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[94]

16/16

i) ZIRLO clad tube $T = 650K$ $t = 300$ days

$t_i = 500mm$

a) $t > t^*$?

$t^* = 6.62\times10^{-7}\exp\left(\frac{11949}{T}\right)$

$= 63.76$ days ✓

$300 > 63.76$ days

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

$= 2.188\ \mu m$

$\delta = \delta^* + K_L(t - t^*)$ ✓ where $K_L = 7.48\times10^6\exp\left(\frac{-12500}{T}\right)$

$= 0.0333$ ✓

$\delta = 2.188 + 0.0333(300 - 63.76)$

$= 10.05\ \mu m$

$\boxed{\delta = 10.05\ \mu m}$ ✓

b) $f = 0.18$ $PBR = 1.56$ $\rho_{Zr}\ 6.5\ g/cc$ $\rho_{ZrO_2} = 5.68\ g/cc$

$C_{H,initial} = 35$ wt. ppm

$$C_H^{clad} = \frac{2 f_i \delta\ \rho_{oxide}\ f^O_{ZrO_2}\ \frac{M_H}{M_O}}{\left(t - \frac{\delta}{P_{BR}}\right)\rho_{metal}} \times 10^6$$ ✓

$\left(\frac{32}{32+91} = 0.26\right)$ ✓

$$= \frac{2(0.18)(10.05\ \mu m)(5.68\ g/cc)(0.26)\left(\frac{1}{16}\right)}{\left(500\ \mu m - \frac{10.05}{1.56}\right)6.5\ g/cc} \times 10^6$$

$= 104.1$ wt. ppm ✓

$C_H = C_{H,initial} + C_H^{clad} = 35 + 104.1$ ✓

$\boxed{C_H = 139.1\ \text{wt. ppm}}$

2) $2.5\times2.5\times0.01$ cm Zr coupon $\delta = 0.005$ cm

0.01 cm = 100 μm

Find weight gain

6/6

$$\delta = \frac{W}{14.7} \rightarrow W\left(\frac{mg}{dm^2}\right) = \delta(14.7) = 0.005\,cm\left(\frac{100\,\mu m}{0.01\,cm}\right)(14.7)$$

$$W = 735\,\frac{mg}{dm^2} = \frac{\Delta m}{area}$$

$$area = 2.5\,cm \cdot 2.5\,cm = 6.25\,cm^2 \rightarrow 0.0625\,dm^2$$

$$\Delta m = W \cdot area = 735\,\frac{mg}{dm^2} \cdot 0.0625\,dm^2$$

$$\boxed{\Delta m = 45.9\,mg}$$

3) Metallic fuel redistribution for metallic fuels can be driven via Soret diffusion up a temperature gradient. For U-Zr, this phenomenon results in distinct zones of Zr concentration across the radial direction. This is because Zr has different solubilities for the U phases.

6/6

3 distinct zones are present:

- U-γ phase with high Zr content (fuel centerline
- U-β phase with low Zr content (outside fuel centerline
- U-α/delta with ~~as-fabricated~~ Zr content (bordering the cladding region/outer fuel radius).

4) - Mox fuels have higher heating rates, can achieve higher burnup, and ~~the~~ fuel assemblies can be more densely packed due to a hexagonal packing structure.

8/8

Mox fuels have a higher power density. Therefore a sodium coolant is used for more efficient heat transfer to the coolant. This also drives smaller pellet diameters, and smaller fuel lengths for fuel assemblies.

5) Regions:

Central Voids - forms from accumulation of voids & pores present along a thermal gradient. They form a lenticular shape

5) Columnar Region:

8/8 - Lenticular pores destroy initial fuel microstructure as they move leaving elongated columnar grains at temperatures >> 1800 C.

Equiaxed Region:

At T<1800C the velocity of the lenticular voids change enough that the grains formed undergo significant growth. Grains are much larger and could be uniform in size

As-Sintered Region

At fuel periphery, temperatures are low enough that grain growth is limited, resulting in minimal microstructural changes.

8/8 6) RIA - reactivity initiated accident.
This type of accident results in a rapid increase in fuel temp resulting in increased bubble pressures. This higher bubble pressure results in increased cracking in the fuel

7) LOCA - Loss of Coolant Accident
LOCA material impacts primarily begin with the cladding since heat is not pulled at the coolant-clad interface, the fuel begins to heat up.

7/8 This results in significant degradation of creep strength in Zirc. Cladding will plastically deform, causing obstructions in flow.

Emergency coolant flow ECCS also embrittles the materials significantly

RIA experiences cladding overheating from fuel melting. Internal gases can create ballooning - - oxidation of cladding is key

8) 1) Departure from nucleate boiling - need to ensure operational heat flux doesn't exceed critical heat flux resulting in severe increase in clad temp.

4/4 2) Normal operation limits - constraints on axial LHR. Could be a max LHR at a certain burnup.

8/8 9) Hydrogen water chemistry is when hydrogen is added to the water coolant in a LWR to control the water's electrochemical potential.
It is used to reduce intergranular SCC. - H acts as O getter

10) Pressure buildup: fission liberates oxygen, forms CO with carbon buffer layer, results in increased pressure

10) Irradiation growth! Fuel kernel will swell w/ time
buffer layer will shrink

8/8

PyC will shrink at first, then begin to swell
This adds compression to the SiC layer,

11) Hydrides can form within micro cracks within the cladding, beginning at cracks through the oxide layer that penetrate to the base cladding metal. - cracks not necessary for hydrides

7/10

Concentrations are driven by temperature & stress gradients. They gravitate towards lower temp, and higher tensile stresses.

H form from corrosion, H can diffuse through cladding & will form hydrides due to H solubility in Zr

Hydrides embrittle the cladding creating a rim or blistering effect, leading to early failure

12) Diffusion is the rate-limiting step of corrosion of Zr in water. This leads to predicting the oxidation rate with diffusion calculations,
- oxygen diffusion specifically

3/4

13) the Pilling-Bedworth ratio (PBR) is ratio of metal oxide volume to the volume per unit of the base metal

$$R_{PB} = \frac{V_{oxide}}{V_{metal}}$$

6/6

If the PBR falls within $1 < PBR < 2$, then the oxide coating on a rod is passivating and protects the base metal from further oxidation.