# NE 533 Final Exam

1. Zirlo cladding, 625K, 400 days in rxr
   $t_0 = 500\ \mu m$

a) Oxide thickness after 400 days?

$$\delta = \delta^* + K_L(t - t^*)$$

$$K_L = 7.48\times10^6 \exp\left(\frac{-12500}{T}\right) = 0.015\ \mu m/d$$

$$\delta^* = 5.1 \exp(-550/T) = 2.115\ \mu m$$

$$t^* = 6.62\times10^{-7} \exp(11949/T) = 133\ d$$

$$t > t^*$$

$$\delta = 2.115 + (0.015)(400-133) = \boxed{6.23\ \mu m}$$

b) $f = .18$, $PBR = 1.56$, $\rho_{Zr} = 6.5\ g/cm^3$, $\rho_{ZrO_2} = 5.68\ g/cm^3$

$$C_H = \frac{2 f \delta \rho_{ox} f^0_{ZrO_2} \; m_H/m_O}{(t - \delta/PBR)\,\rho_m} \times 10^6$$

$$\delta(t = 365\ days) = 2.115 + (0.015)(365-133)$$
$$= 5.69\ \mu m$$

$$C_H = \frac{2(0.18)(5.69)(5.68)\left(32/91+32\right)(1/16)}{(500 - 5.69/1.56)(6.5)} \times 10^6$$

$$\boxed{C_H = 58.7\ wppm\ H}$$

2. The rate limiting step in the aqueas corrosion of Zr cladding is the diffusion of oxygen through the oxide to the Zr cladding. The diffusion process controls the reaction rate.

3. The Piling-Bedworth ratio is the ratio of the volume of the oxide formed to the volume of metal. This ratio gives us an idea of how stable the oxide is, with a PBR between 1 and 2 being ideal because it is likely to form a passivating layer.

4. Hydrides form in the rim of the cladding due to the nature of hydrogen to diffuse to lower temperatures (Soret effect) and to higher tensile stress (hoop stress in clad tubing maximum at rim). Hydrides are stress concentraters, and they are a brittle phase that can decrease ductility of the cladding. They also contribute to DHC (Delayed Hydride Cracking) upon fuel drying, where hydrogen diffuses to crack tips and forms brittle hydrides.

5. RIA, or Reactivity Insertion Accident, is a type of accident that occurs during large increases in reactivity. In a PWR, this is a CREA (control rod ejection accident) where the control rod is ejected up. In a BWR, this is called a control rod drop, where the rod becomes uncoupled from the drive, gets stuck, and falls out of the core.

During a RIA, there is a large power spike that increases the temperature of the system rapidly, especially at low power. This can lead to expansion of the pellet, fission gas release, and eventually the failure of the cladding. PCMI is also a concern with pellet expansion, and FGR can lead to greater SCC.

6. A LOCA (Loss of Coolant Accident) occurs during a pipe break when coolant is unexpectedly released. This decreases the coolant flow, and thus the amount of heat being removed from the fuel system. The loss of coolant pressure also causes the cladding to expand more in high temperature. This can lead to rupture/burst of the cladding, releasing high energy material to the coolant. While a RIA occurs in milliseconds, a LOCA takes a few minutes to occur. The ECCS may further embrittle the cladding by quenching the high temperature cladding.

2. Burnup impacts the type of failure by increasing the specific enthalpy of different failures. Irradiation can embrittle the cladding, help form brittle hydrides, and increase the amount of reactive oxygen for cladding oxidation through radiolysis.

8. Four pathways to make the fuel/cladding system more accident tolerant are:

- Resistance to loss of active cooling / TRISO SiC pellets
- Longer stability in high temperatures - cladding change FeCrAl
- More abrasion resistance of cladding - coatings
- Resistance to high temperature oxidation - Cr coating

9. When zirconium cladding is exposed to high temperatures, it can change phases. For instance, $\alpha \rightarrow \alpha + \beta$ at 863°C, and $\alpha + \beta \rightarrow \beta$ at 1000°C. A phase change can make the cladding easier incorporate soluble oxygen or hydrogen. The $\alpha$ phase can be stabilized at higher temperatures with oxygen, forming a brittle phase. The $\beta$ phase is ductile, but becomes less so with hydrogen ingress. At high enough temperatures, breakaway oxidation occurs, which greatly increases the oxidation rate and degrades the cladding.

10. Three limiting phenomenon governing LWRs are:
- PCMI (pellet cladding mechanical interaction)
- Cladding corrosion/oxidation
- Hydrogen/irradiation embrittlement
- BONUS - IGSCC

11. ~~What fue~~ CRUD impacts fuel performance by attaching to the cladding and degrading the heat transport from the pellet to the coolant. This can impact the safety of the system by increasing temperature. CRUD can also synergistically affect corrosion and SCC of the cladding by introducing impurities.

12. In LWRs, two controls to water chemistry that have been introduced are:
- Limiting oxygen ions in water to reduce oxidation
- Introducing Pt and other noble metals to reduce corrosion of reactor internals.
- BONUS - introducing more hydrogen to the water to balance oxygen ions: Hydrogen water chemistry