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

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

$$\underset{(days)}{t^*} = 6.62 * 10^{-7} \exp\left[\frac{11949}{\underset{625K}{T}}\right] = \boxed{133\ days}$$

Second oxide thickness at transition (δ^*):

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

Then oxide thickness at $t = 400$

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

$$\boxed{K_L = 7.48 * 10^{6} \exp\left[\frac{-12500}{T}\right] = 0.0154\ \mu m/day}$$

$$\therefore \delta(400\ days) = 2.115\ \mu m + 0.0154 * [400 - 133]$$
$$= 2.115\ \mu m + 4.112\ \mu m$$
$$= \boxed{6.23\ \mu m}$$

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

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

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

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

$\delta(1 year)$
$= \delta^* + K_L(365 - 133)$
$= 2.115 + 0.0154 * 232$
$= 5.69\ \mu m$

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

Question (2)

$\alpha_{th} = 11 \times 10^{-6}$, $\dot{f} = 3.5 \times 10^{13}$ fis/cm³.s, $T = 12$
$T_{ref} = 300 K$, $\Delta\rho_0 = 0.01$, $B_D = 5 MWD/kgO$
$\rho(UO_2) = 10.97 g/cm^3$, $t = 85$ days

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

$$\Rightarrow \varepsilon_{th} = \alpha_{th} \Delta T = 11 \times 10^{-6} [1200 - 300] = \boxed{0.01}$$

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

$$= 0.01 \left[\exp\left(\frac{0.01 \times -4.605}{1 \times 0.0053} \right) - 1 \right]$$

$$= \boxed{-0.01}$$

$$\beta = \frac{\dot{f} t}{N_U} = \frac{3.5 \times 10^{13} \times 85 \text{days}}{\frac{\rho_U N_{AV}}{238 + 2 \times 16}}$$

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

$$= \boxed{0.0105 \text{ FIMA}}$$

$C_D = 1$ [for $T \geq T_{750}$]

$$\beta_D = \frac{5}{950} = 0.0053 \text{ FIMA}$$

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

$$= 5.577 \times 10^{-2} \times 10.97 \times 0.0105$$

$$= \boxed{0.0064}$$

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

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

$$= \boxed{6.177 \times 10^{-4}}$$

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

$$= \boxed{0.7\%}$$

Question (3) $\sigma_m = 200\ MPa$, $T = 600K$, $LHR = 150\ W/cm$, $t = 1.5\ y$

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

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

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

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

$$= \boxed{1.51 * 10^{-10}\ s^{-1}}$$

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

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

$C_1 = 0.85$, $C_2 = 1$

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:

(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

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

Question (7) Metallic fuel undergo constituent distribution

because: * Zr diffuse up the temperature gradient
* Zr has different solubility in each phase of U

Question (5) Microstructure-based fuel performance modeling
(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: ~~Models~~ Thermal conductivity model as function of [Temperature, point defect conc., intergranular bubble density, Precipitates, [illegible] / [illegible] bubbles on GB?

Question (8)

* MOX fuel : fuel pins have less diameter than LWR fuel

∴ Higher Power density & Higher heat flux

* MOX fuel ~~operat~~ 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]

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

In PCI
1. Corrosive env : Aggressive fission products (Cs, I) attack
2. ~~Clad~~ 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 150-200nm

& micron-sized bubbles form with multiple grains interecting each bubble

⇒ Potential to occur during (LOCA) temperature transients

Pulverization criterion was developed in BISON informed by phase field modeling

Question (11)

RIA	LOCA
* Departure from criticality	* Reduced or lost coolant flow
* Nuclear reactors are designed with negative reactivity feedback ⇒ when power increase ↳ 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] ② OR Coolant pressure ejecting a control rod assembly out of core due to mechanical failure of control rod housing	

Question (12)

Pathways to ATF → ① providing additional coping time required for the water to boil away

② providing more time required for the fuel to melt.

~~for molten fuel to break~~

One option targeting this is: improved fuel properties

by: → using dopants with UO_2 as [Cr, SiC]

→ Alternate fuels → U_3Si_2

Question (13) Limiting Phenomena

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

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