Homework 497I

1. First cycle $T = 340°C = 613 K$

After 365 days $\Rightarrow$ $\delta_{cubic} = K_c t^{1/3} = 504 \exp\left(\frac{-4600}{613}\right) 365^{1/3} =$

$$\delta_{cubic} = 1.9801\ \mu m$$

a) oxide reaches 2 μm and transition early in second cycle

At the end of the 1st cycle oxide is 1.9801 μm and second cycle starts with an existing oxide layer and @ 320C

$\Rightarrow$ If one calculates the oxide thickness using cubic law @ 320C we get a very short time because it would be the rate for fresh cladding to get that δ, not the additional thickness on 1.9801 μm

To get the correct answer, calculate:

$d\delta = K_c\, \partial t^{1/3}$ $\qquad (2 - 1.9801) = K_c\,(t^{1/3} - 365^{1/3})$

$\downarrow$

$\frac{0.0199}{0.216} = t^{1/3} - 365^{1/3}$ $\qquad 504 \times \exp(-4600/593) = 0.216$

$t = (365^{1/3} + 0.0921)^3 = 377$ days //

For the remaining 353 d of the 2nd cycle, linear regime applies

b) Remaining time = 353 d $\qquad T = 320C = 593K$

$\delta = K_L t \qquad$ For Zircaloy 4 $\delta = 3\times10^{9} \exp\left(\frac{-15700}{593}\right) \times 353 =$

$= 3.36\ \mu m$

For ZIRLO

$\delta = 6\times10^{7} \exp\left(\frac{-13800}{593}\right) \times 353 =$

$= 1.65\ \mu m$

In cycle 3 $\quad T = 330 = 603K$

For Zircaloy-4 $\quad \delta = 3\times10^{9} \exp\left(\frac{-15700}{603}\right) \times 365 =$

$= 5.39\ \mu$

For ZIRLO

$\delta = 6\times10^{7} \exp\left(\frac{-13800}{603}\right) \times 365 =$

$= 3.66\ \mu m$

The total thickness is

Zircaloy 4 $= 2 + 3.36 + 5.39 = 10.75\ \mu m$

ZIRLO $= 2 + 1.65 + 3.66 = 7.31\ \mu$

In reality ZIRLO would reach transition a little later than Zry-4 further widening the difference between the two alloys

c) Highest temperature for $\delta < 15\mu$ in 3 years

$\Rightarrow$ Assume all linear from $t=0$

$$\delta = A \exp\left(-\frac{B}{T}\right) \cdot t \quad \therefore \quad \frac{\delta}{tA} = \exp\left(\frac{-B}{T}\right)$$

$$\ln\left(\frac{\delta}{tA}\right) = \frac{-B}{t} \quad \Rightarrow \quad T = \frac{-B}{\ln\left(\frac{\delta}{tA}\right)}$$

For Zircaloy 4 $\quad T = \dfrac{-15700}{\ln\left(\dfrac{15}{365 \times 3 \times 3 \times 10^{9}}\right)} = 601\,K = 328C$

For ZIRLO

$$T = \frac{-13800}{\ln\left(\frac{15}{365 \times 3 \times 6 \times 10^{7}}\right)} = 621\,K = 348C$$

Thus, ZIRLO could run 20C hotter than Zircaloy-4

2. At 350C $f = 0.15$ how long before ductility is impaired?

$$C_H = \frac{2 \cdot f \times \rho_{ZrO_2} \times f^{O}_{ZrO_2}}{\left(t - \frac{\delta}{PBR}\right) \times \rho_{metal}} \times {}^{M_H}/_{M_O} \times 10^6$$

$$A = \frac{B\delta}{\left(C - \frac{\delta}{F}\right)E} \quad \therefore \quad \delta = \frac{EAC}{B - \frac{EA}{F}}$$

$$\delta = \frac{\rho_{metal} \times C_H \times t}{2 \times f \times \rho_{ZrO_2} \times f^{O}_{ZrO_2} \times 10^6 \times \frac{M_H}{M_O} - \frac{\rho_{metal} C_H}{PBR}}$$

$PBR = 1.56$

$f = 0.15$

$\rho_{ZrO_2} = 5.68$ g/cm^3

$\rho_{metal} = 6.5$ g/cm^3

$M_H = 1$

$M_H = 16$

$f^{O}_{ZrO_2} = \frac{32}{(91+32)} = 0.26$

$C_H = 700$ wt ppm

$t = 600$ μm

$$\delta = \frac{6.5 \times 700 \times 600}{2 \times 0.15 \times 5.68 \times \frac{32}{(32+91)} * \frac{10^6}{16} - \frac{6.5 \times 700}{1.56}} = 110\,\mu$$

In linear regime reach 110 μ at

$\delta = K_L t \qquad t = \frac{\delta}{K_L}$

$K_L^{Zry4} = 3 \times 10^9 \times \exp\left(\frac{-15700}{623}\right) =$

$K_L^{ZL} = 6 \times 10^7 \exp\left(\frac{-13800}{623}\right)$

$\delta_{Zy4} = \frac{110}{3 \times 10^9 \exp(-15700/623)} = 3230\,d \cong 8.8$ years

$\delta_{ZL} = \frac{110}{6 \times 10^7 \exp(13800/623)} = 7651\,d \simeq 20.9$ year

It's unlikely either alloy will reach 110 μ in service, but the margin of ZIRLO > that of Zircaloy 4