

Question(1) $LHR = 250 \text{ W/cm}$
 $r_F = 0.45 \text{ cm}$

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

stress due to thermal expansion:

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

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

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

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

$$\alpha = 8.2 \times 10^{-6} \text{ K}^{-1}, \nu = 0.3$$

$$E = 290 \times 10^3 \text{ MPa}$$

$$T_o - T_s = \frac{LHR}{4\pi k_F} = \frac{250 \text{ W/cm}}{4\pi \times 0.1 \text{ W/cm-K}} \approx 199 \text{ K}$$

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

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

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

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

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

$$\eta = \frac{r}{r_F} = 0.75$$

$$\therefore r = 0.75 \times 0.45 = 0.3375 \text{ cm}$$

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Quasim (1)

(b)

Question (2) Stress ~~the for the~~ in cladding

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(a) Assuming thin-walled cylinder

$$\bar{\sigma}_\theta = \frac{PR}{s}, \quad P = \text{Pressure}, \quad R = \text{average radius}, \quad s = \text{thickness}$$

$$\bar{\sigma}_\theta = \frac{50 \times 5.4}{1.2} = 225 \text{ MPa}$$

$$\bar{\sigma}_z = \frac{PR}{2s} = \frac{1}{2} \bar{\sigma}_\theta \quad \therefore \bar{\sigma}_z = 112.5 \text{ MPa}$$

$$\bar{\sigma}_r = -\frac{1}{2}P = -0.5 \times 50 = -25 \text{ MPa}$$

(b) Assuming thick-walled cylinder

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

where R_o : outer radius = 6 mm
 R_i : inner radius = 4.8 mm

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

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

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

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

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

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

Question (2)

$$(C) \quad \epsilon_{rr} = \frac{1}{E} (\sigma_{rr} - \nu (\sigma_{\theta\theta} + \sigma_{zz})) \quad \checkmark$$

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

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

$$\epsilon_{\theta\theta} = \frac{1}{180 \times 10^6} [190.9 - 0.28(-13.2 + 88.9)]$$
$$= 9.4 \times 10^{-7} \quad \checkmark$$

$$\epsilon_{rr} = \frac{1}{180 \times 10^6} [-13.2 - 0.28(190.9 + 88.9)]$$
$$= -5.09 \times 10^{-7}$$

Question (3) Change in gap thickness due to thermal expansion 15/14

$$\Delta S_{\text{gap}} = \bar{R}_c \alpha_c (\bar{T}_c - T_{\text{lab}}) - \bar{R}_f \alpha_f (\bar{T}_f - T_{\text{lab}})$$

$\nearrow 300\text{K}$ $\nearrow 300\text{K}$

$$R_c = 0.52 \text{ cm} + 0.005 \text{ cm} + \underline{0.08 \text{ cm}} = 0.605 \text{ cm} \quad \bar{R}_c$$

$$\therefore \Delta S_{\text{gap}} = 0.605 \times 4.5 \times 10^{-6} (\bar{T}_c - 300) - 0.52 \times 15 \times 10^{-6} (\bar{T}_f - 300)$$

$$\Delta T_c = \frac{LHR}{2\pi R_f \frac{k_c}{t_c}} = \frac{225 \cancel{\text{W}} + 0.08}{2\pi \times 0.52 \times 0.15} = 36.7 \text{ K} \quad \checkmark$$

$$\therefore T_{c0} = 550 \text{ K} \quad \therefore T_{c1} = 550 + 36.7 = 586.7 \text{ K}$$

$$\therefore \boxed{\bar{T}_c = 588.4 \text{ K}} \quad \checkmark$$

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

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

$$\therefore T_o = 586.7 \text{ K} + 114.8 + 358.1 = 1059.6 \text{ K} \quad \checkmark$$

$$\therefore \boxed{\bar{T}_f = 880.6 \text{ K}} \quad \checkmark \quad \text{switched the } \Delta T$$

$$\therefore \Delta S_{\text{gap}} = 2.72 \times 10^{-6} (880.6 - 300) - 7.8 \times 10^{-6} (588.4 - 300) \\ = 1.58 \times 10^{-3} - 2.09 \times 10^{-3} = \boxed{-5.1 \times 10^{-4} \text{ cm}}$$

Question (4)

$$\dot{F} = 2 \times 10^{13} \frac{\text{atoms}}{\text{cm}^3 \cdot \text{s}}, \quad D = 2 \times 10^{-15} \text{ cm}^2/\text{s}$$

$$y = 0.3017 \quad \text{after } t = 2 \text{ years}$$

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~~Radius~~ $a = 8 \times 10^{-6} \text{ m} = 8 \times 10^{-4} \text{ cm}$

Applying Booth Model (In pile release)

Calculate $\chi = \frac{Dt}{a^2} = \frac{2 \times 10^{-15} \times 2 \times 365 \times 24 \times 60^2}{(8 \times 10^{-4})^2} = \boxed{0.1971}$
 $\rightarrow \pi^{-2}$

\therefore fraction of gas atoms released

$$(f) = 1 - \frac{0.0662}{\chi} \left[1 - 0.93 e^{-\pi^2 \chi} \right]$$
$$= \boxed{0.709} = 70.9 \% \text{ of gas atoms are released}$$

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

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

* # of gas atoms released = $0.709 \times 3.806 \times 10^{20} \frac{\text{atoms}}{\text{cm}^3}$

$$= \underline{2.7 \times 10^{20} \frac{\text{atoms}}{\text{cm}^3}}$$

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

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

- not needed, but yes

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

Causes: Dislocation motion is ~~not~~ impeded ~~because of grain boundaries~~
7/8 & impeded - why?

Question (6) Properties that vary with Stoichiometry: * Melting temperature
6/6 * Thermal conductivity * Creep rate
* Fission gas release rate * Grain Growth rate

Question (7) Fuel performance code must be
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* predict Centerline temperature of fuel pellet
* Calculate stresses on clad walls + temperature
* predict swelling & fission gas release behavior
- gap closure and thermal transport plus pressure

Question (8) Stages of fission gas release:

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- (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:

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- * Densely porous structure \Rightarrow degradation in thermal conductivity
- * reduction of grain size
 - fission gas retained
 - recrystallized grains have higher K_{th}
- * High plutonium production in periphery of fuel pellet
 - \therefore higher fission density at periphery of fuel pellet.
 - leads to HBS, not caused by HBS

Question (10)

0-D defects: vacancies, interstitials

3D defects: precipitates, voids, bubbles

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Question (11)

Driving force for fuel densification:

Lowering surface free energy by decreasing surface area of pores

= Grain growth?

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Question (12)

valence state of U in UO_2 : 4+ ✓

other valence states $5+$, $6+$ also $3+$

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