87/100

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NUCE 497 Final Exam

-3, 22/25

Question 1

1. The fuel has just been heated up in the reactor for the first time. The increase in all temperatures and burnup = 0 indicate this. The fuel has immediately expanded from its fabrication dimensions due to thermal expansion as the fuel is heated to operating temperature.

   The gap has just shrunk from its fabrication size to the designed operating width of 40 microns, as evidenced by the immediate drop in the Gap Width plot. This is due to fuel expansion above.

   The cladding is beginning to oxidize from being exposed to water, but there has been no time for a significant effect yet. It heats up due to the reactor being turned on.

2. The fuel temperature peaks due to maximum gap width, which reduces thermal conductivity. The fuel pellets have shrunk due to densification, which is what caused this. Densification typically stops around 5 MWd/kg U, which matches this point the plot. Solid and gaseous fission product swelling are occuring, and irradiation defects are building up. Beyond this point, together they will overcome the effect of further densification and cause net swelling.

   Gap width has increased to a maximum value due to early densification of the fuel pellet as described above and potential cladding creep and growth described below.

   Cladding is being oxidized and hydrogen pickup is occurring, but there are no signs of it here. Thermal and irradiation creep, as well as irradiation defects that cause growth, could be causing the cladding to expand, further reducing the gap. However I think this effect must be small because the cladding inner surface temperature is constant, suggesting an insignificant change in cladding conductivity.

3. The fuel pellets are expanding and showing signs of corner swellings due to FP and irradiation defect buildup. Centerline temperature is dropping because the gap is shrinking. Fuel surface temperature is dropping faster due to temperature dependence of thermal conductivity in the fuel.

   Gap is filling with fission gasses that reduce its thermal conductivity, but this effect is overcome by gap shrinkage due to fuel pellet expansion.

   Cladding as before.

4. PCMI occurs (gap width = 0). Centerline temperature oscillates as the pellet deforms. The variable centerline and surface temperatures may be due to bonding between fuel and clad, and fuel fracturing with pieces shifting about.

   Gap has shrunk to nothing and continues to be that way hereout.

   -2, Fission gas release causes T increase before gap closure

   Cladding is touching fuel. Probably still expanding, though this isn't shown by cladding inside temperature. Possibly the grains aren't aligned for radial expansion. This would explain the complete lack of change in inner clad surface temperature.

5. PCMI continues. The fuel is likely bonding and fracturing further, causing thermal conductivity of the fuel to drop.

   Gap doesn't exist.

   Cladding presumably has picked up significant H2 and oxidation layer, though there isn't a sign of it. U-Zr-O chemical reactions may be occurring throughout the PCMI (stage 4 and 5).

   -1, Fuel k decreases with burnup (fission product buildup), so T increases

-5, 25/30

Question 2 (30 points)

A fuel pellet with an average grain size of 8 microns is irradiated with a volumetric neutron flux of 2.0e13 fissions/(cm³ s). Assume the pellet is at a uniform temperature of 900 °C.

a) What is the fission gas diffusion coefficient at this temperature? (5 pts)

$$D_1 = 7.6E\text{-}6\, e^{\frac{-3.03}{8.617E\text{-}5\, T}} = 7.28E\text{-}19 \ cm^2/s$$

$$D_2 = 1.41E\text{-}21\, e^{\left(\frac{-1.19}{8.617E\text{-}5(900+273)}\right)} \cdot \sqrt{(2E13)} = 4.86E\text{-}20 \ cm^2/s$$

Double check?

$$D_3 = 2E\text{-}36\,(2E13) = 4E\text{-}23 \ cm^2/s$$

$$D = \sum_1^3 D_i = \boxed{7.76E\text{-}19\, cm^2/s}$$

These equations are from an old slide with typos

D = 8.94e-17 cm2/s

b) How many gas atoms/cm³ are released from the fuel after 2 years of irradiation? Assume the chain yield y = 0.3017. (10 pts)

$$N_{gas\,prod} = y \cdot \dot{F} \cdot t = .3\,(2E13) \cdot 2yr \cdot \frac{60.525600\,s}{yr}$$

$$= 3.81E20 \ cm^{-3}$$

$$f = 4\sqrt{\frac{Dt}{\pi a^2}} - \frac{3}{2}\frac{Dt}{a^2}; \quad a = 8\mu m$$

$$= 4\sqrt{\frac{7.76E\text{-}19\,(60.525600 \cdot 2)}{\pi \cdot 8E\text{-}6}} - \frac{3}{2}\frac{(7.76E\text{-}19)(60.525600) \cdot 2}{(8E\text{-}6)^2} =$$

-1, Calculate tau to see which eqtn to use

$$= 0.0049$$

$$N_{gas\,gap} = N_{gas\,prod} \cdot f = 3.81E20 \cdot .0049 = \boxed{1.88E18 \ cm^{-3}}$$

c) After 2 years of irradiation, the pellet is removed from the reactor and from its cladding, venting all released gas. It is then moved to a furnace and annealed at 2000 °C. Estimate how long before 10% of the gas trapped in the pellet is released. How many gas atoms/cm³ will have been released during this time? (15 pts)

$$f_{anneal} = 6\sqrt{\frac{Dt}{\pi a^2}} \Rightarrow t = \left(\frac{f_a}{6}\right)^2 \cdot \frac{\pi a^2}{D}$$

-4, D needs to be recalculated at T = 2273 K

$$* \ D_{Xe} \sim 8E\text{-}15 \ cm^2/s$$

* Assume grain size back to 8 μm due to annealing

$$t = \left(\frac{.1}{6}\right)^2 \cdot \frac{\pi\,(8E\text{-}4)^2}{8E\text{-}15}$$

$$= 6.98E4\,s$$

$$(3.81E20 - 1.88E18) \cdot (0.1) = \boxed{3.79E19\, cm^{-3}}$$

$$= \boxed{19.4 \ hrs}$$

Problem 3 (30 points) -3, 27/30

A ZIRLO cladding tube is in reactor at 600 K for one year. The initial wall thickness is 0.6 mm.

a) What is the oxide weight gain in mg/dm^2 after this time? (10 pts)

$$t^* = 6.62E{-7}\ e^{\wedge}\left(\frac{11949}{600}\right) = \underline{295.01}\ \text{days}$$

$$\delta^* = 5.1\ e^{\wedge}\left(\frac{-550}{600}\right) = \underline{2.04}$$

$$K_L = 7.48E6\ e^{\wedge}\left(\frac{-12500}{600}\right) = \underline{6.68E{-3}}$$

$$\delta = 2.04 + 6.68E{-3}\,(365 - 295.01) = \boxed{2.51\ \mu m}$$

-2, I asked for wgt gain not thickness

b) What is the ZIRLO wall thickness after this time? (5 pts)

PBR=1.56 ~~0.6 mm + 2.51 μm =~~

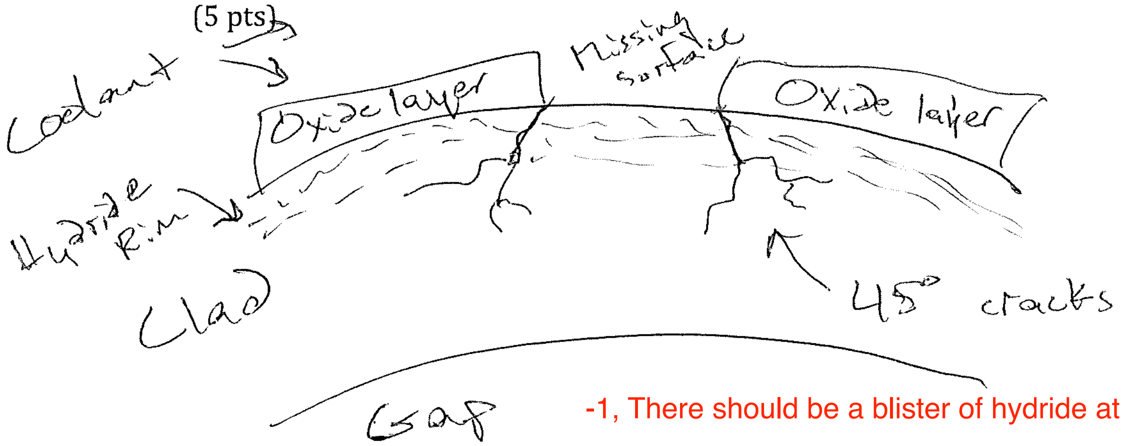
$$t_{clad} = 600\,\mu m - \frac{2.51\,\mu m}{1.56} = \boxed{598\ \mu m}$$

c) Assuming the hydrogen pickup fraction is 15%, what is the weight PPM of hydrogen in the cladding after one year? (10 pts)

$$C_H = \frac{2 \cdot f_H \cdot \delta \cdot \rho_{ox} \cdot F^{O}_{ZrO_2} \cdot M_H/M_O}{\left(t - \frac{\delta}{PBR}\right) \cdot \rho_{metal}} \cdot 10^6 = \frac{2 \cdot .15\,(2.51\,\mu m) \cdot 5.68 \cdot 0.26 \cdot \frac{1}{16} \cdot 10^6}{598 \cdot 6.5}$$

$$= \boxed{17.9\ \text{wt ppm}}$$

d) Draw a section of the cladding, showing the various microstructure changes (5 pts)



-1, There should be a blister of hydride at the missing oxide

-2, 13/15

Problem 4 (15 points)

a) What are the primary differences between a loss of coolant accident and a reactivity insertion accident, regarding the fuel and cladding behavior? (5 pts)

LOCA: Breakaway oxidation in clad, rapid H_2 pickup in clad, Relocation in fuel

-2 RIA must faster than LOCA

RIA: More severe fission gas release effects due to sudden production (cracking more likely), (Rim structure altered)

b) What are similarities between the fuel and cladding behavior in a RIA and a LOCA? (5 pts)

- Both can cause clad ballooning/bursting
- Both result in $\alpha \rightarrow \beta$ in Zr clad ⇒ ↓ clad ductility
- Both can cause fission gas release from fuel → clad → environment
- Both driven by failed T/H, though cause is different

c) List a potential accident tolerant fuel concept and describe how it could meet the primary goal of the accident tolerant fuel program. (5 pts)

Zr clad sleeve - protects against oxidation to improve heat transfer outside, and softens PCMI effects + limits U-Zr-O_2 interactions inside. This meets the ATF goals of reducing steam reactions, improving mech properties of clad, and retaining FP's (by improving PCMI response)