Exam #3 Charles Cheron

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1) Zirlo, $T = 625$ K, $t = 400$ days, $t_0' = 500\,\mu m$.

a) oxide thickness $t^* = 6.62\times10^{-7}\exp\left(\frac{11949}{T}\right) \Rightarrow 133.06$ days

since $t = 400 > t^*$, $\delta = \delta^* + \delta^+$, where δ^+ is the post-transition oxide thickness

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$\delta = \underbrace{5.1\exp\left(\frac{-550}{T}\right)}_{\delta^*} + k_L(t - t^*)$, $k_L = 7.48\times10^6\exp\left(\frac{-12{,}500}{T}\right) \Rightarrow 0.015417$ um/day

$\delta = 2.1153\,\mu m + 0.015417(400 - 133.06\text{ days})$

$\delta = 2.1153\,\mu m + 4.1155\,\mu m \Rightarrow \boxed{\text{oxide thickness} = 6.2309\,\mu m}$

b) $\delta = 0.18$, $PBR = 1.56$, $\rho_{Zr} = 6.5\,g/cm^3$, $\rho_{ZrO_2} = 5.68\,g/cm^3$

Find weight ~~frac~~ of Hydride after 1 year

We know $M_H = 1$, $M_O = 16$, $M_{Zr} = 91$

t = cladding thickness = 500 um

* $\delta(1\text{ yr} = 365\text{ days}) = 2.1153\,\mu m + 0.015417(365 - 133.06) =$

$\underline{\delta = 5.69\text{ um}}$

~~$C_H = \frac{2\delta m_O}{m_{Zr}} = \frac{2\cdot\delta\cdot f^o_{ZrO_2}\times\frac{M_H}{M_O}}{\left(t - \frac{\delta}{PBR}\right)\rho_{Zr}}$~~

~~$f^o_{ZrO_2} = \frac{2\times M_O}{(2\times M_O + M_{Zr})} = \frac{2\times16}{(2\times16+91)} \Rightarrow 0.26 = f^o_{ZrO_2}$~~

~~Now solve $C_H = \frac{2\times(0.18)\times(6.2309\,um)\times(0.26)\times\frac{1}{16}}{\left(500\,um - \frac{6.2309\,um}{1.56}\right)\cdot 6.5\,g/cm^3}$~~

(~~Units are off.~~)

This was all right but missed $\times10^6$ for the eqn.

$C_H = \frac{2\times\delta\times m_O}{m_{Zr}}$, $\delta = 0.18$, $m_O = \frac{\delta\times w\times N_A}{M_O}$, $w = \ldots$

$f^o_{ZrO_2}\times\rho_{ZrO_2} = 0.26\times5.68\,\frac{g}{cm^3} = 1.47\,\frac{g}{cm^3}$ of Oxygen

so 1 um of oxide $\Rightarrow 14.7\,mg/dm^2 = W$

5.69E-3 dm

Thus $m_O = \frac{(5.69\,um)\times(14.7\,mg/dm^2)\times(6.022E23/mol)}{16}$

$m_O = 5.0389E22$

- then you went off the rails here...

$m_{Zr} = \rho_{Zr}\cdot V_{Zr}$, V_{Zr} = uncorroded thickness $\times$ cross-section,

uncorroded thickness = $\frac{500\,um - 5.69\,um}{PBR = 1.56} = 316.86$

Take cross section 10×10 cm $= 100$ cm

$V_{Zr} = 31{,}686\,\mu m^3$

Not sure where I lost it but I did.

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2). The rate limiting step in the aqueous corrosion of Zr cladding is the diffusion of
4/4 oxygen through the oxide layer (Step 3)

3) The Pilling-Bedworth Ratio is the ratio of oxide volume to metal volume of corroded material. It tells us whether a material is protected by the oxide & if the oxide layer is broken or chipped. If PBA ≤ 1, the oxide is thin, offers little to no protection & is likely broken. If
4/4 PBR > 2, the oxide is too thick, likely chipping, & offers little to no protection. If 1 ≤ PBR ≤ 2, the oxide is passivated & protects the metal from the environment

4) hydrides form on the cladding outside, either uniformly (most common), in deep blisters at localized portion of the cladding or shadowing larger components. They form following oxidation
12/12 that frees electrons, allowing a reduction of free hydrogen in the water. The hydrides will form because hydrogen has a low solubility in Zirconium, so a lower concentration of H is needed to form. Once formed, they migrate towards zones of high tensile stress, & towards lower temperatures (Soret Effect). Hydrides cause embrittlement, a loss of fracture toughness, accelerated corrosion, accelerated irradiated growth, & delayed hydride cracking.

5) A Reactivity Insertion Accident (RIA) is a design basis accident in LWRs where a large amount of excess reactivity is inserted into the reactor core. Typical RIAs in PWRs are Control Rod Ejections & for BWRs are Control Rod drops. A CR ejection is worst
12/12 at hot zero power & a CR drop is worst at Cold zero power. In an RIA, the sudden increase in reactivity cause an instant increase in fission rate & LHR, followed milliseconds later by increase in fuel temperature. The thermal expansion of the fuel rod & the plenum gases cause a rapid increase in rod internal pressure, & the fuel rod can fragment and/or disintegrate. The coolant quickly heats up & can reach DNB or critical point in BWRs, causing the coolant heat transfer coefficient to rapidly lower. This cause fuel temperatures to rise further, prompting fuel melt, cladding burst, & DNB safety limits to be met or exceeded. All in all, not a good time.

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6) A Loss of Coolant Accident (LOCA) occurs when the flow of coolant is interrupted by a break in the primary coolant loop. This causes system pressure to equalize to containment pressure & the flow of coolant over the fuel rods is slowed or stopped. With time, the LHR will cause the coolant in the core to evaporate, leading to DNB & dryout. This raises thermal design safety concern & can lead to fuel or cladding melt, cladding plastic deformation further restricting coolant flow through an assembly & even cladding rupture & ballooning. Biggest difference between an RIA & a LOCA is that in an RIA, there is always coolant available. In a LOCA, coolant loop is broken & unless coolant is continuously pumped from an outside tank, fuel elements could be uncovered.

10/10

- longer time for LOCA allows for oxidation + creep

7) 1) Improve fuel capabilities by increasing melting temperature, operating at lower temperature, Reduce fuel fragmentation, relocation, & dispersal, & reduce internal rod oxide formation.
For this, alternative fuels are proposed, for example USi, or UC

4/6

2) Improve Steam kinetics by reducing heat of oxidation, lowering oxidation rate, lowering hydrogen production, etc.
One way of doing this is adding coatings to the fuel, or using alternative cladding materials such as FeCrAl

8) When exposed to high temperature steam, Zirc cladding oxidizes more rapidly. This can cause breakaway oxidation, greatly embrittling the cladding & causing hydrogen accumulation in the reactor system.

6/6

9) To improve steam oxidation resistance in LWR cladding coatings that are more resistant to corrosion are suggested or new cladding materials or alloys like MS are offered that provide a greater corrosion resistance
Like SiC or FeCrAl.

4/4

10) Limiting phenomena include PCMI formation, & cladding wear @ contact points, as well as fuel cladding chemical interaction (FCCI), & fission gas release

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The PCMI causes transfer of mechanical force to transfer between pellet & cladding. At contact points between the cladding & Rx structure, the cladding can wear down & weaken. FCCI also causes corrosion issues due to oxide formation & hydrogen cracking. Fission Gas Release can cause rod internal pressure to increase to a point where the cladding ruptures.

- really this is just PCI, talked near end limit, e.g. internal pressure

11) CRUD is "Chalk River Unidentified Deposits", but now refers to an accumulation of foreign materials (e.g. Nickel, Iron, Cobalt) from outside the fuel Rod system on

5/6 the cladding surface. CRUD lowers the thermal conductivity at the rod surface, & can accelerate local irradiation rate due to the presence of radioactive isotopes such as Co-60 & Ni-63

- larger impact on radiation source in primary coolant

12) 2 Chemistry controls are [lithium hydroxide (?)] LiOH addition to the coolant & zinc injection to the coolant. The LiOH serves to keep the coolant alkaline with a pH of at least 6.9 to avoid crud build-up & the zinc is injected to eliminate rod buildup & clean the coolant. Zinc is preferentially taken over Co & Ni in the

6/6 tetrahedral lattice sites of stainless steel, so the Cobalt & Nickel stays in the coolant & has a greater chance of getting caught by the core coolant cleaning system.

13) MOX fuel has a smaller fuel radius, shorter fuel column height, & a larger plenum. Outside of the geometrical difference, MOX fuel has a higher metal density, much higher LHR, goes

7/9 to a higher burnup (~150 GWd/ton), & has a significantly higher flux than conventional light water reactors. They are also usually salt cooled/moderated & use Hexagonal fuel assemblies, though VVERs also use hex lattices. They go to higher temperatures than LWRs as well (~1800C for the max fuel pin temp.)

- phenomena that occur? restructuring, IDG, etc.