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NucE 497 Fuel Performance Exam 1 covering modules 1 - 3

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Question 1:

U_3Si_5 is a uranium silicide fuel being considered for use in light water reactors. It has a thermal conductivity of 12.5 W/(m K) and a density of Uranium metal of 7.5 g of U/cm^3. Answer the following questions

$k_f = 12.5$ W/m-K

$\rho_U = 7.5$ g/cm^3

a) What is the fissile isotope in U_3Si_5? What would be the enrichment of this isotope in the natural (unenriched) form of the fuel? (7 points)

-Uranium-235 is the fissile isotope

-0.7% enriched

b) What enrichment would be required for U_3Si_5 to have the same energy release rate of U_3Si_2 enriched to 3% with a neutron flux of 3.2e13 n/(cm^2 s)? You can assume that U_{235} has a negligible impact on the total molar mass of U in the fuel (15 points)

• $U_3Si_2 \rightarrow 3\%$; $\phi = 3.2 \cdot 10^{13} \frac{\#}{cm^2\text{-}s}$; $N_{U235} = \frac{q N_a \rho}{M_{UO_2}}$

$\rightarrow q = 0.03$; $N_a = 6.022 \cdot 10^{23}$; $\rho = 11.31$; $M_U = 0.03(235) + (1-0.03)238 = 237.91$

$\rightarrow Q = E_f N_f \sigma_f \phi_{th}$ → to compare the Q must be the same, $E_f, \sigma_f \phi_{th}$ are the same so:

$$(N_F)_{U_3Si_5} = (N_F)_{U_3Si_2} = \frac{(0.03)(6.022 \cdot 10^{23})(11.31)}{237.9} = \frac{q' \cdot 6.022 \cdot 10^{23} \cdot 7.5}{237.91}$$

(same due to assumption above)

so $0.03(11.31) = q'(7.5)$

$$\boxed{q_U = 4.52\% \text{ for } U_3Si_5}$$

c) How would you rank U_3Si_5 as a potential fuel compared to U_3Si_2? Why? (8 points)

I would rank U_3Si_5 as a worse fuel soley based of the fact that it has lower density compared to U_3Si_2 → which means less U-235 in the same unit of volume → thus less fission

-3, Thermal conductivity?

$R_f = 0.45cm$ $t_c = 0.06\,cm$; $LHR = 250\,W/cm$
$t_g = 0.008\,cm$ $T_{cool} = 580K$
5% Xe, 95% He ; $h_{cool} = 2.5\,w/cm^2K$

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Question 2:
Consider a fuel rod with a pellet radius of 4.5 mm, an 80 micron gap, and a zircaloy cladding thickness of 0.6 mm. It is experiencing a linear heat rate of 250 W/cm with a coolant temperature of 580 K. The gap is filled with He and 5% Xe and the coolant conductance is 2.5 W/(cm² K).

a) What is the surface temperature of the fuel rod? (15 points)

$$\bullet\ T_{co} = T_{cool} + \frac{LHR}{2\pi R_f h_{cool}} = \frac{250}{2\pi(0.45)(2.5)} + 580 = 35.37 + 580 = \boxed{615.37K = T_{co}}$$

$$\cdot\ T_{zc} = T_{co} + \frac{LHR\, t_c}{2\pi R_f k_c} = \frac{250\,(0.06)}{2\pi\,(0.45)(0.17)} + 615.37 = 31.21 + 615.37 = \boxed{646.56\,K = T_{zc}}$$

$$\bullet\ T_s = T_{zc} + \frac{LHR\, t_{g}}{2\pi R_f\, k_{gap}} \rightarrow k_{gap} = \left[16\cdot10^{-6}(646.56)^{0.79}\right]_{He}^{1-0.05}\left[0.7e^{-6}(646.56)^{0.79}\right]^{0.05} = 0.002278$$

$$T_s = 646.56 + \frac{250\cdot0.008}{2\pi0.45\cdot0.\overline{2}} = 311.235 + 646.56 = \boxed{957.795K = T_s}$$

Significant digits?

b) Assume the pellet is made from Uranium Nitride. What is the maximum stress experienced by the pellet, given that uranium nitride has E = 246.7 GPa, ν = 0.25, and α = 7.5e-6 1/K? (10 points)

$E = 246.7\ GPA$
$V = 0.25$
$\alpha = 7.5e^{-6}$

• max stress is hoop stress: $\sigma_{\theta\theta} = \sigma^*(1-3\eta^2)$

$$\bullet\ \sigma^* = \frac{\alpha E(T_0 - T_s)}{4(1-v)};\quad T_0 = \frac{250}{4\pi(0.2)} + 957.795 = 1057.28120\,k$$

$$\hookrightarrow \sigma^* = \frac{7.5\cdot10^{-6}\cdot 0.246.7\cdot10^3\,[99.522]}{4(1-0.25)} = 61.38\,MPa$$

$\eta = r/R_f = 1 \Rightarrow$ Max stress at outside

$$\sigma_{\theta\theta} = \sigma^*(1-3(1)^2) = -61.38\,MPa\cdot 2$$

$$\boxed{\sigma_{\theta\theta} = 122.76\,MPa}$$

c) Would you expect this stress to be higher or lower if the pellet was UO_2? Why? (5 points)

$\alpha_{UN} = 7.5\cdot10^{-6}$
$\alpha_{UO_2} = 11\cdot10^{-6}$

For UO_2 I would expect a higher stress because α is larger, the ΔT_{fuel} is larger, and so σ^* would be larger; also a note to make is UN has better thermal stability → Lecture notes

-3, Primarily due to lower thermal conductivity and thus higher DT

d) What assumptions were made in your calculations for a) and b)? (5 points)

In calculations a:
• steady state
· axissymmetric behavior (r, z)
· T is constant in z
• thermal conductivity is constant

In part B:
• static body
• gravity is negligible
· axis symmetric
· isotropic material response → And some assumptions

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Question 3:

Consider the stress state in a zircaloy fuel rod pressurized to 6 MPa with an average radius of 5.6 mm and a cladding thickness of 0.6 mm.

a) What assumptions are made in the thin walled cylinder approximation for the stress state? (5 points)

Thinwalled assumption is stress is constant through wall of cylinder, because it is thin

-2, isotropic and small strain

b) Calculate all three components of the stress using the thin walled cylinder approximation. (10 points)

$$\bullet\ \sigma_\theta = \frac{PR}{S} = \frac{6 \cdot 5.6}{0.6} = \boxed{56\ MPa = \sigma_\theta}$$

$$\sigma_z = \frac{PR}{2S} \Rightarrow \boxed{\sigma_z = 28\ MPa}$$

$$\bar{\sigma}_r = -\frac{1}{2}P \Rightarrow \boxed{\sigma_r = -3\ MPa}$$

c) Quantify how accurate the thin walled cylinder approximation is for the cladding. Would the thin walled cylinder approximation be conservative if used to estimate if the cladding would fail? (10 points)

The thinwalled assumption is non conservative because it underestimates the stress: Avg radius $\Rightarrow$ 5.6 mm ; $t_c = 0.6$ mm

so $R_i = 5.3$ mm ; $R_o = 5.9$ mm

ex) $\sigma_{\theta\theta}(r) = P \frac{(R_o/r)^2+1}{(R_o/R_i)^2-1}$; Lowest at $r = R_i \Rightarrow$

$$= 6\left[\frac{(5.9/5.6)^2+1}{(5.9/5.6)^2+1}\right] = \underset{\text{thickness}}{115\ MPa} > \underset{\text{thin}}{56\ MPa}$$

-4, Calculate stress at two radii and compare

d) Write the stress and strain tensors for the stress state in the thin walled cylinder, with E = 70 GPa and ν = 0.41. (10 points)

$\bullet\ \sigma_\theta = 56\ MPa$; $\sigma_z = 28\ MPa$; $\sigma_r = -3\ MPa$

$$\boxed{\bar{\sigma} = \begin{array}{c} \begin{array}{ccc} \theta & r & z \end{array} \\ \begin{bmatrix} 56 & 0 & 0 \\ 0 & -3 & 0 \\ 0 & 0 & 28 \end{bmatrix} \end{array} MPa} \; ; \; \boxed{\bar{\epsilon} = \begin{bmatrix} 6.54 \cdot 10^{-4} & 0 & 0 \\ 0 & -5.348 \cdot 10^{-4} & 0 \\ 0 & 0 & 8.957 \cdot 10^{-5} \end{bmatrix}}$$

$$\bullet\ \epsilon_{rr} = \frac{1}{E}\left[\sigma_{rr} - \nu(\sigma_{\theta\theta} + \sigma_{zz})\right] = \frac{1}{70 \cdot 10^3}\left[-3 - .41[56+28]\right] = -5.348 \cdot 10^{-4}$$

$$\bullet\ \epsilon_{\theta\theta} = \frac{1}{E}\left[\sigma_{\theta\theta} - \nu(\sigma_{rr} + \sigma_{zz})\right] = \frac{1}{70 \cdot 10^3}\left[56 - 0.41[28-3]\right] = 6.54 \cdot 10^{-4}$$

$$\cdot\ \epsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - \nu(\sigma_{\theta\theta} + \sigma_{rr})\right] \frac{1}{70 \cdot 10^3}\left[28 - 0.41[56-3]\right] = 8.957 \cdot 10^{-5}$$