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Q(1)

Zirlo - clad.

$T = 625$ K

$t = 400$ days.

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

$\delta = ?$

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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.

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

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

$$K_\ell = 0.0154$$

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

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

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

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

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

$$f^{o}_{ZrO_2} = \frac{2 \times 16}{2 \times 16 + 91} = 0.26$$

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

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

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

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

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

$T = 1200K$

$T_{ref} = 300K$

$\delta \rho_0 = 0.01$

$B_D = 5$ MWD/kgU

$\rho(UO_2) = 10.97$ g/cm^2

$t = 85$ days.

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

→ due to thermal expansion.

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

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

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

$N_u = ?$

→ $M_{UO_2} = 269.9$ 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

$*$ $\epsilon_D = \delta \rho_0 \left(e^{\frac{\beta \ln(0.01)}{C_D B_D}} - 1 \right)$

$C_D = 1$

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

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

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

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

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

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

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

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

Q(7) total Creep = ?

total creep = thermal + irradiation creep.

$\sigma_m = 200$ MPa.

$T = 600$ K

A) thermal Creep.

$LHR = 150$ W/cm

$t = 1.5$ year.

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

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

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

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

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

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

$n = 5$

$R = 8.314.$

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

B) irradiation Creep.

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

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

$C_1 = 0.85$

$C_2 = 1$

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

$$\phi = 3 \times 10^{11} * 150 = 4.5 \times 10^{13} \quad n/cm^2\text{-}s$$

$$\dot{\epsilon}_{irr} = 3.557 \times 10^{-24} * (4.5 \times 10^{13})^{0.85} * (200)^1$$

$$\dot{e}_{irr} = 2.866 \times 10^{-10}$$

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

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

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

Q(4) fission products types.

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1 - solouable 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)

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

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

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

Q(6)

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· benifits of using Zr cladding.

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

Q(7)

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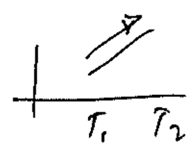
- Zr diffuse via soret diffusion



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

  γ-phase → high Zr
  β-phase → low Zr
  α/δ → as sintered

Q(8) differences in MOX Fuel

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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
~~also~~ 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

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A) Corrosive environment.
due to chemically aggresive FP 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)

6/6

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~~ .

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ATF options.

1 - improved reaction kinetics with steam.

2 - Improved fuel properties.

3 - improved cladding properties.

4 - enhanced fission product retention.

⇒ Cladding coatings.
protect Zr.

⇒ Alternate cladding.
SiC, FeCrAl

⇒ UO_2 dopants
Cr, SiC, BeO.

⇒ Alternate fuels.
U_3Si, UN, UC.

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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.

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