① $T = 625K$ $t = 400$ days $\delta_{\substack{initial \\ cladding}} = 500\,\mu m$

Gwen White

$\boxed{80}$

a) • $t^* = 6.62\times10^{-7}\exp(11949/625K) = 133$ days ✓ $t > t^*$ ✓ ✓

• $\delta^* = 5.1\exp(-550/625K) = 2.12\,\mu m$ ✓

15/18 • $k_L = 7.48\times10^6\exp(-12500/625K) = 0.0154\,\mu m/day$ ✓

• $\delta = (2.12\mu m) + (0.0154\mu m/d)(400d - 133d) = \boxed{6.23\,\mu m}$ ✓

b) $f = 18\%$, $PBR = 1.56$, $\rho Zr = 6.5$ g/cc, $\rho ZrO_2 = 5.68$ g/cc $t = 365$ d

f specified in problem $f: 0.18$

if hydrogen is produced twice as fast as oxygen ⇒ oxygen $f = 0.09$ (?)

yes

$$C = \frac{2(0.09)(5.68)(0.2602)(0.0625)}{(500 - (6.23/1.56))(6.5)} \times 10^6 = \boxed{0.91 \text{ wt ppm}}$$

forgot to multiply by oxide thickness in numerator $\delta = K_L\, t^{1/2} = (0.0154)(365)^{1/2} = 0.29$

---

② Zr Corrosion: $Zr(s) \rightarrow Zr^{4+}(aq) + 4e^-$] oxidation

2/4 $Zr(aq)^{4+} + 2H_2O(l) \rightarrow ZrO_2(s) + 4H^+(aq)$]

$4e^- + 4H^+(aq) \rightarrow 2H_2$] reduction

The formation of the oxide layer I would think is rate limiting because the oxide layer has a lower thermal conductivity which would decrease the rate of heat transfer and diffusion.

Additionally, the initial oxide layer slows further oxidation (aka, passivation).

---

③ The Pilling-Bedworth Ratio (PBR) is the ratio of the volume of the oxide to the volume of the metal. It describes the protectiveness of the oxide. Ideally you would want a PBR value of $1 < PBR < 2$. This is where the oxide coating is a passivating layer and protects against further surface oxidation. Zirconium has a favorable PBR of ~1.56.

4/4

---

④ Circumferential hydrides align with the hoop stresses in the cladding during reactor operation. , Soret, tensile stress

Radial hydrides align with radial stresses and act as crack propogation pathways (after shutdown)

12/14 Since the oxide layer is more brittle than Zircaloy, hydrogens enter the cladding and form brittle hydrides. Hydrides can reduce ductility, form hydride rim/blisters, influence crack propogation, and impact diffusion time. Hydrides also reduce fracture toughness because they are brittle in Zr.

---

⑤ RIA is a reactor initiated accident. This involves a control rod ejection/drop from the core which leads to sudden power spikes. This can effect pellet expansion, fission gas release, PCMI, and fuel fragmentation. PWR vs BWR - needed more here...

10/14

---

⑥ LOCA is a loss of coolant accident. This occurs when an accident (such as a burst pipe) results in a loss of access to coolant. As a result, the fuel rod can overheat and cause the cladding to soften and balloon, which can cause the cladding to burst/fracture.

10/14 The difference between a LOCA and RIA is that a LOCA occurs during loss of coolant (aka high Temp) while RIA occurs during normal temperature and pressure. - needed more

---

⑦ At high burnup, the thermal conductivity drops, which reduces the power-to-melt margin, and increases the risk of overheating. This is because of the increase in fission gas release, which results in a thicker oxide layer, more hydrydes, and reduced ductility. This increases RIA failure susceptibility at lower enthalpy. - Seems a bit of word salad...

3/5

(8) Four ways to make fuel/cladding system more tolerant: - wrong list

1. near term: coatings on cladding and/or UO_2 additives
2. novel ATF: Introduce new materials (i.e. U_3Si_2 fuel, and/or FeCrAl cladding)
3. Transformational ATF: FCM fuel and/or SiC cladding
4. WATER Chemistry: maintain pH ~6.9, decrease CRUD

- decrease corrosion & H pickup
- good oxidation resistant
- Stable at high temp

3/8

→ FeCrAl form Al_2O_3 at high temp which forms a passivation layer and is a more stable oxide than Zircolay

(9) When Zirconium cladding is exposed to high temp steam, the high temperature increases the rate of diffusion and increases corrosion of the material. At high temperatures the heat from oxidation exceeds removal and begins to crack? This exposes more of the Zirconium metal, and generates more hydrides. - needed more

4/6

(10) 1. Fuel rod internal pressure: non-lift off criterion (i.e. cladding should not creep away from pellet.)

2. PCMI: pellet swelling and cladding contact causes local strain and possible failure.

3. Cladding oxidation: Must limit the thickness loss ~100 μm.

4/6

(11) CRUD (Chalk River Unidentified deposition) is essentially when Ni, Fe, or Co deposit onto cladding surface. This can result in heat transfer loss, boron accumulation, CRIP, and can increase oxide/promote hydride formation. CRUD is caused by the chemistry of the water used for coolant.

- safety? activation products

5/6

(12) 1. LiOH + Boric Acid can be added to water to maintain a pH ~6.9, while controlling reactivity.

2. Zn injection can be used to reduce stress corrosion cracking, limit radiation fields and corrosion, and decrease Co deposition.

4/4