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1 (a) Given, $T = 625\,K$, $t = 400$ days.

$$t^* = 6.62\times10^{-7}\exp\left(\frac{11949}{T}\right) = 6.62\times10^{-7}\exp\left(\frac{11949}{625}\right).$$

$$= 133 \text{ days.}$$

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Here, $t > t^*$, then the oxide is past transition.

Oxide thickness at transition:-

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

$$\delta^* = 5.1\exp\left(-\frac{550}{625}\right) = 2.115\,\mu m.$$

$$K_L = 7.48\times10^6 \times \exp\left(-\frac{12500}{625}\right) = 0.0154.$$

Final oxide thickness,

$$\delta = \delta^* + K_L(t - t^*).$$

$$= 2.115 + 0.0154(400-133)$$

$$= 6.2268\,\mu m$$

(b) $$C_H^{int.} = \frac{2f\delta\,\rho_{ox}\cdot f^o_{ZrO_2}\cdot \frac{M_H}{M_O}\times10^6}{\left(t - \frac{\delta}{PBR}\right)\times\rho_{metal}}$$

$f = 0.18$.

~~$\delta = 6.2268\,\mu m$~~. $\delta = ?$

$\rho_{ox} = 5.68$ g/cc.

$f^o_{ZrO_2} = \frac{2\times16}{2\times16+91} = 0.26.$

$M_H/M_O = \frac{1}{16}.$

$t = 500\,\mu m$.

$PBR = 1.56$.

$\rho_{Zr} = \rho_{metal} = 6.5$.

$$= \frac{2\times0.18\times\cancel{6.2268}\,6.2268\times5.68\times0.26\times\frac{1}{16}\times10^6}{\left(\cancel{500}\,500 - \frac{6.2268}{1.56}\right)\times6.5}$$

$$= 64.18 \text{ wt.ppm.}$$

= ~~64.18 wt.ppm.~~ ~~64.18 wt.ppm.~~

Here, $t = 365+400 = 765$ days.

$$\delta^* = 2.115 + 0.0154(765-133).$$

$= \cancel{5.6878}$ 11.8478. μm. - not one additional year, just 1 yr - right process

Then, $$C_H^{clad} = \frac{2\times0.18\times\cancel{5.6878}\,11.8478\times5.68\times0.26\times\frac{1}{16}\times10^6}{\left(500 - \frac{\cancel{6.2268}\,11.8478}{1.56}\right)\times6.5}$$

$= \cancel{58.58}$ wt.ppm.

Total = 123 + 64.18 = 187.18 wt.ppm.

② The rate limiting step for aqueous corrosion of Zr cladding is ~~O/M ratio~~. Oxygen in the coolant.

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Oxygen in the coolant, dissolved or produced by radiolysis of water can accelerate aqueous corrosion of Zr cladding.   - close, but it's diffusion of O through the oxide

① Dissociation of water at oxide/water interface.

② Absorption of O_2^{2-} in oxide layer.

③ Reaction of O^{2-} with Zr.

③ Pilling - Bedworth ratio (PBR) is defined as:

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$$PBR = \frac{V_{oxide}}{V_{metal}}$$

where, V_{oxide} = vol^m/unit for oxide

V_{metal} = vol^m/unit for metal.

If PBR<1 : Oxide layer is thin, no protective effect.

PBR>2: Oxide layer is very thick and it chips off.

1<PBR<2: Oxide coating is passivating and adds protective effect.

(4) More oxidation results into production of H_2 that can enter the cladding and form brittle hydrides. The reason of hydride forming in the cladding is formation of H_2 by oxidation and H_2 uptake effect of Zircaloy.

- where in the cladding? outside portion. T solubility, Soret, stress

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$$Zr(s) \rightarrow Zr^{4+}_{(aq)} + 4e^-$$

$$Zr^{4+} + 2H_2O_{(l)} \rightarrow ZrO_2(s) + 4H^+.$$

$$4H^+_{(aq)} + 4e^- \rightarrow \underline{2H_2}$$

Hydrogen supply by oxidation.

Impacts:-

hydride ZrH_x

(i) H_2 embrittlement.

(ii). Loss of fracture toughness.

(iii). Delayed hydride cracking.

(iv) Accelerated irradiation growth.

(v). Corrosion. - H doesn't really "corrode"

(5)

RIA: Reactivity initiated accident is a result of control rod(CR) ejection (PWR) or drop (BWR) which can occur by

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mechanical failure of CR drive mechanism and reactivity of the core rapidly increase due to decreased neutron absorption.

RIA – PWR

Coolant pressure ejects a CR assembly out of the core, sudden reactivity in inserted.

RIA – BWR

Initiated by separation of CR blade from it's drive mechanism.

RIA leads to fast rise in fuel power & temperature. This can lead to rod failure and release of radioactive material into the coolant. It can cause rapid steam generation & pressure pulses. Coolant pressure pulse can break coolant boundary or damage the fuel and other core internals.

- could add more, but pretty good

⑥

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LOCA: Loss of coolant accident where coolant flow is reduced and pressure drops. Average temperature of the reactor rises due to radioactive decay in fuel & less cooling. This causes large plastic deformation. Rod pressure becomes higher, creep strength of Zr cladding decreases.

In RIA, the power of the reactor rises at around normal operating pressure. During LOCA, pressure rises up. Coolant is lost during LOCA which is not the case in RIA.

⑦

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(i) Improved reaction kinetics with steam.
(ii) Improved cladding properties.

ATF like USi, Un, UC with alternal cladding such as SiC or, FeCrAl is being considered that targets these pathways.

- well, USi/UN don't address either of the listed pathways, but are examples for other pathways

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PCMI

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→ is a complex process with max^m risk for failure where fuel pellet to cladding gap closes firmly.

→ Pellet fragments induces local strain on the cladding.

Cladding elongation & bow.

→ Anisotropic & preferential migration of vacancies & interstitials to specific lattice planes drive an overall cladding axial growth.

- cladding creep becomes even more important

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Coating can be used to improve Zr steam oxidation.

It can enhance the passivity of Zr cladding with temp. upto 1200°C. - what kind of coating?

(8) <600°C : Oxidation increases at parabolic rate which results into Uniform & passivating oxide layer.

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At higher temperature :

(i) Oxide layer can break due to surface stress.

(ii) Breakaway oxidation can start to take place.

- more hydrides, brittle, etc.

(11)

CRUD: Chalk river un-identified material is the deposition of some kind of metal -oxide on ~~Ni~~ the surface. cladding, Composed of either dissolved ions / solid particles such as Ni, Fe & Co on fuel rod cladding.

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Impacts:

→ Reduced heat transfer.

→ Fuel temp. goes up.

→ In PWRs, CRUD induced power shift (CRIPs) can take place. by trapping Boron in the cladding. , changing power distribution.

- Source of activated material in primary coolant

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(1) Imposing H_2 overpressure on primary coolant sys. in PWR.

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Reason: Reduces corrosion potential and raises primary system pH.

(2) Decreasing concentration of Boric acid as a chemical

- boron is more related to reactivity control
- has secondary impact on water chem.

Reason: to control reactivity through fuel cycle, Which results in use of lithium hydroxide to control pH.

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Differcenies

~~In-reactor behavior~~

MOX fuel

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① Opercates in higher temperature ~~than~~ than LWR fuels. Centerline temp. is around 2000 C.

② Shorter fuel rod diameter/ length for MOX fuel results in higher power density than LWR fuels.

③ MOX fuels are targeted to reach higher burnup than LWR fuels, around 150 GWd/ton.

④ SS cladding is used for MOX fuels whereas Zr cladding for UO_2/LWR fuels.

⑤ Neutron flux is more intense for MOX fuels (~ 7×10^{15} n/cm²s in core).

- Structural phenomena? reconstruction, JOG, increased FP inventory