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Q(1)

Zirlo - clad.

$T = 625\ K$

$t = 400$ days.

initial thickness $\delta_0 = 500\ \mu m$.

$\delta = ?$

A)

* find the critical time for transition

$$t^*(d) = 6.62 \times 10^{-7} \exp\left(\frac{11949}{T}\right)$$

$$t^*(d) = 6.62 \times 10^{-7} \exp\left(\frac{11949}{625}\right) = \underline{133 \text{ day}} < 400 \text{ days}.$$

which means we passed the transition

* Critical oxide thickness for transition.

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

$$* \Rightarrow K_\ell \left(\frac{\mu m}{d}\right) = 7.48 \times 10^6 \exp\left(\frac{-12500}{625}\right)$$

$$K_\ell = 0.0154$$

$$\Rightarrow \boxed{\delta = \delta^* + K_\ell (t - t^*)}$$

$$\delta = 2.115 + 0.0154 (400 - 133)$$

$$\delta = 6.23\ \mu m$$

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B) H - pick up fraction = 18%

weight PPM of H in the cladding after 1 year.

PBR = 1.56

$\rho_{Zr} = 6.5$ g/cc

$\rho_{ZrO_2} = 5.68$ g/cc

$$C_H^{clad} (wt.ppm) = \frac{2 f \times \overset{6.23}{\delta} \times \overset{5.68}{\rho_{oxide}} \times f^{o}_{ZrO_2} \times \frac{M_H}{M_O}{}^{1}_{16}}{(\underset{365}{t} - \frac{\delta}{\underset{1.56}{PBR}}) \times \rho_{metal}} \times 10^6$$

$$f^{o}_{ZrO_2} = \frac{2 \times 16}{2 \times 16 + 41} = 0.26$$

$$C_H^{clad} (wt.ppm) = \frac{2 \times 0.18 \times 6.23\ \mu m \times 5.68 \times 0.26 \times \frac{1}{16}}{\left(500 - \frac{6.23}{1.56}\right) 6.5} \times 10^6$$

$$C_H (wt.ppm) = 64.2 \text{ wt. ppm}.$$

Q(2) $\Delta V_{total} = ?$

$\alpha_{th} = 11 \times 10^{-6}$

$\dot{F} = 3.5 \times 10^{13}$ fiss/cm$^3$ s

$T = 1200K$

$T_{ref} = 300K$

$\Delta P_0 = 0.01$

$B_D = 5$ MWD/kgU

$\rho(UO_2) = 10.97$ g/cm$^3$

$t = 85$ days.

$\Delta V_{total} = \epsilon_{th} + \epsilon_D + \epsilon_{sfp} + \epsilon_{gfp}$.

due to thermal expansion.

$\epsilon_{th} = \alpha \Delta T = 11 \times 10^{-6} (1200 - 300)$

$\epsilon_{th} = 9.9 \times 10^{-3}$

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$\beta(FIMA) = \frac{\dot{F} t}{N_U}$.

$N_U = ?$

$\rightarrow M_{UO_2} = 269.9$ g/mol

$N_U = \frac{N_A \rho_{UO_2}}{M_{UO_2}} = \frac{6.023 \times 10^{23} \times 10.97}{269.9} = 2.45 \times 10^{22}$

$\beta = \frac{3.5 \times 10^{13} \times 85 \times 24 \times 60 \times 60}{2.45 \times 10^{22}} = 0.01$ FIMA

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$$\epsilon_D = \Delta P_0 \left( e^{\frac{\beta \ln(0.01)}{C_D B_D}} - 1 \right)$$

$C_D = 1$

$B_D = \frac{5}{950} = 0.0053$ FIMA

$$\epsilon_D = 0.01 \left( e^{\frac{0.01 \ln(0.01)}{0.0053}} - 1 \right) = -1 \times 10^{-2} \Rightarrow 9.9 \times 10^{-3}$$

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$\epsilon_{sfp} = 5.577 \times 10^{-2} \rho \beta$

$\epsilon_{sfp} = 5.577 \times 10^{-2} \times 10.97 \times 0.01 = 6.1 \times 10^{-3}$

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$$\epsilon_{gfp} = 1.96 \times 10^{-28} \times 10.97 \times 0.01 (2800 - 1200)^{11.73} e^{-0.0162(2800-1200)} e^{-17.8 \times 10.97 \times 0.01}$$

$\epsilon_{gfp} = 6.48 \times 10^{-4}$

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Change in volume $\epsilon_{total} = (6.48 \times 10^{-4}) + (6.1 \times 10^{-3}) + \cancel{(9.9 \times 10^{-3})} + 9.9 \times 10^{-3}$

$\epsilon_{total} = 6.79 \times 10^{-3}$

Q(7) total Creep = ?

total creep = thermal + irradiation creep.

$\sigma_m = 200$ MPa.

$T = 600$ K

$LHR = 150$ W/cm

$t = 1.5$ year.

A) thermal Creep.

$$\dot{\epsilon}_{th} = \left( A_0 \left(\frac{\sigma_m}{G}\right)^m e^{-\frac{Q}{RT}} \right)$$

$A_0 = 3.14 \times 10^{29}\ s^{-1}$

$G = 4.2519 \times 10^{10} - 2.2\times10^{7} T$

$G = 2.92 \times 10^{10}$ Pa.

$Q = 2.7 \times 10^{5}$ J/mol

$n = 5$

$R = 8.314$.

$$\dot{\epsilon}_{th} = \left( 3.14 \times 10^{24} * \left(\frac{200}{2.92\times10^{4}}\right)^5 e^{-\frac{2.7\times10^5}{8.314 \times 600}} \right)$$

$$\dot{\epsilon} = 1.47 \times 10^{-10}$$

B) irradiation creep.

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

$C_0 = 3.557 \times 10^{-24}$

$C_1 = 0.85$

$C_2 = 1$

$\phi = 3e^{11}$ LHR.

$\phi = 3\times10^{11} * 150 = 4.5\times10^{13}$ n/cm²-s

$$\dot{\epsilon}_{irr} = 3.557\times10^{-24} * (4.5\times10^{13})^{0.85} * (200)^1$$

$$\dot{\epsilon}_{irr} = 2.866\times10^{-10}$$

$$\dot{\epsilon}_{total} = (2.866\times10^{-10} + 1.47\times10^{-10}) = 4.34\times10^{-10}\ s^{-1}$$

$$\epsilon_{total} = 4.34 \times 10^{-10} * 1.5 * 365 * 24 \times 3600$$

$$\epsilon_{total} = 2.05\ \%$$

Q (4) fission products types.

1 - solubable oxides (Y, La and rare earth ele —)

2 - insoluable oxides (Zr, Ba ., Sr)

3 - Metals (Mo, Ru, Pd and Tc)

4 - Volatiles (Br, Rb, Te, I . and Cs)

5 - Noble gases (Xe, Kr)

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Q (5) instead of depending on temp and burn up only in modelling, it dependes on the state of the microstructure and the evolution of micro structure based on aset of variables

⇒ takes into account many variables like temp. displacement stoichio —

⇒ utilize the updated microstructure to inform anumber of structure/property relationships.

Q(6)

· benifits of using Zr cladding.

- low neutrons absorption.
- ~~2.~~ corrosion resistance $T < 300°C$
- resistance to void swelling
- good mechanical properties
- good thermal Conduct—
- Cost / availability.

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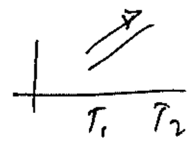
Q(7)

- Zr diffuse via soret diffusion




- Zr has different soluability in each phase.
- distinct zones of Zr-Content in radial rings.

  $\gamma$-phase → high Zr
  $\beta$-phase → low Zr
  $\alpha/\delta$ → as sintered

Q(8) differences in MOX Fuel

behavior.

- Restructuring takes place due to high temp.
- Redistribution.
- Gap Closure.
- JOG

performance.

operate at high linear heat generation rate
higher power density and heat fluxes
highly radiation tolerant.

environment.

very intense neutron flux.

Na at 400°C $\xrightarrow[\text{bottom}]{\text{input from}}$ average Coolant temp above the core is 550°C

(9)

A) Corrosive environment.
due to chemically aggressive F.P. accumulation in the fuel clad gap.

B) Susceptible material.
- the susceptibility is influenced by composition, micro structure texture
- Zr-alloys are prone to PCI

C) Sufficient Stress
stress coming from coolant pressure, creep, internal stress.

D) sufficient time.
time is required for SCC to develop in the clad.

⇒ stages of SCC

- development of Corrosive environment.
- initiation of SCC
- propagation of SCC
- failure.

in PCI

- environment.
FP accumulation.
- susceptible material
Zr is prone to SCC
- Stress.
mechanical stress from the contact between P-C
- time
sufficient time for Contacting between P-C.

(10)

trapped gas in bubbles heats up and becomes overpressurized.

Cracking initiates at these overpressurized bubbles.

Current model.

empirical.

based on T and burn up.

Scientists are working on developing a physics based criterion in Bison that account for microstructure.

Focus on HBS.

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## RIA

leads to a fast rise in fuel power and temp.
power ramp lead to failure of fuel rods.
rapid steam generation
pressure pulse.
types ( CREA, CRDA)

## LoCA

the coolant is reduced or lost
pressure drop
SCRAMS.
T ↑ , P ↓
clad ballooning , burst.
similar to RIA but more slow
T↑ → gas bubbles P ↑, fuel fragmentation, FCMI

## Example of RIA

Chernobyl RIA

- ~~accident occur due to lack of reactor~~ :

(12)

ATF options.

⇒ Cladding coatings.
protect Zr.

⇒ Alternate cladding.
SiC, FeCrAl

⇒ $UO_2$ dopants
Cr, SiC, BeO.

⇒ Alternate fuels.
USi, UN, UC.

1 - improved reaction kinetics with steam.

2 - improved fuel properties.

3 - improved cladding properties.

4 - enhanced fission product retention.

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(13) limiting phenomena

1 - PCMI

2 - Cladding elongation and assembly bow

3 - Cladding oxidation and H pick up.

4 - clad wear

5 - Power to melt

6 - internal pressure.

7 - DNBR.