1)

a) 625 K for 400 days $t_c = 500\ \mu m$ Vaughn

$\delta^* = 5.1 e^{\frac{-550}{625}} = \cancel{12.3}\ 2.115\ \mu m$ ✓

$t^* = 6.62 \cdot 10^{-7} \cdot e^{\frac{11949}{625}} = 133$ days ✓

15/18

$\delta = \delta^* + K_L(t - t^*)$ ✓

$K_L = 7.48 \cdot 10^{-6} e^{-\frac{12500}{T}} = 1.542 \cdot 10^{-14} \frac{\mu m}{day}$

from Olander, Motta

94

$\star$ seems low, I probably have a mistake on my equation sheet or entered it in my calculator wrong ✓

Instead I'll approximate $K_L \approx \frac{\delta^*}{t^*}$

because of cyclic nature of corrosion, the linear regime is effectively many cubic regimes so

$K_L = 0.0159 \frac{\mu m}{day}$ $\star$ Far more realistic

$\delta = \delta^* + K_L(t - t^*) = 2.115 + 0.0159(400 - 133)$

$= \boxed{\cancel{6.361\ \mu m = \delta(400\ days)}}$ See ~~test~~ other sheet for corrected equation $\boxed{\delta = 6.2315\ \mu m}$ ✓

b)

$f = 0.18$ $\rho_{Zr} = 6.5$ $\rho_{ZrO_2} = 5.68$ $PBR = 1.56$

Use equation from class

time = 365 day, update δ

$\frac{32}{32+91}$

$$C_H^{clad} = \frac{2f \cdot \delta\, \rho_{ZrO_2} \cdot f^o_{ZrO_2} \cdot \frac{M_H}{M_O}}{\left(t_{clad} - \frac{\delta}{PBR}\right)\rho_{Zr}} \cdot 10^6 = \frac{2 \cdot 0.18 \cdot 6.361 \cdot 5.68 \cdot \frac{2}{3} \cdot \frac{1}{16}}{\left(500 - \frac{6.361}{1.56}\right) 6.5} \cdot 10^6$$ ✓

$$= 1.68128 \cdot 10^{-4} \cdot 10^6 = \boxed{168.13\ \text{wt. PPM} = C_H^{clad}}$$

2) 3/4

Inward diffusion of O_2 is the rate limiting step.

- through oxide layer

3) The PB ratio measures the effictive volume occupied by a metal atom in an oxide against the volume occupied by the atom in matrix.

4/4

~~For Zr, a~~ ~~for a metal M, if its PB ratio~~

So for Zr, we have the unit cell volume V_{Zr} divided by the number of Zr atoms per unit cell N_{Zr}, if the same factors are defined for zirconia the PB ratio is:

$$\frac{\frac{V_{ZrO_2}}{N_{ZrO_2}}}{\frac{V_{Zr}}{N_{Zr}}}$$

If $PBR \in (1, 2)$ the oxide is likely stable and adherent.

4) Hydrides often form an outer rim in the cladding. This is due to the preferential precipitation of hydrides in regions of high stress and low temperatere (i.e. solubility). The can also form/migrate to crack tips as we covered in DHC. The main factor in the rim precipitation is the intense hoop stress on the outer region of the pellet. They are also subject to local corrosion kinematics. If an area has unusually rapid oxidation (possibly due to spallation) there will be more released hydrogen for the cladding to uptake.

12/14

- impacts of hydrides? embrittlement

5) A Reactivity Initiated (or insertion) accident Vaughn
occur most frequenty when control rods are
unexpectedly removed from the system. In PWR
this is often a Control Rod Ejection Accident
(CREA) while in BWR it is a Control Rod Drop
Accident (CRDA). In both cases a mechanical
14/14 failure enables either coolant pressure (in CREA)
or gravity (in CRDA) removes the control rod/blade
from the core. +Pressure pulses are a key concern

The loss of control rod causes a sharp increase
in core temperature (~0.1 s) this can lead to several
negative outcomes+ starting with rapid fuel swelling
and consequent PCMI, ~~then~~ as well as cracking
and hydride failure in cladding. It can also
cause departure from nucleate boiling, ballooning,
fuel fragmentation and release.

6) A Loss of Coolant Accident occurs when the
13/14 flow of coolant to the core is redused or lost altogether.

The timescales for LOCAs are much longer
and they occur on the order of tens of
seconds to minutes. Other than the timescales,
LOCAs and RIAs have different safety concerns,
in LOCAs, superheated steam poses a major
oxidation risk. Runaway oxidation, as well as
quenching from ECCS are major concerns.
Oxidation is particularly dangerous due to the buildup
of H_2 in the core. - got most of it

7)
One major way burnup impacts type of failure
is in cladding failure. Irradiation embrittles
4/5
Zr cladding making brittle failure more likely in
accidents involving high burn-up fuel. This is
especially pronounced in LOCA as the typical
failure mechanism is severe plastic deformation.

- for RIA also - corrosion + hydrides

8)
8/8

- Improved Corrosion Kinetics
  FeCrAl alloys are attractive for their corrosion
  performance under LOCA conditions ~~to their~~ (thin films also look promising)
- ~~B~~ Improved Fuel Properties
  Urania based fuels with additives and dopants
  might offer better thermal conductivity
  ~~A~~ which may allow for lower operating
  temperatures
- Improved cladding properties
  SiC composite cladding
- Retention of fission products
  Fully ceramic microencapsulated fuels

9)
4/6

Zr cladding undergoes rapid oxidation releasing
significant amounts of hydrogen. ZrO_2 is
less thermodynamically stable in superheated steam
which ~~also~~ allows for "break away" corrosion.
O_2 dissolves into some of the matrix, ~~forming~~
stabilizing αZr, while some of the cladding
will transition to βZr, the combination of
α, β can allow for super-plasticity. Even
without these phase changes creep is accelerated
in Zr at high temperatures.

Vaughn

10)

- Cladding oxidation and Hydrogen Pickup
obviously plays a huge role as a limiting
4/6 Phenomena given it is ~~a caus~~ deleterious
under operating and some accident conditions.

- PCMI

Pellet cladding mechanical interaction
Poses a high risk factor for failure.
Limits focus on hoop strain ~~in the~~
and keeping it below 1%

- Power to Melt
Seems like a well met limit with
current fuels the Powers needed
to melt are much higher than
operational range ~ LHR ≳ 600 $\frac{W}{cm}$

11)
Crud can negatively impact water chemistry
3/6 and corrosion. It can also sequester boric
acid and cause CRIPs.

12) - needed more
~~DH~~
Dissolved hydrogen is injected into coolant
4/6 to react with radiolysis products (e.g. OH) so
that oxidizing species in the coolant are
minimized.

Lithiation ~~controls th~~ is often used to control
the pH to ~6.9. This promotes oxide
stability and helps mitigate corrosion.

For 1 Vaughn

I have 10^{-6} where it should be 10^{6} on my sheet

$K_L = 0.015417$

$$\boxed{\delta = 2.115 + 0.015417(267) = 6.2315\ \mu m}$$ ✓

$K_L = 7.48 \cdot 10^{6} \cdot e^{-\frac{12500}{T}} = 0.015417$ ✓

checks out with $\frac{\delta^*}{t^*}$ solution