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Question (1) $T = 625K$, $t = 400$ days, initial thickness $= 500\ \mu m$

a) First Calculate when transition occurs: t^* ??

$$t^*_{(days)} = 6.62 * 10^{-7} \exp\left[\frac{11949}{T}\right] = \boxed{133 \text{ days}}$$

($T = 625K$) 16/16

Second oxide thickness at transition (δ^*):

$$\delta^*_{(\mu m)} = 5.1 \exp\left[\frac{-550}{625}\right] = \boxed{2.115\ \mu m}$$

Then oxide thickness at $t = 400$

$$\delta(400 \text{ days}) = \delta^* + K_L (t - t^*)$$

$$\therefore \delta(400 \text{ days}) = 2.115\ \mu m + 0.0154 * [400 - 133]$$

$$= 2.115\ \mu m + 4.112\ \mu m$$

$$= \boxed{6.23\ \mu m}$$

$K_L = 7.48 * 10^6 \exp\left[\frac{-12500}{T}\right]$

$= 0.0154\ \mu m/day$

b) If $f_H = 0.18$, PBR $= 1.56$, $\rho_{Zr} = 6.5\ g/cm^3$, $\rho_{ZrO_2} = 5.68\ g/cm^3$

$$C_{H\ (1\ year)} = \frac{2 f_H \delta \rho_{ZrO_2} f_{(O \text{ in } ZrO_2)} \frac{M_H}{M_O}}{\left[t_c - \frac{\delta}{PBR}\right] \rho_{metal}}$$

$$= \frac{2 * 0.18 * 5.69 * 5.68 * 0.26 * \frac{1}{16}}{\left[500 - \frac{5.69}{1.56}\right] * 6.5}$$

$$= 5.86 * 10^{-5} = \boxed{58.6 \text{ ppm}}$$

$\delta(1 \text{ year}) = \delta^* + K_L (365 - 133)$

$= 2.115 + 0.0154 * 232$

$= 5.69\ \mu m$

$f_{O \text{ in } ZrO_2} = \frac{16 \times 2}{16 \times 2 + 91} = 0.26$

Question (2)

$q_{th} = 11 * 10^{-6}$, $f = 3.5 * 10^{13}$ f/cm³.s, $T = 12$

$T_{ref} = 300 + T$, $\Delta\rho_0 = 0.01$, $B_D = 5$ MWD/kgU

$\rho(UO_2) = 10.97$ g/cm³, $t = 85$ days

$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_D + \varepsilon_{SFP} + \varepsilon_{GFP}$ ✓

$\Rightarrow \varepsilon_{th} = q_{th} \Delta T = 11 * 10^{-6} [1200 - 300] = 0.01$ ✓

$\Rightarrow \varepsilon_D = \Delta\rho_0 \left[\exp\left(\frac{\beta \ln 0.01}{C_D \beta_D} \right) - 1 \right]$ ✓

$= 0.01 \left[\exp\left(\frac{0.01 * -4.605}{1 * 0.053} \right) - 1 \right]$

$= -0.01$ ✓

$\beta = \frac{ft}{N_U} = \frac{3.5 * 10^{13} * 85 \text{ days}}{\frac{\rho_U N_{Av}}{238 + 2*16}}$

$= \frac{3.5 * 10^{13} * 85 * 24 * 60 * 60}{\frac{10.97 * 6.02 * 10^{23}}{270}}$

$= 0.0105$ FIMA ✓

$C_D = 1$ [for T < 750]

$\beta_D = \frac{5}{95} = 0.053$ FIMA

$\Rightarrow \varepsilon_{SFP} = 5.577 * 10^{-2} \rho\beta$

$= 5.577 * 10^{-2} * 10.97 * 0.0105$

$= 0.0064$ ✓

$\Rightarrow \varepsilon_{GFP} = 1.96 * 10^{-28} \rho\beta (2800 - T)^{11.73} \exp[-0.0162(2800 - T)] * \exp[-17.8\rho\beta]$

$\therefore \varepsilon_{GFP} = 1.96 * 10^{-28} * 10.97 * 0.0105 * (1600)^{11.73} \exp[-25.92] \exp[-2.05]$

$= 6.177 * 10^{-4}$ ✓

$\Rightarrow \varepsilon_{tot} = 0.01 - 0.01 + 0.0064 + 6.177 * 10^{-4} = 0.007$ ✓

$= 0.7\%$

Question (3) $\sigma_m = 200\ MPa$, $T = 600K$, $LHR = 150\ W/cm$

$t = 1.5\ y$

$\dot{\varepsilon}_{tot} = \dot{\varepsilon}_{ss} + \dot{\varepsilon}_{irr}$ ✓ 12/12

$\Rightarrow \dot{\varepsilon}_{ss} = A_0 \left[\frac{\sigma_m}{G}\right]^n e^{-Q/RT}$ ✓

$= 3.14 * 10^{24} \frac{1}{s} * \left[\frac{200 * 10^6}{4.2519 * 10^{10} - 2.2185 * 10^7 * 600}\right]^5 e^{-\frac{2.7 * 10^5}{8.314 * 600}}$

$= 3.14 * 10^{24}\ s^{-1} \left[\frac{200\ MPa}{29208\ MPa}\right]^5 * e^{-54.1}$

$= \boxed{1.51 * 10^{-10}\ s^{-1}}$ ✓

$\Rightarrow \dot{\varepsilon}_{irr} = C_0 \Phi^{C_1} \sigma_m^{C_2} = 3 * 10^{-24} * [4.5 * 10^{13}]^{0.85} [200]^1$ ✓

$= 2.42 * 10^{-10}\ s^{-1}$

$C_1 = 0.85$, $C_2 = 1$ ✓

C_0 is of the order $3 * 10^{-24}$

$\therefore \dot{\varepsilon}_{tot} = \dot{\varepsilon}_{ss} + \dot{\varepsilon}_{irr} = 3.93 * 10^{-10}\ s^{-1}$ ✓

$\Phi = 3 * 10^{11} * LHR$

$= 3 * 10^{11} * 150$

$= 4.5 * 10^{13}\ \frac{1}{cm^2 \cdot s}$

$\varepsilon_{tot}\Big|_{t=1.5y} = 3.93 * 10^{-10} * 365 * 24 * 60 * 60 * 1.5$

$= 0.0186 = \boxed{1.86\%}$ ✓

Question (4) Types of Fission products in fuel: 5/5

(1) Soluble oxides (Y, La) (dissolved in Cation sublattice)
(2) Insoluble oxides (Zr, Ba, Sr)
(3) Metallic precipitates (Mo, Pd, Tc)
(4) Volatiles (Cs, Br, I) gas at high T, solid at low T
(5) Noble gases (Xe, Kr)

Question (6) Three benefits of Zr cladding 6/6

(1) Good thermal conductivity (2) low neutron absorption cross section
(3) Corrosion resistance with water at T = 300°C
* Also affordable and abundant

Question (7) Metallic fuel undergo constituent distribution 5/5
because: * Zr diffuse up the temperature gradient
* Zr has different solubility in each phase of U

Question (5) Microstructure-based fuel performance modeling 8/8
(Mechanistic)

Instead of models correlating performance to temperature and Burnup (empirically)
⇒ Mechanistic models are based on understanding the physics of microstructure evolution through multiscale modeling
* Atomistic modeling (DFT, MD
* phase field
* Engineering scale
⇒ These mechanistic models have much more predictive capabilities
⇒ For example: Thermal conductivity model as function of [Temperature, point defect conc., intergranular bubble density

Question (8)

* MOX fuel : fuel pins have less diameter than LWR fuel
  ∴ Higher Power density & Higher heat flux

* MOX fuel ~~are~~ used in fast reactors which operate at high neutron flux
  ∴ Higher radiation damage than LWR fuels
  [~100dpa at high Burnup]

* MOX fuel is designed to operate at high LHR ~ 400-500 W/cm (twice LWR fuels)

* stainless steel cladding is used with MOX fuel (instead of Zircaloy in LWR)
  - higher temperature, reconstruction

6/8

Question (9) Conditions for SCC : ① Corrosive environment
② Susceptible material
③ sufficient Stress
④ sufficient time

7/8

In PCI ① Corrosive env : Aggressive fission products (Cs, I) attack

② material : Zircaloy is prone to PCI Failure

③ Stress : internal stress from fuel swelling & Thermal expansion

④

Question (10) In HBS ⇒ Grain size decrease to 150-200 nm & micron-sized bubbles form with multiple grains interacting each bubble

⇒ Potential to occur during (LOCA) temperature transients

Pulverization criterion was developed in BISON informed by phase field modeling

⇒ ↑ T causes ↑ P in bubbles 5/6

Question (11)

RIA	LOCA
* Departure from criticality	* Reduced or lost Coolant flow 7/8
* Nuclear reactors are designed with negative reactivity feedback ⇒ when power increases ↳ reactivity will drop to decrease power	* when coolant pressure drops ↳ Emergency Shutdown System will SCRAM the reactor Then, Emergency Core Cooling System will remove the heat
* very fast change (0.1s in worst case scenario)	* Relatively slower
example ① ejection of control rod due to mechanical failure of control rod drive [PWR] ① OR ② Coolant pressure ejecting a control rod assembly out of core due to mechanical failure of control rod housing	Wanted some material description here too

Question (12) Pathways to ATF ① providing additional coping time required for the water to boil away

S/C ② providing more time required for the fuel to melt.

~~③ for molten fuel to breach~~

One option targeting this is: improved fuel properties by: ⇒ using dopants with UO_2 as [Cr, SiC]

⇒ Alternate fuels ⇒ U_3Si_2

- wanted the material changes that allow for your 1 & 2

Question (13) Limiting Phenomena 4/4

1. Cladding wear ✓
2. Pellet - Clad Mechanical interaction ✓
3. Power to melt ✓
4. Departure from nucleate Boiling ✓

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