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Question(1) $LHR = 250\,W/cm$
$r_f = 0.45\,cm$

a) Max stress is hoop stress σ_θ at $\eta = 1$

stress due to thermal expansion: $\boxed{\sigma_\theta = -\sigma^*(1-3\eta^2)}$

where $\eta = \frac{r}{r_F}$

$\sigma^* = \frac{\alpha E (T_0 - T_s)}{4(1-\nu)}$

$\alpha = 8.2\times10^{-6}\,K^{-1}$, $\nu = 0.3$
$E = 290\times10^3\,MPa$
$T_0 - T_s = \frac{LHR}{4\pi K_f} = \frac{250\,W/cm}{4\pi \times 0.1\,W/cm\text{-}K}$
$\approx 199\,K$

$\therefore \sigma^* = \frac{8.2\times10^{-6} \times 290\times10^3 \times 199}{4(1-0.3)}$
$= 169\,MPa$

$\therefore \sigma_\theta^{max} = -169\,MPa\,[1-3] = \boxed{338\,MPa}$

b) $\sigma_{fracture} = 120\,MPa = \sigma_\theta$

$120 = -\sigma^*(1-3\eta^2)$

$120 = -169[1-3\eta^2]$

$-0.71 = 1-3\eta^2 \Rightarrow 3\eta^2 = 1.71$

$\eta = 0.75 = \frac{r}{R_F}$ $\quad\therefore r = 0.75 \times 0.45$
$= 0.3375\,cm$

Question (1)

(b)

Question (2) Stress ~~[illegible]~~ in cladding

(a) Assuming thin-walled cylinder

$$\bar{\sigma}_\theta = \frac{pR}{\delta}, \quad p = \text{pressure}, \quad R: \text{average radius}, \quad \delta: \text{clad thickness}$$

$$\bar{\sigma}_\theta = \frac{50 * 5.4}{1.2} = \boxed{225\ MPa}$$

$$\bar{\sigma}_z = \frac{pR}{2\delta} = \frac{1}{2}\bar{\sigma}_\theta \quad \therefore \quad \bar{\sigma}_z = \boxed{112.5\ MPa}$$

$$\bar{\sigma}_r = -\frac{1}{2}p = -0.5 * 50 = \boxed{-25\ MPa}$$

(b) Assuming thick-walled cylinder

$$\sigma_r(r) = \frac{-p\left(\frac{R_o}{r}\right)^2 - 1}{\left(\frac{R_o}{R_i}\right)^2 - 1}$$

where R_o: outer radius $= 6$ mm

R_i: inner radius $= 4.8$ mm

$$\sigma_r(r = 5.6mm) = \frac{-50\left(\frac{6}{5.6}\right)^2 - 1}{\left(\frac{6}{4.8}\right)^2 - 1}$$

~~$= -100.6$ MPa~~ ~~$= -200.3$ MPa~~

~~$\therefore \sigma_\theta(r = 5.6mm) = 303.8$ MPa~~

$$\therefore \boxed{\sigma_r(r = 5.6mm) = -13.2\ MPa}$$

$$\sigma_\theta(r = 5.6mm) = 50\ \frac{\left(\frac{6}{5.6}\right)^2 + 1}{\left(\frac{6}{4.8}\right)^2 - 1}$$

$$\therefore \boxed{\sigma_\theta(r = 5.6mm) = 190.9\ MPa}$$

$$\sigma_z(r = 5.6mm) = p * \frac{1}{\left(\frac{R_o}{R_i}\right)^2 - 1} = 50 * \frac{1}{\left(\frac{6}{4.8}\right)^2 - 1}$$

$$\therefore \boxed{\sigma_z(r = 5.6mm) = 88.9\ MPa}$$

Question (2)

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

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

$\cancel{\varepsilon_{zz} = \frac{1}{E}}$

$\varepsilon_{\theta\theta} = \frac{1}{180 \times 10^{6}}\left[190.9 - 0.28(-13.2 + 88.9)\right]$

$= 9.4 \times 10^{-7}$

$\varepsilon_{rr} = \frac{1}{180 \times 10^{6}}\left[-13.2 - 0.28(190.9 + 88.9)\right]$

$= -5.09 \times 10^{-7}$

Question (3) Change in gap thickness due to thermal expansion

$$\Delta\delta_{gap} = \bar{R}_c \alpha_c (\bar{T}_c - \underbrace{T_{fab}}_{300K}) - \bar{R}_f \alpha_f (\bar{T}_f - \underbrace{T_{fab}}_{300K})$$

$R_c = 0.52\,cm + 0.005\,cm + 0.08\,cm = 0.605\,cm$

$$\therefore \boxed{\Delta\delta_{gap} = 0.605 * 4.5*10^{-6} * (\bar{T}_c - 300) - 0.52 * 15*10^{-6} (\bar{T}_f - 300)}$$

$$\Delta T_c = \frac{LHR}{2\pi R_f \frac{k_c}{t_c}} = \frac{225 * 0.08}{2\pi * 0.52 * 0.15} = 36.7\,K$$

$\because T_{co} = 550\,K$, $\therefore T_{cI} = 550 + 36.7 = 586.7\,K$

$$\therefore \boxed{\bar{T}_c = 568.4\,K}$$

$$\Delta T_f = \frac{LHR}{4\pi k_f} = \frac{225}{4\pi * 0.05} = 358.1\,K$$

$$\Delta T_{gap} = \frac{LHR}{2\pi k_g / t_g} = \frac{225 * 0.005}{2\pi * 0.52 * 0.003} = 114.8\,K$$

$\therefore T_0 = 586.7\,K + 114.8 + 358.1 = 1059.6\,K$

$$\therefore \boxed{\bar{T}_f = 880.6\,K}$$

$$\therefore \Delta\delta_{gap} = 2.72*10^{-6} (880.6 - 300) - 7.8*10^{-6} (568.4 - 300)$$

$$= 1.58*10^{-3} - 2.09*10^{-3} = \boxed{-5.1*10^{-4}\,cm}$$

Question (4) $\dot{F} = 2 * 10^{13} \frac{\text{fissions}}{cm^3\text{-}s}$, $D = 2*10^{-15} cm^2/s$

$y = 0.3017$ after $t = 2$ years

~~Rakess~~ $a = 8*10^{-6} m = 8*10^{-4}$ cm

Applying Booth Model (In pile release)

calculate $\tau = \frac{Dt}{a^2} = \frac{2*10^{-15} * 2 * 365 * 24 * 60^2}{(8*10^{-4})^2} = \boxed{0.1971} > \pi^{-2}$

∴ fraction of gas atoms released

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

$= \boxed{0.709}$ = 70.9 % of gas atoms are released

* Total no of gas atoms produced is $\boxed{y \dot{F} t}$

$= 0.3017 * 2*10^{13} * 2 * 365 * 24 * 60^2 = \boxed{3.806*10^{20} \text{ atoms}/cm^3}$

* # of gas atoms released $= 0.709 * 3.806 * 10^{20}$ atoms/cm³

$= 2.7 * 10^{20}$ atoms/cm³

* For each grain (assuming spherical grains) : $2.7*10^{20} * \frac{4}{3} \pi * (8*10^{-4})^3$

$= 5.8 * 10^{11}$ (gas atoms) were released from each grain (on average)

Question (5) Strain Hardening: increase in yield stress due to plastic deformation.

Causes: Dislocation motion is ~~impeded because of grain boundaries~~ impeded

Question (6) Properties that vary with Stoichmetry: * Melting temperature

* Thermal Conductivity * creep rate
* Fission gas release rate * Grain Growth rate

Question (7) Fuel performance code must be able to:

* predict Centerline temperature of fuel pellet
* Calculate stresses on clad walls
* predict swelling & Fission gas release behavior

Question (8) Stages of fission gas release:

(1) Diffusion of gas atoms within grains until reaching grain boundaries to form bubbles
(2) Growth and interconnection of intergranular gas bubbles
(3) Transport of gas bubbles to free surface

Question (9) High Burnup structure results in:

* Densely porous structure ⇒ degradation in thermal conductivity
* reduction of grain size
* High plutonium production in periphery of fuel pellet
∴ higher fission density at periphery of fuel pellet.

Question (10) 0-D defects: vacancies, interstitials

3D defects: precipitates, voids, bubbles

Question (11) Driving force for fuel densification:
lowering surface free energy by decreasing surface area of pores

Question (12) valence state of U in UO_2 : $\boxed{4+}$

other valence states 5+, 6+

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