Nuclear Fuel Performance

NE 533

Exam & Solutions

1) $R_f = 0.45$ cm LHR: 250 W/cm

a) max stress? $\rightarrow \sigma_\theta$

$$\sigma_\theta = -\sigma^* (1 - 3\eta^2) \qquad \sigma^* = \frac{\alpha E \Delta T}{4(1-\nu)}$$

$k_f = 0.1$ W/cm·K $E = 240$ GPa $\nu = 0.25$ $\alpha = 12\times10^{-6}$ 1/K

max @ $r = R_f \rightarrow \eta = \frac{r}{R_f} = 1$

$$\Delta T = \frac{LHR}{4\pi k_f} = \frac{250}{4\pi(0.1)} = 199\,K \qquad \sigma^* = \frac{(12\times10^{-6})(240\times10^3)(199)}{4(1-0.25)}$$

$\sigma^* = 231$ MPa

$$\sigma_\theta = -231\,(1 - 3(1)^2)$$

$= \underline{462 \text{ MPa}}$

b) $\sigma_{fr} = 120$ MPa

$$\sigma_{fr} = -\sigma^* (1 - 3\eta^2)$$

$$120 = -231\,(1 - 3\eta^2)$$

$\eta^2 = 0.506$ $\eta = 0.71$ $\rightarrow$ 29% into the fuel

2) $p = 25\,MPa$ $\quad \bar{R}_c = 0.52\ cm$ $\quad t_c = 0.08\ cm$

$R_i = 0.48$ $\quad R_o = 0.56$

a) $\sigma_\theta = \frac{pR}{t}$ $\quad \sigma_z = \frac{pR}{2t}$ $\quad \sigma_r = \frac{-p}{2}$

$\sigma_\theta = \frac{25\,(0.52)}{0.08} = \underline{162.5\ MPa}$ $\quad \sigma_z = \frac{\sigma_\theta}{2} = \underline{81.25\ MPa}$

$\sigma_r = \frac{-25}{2} = \underline{-12.5\ MPa}$

b) $r = 0.5\ cm$

$\sigma_\theta = p\,\frac{(R_o/r)^2 + 1}{(R_o/R_i)^2 - 1}$ $\quad \sigma_z = \frac{p}{(R_o/R_i)^2 + 1}$ $\quad \sigma_r = p\,\frac{(R_o/r)^2 + 1}{(R_o/R_i)^2 - 1}$

$R_o/r = \frac{0.56}{.5} = 1.12$ $\quad \frac{R_o}{R_i} = \frac{0.56}{0.48} = 1.167$

$\sigma_\theta = 25\,\frac{(1.12)^2 + 1}{1.167^2 - 1} = \underline{156\ MPa}$ $\quad \sigma_z = \frac{25}{1.167^2 - 1} = \underline{69.1\ MPa}$

$\sigma_r = 25\,\frac{1.12^2 - 1}{1.167^2 - 1} = \underline{17.6\ MPa}$

c) $\epsilon_\theta = \frac{1}{E}\left(\sigma_\theta - \nu(\sigma_r + \sigma_z)\right) = \frac{1}{160\times10^3}\left(156 - 0.3\,(17.6 + 69.1)\right)$

$= \underline{8.12\times10^{-4}}$

3) $\Delta t_g = \bar{R}_c \alpha_c \Delta T_c - R_f \alpha_f \Delta T_f$

$R_f = 0.52$ cm $\quad t_g = 0.005$ cm $\quad T_{c0} = 550$ K $\quad t_c = 0.08$ cm $\quad K_f = 0.04$ W/cm-K

$K_g = 0.003$ W/cm-K $\quad K_c = 0.15$ W/cm-K $\quad LHR = 400$ W/cm $\quad \alpha_c = 12\times10^{-4}$

$\alpha_f = 8\times10^{-6}$

$$\Delta T_c = \frac{LHR}{2\pi R_f}\frac{t_c}{k_c} = \frac{400}{2\pi(0.52)}\frac{0.08}{0.15} = 65 \text{ K} \qquad T_{c1} = 615 \text{ K}$$

$$\Delta T_g = \frac{LHR}{2\pi R_f}\frac{t_g}{K_g} = \frac{400}{2\pi(0.52)}\frac{0.005}{0.003} = 204 \text{ K} \qquad T_s = 819 \text{ K}$$

$$\Delta T_f = \frac{LHR}{4\pi K_f} = \frac{400}{4\pi(0.04)} = 796 \text{ K} \qquad T_0 = 1615 \text{ K}$$

$$\bar{T}_c = \frac{T_{c0} + T_{c1}}{2} = \frac{550 + 615}{2} = 582.5 \text{ K}$$

$$\bar{T}_f = \frac{T_0 + T_s}{2} = \frac{819 + 1615}{2} = 1217 \text{ K}$$

$$\bar{R}_c = 0.52 + 0.005 + \frac{0.08}{2} = 0.565 \text{ cm}$$

$$\Delta t_g = 0.565(12\times10^{-6})(582.5 - 300) - 0.52(8\times10^{-6})(1217 - 300)$$

$$\Delta t_g = 0.0019 - 0.0038 = -0.0019$$

$$t_g = 0.005 - 0.0019 = \underline{0.003} \text{ cm}$$

4) Forward Euler

$$\frac{dy}{dt} = -5y \qquad dt = 0.25 \qquad t_0 = 0 \qquad y_0 = 1$$

$$y_1 = y_0 + dt\, y_0'$$

$t_1 = 0.25$ $\qquad y_1 = 1 + 0.25\left(-5(1)\right) = -0.25$

$t_2 = 0.5$ $\qquad y_2 = y_1 + dt\, y_1'$

$= -0.25 + 0.25\left(-5(-0.25)\right)$

$= 0.0625$

$t_3 = 0.75$ $\qquad y_3 = y_2 + dt\, y_2'$

$= 0.0625 + 0.25\left(-5(0.0625)\right)$

$= -0.0156$

$t_4 = 1$ $\qquad y_4 = y_3 + dt\, y_3'$

$= -0.0156 + 0.25\left(-5(-0.0156)\right)$

$= 0.0039$

5) max σ_θ ?

$\Delta T_c = 250\ K$ $\alpha_c : 9 \times 10^{-6}\ 1/K$ $E : 250\ GPa$ $\nu : 0.3$

$t_c = 0.1$ $R_i : 0.55\ cm$

σ_θ max @ $r = R_i$

$$\sigma_\theta = \frac{1}{2}\Delta T \frac{\alpha E}{1-\nu}\left(1 - \frac{2R_i}{\delta}\left(\frac{r}{R_i} - 1\right)\right)$$

$$= \frac{1}{2}\frac{(250)(9\times10^{-6})(250\times10^{3})}{1-0.3}\left(1 - \cancel{\frac{2(0.55)}{0.1}}\left(\cancel{\frac{0.55}{0.55} - 1}\right)\right)$$

$\sigma_\theta = 357\ MPa$

$\sigma_\theta = 0$ @ $r = R_i + \frac{\delta}{2}$

$$0 = \left(1 - \frac{2R_i}{\delta}\left(\frac{r}{R_i} - 1\right)\right)$$

$$1 = \frac{2r}{\delta} - \frac{2R_i}{\delta} \rightarrow \frac{2r}{0.1} - \frac{2(0.55)}{0.1} = 1$$

$r = 0.6\ cm = R_i + \frac{\delta}{2}$

6) finite difference : fast, easy to implement

finite volume : continuous, flexible, flux B.C.s

finite element : any B.C.s, continuous, computationally expensive

7) Increase in yield strength due to plastic deformation. Plasticity induces dislocation generation and diffusion, but these dislocations interact and repel one another. With an increase in plastic deformation, there are more barriers to allow further plastic deformation to take place, thus the yield strength increases.

8) Model the temperature in the fuel, describe temperature and stress in the cladding, handle gap heat transport + closure.

9) 0-D : vacancy, interstitial, substitutional

3-D : bubble, precipitate

10) Utilizing the underlying microstructure to guide the evolution of the state variables and material properties of the system. Removes the dependence upon empirical correlations that only account for burnup, and instead relate the actual changes in the material to the evolution of material quantities. Allows for predictive behavior of fuel performance outside of known experimental conditions. Improves descriptive performance.

11) Fission gas bubbles are present in the HBS, which is a nano-grained structure on the periphery of the fuel. Under a transient, temperature spikes, leading to increased pressure in bubbles, which can induce intergranular fracture of the HBS. Phase field and multiscale modeling are exploring the interactions of microstructure and material properties on pulverization.

12) Anything that can be seen with ~25x magnification. Includes grain structure, second phases, precipitates, voids, etc. Processing such as cold working or annealing can refine or homogenize the microstructure, leading to changes in macroscale properties.