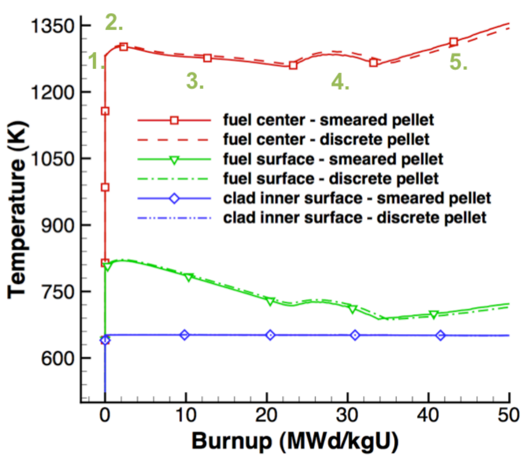
98/100

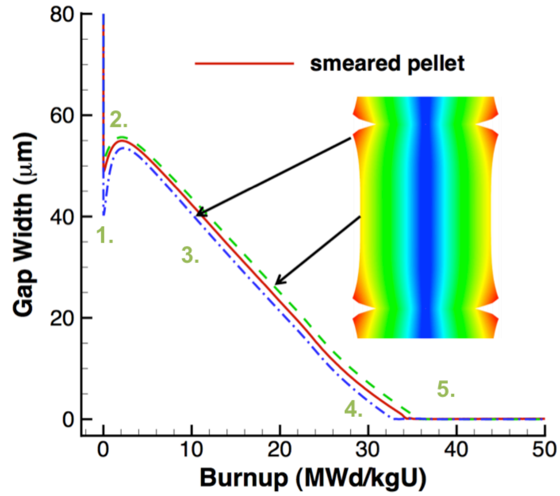
NucE 497 Fuel Performance Exam 2 covering modules 4 – 6

Name

Question 1 (25 points):

The temperature and gap width of a fuel pellet, as predicted by a fuel performance code, is shown below. Using the plots as your guide, determine what is currently occurring within the cladding, gap, and pellet at each number. Note that the numbers are at the same burnups on the two plots.





For each number, describe what is occurring in the cladding, gap, and pellet. Also, describe what features in the plots indicated these behaviors.

1.

2.

3.

4.

5.

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/(cm^3 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)

b) How many gas atoms/cm^3 are released from the fuel after 2 years of irradiation? Assume the chain yield y = 0.3017. (10 pts)

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/cm^3 will have been released during this time? (15 pts)

Problem 3 (30 points)

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)

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

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

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

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)

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

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)

Josh
Bowman
NucE 497

Exam 2

-2, 23/25

Features:
• Sudden onset of temp. and gap change at zero burnup

1) ① => This is the initial Startup of the reactor, as it is at 0 Burnup. At this point, the fuel and cladding rise to their initial operating temperatures. The rise in temperature results in thermal expansion of the fuel, making the gap smaller. Additionally, the fuel cracks due to the newly introduced temperature gradient. Both fuel and cladding begin experiencing radiation effects.

Features:
• Temp. spike
• Gap peak

② => At low burnups, the fuel densifies, closing most porosity from production. The shrinking fuel causes an increase in gap size until maximum density is reached, hence the peak in gap width. Additionally, the cladding is still largely unchanged, as shown by the blue line in the temperature diagram. Additionally, the larger gap results in worse heat transfer and a temperature peak.

Features:
• Decreasing gap width
• Decreasing temp.

③ => The gap width is decreasing, showing that fuel swelling now dominates since densification is complete and the fuel continues to be irradiated. The temperature increases due to the shrinking gap which actually improves heat transfer. The cladding continues to experience some minor creep and growth, but maintains at a steady temperature

Features:
• blue gap line reaches zero
• remaining gap still above zero
• Temp. plateau

④ => The gap is so small that the edges of the fuel make contact, resulting in bambooing of the cladding, forming ridges where the fuel contacts. The temperature also plateaus due to balancing of decreasing fuel conductivity and the increased gap conductivity as the fuel continues to experience swelling.

-2, Fission gas release raises temperature before gap closure

Features:
• no gap
• increasing temp.

⑤ => The fuel makes full contact with the cladding, causing full pellet-clad-mechanical-interaction. The gap conductivity is maximized while the fuel conductivity continues to decrease, resulting in increasing temperature in the fuel.

Note: Cladding temp. const. throughout due to small thickness and assumed constant coolant temp.

$K_b = 8.617 \times 10^{-5}$ eV/K

-0, 30/30

Exam 2

(2) $\dot{F} = 2.0 \times 10^{13}$ f/cm^3 s $T = 900°C$ $a = 8$ μm $T = 1173.15$ K

a) $D = D_1 + D_2 + D_3$

$D_1 = 7.6 \times 10^{-6} \cdot \exp(-3.03/K_bT) = 7.305 \times 10^{-19}$ cm^2/s

$D_2 = 1.41 \times 10^{-18} \cdot \exp(-1.19/K_bT) \cdot \sqrt{\dot{F}} = 4.868 \times 10^{-17}$ cm^2/s

$D_3 = 2.0 \times 10^{-30} \cdot \dot{F} = 4 \times 10^{-17}$ cm^2/s

$\boxed{D = 8.941 \times 10^{-17} \text{ cm}^2/\text{s}}$

b) $y = .3017$

$N_{gen} = y\dot{F}t = (.3017)(2.0 \times 10^{13}\ \text{cm}^{-3}\text{s}^{-1})(63072000\text{s}) = 3.806 \times 10^{20} \frac{\text{gas atom}}{\text{cm}^3}$

$\tau = Dt/a^2 = (8.941 \times 10^{-17}\ \text{cm}^2/\text{s})(63072000\text{s})/(8 \times 10^{-4}\ \text{cm})^2 = .0088$

$\pi^{-2} = .1013 \therefore \tau < \pi^{-2}$

$\therefore f_1 = 4\sqrt{\frac{Dt}{\pi a^2}} - \frac{3}{2}\frac{Dt}{a^2} = .1986$

$N_{release} = f_1 \cdot N_{gen} = \boxed{7.56 \times 10^{19} \text{ atoms/cm}^3 \text{ released}}$

c) $f_2 = .1$ $T = 2273.15$ K $\dot{F} = 0$

$\therefore D = 7.6 \times 10^{-6} \cdot \exp(-3.03/K_b(2273.15K)) = 1.45 \times 10^{-12}$ cm^2/s

out-of-pile, assuming $\tau < \pi^{-2}$

$f_2 = .1 = 6\sqrt{\frac{Dt}{\pi a^2}} - 3\cancel{\frac{Dt}{a^2}}^{\to 0}$ assuming very low time

$f_2 = .1 = 6\sqrt{Dt/\pi a^2} \therefore \frac{.01}{36} \cdot \frac{\pi a^2}{D} = \boxed{t = 385.185}$

$N_{gas,i} = (1 - f_1) \cdot N_{gen} = 3.05 \times 10^{20}$ atoms/cm^3

$N_{release,anneal} = f_2 \cdot N_{gas,i} = .1 N_{gas,i} = \boxed{3.05 \times 10^{19} \text{ atoms/cm}^3 \text{ released annealing}}$

-0, 30/30

Exam 2

3) $T = 600K$ $\quad$ $thick_i = .6\ mm$ $\quad$ $t = 1yr = 31536000\ s$

a) $t^* = 6.62 \times 10^{-7} \cdot \exp(11949/600K) = 295$ days

$\delta^* = 5.1 \cdot \exp(-550/600K) = 2.04\ \mu m$

$K_L = 7.48 \times 10^6 \cdot \exp(-12500/600K) = .0067\ \mu m/d$

$\delta = \delta^* + K_L \cdot (t - t^*) = 2.04\ \mu m + .0067 \frac{\mu m}{d} (365 - 295) d$

$\delta = 2.51\ \mu m$

$w = 14.7 \cdot \delta = 36.9\ mg/dm^2$

$\boxed{w = 36.9\ mg/dm^2}$

b) $PBR = 1.56$

$\Delta thick = \delta/1.56 = 1.61\ \mu m$

$\therefore thick_F = thick_i - \Delta thick = 600\mu m - 1.61\mu m$

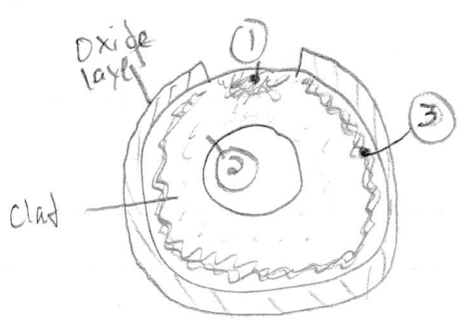
$\boxed{thick_F = 598.39\ \mu m}$

c) $f = .15$ $\quad$ $\rho_{ox} = 5.86\ g/cm^3$ $\quad$ $f^0_{ZrO_2} = .26$ $\quad$ $M_H = 1$ $\quad$ $M_O = 16$ $\quad$ $\rho_{metal} = 6.5\ g/cm^3$

$$C_H^{clad} = \frac{2 \cdot f \cdot \delta \cdot \rho_{ox} \cdot f^0_{ZrO_2} \cdot M_H/M_O}{(t - \delta/PBR) \cdot \rho_{metal}} = \frac{2(.15)(2.51\ \mu m)(5.68\ g/cm^3)(.26)(1/16)}{(598.39\ \mu m) \cdot (6.5\ g/cm^3)} \times 10^6$$

$\boxed{C_H^{clad} = 17.9\ wt.\ ppm}$

d)



(1) => Hydride blister from increased Soret effect and solubility effects due to low temperature where oxide layer breaks

(2) => Interior region is hotter, leading to higher hydrogen solubility and hydrogen diffusing toward colder regions

(3) => Lower temperatures near outside lead to more precipitation of hydrogen and diffusion of hydrogen towards the outside

-0, 15/15

Exam 2

4) a)

RIA	Differences	LOCA
• Rapid expansion of fuel		• Slow increase in temperature
• Can be sudden enough that cladding temperature remains fairly constant		• Cladding affected at similar rate and also first since it contacts coolant
• No clad phase change		• Phase transformation of clad. ($\alpha \to \beta$)
• No rapid hydrogen pickup		• Rapid hydrogen pickup
• No breakaway oxidation		• Breakaway oxidation in cladding
• Damage mainly from PCMI		• Damage mainly from lack of cooling /melting

b)

RIA	Similarities	LOCA
• Can result in clad ballooning if low enough temp. gradient		• Can result in ballooning without enough coolant flow and decreased coolant pressure
• Shatters fuel from gradient		• Can shatter fuel with fuel relocation
also burst → • Can result in fuel dispersal	←	Same as RIA
• High Burnup fuel behaves worse	←	Same as RIA
• Possible to have no failure	←	Same as RIA

c) Advanced Steel (FeCrAl) is a concept for replacing cladding material as an accident tolerant fuel. It could meet the goal of tolerating loss of active cooling for a considerably longer period. This primarily due to its safety characteristics of high strength, high ductility, corrosion resistance and low creep. It would struggle to fulfill the second part of the main goal of maintaining or improving performance in normal operation due to its substantially higher neutron cross-section