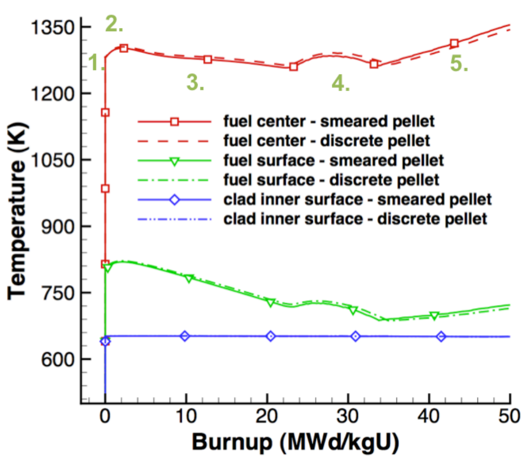
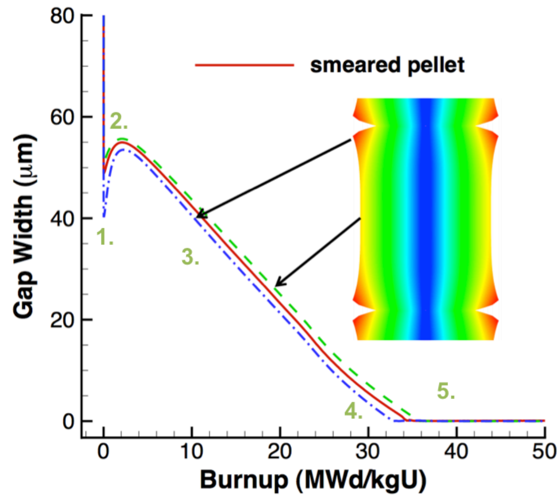
TOTAL TIME : 75 mins

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. Fuel temperature increases due to fission causing gap width to decrease due to thermal expansion. This can be seen in fig.2

2. Thermal expansion of the fuel decreases the fuel temperature slightly. Afterwards, fuel densification occurs Therefore, gap width increases slightly which can be seen in fig 2.

3. Fission gas concentration builds up and causes fuel swelling in addition to the thermal expansion. Therefore, gap width decreases. This reduction can be seen in Fig.2. As gap width decreases fuel temperature also decreases due to better heat transfer. However, clad inner surface temperature remains constant.

4. Thermal expansion of the fuel causes fuel pellet to change its shape similar to hourglass such that the corners of the fuel pellets sticking out to the cladding while the sides bowing inwards resulting the gap width to increase as indicated in the schematical representation of the fuel pellet. Therefore, fuel temperature increases. At some point, gap is fully closed and pellet mechanically interact with the cladding which causes the reduction of fuel temperatures.

5. Due to the high irradiation, fuel temperature increases as thermal conductivity of the fuel decreases, even though gap is closed.

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) to a burnup of 30 MWd/kgU. Assume the pellet is at a uniform temperature of 900 °C.

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

$$D = D_1 + D_2 + D_3$$

$$\to 2\times10^{-30}\,\dot{F} = 2\times10^{-30}(2\times10^{13}) = 4\times10^{-17}\ \text{cm}^2/\text{s}$$

$$\to 1.41\times10^{-18}\exp\left[-\frac{1.19}{(8.62\times10^{-5})(1173)}\right]\sqrt{\dot{F}} = 4.89\times10^{-17}\ \text{cm}^2/\text{s}$$

$$\to 7.6\times10^{-6}\exp\left[-\frac{3.03}{(8.62\times10^{-5})(1173)}\right] = 7.382\times10^{-19}\ \text{cm}^2/\text{s}$$

$$= 7.382\times10^{-19} + 4.89\times10^{-17} + 4\times10^{-17} = \boxed{8.955\times10^{-17}\ \text{cm}^2/\text{s}}$$

b) How many gas atoms/cm^3 are released from the fuel after 2 years of irradiation? (10 pts)

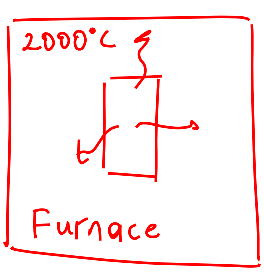
$$N_{released} = f\,\dot{F}\,t \quad \text{where} \quad t = 2\times365\times24\times3600\ \text{s}, \quad \dot{F} = 2\times10^{13}\ \text{fission/cm}^3\cdot\text{s}$$

$$f = 4\sqrt{\frac{Dt}{\pi a^2}} - \frac{3}{2}\frac{Dt}{a^2} = 4\sqrt{\frac{(8.95\times10^{-17})(63072000)}{\pi\,(8\times10^{-4})^2}} - \frac{3}{2}\frac{(8.955\times10^{-17})(63072000)}{(8\times10^{-4})^2}$$

$$= 0.199$$

$$= (0.199)(2\times10^{13})(63072000) = 2.51\times10^{20}\ \text{atom/cm}^3$$

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. How long before 50% of the gas trapped in the pellet is released? How many gas atoms/cm^3 will have been produced at this time? (15 pts)



$$N_{released} = N_{produced}/2 = \dot{F}t/2$$

$$f\dot{F}t = \dot{F}t/2 \longrightarrow f = 0.5$$

For post irradiation annealing:

$$f \cong 6\sqrt{\frac{\boxed{D}t}{\pi a^2}}, \quad D \to D_1 + \underbrace{D_2 + D_3}_{=0 \text{ since } \dot{F}=0}$$

$$D_1 = 7.6\times10^{-6}\exp\left[-\frac{3.03}{(8.62\times10^{-5})(2273)}\right] = 1.46\times10^{-12}\ \text{cm}^2/\text{s}$$

$$0.5 = 6\sqrt{\frac{1.46\times10^{-12}\,t}{\pi\,(8\times10^{-4})^2}} \Rightarrow t \cong 9557\ \text{s or } 2.65\ \text{hr}$$

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 hydrogen pickup in mg/dm^2 after this time? (10 pts)

Oxide Transition $\Rightarrow t^* = 6.62\times10^{-7}\exp\left[\frac{11949}{600}\right] = 295\text{ d} \rightarrow \delta^* = 5.1\exp\left[\frac{-550}{600}\right] = 2.04\,\mu m$

$$\delta = \delta^* + K_L[365-295] \quad \text{where} \quad K_L = 7.48\times10^6\exp\left[\frac{-12500}{600}\right] = 6.7\times10^{-3}$$

$$= 2.51\,\mu m$$

$$W = \delta\times14.7 = 2.51\times14.7 = 36.9\text{ mg/dm}^2$$

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

$$\delta_{Zr} = 600 - \frac{\delta}{PBR} = 600 - \frac{2.51}{1.56}$$

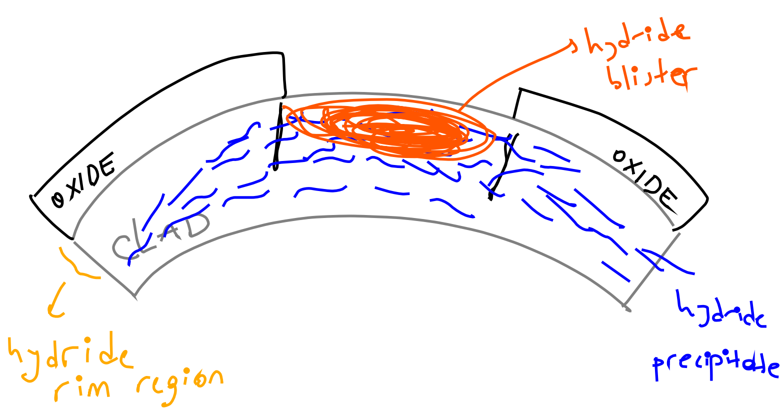
$$= 598.4\,\mu m$$

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

$$f = \frac{2f\times\delta\times\rho_{oxide}\times f_{ZrO_2}\times M_H/M_m\times10^6}{\left(t-\frac{\delta}{PBR}\right)\times\rho_{metal}} = \frac{2\times0.15\times2.51\times5.68\times0.26\times1/16\times10^6}{\left(600-\frac{2.51}{1.56}\right)\times6.5}$$

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

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)

In LOCA, heat cannot be removed to the coolant. Therefore, fuel and clad temperature and internal pressure increase resulting ballooning and burst, enhanced corrosion and more hydrogen pickup.
In RIA, fuel thermally expands in milliseconds due to the large and rapid insertion of reactivity resulting rapid fission gas production, pellet clad mechanical interaction and ballooning.
(Note that RIA is much faster compared to the LOCA)

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

In both case, the temperature of fuel and clad increases and may cause fuel failure via ballooning, even though the behavior of the fuel and clad 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)

- Cladding coatings,
- Thin walled high strength steel alloy cladding,
- High performance UO_2,
- Moly claddings,
- High density fuels,
- Ceramic claddings,
- High fission product redention.

ATF have high tolerance to loss of active cooling for a considerable longer period while maintaining or improving performance during the normal operation.
This will be achieved by
- improving reaction kinetics with steam (i.e., decreased heat of oxidation, lower oxidation rate, lower hydrogen pickup which reduce hydrogen embrittlement etc.),
- improving cladding properties (i.e., resilience to clad fracture, thermal shock resistance, higher cladding melt temperatures, etc.)
- improving fuel properties (i.e., minimized cladding internal oxidation, minimized fuel relocation/dispersion, higher fuel melt temperatures etc.),
- enhancing fission product retention