NucE 497 Fuel Performance Exam 1 covering modules 1 - 3

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/cm3. Answer the following questions

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)

The fissile isotope is U-235. The natural enrichment is 0.7% 235 and 99.3% 238.

3.5 pts for isotope, 3.5 pts for enrichment.

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 U235 has a negligible impact on the total molar mass of U in the fuel (15 points)

$Q_f = E_f\, N_f\, \sigma_f\, \varphi_f$ (3 pts)

$E_f\, N_{U3Si5}\, \sigma_{f235}\, \varphi_n = E_f\, N_{U3Si2}\, \sigma_{f235}\, \varphi_n$ (3 pts)

$N_{U3Si5} = N_{U3Si2}$ (3 pts)

$q_1\, \delta_{U,U3Si5} / M_U = q_2\, \delta_{U,U3Si2} / M_U$ (3 pts)

$q_1 = q_2\, \delta_{U,U3Si2} / \delta_{U,U3Si5}$ (2 pts)

q1 = 11.31*0.03/7.5 = 0.0452 (1 pt)

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

U3Si5 is a worse fuel because it has a lower density of Uranium and will produce less power, and because it has a lower thermal conductivity and will conduct the heat out less efficiently.

2 – for worse fuel
3 – lower thermal conductivity
3 – lower power generation

Question 2:

Consider a fuel rod with a pellet radius of 4.5 mm, a 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/(cm^2 K).

a) What is the surface temperature of the fuel rod? (10 points)

2 – TCO
3 – TCI
3 – kgap
2 – Ts

TCO = Tcool + LHR/(2πRf hcool) = 580 + 250/(2*pi*0.45*2.5) = 615.4 K

TCI = TCO + LHR/(2 π Rf kclad/tclad) = 615.4 + 250/(2*pi*0.45*0.17/0.06) = 646.6

kHe = 16e-6*TCI$^{.79}$ = 0.00266 W/cmK, kXe = 1.16e-4 W/cmK

kgap = 0.00266^(1-.05)*(1.16e-4^0.05) = 0.00227 W/cmK, hgap = 0.2838 w/cm2K

Ts = TCI + 250/(2 π Rf kgap/tgap) = 646.6 + 250/(2*pi*0.45*0.00227/80e-4) = **958.2 K**

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? (20 points)

6 – Correct DT
*6 – Sigma**
4 – Correct hoop and radius
4 – sigma_tt

DT = 250/(4πk) = 250/(4*pi*0.2) = 99.5 K

σ* = αE(ΔT)/(4(1-ν)) = 7.5e-6*246.7*99.5/(4(1-0.25)) = 0.0614 GPa

σθθ(r/Rf=1) = - σ* (1 – 3 η^2) = - 0.0491*(1-3) = 123 MPa

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

Higher, because the temperature difference would be much higher due to the much lower thermal conductivity

2 pts for higher, 3 pts for reason

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

Axisymmetry, long rod, **properties are independent of temperature**, constant Q, constant Tcool, steady state, static body, gravity was neglected, no shear stress

At least five assumptions are required. One point for each assumption.

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)

-3 – constant stress across r
-2 Some others

Small strains,
isotropic material response
That the stress is constant through the thickness of the cylinder

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

$\sigma_{rr} = - p/2 = -3$ MPa
$\sigma_{\theta\theta} = pR/\delta = 6(5.6/0.6) = 56$ MPa
$\sigma_{zz} = pR/2\delta = 6\ (5.6/1.2) = 28$ MPa

2 pts each for equations
4 pts for correct values

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)

Ri = 5.6-0.3 = 5.3 mm, Ro = 5.6+0.3 = 5.9 mm
For r = Ri, $\sigma_{\theta\theta} = p\ ((Ro/Ri)^2 + 1)/(Ro/Ri)^2 – 1) = 6*((5.9/5.3)^2 + 1)/((5.9/5.3)^2 – 1) = 56.2$ MPa
For r = Ro, $\sigma_{\theta\theta} = p\ ((Ro/Ro)^2 + 1)/(Ro/Ri)^2 – 1) = 6*(1 + 1)/((5.9/5.3)^2 – 1) = 50.2$ MPa
The stress varies by more than 10% across the thickness, so it is not very accurate. The thin walled answer is close at the inner radius but too high at the outer radius. It would be conservative because it is too high except near the inner surface.

4 – Checked value at multiple pts
4 – Correct evaluations
2 – Correct reasoning

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)

$$\sigma = \begin{bmatrix} -3 & 0 & 0 \\ 0 & 28 & 0 \\ 0 & 0 & 56 \end{bmatrix}$$

2 – Stress tensor
6 – Strains
2 – Strain tensor

$\varepsilon_{rr} = 1/E(\sigma_{rr} – \nu\ (\sigma_{\theta\theta}+ \sigma_{zz})) = 1/70e3*(-3 – 0.41*(28 + 56)) = -53e-5$
$\varepsilon_{\theta\theta} = 1/E(\sigma_{\theta\theta} – \nu\ (\sigma_{rr}+ \sigma_{zz})) = 1/70e3*(56 – 0.41*(-3 + 28)) = 65e-5$
$\varepsilon_{zz} = 1/E(\sigma_{zz} – \nu\ (\sigma_{\theta\theta}+ \sigma_{rr})) = 1/70e3*(28 – 0.41*(-3 + 56)) = 9e-5$

$$\epsilon = \begin{bmatrix} -53 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 65 \end{bmatrix} \times 10^{-5}$$