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[1]

ZIRLO, $T = 625\,K$, $t = 400$ days, $\delta = 500\,\mu m$

a) oxide thickness:

=> To check if we are in the linear regieme?

$$t^*(d) = 6.63 \times 10^{-7} \exp\left[\frac{11949}{T}\right]$$

$$= 6.63 \times 10^{-7} \exp\left[\frac{11949}{625}\right] = 133.2$$

since $t > t^*$ => we are in the linear regieme.

$$\therefore \delta(\mu m) = \delta^* + K_L(t - t^*)$$

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

$$= 2.11\ \mu m$$

$$K_L(\mu m/d) = 7.48 \times 10^6 \exp\left[\frac{-12500}{T}\right]$$

$$= 7.48 \times 10^6 \exp\left[\frac{-12500}{625}\right] = 0.01541\ \mu m/d$$

$$\therefore \delta = 2.11 + (0.01541)(400 - 133.2)$$

$$\boxed{\therefore \delta = 6.22\ \mu m}$$

[1] Cont

(b) $f = 18\%$, wt (ppm) of H , $t = 1$ year

PBR $= 1.56$, $\rho_{Zr} = 6.5$ g/cc , $\rho_{ZrO_2} = 5.68$ g/cc.

$$C_H = \frac{\alpha f \delta \rho_0 f^{O}_{ZrO_2} * \left(\frac{M_H}{M_O}\right)}{\left(t - \frac{\delta}{PBR}\right) \rho_m} * 10^6$$

$M_H = 1$, $M_O = 16$, $\alpha = 2$

$$f^{O}_{ZrO_2} = \frac{16*2}{(16*2)+91} = 0.26$$

$$\therefore C_H = \frac{2*0.18*6.22*5.68*0.26*\frac{1}{16}}{\left(500 - \frac{6.22}{1.56}\right)(6.5)} *10^6$$

$$\boxed{C_H^{clad} = 64.10 \text{ wt. ppm}}$$

[2] Total change in Volume.

$\alpha_{th} = 11 * 10^{-6}$, $\dot{f} = 3.5 * 10^{13}$ fiss/cm^{-3}.sec

$T = 1200$ k $T_{ref} = 300$ K , $\Delta\rho_0 = 0.01$

$B_D = 5$ MWD/kg U , $\rho(UO_2) = 10.97$ g/cc , $t = 85$ days

$\epsilon_{tot} = \epsilon_{th} + \epsilon_D + \epsilon_{SFP} + \epsilon_{GFP}$

$\Rightarrow$ B (FIMA) @ $t = 85$ days

$$B = \frac{\dot{f} t}{N_u}$$

$\therefore N_u = 10.97 * \frac{1}{270 \text{ gm}} * 6.022 * 10^{23} / 1\text{mol} * \frac{1U}{1 UO_2} = 2.45 * 10^{22}$ U/cc

$\Rightarrow \dot{\epsilon}_{th} = \alpha \Delta T = (11 * 10^{-6})(1200 - 300) = 0.0099$

$$\Rightarrow \epsilon_D = \Delta\rho_0 \left[\exp\left(\frac{B \ln(0.01)}{C_d B_0} \right) - 1 \right]$$

$B_0 = 5$ MWD/kg.U $\frac{1}{950} = 0.0053$ FIMA

$\therefore C_D = 1$ we are at $T > 750\,^\circ C$

$$\therefore \epsilon_D = 0.01 \left[\exp\left(\frac{0.01049 * \ln(0.01)}{1 * 0.0053} \right) - 1 \right]$$

$= -0.00999 \cong -0.01$

$$B = \frac{3.5 * 10^{13} * 7344000}{2.45 * 10^{22}} = 0.01049 \text{ FIMA}$$

2) Cont'd

$\epsilon_{SFP} = 5.577 * 10^{-2} \rho B$

$= 5.577 * 10^{-2} * 10.97 * 0.01049$

$= 0.00641$

$\epsilon_{GFP} = 1.96 * 10^{-28} \rho B (2800 - T)^{11.73} e^{-0.0162(2800-T)} e^{-17.8\rho B}$

$= 6.1811 * 10^{-4}$

$\therefore \epsilon_{tot} = 0.0099 - 0.00999 + 0.00641 + 6.1811 * 10^{-4}$

$\boxed{\epsilon_{tot} = 0.026918 \cong 2.6\%}$

3

$\sigma_m = 200\ MPa$, $T = 600\ K$, $\Sigma HR = 150\ w/cm$

$t = 1.5$ year.

⇒ for thermal creep:

$$\dot{\epsilon}_{ss} = A_0 \left(\frac{\sigma_m}{G}\right)^n \exp\left(-\frac{Q}{kT}\right)$$

$A_0 = 4 * 10^{-24}\ s^{-1}$, $G = 4.1 * 10^{+10} - 2.3 * 10^{7}\, T\ (Pa)$

$\cancel{\therefore G|_{T=600} \simeq 28350\ MPa}$

$G = 2.92 * 10^4\ MPa$

$n = 5$

$Q = 27 * 10^5\ J/mol$

$$\therefore \dot{\epsilon}_{ss} = (4 * 10^{-24}) \left(\frac{200}{2.92 * 10^4}\right)^5 \exp\left(\frac{-27 * 10^5}{8.314 * 600}\right)$$

$$= 3.5 * 10^{-12}\ sec^{-1}$$

$$\dot{\epsilon}_{irr} = C_0\, \phi^{C_1}\, \sigma_m^{C_2}$$

$C_0 = 2.714 * 10^{-24}$, $C_1 = 0.85$, $C_2 = 1$

$$\therefore \dot{\epsilon}_{irr} = (2.714 * 10^{-24})(4.5 * 10^{13})^{0.85} (240)$$

$$= 2.624 * 10^{-10}\ sec^{-1}$$

$$\therefore \dot{\epsilon}_{tot} = 3.5 * 10^{-12} + 2.624 * 10^{-10} = 2.65 * 10^{-10}$$

$\phi = 3 * 10^{11} * \Sigma HR = 4.5 * 10^{13}\ n/cm^2 \cdot sec$

$\therefore$ at 1.5 year $\epsilon = 2.65 * 10^{-10} * 47304000 = 0.0125$

[4] Types of FPs:

[1] Soluble oxides

* Y, La, rare earths
* dissolved in the cation ~~struct~~ sublattice

[2] Insoluble oxides

* Zr, Ba, Sr
* Form insoluble oxides in the fluorite lattice

[3] Metals:

* Mo, Ru, Pd, Tc
* Form metallic precipitates (white inclusions)

[4] Volatiles:

* Br, Rb, Te,
* exist as gas in the high temp areas and solids at the cooler

[5] Noble gases:

* Xe, Kr
* Insoluble in the fuel matrix
* form → intragranular voids or bubbles
  ↳ intergranular bubbles.

[5] Microstructure - based fuel performance modeling:

This concept is a new concept relate, theories which explains phenomena in purly physical or deterministic terms. Codes that are based on this concept employ mechanistic materials models that are based on the current state of the evolving microstructure rather than burnup or time.

The importance of such concept lies on the insights provided into the properties and mechanisms that can be used in large-scale modeling lead to more predictive fuel performance capabilities.

6 Benefits of using Zr cladding:

① low neutron cross-section

② Corrosion resistance in 300 °C water

③ Resistance to void swelling

④ Good mechanical properties.

7 Metallic fuel constituent & redistribution:

This is because the chemical constituent, such as Zr, can possesses different solubilities in each phase of the U. Also they diffuse up to the temperature gradient ~~under~~ via Soret diffusion. This will lead to having different zones with different chemical content. For example, for Zr:

a) γ-phase => higher Zr content
b) β-phase => low Zr content (depleted)
c) α/δ phase => as-fab Zr content.

8)

MOX => high burn up on ZHR

10)

it occurs during LOCA and includes formation of fine fragments.

They used phase-field to buildup a criteria for this phenomena.

[9] Conditions for SCC:

[1] Corrosive environment:

* in the fuel and due to fission process, we have different species of chemically aggressive FPs. These FPs can accumale in the fuel-clad gap easily especially volatile FPs or FPs that can form volatile compounds. Also, they can diffuse down the temperature gradient through fuel cracks.

[2] Susceptible Material:

* As these aggressive FPs exist ~~insid~~ in the gap, the fuel clad will be susceptible to them. It's susceptibility influenced by many factors, such as chemical composition, microstructure, texture, etc.

[3] Sufficient stress:

* In nuclear fuel we have many sources that impose stress on the cladding material, such as thermal expansion, solid and gaseous FP swelling, thermal and irradiation creep, irradiation-induced densification and cracking.

[4] Sufficient time:

* SCC process is divided into 4 stages. The time of the 1st stage which is required to initiate SCC (incubation time) is very short relative to the fuel-life-time, which gives SCC the enough time to propagate until we have failure.

III Difference between RIA and LOCA:

* In RIA:

- Due to the increase in the power, hence the temperature, there will be an increase in the bubble pressure which lead to grain boundaries separation and then cracking in the fuel. In addition to that there will be an increase in the volume of the fuel due to thermal expansion.
Along with the direct effect on Cladding (corrosion, damage accumulation, etc), there will be a higher chance to have FCMI results from the fuel pushing out the cladding, causing it to break which may lead to the release of radioactive materials or fuel to the Coolant. This will Cause rapid steam generation and pressure pulses damaging other core internals.

* In LOCA:

- Due to the loss in the Coolant Flow, there will be an increase in the average temperature of the reactor due to radioactive decay (α decay mainly) so this increase in temp is relatively slower than RIA. As the coolant pressure decrease, the fuel internal pressure will increase and causing severe plastic deformation for the cladding which lead to clad ballooning out and potentially burst. This ballooning may also lead to the blockage of the Coolant channels. ~~affecting cold~~

* Example of a RIA is what happened in Chernobyl reactor (RBMK)

11 Cont

* Example of a RIA:

when we have a large and rapid reactivity increase caused by inadvertent ejection (for PWRs) or drop (BWR) of a control rod due to mechanical failure in the control rod drive mechanism or its housing. This leads to a rapid increase in the fuel power, temperature and pressure

[12] ATF pathways;

[1] Improve reaction kinetics with steam
- Decrease heat of oxidation
- lower oxidation rate
- reduce H-production

[2] Improve cladding properties:
- resilence to clad fracture
- robust geometric stability
- Thermal shock resistance.

* Examples of ATFs:

* Cladding Coating
  - coating Zircaloys with Ti_3SiC_2

* Alternate cladding
  - SiC, FeCrAl,

* UO_2 doping with Cr, SiC, BeO.

[13] Limiting Phenomena in LWR,

[1] PCMI

[2] Cladding elongation and assembly bow

[3] Cladding oxidation and H-pickup.

[4] Cladding wear.