Alexandra Doherty

92

1. $T = 625\ K$ $\quad t = 400d$ $\quad t = \overset{500\ \mu m}{500 \times 10^{-4} cm} = 0.5\ cm$

18/18 a.) $\delta = ?$ $\quad \delta(\mu m) = \delta^* + K_L(t - t^*)$

$$(\mu m)\ \delta^* = 5.1 \exp\frac{-550}{T} = 5.1 \exp\frac{-550}{625} = 2.115\ \mu m$$

$$K_L\left(\frac{\mu m}{d}\right) = 7.48 \times 10^6 \exp\frac{-12500}{T} = 7.48 \times 10^6 \exp\frac{-12500}{625} = 0.0154\ \frac{\mu m}{d}$$

$$t^*(d) = 6.62 \times 10^{-7} \exp\frac{11949}{T} = 6.62 \times 10^{-7} \exp\frac{11949}{625} = 133.007\ d$$

$$\delta = \delta^* + K_L(t - t^*) = 2.115\ \mu m + 0.0154\ \frac{\mu m}{d}(400d - 133d)$$

$$= 2.115\ \mu m + 4.116\ \mu m$$

$$\delta = 6.231\ \mu m$$

→ thats like a lot right? actually its thick clad it may not be that bad... good PBR!!!

b.) $$C_H^{clad} = \frac{2 f \delta \rho_{oxide} f^o_{ZrO_2} \cdot m_H / m_O}{\left[t - \frac{\delta}{PBR}\right] \rho_{metal}} \times 10^6$$

$PBR = 1.56$ $\quad \rho_{Zr} = 6.5\ g/cc$ $\quad \rho_{ZrO_2} = 5.68\ g/cc$

$$f^o_{ZrO_2} = \frac{32}{32 + 91} = 0.26 \quad f = 18\%$$

$t = 0.5\ cm$

$$C_H^{clad} = \frac{2(0.18)(5.68\ g/cm^3)(\overset{\delta}{6.231 \times 10^{-4} cm})(0.26)(\frac{1}{16}) \times 10^6}{\left[0.5_{cm} - \frac{\overset{\delta}{6.231 \times 10^{-4}\ cm}}{1.56}\right](6.59/cm^3)(16\ g/mol)}$$

$m_H = 1$ or 2, $m_O = 16$ or 32 but same thing

~~$\delta = 6.231 \times 10^{-4}$ cm $t = 0.5$ cm~~

$$C_H^{clad} = \frac{2(0.18)(\overset{5.692}{\cancel{6.231}} \times 10^{-4} cm)(5.68\ g/cm^3)(0.26)\left(\frac{1 g/mol}{16 g/mol}\right)}{\left[0.5 cm - \frac{\overset{5.692}{\cancel{6.231}} \times 10^{-4} cm}{1.56}\right](6.5\ g/cm^3)} \times 10^6$$

$\delta = \delta^* + K_L(365 - 133)$

$\delta = 5.692\ \mu m$
$= 5.692 \times 10^{-4}\ cm$

~~$C_H^{clad} = \frac{2.07 \times 10^{-5}}{3.24774} \times 10^6 = 6.376$ wt ppm~~ $= \boxed{C_H^{clad} = 6.376 \text{ wt. ppm}}$

got me for a sec

☹ ☺

$$C_H^{clad} = \frac{1.891 \times 10^{-5}}{3.24976} \times 10^6 \quad \boxed{C_H^{clad} = 5.82 \text{ wt. ppm}}$$

- off by factor of 10
- don't know where...

Alexandra Doherty

2. Diffusion of Oxygen - through the oxide layer

3/4

3. PBR is the ratio of $\frac{M_{oxide} \rho_{metal}}{n \cdot M_{metal} \rho_{oxide}}$ and tells the thickness of the oxide layer relative to the metal Zr

4/4

$<1 \rightarrow$ thin uniform oxide layer, minimal protection, likely broken

$1 < PBR < 2 \rightarrow$ passivating oxide layer

$>2 \rightarrow$ thick and oxide may chip off, not much protection

4. Hydrides form within the ~~oxide layer on the~~ cladding due to the radiolysis or oxidation reaction with water $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$. They form 2x as much as oxides do (more fraction) -twice the H is made, but H pickup is like 1/6 hydrides can be radial / circumferential and migrate towards high stress → which leads to Appt at the crack tip. Hydrogen is more brittle than ductile Zr, and causes hydride embrittlement. → hydrides... H embrittlement decreases ductility of the fuel clad and leads to further crack propagation

10/14

- hydride rim, Soret diffusion

5. RIA = Reactivity Initiated Accidents → large/rapid insertion of reactivity caused by ejection (PWR) or drop (BWR) of a control rod. This causes a rapid decrease in n adsorption of non-fuel and increasing reactivity leads to a rapid power spike / Rise in Temp. A fuel rod failure can also include radioactive material being released into coolant, causing rapid steam generation and pressure pulses which can damage the core / break internal pressure boundary

11/14

PWR → ejection of control rod BWR → drop control rod

-needed more of what happens to the material

Alexandra Doherty

6. LOCA → loss of coolant Accident → Different from RIA because it has a longer time scale (minutes) opposed to Severe RIA (0-1s) so there is a better chance at recovery.

LOCAs occur when a pipe bursts or something else occurs obstructing coolant flow lowering P coolant. This leads to a T↑ which increases FG/FP release rate, increasing pressure and thorm expansion. ↑ Temp also increases oxidation by increasing diffusion rate and because oxidation is exothermic, it begins to "self-oxidize" causing further O/H embrittlement, more cracks, and therefore more metal exposed for oxidation. ~~Pressure increase forced~~ As T↑, α phase of Zr transitions to more brittle β phase. With a decrease in ductility, increase in pressure, and increase in cracking, cladding balloons and eventually bursts, releasing fuel outside the cladding. Can be ~~prevented~~ mitigated with ECCS (which can quench rod and lead to fragmentation of oxide) limits in place to control allowed amount of oxidation (17%)

14/14

7. ductility is already reduced from H embrittlement, also experiences more corrosion/irradiation hardening. Although in a LOCA, could go to a higher temp before burst and retain ductility for longer due to lesser → slower change in T during LOCA. However T_m of fuel decreases in HBS (still < 2750°C? I think?) so it is important to incorporate a changing T_m into the design so there is no meltdown

4/5

- most of it

Alexandra Doherty

8. Improved reaction kinetics with steam → ductile Zr based clad, also FeCrAl for passivation layer from steam oxidation

8/8 Improved cladding properties → FeCrAl clad for formation of Al_2O_3 / ~~[illegible]~~ chromium Oxide passivation layer

Improved fuel properties → additives to ↑ thermal conductivity

Enhanced fission product retention → SiC → temp resistant

9. High T steam leads to ↑ oxidation rate → exothermic and oxidizes parabolically until oxide layer is thick and loses

4/6 passivation (PBR > 2) then linear/localized oxidation continues and breakaways can occur in oxides due to high strain paired with thick layer

- phase transitions

10. PCMI → when ~~[illegible]~~ pellet gap closes and cladding hoop stress increases when reactivity is high. Determine gap param. Can model FG pressure

6/6 Cladding oxidation / H pickup → H gen < 1% possible throughout clad

Oxide limit 17% to prevent further embrittlement

Normal operating limits → constraints on axial LHR to guarantee conditions dont exceed worst case

Alexandria Doherty

11. CRUD → Chalk River Unidentified Deposit
is corrosion products composed of dissolved ions or solid particles (Ni, Fe, Co) which degrade heat production because they are slowly eroded by circulation of hot pressurized
4/6 water. ~~Then~~ It can accelerate corrosion of cladding. halts fuel performance and limits cladding lifespan. Heavy CRUD buildup on fuel clad surfaces from corrosion product transport

- halfway

12. Coordinated Boron and Lithium → Boric Acid is used to control reactivity, LiOH is used conversely to balance the pH
6/6 so it is > 6.9, which is important because Ni/Fe solubility is pH dependent

Zn injection is used to reduce radiation fields / inhibit stress corrosion cracking. (BWR) ~~Znaq promotes a protective spinel structured corrosion film on SS~~ (Due to Zn aq promoting a protective spinel structured corrosion film on SS clad.
4/2 Corrosion products deposited on fuel, are activated and released into coolant) ← ignore if you want I could be overexplaining