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103

1) $T = 625K$, $t = 400$ dy, $t_i = 500 \mu M$

a) δ after this time?

17/18

$t^* = 6.62 \times 10^{-7} \exp\left(\frac{11949}{T}\right) = 133.00673$ dy

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

$t > t^*$

$= 0.01541743 \frac{\mu m}{dy}$

$\delta^* = 5.1 \exp\left(\frac{-550}{T}\right) = 2.115393\ \mu m$

$\delta = \delta^* + K_L(t - t^*) = 2.115 + 0.01542 \times (400 - 133.01) = \boxed{6.2317\ \mu M}$

b) $f_H = .18$, C_H(wt. ppm) after $t = 365$ dy? $PBR = 1.56$, $\rho_{Zr} = 6.5$ g/cc, $\rho_{ZrO_2} = 5.68$ g/cc

New $\delta = \delta^* + k_L(365) - t^* = 5.692286\ \mu M$

$$C_H(\text{wt. ppm}) = \frac{2 f \delta \rho_{ZrO_2} f^{o}_{ZrO_2} \times \frac{M_H}{M_O} \times 10^6}{\left(t_i - \frac{\delta}{PBR}\right) \times \rho_{Zr}} = \frac{2 \times .18 \times 5.6923 \times \left(\frac{32}{32+91}\right) \times \frac{1}{16} \times 10^6}{\left(500 \mu m - \frac{4.6923 \mu m}{1.56}\right) \times 6.5}$$

did you use right value here?

$= \boxed{10.32792\text{ wt. ppm}}$

- off by 5x

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2) The rate 4/4 limiting step is the diffusion of oxygen through the passivating oxide layer that forms on Zircaloy clad.

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3) PBR is the ratio of volume of oxide to volume of metal. It characterizes the behavior of the oxide layer that forms on the surface of the cladding system of interest.

4/4 <1, thin, easily falls away, not protective (not passivating)

>2, thick, chips off in large pieces, not protective

$1 < PBR < 2$, passivating, stays on clad and is thick enough to delay diffusion and oxidation of cladding.

Zircaloy's PBR is 1.56 which makes it a desireable material from this consideration point.

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4) Hydrides can form everywhere in the cladding due to the

14 rapid diffusion of hydrogen through materials. However,

14 due to the soret effect, hydrides seek the lower end of temperature gradients and they seek higher tensile states (more space in the lattice for H interstitials and ppts.). Thus, most commonly one may observe a "rim structure" on the outer surface of the clad because hoop stress is maximized there. Additionally, hydrogen "blisters" or clusters may be found from the exterior to halfway through →

4) (cont.) the cladding. Hydrides inhibit dislocation motion + thus creating embrittlement, loss of fracture toughness, delayed hydride cracking, and irradiation growth. They can contribute to brittle failure of the cladding system.

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5) A RIA is a Reactivity Initiated Accident and refers to a rapid transient insertion or removal of reactivity that leads to an accident scenario. In PWR's, an inadvertent ejection of a control rod may occur due to a mechanical failure. They are most severe at normal coolant T and pressure with low reactor power. In BWR's, a control rod drop due to disengagement with the control rod drive mechanism may occur. They are most severe at near room temperature coolant and 1 atm of pressure, with low reactor power. Because this rapid loss of a neutron absorbing material leads to a spike in flux, the reaction rate increases, which increases local power and heat generation. This can cause failure of rods which leads to steam generation and pressure pulses. The rapid insertion of reactivity causes great stress on the materials by imposing a large temperature gradient, which leads to pellet expansion + gas expansion and can cause PCMI.

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6) A LOCA is a Loss of Cooling Accident, which can occur with the "guillotine split" of a coolant pipe. A SCRAM will occur from the signal received by the coolant monitoring and measuring channels. The decay heat continues to be produced even after this shutdown and heat is not being as efficiently removed from the core so temperature and internal pressure rise as the hydraulic pressure on the outer side of the clad is greatly reduced. As the Zircaloy at this higher temp experiences β or $\alpha+\beta$ superplastic phase, it deforms and undergoes ballooning which further impedes cooling. There is some stabilization of the α phase by the O_2. The oxidation rate increases and so does H_2 generation and H embrittlement as a result. There can be thermal expansion, fuel fragmentation, and PCMI. Then the emergency core cooling system re-wets the clad and puts a thermal shock on the system from this quenching which can then lead to rupture of the cladding if it has become too brittle. This is on the timescale of minutes, while RIA's are in seconds. It also is driven by decay heat generation and not fission like RIA's.

14/14

7) Burnup means a lower enthalpy is needed to induce failure and means that the material has undergone radiation hardening and is less ductile. It also means the cladding has undergone corrosion and hydrogen embrittlement. As bu↑, the type of failure is brittle and the probability of failure is elevated, thus limits are enforced to ensure that in accident scenarios, the burnup levels are not so high as to fully undermine the integrity of the barriers to fission products (cladding systems).

5/5

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8) 1) Improved cladding properties
2) Improved reaction kinetics w/steam
3) Enhanced fission product retention
4) Improved fuel properties.

8/8

An ATF option of the FeCrAl clad seeks to improve the cladding reaction kinetics with steam. The Al_2O_3 oxide that forms with this system is more stable than ZrO_2 at higher temperatures which means it will resist breakaway oxidation much better when it encounters steam since it will continue to passivate.

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4) When Zr clad is exposed to high temperature steam, the oxide layer cracks and ceases passivating the new oxides resulting in a breakaway oxidation. After this point, there is a linear correlation with time and in the worst cases, nearly all of the cladding will become oxide all while the combustable gas of H_2 is generated and accident scenarios may ensue.

- talked through some in LOCA Q

5/6

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0) 1) Cladding oxidation and Hydrogen pickup
2) Clad wear (vibrations), limited to 10% reduction
3) Power to melt, ($2750°C = T_M$) at highest burnup (levels higher than 50 $\frac{MWd}{KgU}$), the LHR must be ≥ 600 W/cm.

4/4

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1) Chalk River Unidentified deposites (CRUD) accumulates on surfaces of SS and Ni. It can inhibit heat transfer from fuel rods or guide tubes thereby degrading heat production and it also has harmful radiological effects from the activation of the Co and Ni which can be deposited throughout the coolant loop. CRUD deposition on the heat exchanger can also inhibit heat removal which is a safety concern. This is why minimizing particulates is important.

4/4

12) PWR's use zinc injection to minimize radiation fields and inhibit stress corrosion cracking (SCC). Zn fills tetrahedral sites in SS and prevents Co-60 from depositing in these sites therefore enabling its removal through demineralizer systems by forcing it to remain in the coolant for longer. In BWR's noble metals are used as coatings or injected into the coolant to enhance the efficiency of the hydrogen water chemistry which seeks to lower the redox potential and in turn limit crack growth (IGSCC of the core internals, especially those comprised of 304SS). Removing Co-60 is good from a radiological perspective because Co-60 is a radioisotope

6/6