Post irradiation annealing FGR

$t = 10\,\mu m$ $T = 1200K$ $t = 24$ hrs

Booth model, post irradiation annealing $\tau \lessgtr \pi^{-2}$

$$\tau = \frac{D t}{a^2}$$

$$D? = D_{Xe} = D_1 = 7.6\times10^{-6} \exp\left(\frac{-3.03}{kT}\right)$$

$\to T = 1000K$ $k_B = 8.617E-5$

$D_{Xe} = 1.43\times10^{-18}\ cm^2/s$

$a = 10\,\mu m \to 1\times10^{-3}\ cm$

$$\tau = \frac{(1.43\times10^{-18})(24\times3600)}{(1\times10^{-3})^2} = 1.235\times10^{-7}$$

$\pi^{-2} = 0.101$ $\tau < \pi^{-2}$ "short"

$$f = 6\sqrt{\frac{Dt}{\pi a^2}} - 3\frac{Dt}{a^2} = 6\sqrt{\frac{\tau}{\pi}} - 3\tau$$

$$= 6\sqrt{\frac{1.235\times10^{-7}}{\pi}} - 3(1.235\times10^{-7}) = \boxed{0.001189 \quad 0.1\%}$$

$t = 100$ days $\to \tau = 1.235\times10^{-5} \to$ "short time"

$\downarrow$

$f = 0.0118 \to 1.2\%$

in-pile

$D = D_1 + D_2 + D_3$

$D_2 \propto \sqrt{\dot{F}}$

$D_3 \propto \dot{F}$

Fuel dimensional change

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

$\dot{F} = 4 \times 10^{13}\ f/cm^3\text{-}s \qquad T = 1200K \qquad T_{ref} = 300K$

$\Delta\rho_0 = 0.01 \qquad \beta_D = 5\ MWd/kgU \qquad \alpha_F = 11 \times 10^{-6}\ 1/K$

$t = 6$ weeks?

$$\epsilon_{TE} = \alpha\Delta T = (11\times10^{-6})(1200-300) = 0.0099$$

$$\epsilon_D = \Delta\rho_0\left(\exp\left(\frac{\beta \ln 0.01}{C_D\,\beta_D}\right) - 1\right) \qquad \beta?$$

$$\beta = \frac{\dot{F}t}{N_U} \qquad N_U = 10.97\ g/cc\ \frac{1\ mol}{270\ g}\ \frac{6.022\times10^{23}}{1\ mol}\ \frac{1U}{1UO_2} = 2.44\times10^{22}\ U/cm^3$$

$$= \frac{(4\times10^{13})(6\times7\times24\times3600)}{2.44\times10^{22}} = \underline{0.0059\ FIMA}$$

$$\beta_D = 5\ MWd/kgU \times \frac{1}{1000} = 0.005\ FIMA \qquad \underline{\beta > \beta_D}$$

$$\epsilon_D = -\Delta\rho_0 = -0.01$$

$$\epsilon_{SFP} = 5.577\times10^{-2}\,\rho\beta = 5.577\times10^{-2}\,(10.97)(0.0059) = \underline{0.0036}$$

$$\epsilon_{GFP} = 1.96\times10^{-28}\,\rho\beta\,(2800-T)^{11.73}\exp(-0.0162(2800-T))\exp(-17.8\rho\beta)$$

$$\rho\beta = 10.97\times0.0057 = 0.0647 \qquad 2800 - T = 1600K$$

$$\epsilon_{GFP} = \underline{8.52\times10^{-4}}$$

$$\epsilon_{tot} = 0.0099 - 0.01 + 0.0036 + 8.52\times10^{-4}$$

$$\epsilon_{tot} = \underline{0.0044} \qquad \underline{0.44\%}$$

Zirconium Creep Rates

- PRXA $\quad \sigma_m = 150\ MPa \quad T = 625\ K \quad LHR = 175\ W/cm$

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

$A_0 = 3.14 \times 10^{24}\ 1/s$

$G = 4.2519 \times 10^{10} - 2.2185 \times 10^{7}\, T \quad (Pa)$

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

$G = @\ 625\ K = 28.65\ GPa$
$\rightarrow 28.65 \times 10^{3}\ MPa$

$$\dot{\epsilon}_{ss} = (3.14\times10^{24}) \left(\frac{150}{28.65\times10^{3}}\right)^5 \exp\left(\frac{-2.7\times10^5}{8.314 \times 625}\right) = \underline{3.365\times10^{-10}\ 1/s}$$

$$\dot{\epsilon}_{ir} = C_0\, \Phi^{C_1}\, \sigma_m^{C_2}$$

PRXA $\Rightarrow$ $C_0 = 3.557 \times 10^{-24}$
$C_1 = 0.85$
$C_2 = 1$

$\Phi = 3\times10^{11}\ LHR \rightarrow 5.25\times10^{13}\ n/cm^2 s$
$\quad$ 175 W/cm

$$\dot{\epsilon}_{ir} = (3.557\times10^{-24})(5.25\times10^{13})^{0.85}(150) = \underline{2.451\times10^{-10}\ 1/s}$$

$$\dot{\epsilon}_{tot} = \dot{\epsilon}_{ss} + \dot{\epsilon}_{ir} = \underline{5.816\times10^{-10}\ 1/s}$$

UO_2 system @ 2000K   initial grain size 5 μm

grain size after 2 hrs?

$$\frac{dD}{dt} = K\left(\frac{1}{D} - \frac{1}{D_m}\right)$$

$K = 2 M_{GB} \gamma_{GB}$

$\gamma = 1.58\ J/m^2$

$M_{GB} = M_0 \exp\left(-\frac{2.77}{kT}\right)$

$M_0 = 4.6 \times 10^{-9}\ m^4/J\text{-}s$

$M_{GB} = 4.815 \times 10^{-16}\ m^4/J\text{-}s$

$K = 2(4.815 \times 10^{-16})(1.58)$

$K = 1.5023 \times 10^{-15}\ m^2/s$

$D_m = ? = 2.23 \times 10^3 \exp\left(-\frac{7620}{T}\right) = 49.4\ \mu m$

$= 4.94 \times 10^{-5}\ m$

explicit time integration

$D_1 = D_0 + dt\, D_0'$

$dt = 3600 s$

$D_1 = 5 \times 10^{-6} + 3600\left(1.5023 \times 10^{-15}\left(\frac{1}{5 \times 10^{-6}} - \frac{1}{4.94 \times 10^{-5}}\right)\right)$

$D_1 = 5.972 \times 10^{-6}\ m$

$t = 2 = 7200 s$
2 hrs

$D_2 = D_1 + dt\, D_1'$

$= 5.972 \times 10^{-6} + 3600\left(1.5023 \times 10^{-15}\left(\frac{1}{5.972 \times 10^{-6}} - \frac{1}{4.94 \times 10^{-5}}\right)\right)$

$D_2 = 6.77 \times 10^{-6}\ m$ $\approx \boxed{6.8\ \mu m}$