in the barrier to dislocation motion, increasing the yield strength.



$\sigma_Y' > \sigma_Y$

6) Thermal Conductivity, lattice constant, thermal expansion, heat capacity, density, Gibbs energy of formation, etc.

7) Model the temperature profile and stress in the fuel, model stress in the cladding, account for gap thermal conductivity and closure

8) Stage 1: gas is produced in the grains and diffuses towards the grain boundaries

Stage 2: fission gas bubbles form and grow along the grain boundaries, begin to coalesce

Stage 3: intergranular gas bubbles fully percolate along the grain boundaries, providing a path to a free surface and gas release

9) Large grain changes to nano grained structure. Dramatically increases the porosity. Fission gas is retained in the larger fission gas bubbles, limiting plenum pressure.

Thermal Conductivity is increased. Recrystallization removes point defects from the grains and fission gas bubbles have higher thermal conductivity than voids.

10) 0-D → interstitial, vacancy, substitutional

3-D → precipitate, Second phase, void, bubble

11) Densification : reducing of the surface area in the system. Serves to remove small pores as a continuation of the sintering process.

Grain growth : reducing of the grain boundary length, total decrease in the free energy of the system. Leads to larger grains growing at the expense of small grains.

12) U^{4+}, can exist as $U^{3+}, {}^{5+}, {}^{6+}$

Allows for incorporation of fission products into the fluorite lattice while maintaining charge neutrality