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1. ZIRLO: $T = 625K$, $t = 400$ days, $t_0 = 500\,\mu m$

a) $t^* = 6.62 \times 10^{-7} \exp\left(\frac{11949}{625K}\right) = 133$ days < 400 days ✓

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

$K_L = 7.48 \times 10^{6} \exp\left(-\frac{12500}{625K}\right) = 0.015\,\mu m/day$

$\delta = 2.115\,\mu m + 0.015\,\mu m/day\,(400 - 133)\,days$

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$$\boxed{\delta = 6.232\,\mu m}$$

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

$$C_H = \frac{2 f \delta \rho_{ox} f^{o}_{ZrO_2} (M_H/M_O)}{(t_0 - \frac{\delta}{PBR})\rho_{metal}} \times 10^6$$

time = 365 dys

new δ

$$\hookrightarrow C_H = \frac{2(0.18)(5.68\,g/cc)(\frac{32}{91+32})(1/16)(6.232\,\mu m)}{(500\,\mu m - \frac{6.232\,\mu m}{1.56})\,6.5\,g/cc} \times 10^6$$

$$\boxed{C_H = 64.27 \text{ wt. ppm}}$$

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2. The diffusion of oxygen through the growing oxidation layer.

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3. PBR is the ratio of the oxide volume to the cladding metal volume. It gives an idea in regards to the relative size of the oxide layer, its stability, and if it is passivating or not.

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4. Hydrides form in high tensile stress, low temperature regions (Soret effect) due to the lower potential →? and low solubility in Zr.

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Hydride phases generally decrease ductility leading to earlier failure or effects like delayed hydride cracking. Fracture toughness also decreases.

5. RIA is a reactivity insertion event, so an event where reactivity (+) is inserted due to change in control setup/geometry.

- PWR: Control rod ejection
- BWR: Control blade drop

During a RIA, a sudden power ramp occurs; depending on the width of the ramp/clad state, varying degrees of damage can occur. (Pressure pulse → damage.) Some phenomena, dictated by DNBR is shown on the next page (PWR) →

5. i) Pre-DNBR: Hydride-assisted PCMI failure
(Hydride embrittlement)

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ii) Post-DNBR: Oxidation/Ballooning/Rupture (T↑, ΔP) failure

iii) Post-failure: Fuel fragmentation, fuel fragments + coolant
↳ mechanical Energy

iv) Melting of fuel (least likely)

- would have liked how/why these are occurring, not just a list

6. A LOCA is when a breakage in a coolant line leads to a loss in coolant for the reactor.

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Generally, temperature increases due to less coolant and decay heat. (OX↑). Also, coolant pressure decreases beyond internal rod pressure, this leads to plastic deformation of clad and possible rupture depending on oxidation/H pickup. This ballooning can block coolant which can worsen the situation. The ECCS reintroducing coolant can also cause more rupture/fuel fragmentation potential (Oxidation/Hydride dependent). It is different from a RIA because it happens over minutes instead of seconds, and depending on the break severity, can be easier controlled. Also the behavior that leads to them is much different.

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7. Burnup generally increases the likelihood of failure.

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i) For RIAs, burnup lowers the enthalpy increase in the fuel required for clad failure

ii) For LOCAs, burnup reduces fuel ductility which leads to fragmentation/stress concentration

↳ this is for both

→ for RIA, max enthalpy increase goes down w/ burnup

8. i) Improved Kinetics w/ steam (Clad coatings - Cr)

ii) Improved Cladding Properties (FeCrAl cladding)

iii) Improved Fuel Properties (Urania-based fuel)

iv) Enhanced Fission Product Retention (FCM fuels)

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9. Changes phases from α to β at 863°C. This leads to the formation of an oxygen-stabilized α layer between the oxide-β metal interface; this lowers ductility. Also, the steam can oxidize the clad (T>600°C), which can lead to runaway oxidation/T↑ due to the exothermic oxidation rxn that Zircaloy has.

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10. i) Rod internal pressure (radial creep out (int. P) must not exceed pellet expansion)

4/6 ii) Clad oxidation

- Below 10% wall thickness reduction from oxidation (~100 μm)

iii) Power to melt

- Below 600 W/cm (not likely to exceed this)

11. CRUD has lower k_{th}, so it can decrease heat transfer to coolant, which leads to an increase in T → higher oxidation rates.
5/6 CRUD can also trap boron which leads to power shifts. Both can lead to earlier failure.
- safety? activation products

12. i) Boric acid / LiOH

- Reactivity control and pH control, the latter limits Fe and Ni solubility in clad.

4/6 ii) Zn injection

- Preferentially occupies in spinel on stainless steel where ^{60}Co would usually occupy
  ↳ more time ^{60}Co is in coolant increasing chance of filter/removal.
- Reactivity control