Hamdy Abouelella.

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Q(1)

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$$\Delta T = \frac{lHR}{4\pi k} = \frac{280}{4\pi \times 0.1} = 198.9.$$ ✓

$$\sigma^* = \frac{\alpha E (\Delta T)}{4(1-\nu)} = \frac{8.2e^{-6} \times 290 \times 100 \times 198.9}{4(1-0.3)}$$ ✓

How far will the crack go.

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

$$\frac{120\ MPa.}{\sigma^*} = -1 + 3\eta^2$$

$$\frac{120}{\sigma^*} + 1 = 3\left(\frac{r}{R}\right)^2.$$

we know σ^* from above. $R = 4.5\ mm$ ✓

$r = \boxed{\quad}$ Crack length.

- on your way, but did not complete

max

at $\eta = 1$

$$\sigma_{\theta\theta} = -\sigma^*(1-3.)$$

$$\sigma_{\theta\theta} = 2\sigma^*$$

we know σ^* from previous calculations

$$\sigma_{\theta\theta} = \sigma_{max} = 2\sigma^*$$

Q(2)

$\sigma = 50$ MPa. fuel rod.

$r_{av} = 5.4$ mm

$t_{clad} = 1.2$ mm.

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a)

$$\sigma_\theta = \frac{PR}{\delta} = \frac{50 \text{ MPa} * 5.4 \cancel{\text{mm}}}{1.2 \cancel{\text{mm}}} = 225 \text{ MPa.}$$

$$\sigma_z = \frac{PR}{2\delta} = \frac{50 * 5.4 \text{ mm}}{2 * 1.2 \text{ mm}} = 112.5 \text{ MPa.}$$

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

b) $r = 5.6$ mm.

$$\sigma_{rr} = \frac{-P\left[\left(\frac{R_o}{r}\right)^2 - 1\right]}{\left(\frac{R_o}{R_i}\right)^2 - 1} = \frac{-50\left(\frac{5.6}{5.4}\right)^2 - 1}{\left(\frac{5.6}{5.4}\right)^2 - 1} = -725.98 \text{ MPa.}$$

$$\sigma_{\theta\theta} = \frac{P\left[\left(\frac{R_o}{r}\right)^2 + 1\right]}{\left(\frac{R_o}{R_i}\right)^2 - 1} = \frac{50\left(\frac{5.6}{5.4}\right)^2 + 1}{\left(\frac{5.6}{5.4}\right)^2 - 1} = 725.98 \text{ MPa.}$$

$$\sigma_{zz} = \frac{P}{\left(\frac{R_o}{R_i}\right)^2 - 1} = \frac{50}{\left(\frac{5.6}{5.4}\right)^2 - 1} = 662.72 \text{ MPa}$$

(c) ϵ_{max}

$E = 180$ GPa.

$\nu = 0.28$

max strain is in the hoop direction.

$$\epsilon_{\theta\theta} = \frac{1}{E}\left(\sigma_{\theta\theta} - \nu\left(\sigma_{rr} + \sigma_{zz}\right)\right)$$

$$\epsilon_{\theta\theta} = \frac{1}{180 * 1000 \text{ MPa}}\left(726 \text{ MPa} - 0.28\left(-726 + 663\right)\right)$$

$$\epsilon_{\theta\theta} = 4.1 * 10^{-3}$$

$$\epsilon_{\theta\theta} = 0.413 \%$$

but with wrong stresses

① (3) Change in gap thickness. → thermal expansion.

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$R_F = 0.52$ 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

$\alpha_c = 4.5 \times 10^{-6}$ K^{-1}

$\alpha_f = 15 \times 10^{-6}$ K^{-1}

$T_{ref} = 300$ K

fuel	gap	clad
R_F 0.52	t_{gap} 0.005	α_c 0.08
K = 0.05	K = 0.003	K = 0.15
α_f		↓ higher conductivity ⇓ lower temp.
lHR		$T_{co} = 550$ °K

$$\Delta\delta = R_c \alpha_c (T_{co} - T_{ref}) - R_f \alpha_f (T_f^{?} - T_{ref})$$

change in gap

$T_f = ?$

$R_c = 0.52 + 0.005 + 0.04$

$R_c = 0.565$

Fuel.

$$T_0 = \frac{lHR}{4\pi K} + T_f$$

$$T_0 = \frac{225}{4\pi \times 0.05} + \boxed{701.5}K$$

$T_0 = 1059.6$ K

gap

$$T_f - T_{ci} = \frac{lHR}{2\pi R_f \, h_{gap}}$$

$$h_{gap} = \frac{k_{gap}}{t_{gap}}$$

$$h_{gap} = \frac{0.003}{0.005} = 6.6$$

$$T_F = \frac{lHR}{2\pi R_f \cdot 0.6} + T_{ci}$$

$$T_f = \frac{225}{2\pi \times 0.52 \times 6.6} + \boxed{586.7}K.$$

$T_f = \boxed{701.5}$ K

clad

$$T_{ci} - T_{co} = \frac{lHR \cdot t_c}{2\pi R_f \cdot K_{clad}}$$

$$T_{ci} = \frac{lHR \cdot t_c}{2\pi R_f \cdot K_{clad}} + T_{co}.$$

$$T_{ci} = \frac{225 \times 0.08}{2\pi \times 0.52 \times 0.15} + 550\,°K$$

$T_{ci} = \boxed{586}.7$ °K

$$\frac{586+550}{2} \qquad \frac{1060+201}{2}$$

$$\Delta \delta = R_c \alpha_c (T_c - T_{ref}) - R_f \alpha_f (T_f - T_{ref})$$

$$\Delta \delta = \left[(0.565) * 4.5 * 10^{-6} (550 - 300)\right] - \left[(0.52) * 15 * 10^{-6} (1060 - 300)\right]$$

$$\Delta \delta = \boxed{}$$

almost there

Question (4)

8/12

Fuel pellet.

grain size $D = 8\ \mu m$. irradiated.

$$\phi = 2e^{13}\ f/cm^3.s$$

$$D_{Diffusion} = 2*10^{-15}\ cm^2/s$$

gas atoms/cm^3 ? released.

after 2 years.

$$Y = 0.3017$$

using Booth model.

$$\tau = \frac{D*t}{a^2} = \frac{2*10^{-15}*(2*365*24*60*60)}{(8*10^{-4})^2}$$

$$\tau = 0.1971 > \pi^{-2}$$

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

→ this is annealing eqn

we want in-pile eqn

$$f = 1 - \frac{6}{\pi^2} e^{-\pi^2 \frac{2*10^{-15}*(2*365*24*60*60)}{(8*10^{-4})^2}}$$

$$f = 0.913$$

if we multiplied the fraction by the total gas production we will get the # of atoms escaped.

total Gas production. $= Y\dot{F} \cdot t$

$$N_t = 0.3017 * 2 * 365 \times 60 \times 60 * \dot{F}$$ we provide you $\dot{F}$ w/ volumetric

$$\dot{F} = \underline{N_u^{235} \phi \sigma_f} V.$$ we have the neutron flux.

$$N_t = 0.3017 \times 2 \times 365 \times 60 \times 60 \times 2 \times e^{13} = 1.68 * 10^{13}$$

gas atoms released

$$= f * N_t = 0.913 * 1.68 \times 10^{13} = 1.5 * 10^{13} \text{ atom.}$$

numbers might have some ~~calculat~~ errors. !!!

Q (5)

8/8

→ Strain hardening.

~~the increase in the stress~~ the region at which the stress relates to strain through $\sigma = K \epsilon^n$ where dislocations starts to multiplicate and interact with each other.

→ what causes strain hardening.

- multiplication of dislocations.
- dislocations will be entangled and will impede the motion of each other.

Q (6) Stoichiometry of UO_2 impacts.

6/6

- melting temperature.
- thermal conductivity.
- process dependent diffusion
  - grain growth.
  - fission gas release.
  - creep.
- Chemical reactions at inner cladding surface.
-

Q(7)

three things all fuel performance codes should be able to do.

→ Fuel → temp profile
Volumetric change

6/6

→ Cladding → temp profile.
→ stress.

→ Gap → Gap heat transport.
→ mechanical interaction between fuel and clad.
→ Gap pressure.

Q(8) fission gas release stages.

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stage I : gas atoms produced from fission.
diffusion towards GBs
intragranular bubbles formed.

Stage II → Gas bubbles nucleate → grow → interconnect.

Stage III → Gas travel through interconnected bubbles.
to the surface of the fuel.

Q(9)

performance Results from high burn up structure.

6/6

- instability of crystalline ~~mater~~ structure.
- restructuring driven by energy stored.
- Pu production in the periphery and increased fissile density
- grains subdivide from 10 μm ⟶ 100-200 nm.
- densely porous structures are formed.
- material Conductivity degrades due to pores.
- fission gas is retained in the pores

Q(10) 0-D defect
- → vacancy.
- → interstitial.
- → substitutional.

4/4

3D defects.
- → voids / bubbles.
- → grain boundaries.
- → precipitates / inclusions.

Q (11) driving force for fuel densification.

⇒ change in free energy from the decrease in surface area of pores and lowering of surface free energy.

* driving force for grain growth.

- reduction of grain boundary energy. 6/6
↳ curvature driving force because it derives the GB to be straight.
- temp gradient.
- elastic energy gradient.
- dislocation energy gradients.

in General ⇒ you are trying to reduce Gibbs free energy.

Q (12) valence state of UO_2 → +4 4/4

possible valence states of U.

U^{4+}, U^{5+}, U^{6+}.