(1) $R_F = 0.45$ cm  LHR: 250 W/cm

$K_f = 0.15$ W/cm-K  $E = 180$ GPa  $\alpha_F = 14\times10^{-6}$ 1/K  $\nu = 0.4$

max stress? → $\sigma_\theta$  $\sigma_\theta(\max) = \sigma_\theta(r = R_F)$

$$\sigma_\theta = -\sigma^*(1-3\eta^2) \qquad \eta = \frac{r}{R_F} \rightarrow \frac{R_F}{R_F} = 1$$

$$\sigma^* = \frac{\alpha E (T_0 - T_S)}{4(1-\nu)}$$

$$\Delta T_F = \frac{LHR}{4\pi K_F} = \frac{250}{4\pi(0.15)} = 132.6\ K$$

$$\sigma^* = \frac{(14\times10^{-6})(180\times10^3)(132.6)}{4(1-0.4)} = 139.3\ MPa$$

$$\sigma_\theta = -(139.3)(1-3(1)^2) = \boxed{278.5\ MPa}$$

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

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

$$120 = -139.3(1-3\eta^2)$$

$$0.86 = 3\eta^2 - 1$$

$$\eta^2 = 0.62$$

$0.45 - 0.354 = 0.095$

$$\eta = 0.788 = \frac{r}{R_F} \Rightarrow r = 0.354\ cm$$

→ cracks extend about 0.1 cm into the fuel

② $p = 55\ MPa$ $\quad \bar{R}_c = 0.52\ cm$

$t_g = 0.05\ cm$ $\quad \rightarrow R_i = 0.495\ cm$

$R_o = 0.545\ cm$

thin

$$\sigma_\theta = \frac{pR}{\delta} \qquad \sigma_z = \frac{pR}{2\delta} \qquad \sigma_r = -\frac{p}{2}$$

$$\sigma_\theta = \frac{55(0.52)}{0.05} = \underline{572\ MPa} \qquad \sigma_z = \frac{(55)(0.52)}{2(0.05)} = \underline{286\ MPa}$$

$$\sigma_r = \frac{-55}{2} = \underline{-27.5\ MPa}$$

thick @ $r = 0.5\ cm$

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

$$R_o/R_i = \frac{0.545}{0.495} = 1.10 \qquad \frac{R_o}{r} = \frac{0.545}{0.5} = 1.09$$

$$\sigma_r = -55\,\frac{(1.09^2) - 1}{1.10^2 - 1} = \underline{-49.3\ MPa}$$

$$\sigma_\theta = 55\,\frac{1.09^2 + 1}{1.1^2 - 1} = \underline{573.1\ MPa}$$

$$\sigma_z = \frac{55}{1.1^2 - 1} = \underline{261.9\ MPa}$$

3) Gap thickness due to thermal expansion

$R_f = 0.52$ cm $\quad t_g = 0.005$ cm $\quad T_{co} = 550K \quad t_c = 0.08$ cm

$K_f = 0.04$ W/cm-K $\quad k_g = 0.003$ W/cm-K $\quad K_c = 0.15$ W/cm-K

$LHR = 175$ W/cm $\quad \alpha_c = 10\times10^{-6}$ 1/K $\quad \alpha_f = 14\times10^{-6}$ 1/K $\quad T_{ref} = 300K$

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$$\Delta t_g = \bar{R}_c \alpha_c (\bar{T}_c - T_o^c) - R_F \alpha_F (\bar{T}_F - T_o^F)$$

$$\Delta T_c = \frac{LHR}{2\pi R_F}\frac{t_c}{K_c} = \frac{175}{2\pi(0.52)}\frac{0.08}{0.15} = 28.6\,K \qquad T_{c1} = 550 + 28.6 = 578.6\,K$$

$$\bar{T}_c = \frac{T_{c1} + T_{co}}{2} = \underline{564.3\,K} \qquad \bar{R}_c = 0.52 + 0.005 + \frac{0.08}{2}, \quad \bar{R}_c = \underline{0.565\,cm}$$

$$\Delta T_g = \frac{LHR}{2\pi R_F}\frac{t_g}{k_g} = \frac{175}{2\pi(0.52)}\frac{0.005}{0.003} = 89.3\,K \qquad T_s = 667.9\,K$$

$$\Delta T_F = \frac{LHR}{4\pi k_f} = \frac{175}{4\pi(0.04)} = 348.2\,K \qquad T_o = 1016.1\,K$$

$$\bar{T}_F = \frac{T_o + T_s}{2} = \underline{842\,K}$$

$$\Delta t_g = 0.565(10\times10^{-6})(564.3 - 300) - 0.52(14\times10^{-6})(842 - 300)$$

$$\Delta t_g = 0.0015 - 0.0039 = \underline{-0.0024}$$

$$t_g' = t_g + \Delta t_g = 0.005 - 0.0024 = \boxed{0.0026\ cm}$$

(4) $\Delta T = 50\,K \quad \alpha_c = 8\times10^{-6}\ 1/K \quad E = 100\ GPa \quad \nu = 0.34$

$t_c = 0.06 \quad R_i = 0.55\ cm \quad @\ r = 0.59\ cm$

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

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

$$\frac{\Delta T}{\alpha}\frac{\alpha E}{1-\nu} \rightarrow \frac{50}{\alpha}\frac{(8\times10^{-6})(100\times10^{3})}{1-0.34} = 30\ MPa$$

$$\sigma_r = 30\left(\frac{0.59}{0.55}-1\right)\left(1-\frac{0.55}{0.06}\left(\frac{0.59}{0.55}-1\right)\right)$$

$$\underline{\sigma_r = 0.73\ MPa}$$

$$\sigma_\theta = 30\left(1-2\frac{0.55}{0.06}\left(\frac{0.59}{0.55}-1\right)\right)$$

$$\underline{\sigma_\theta = -10\ MPa}$$

(5) Elasticity is a reversible deformation due to the stretching of atomic bonds.

Plasticity is a permanent deformation from the breaking of bonds and displacement of dislocations along slip planes or the nucleation of twins.

(6) Strain hardening is the increase in yield strength after a material has been plastically deformed. This is caused by the interaction of dislocations w/ existing defects, e.g. grain boundaries, and the interaction of dislocations with each other. Dislocations repel each other and pile-up can occur, inhibiting the motion of dislocations, making it harder to induce plasticity.

(7). 1) Define/describe fuel heat transfer & stresses
2) Define/describe cladding heat transfer + stresses
3) Model gap conductance + closure.

Bison, Frapcon, OFFBEAT, Falcon, etc.

(8). 0-D → vacancy, interstitial, substitutional, etc.
3-D → void, precipitate, bubble, etc.

(9). Individual powder particles come into contact w/ each other during sintering. Each particle has a unique orientation w/ respect to the other particles. During heating and pressing, the particles bond, w/ the original particle boundaries as the grain boundaries.

(10) Microstructure-based modeling is the use of mechanistic models which describe fundamental physics-based processes utilizing variables and parameters from lower length scales. The microstructure and its evolution can be used to predict the macroscale property evolution and the behavior of the system. This is in contrast to burnup dependent models which are empirical in nature and rely on a robust experimental data set for fitting. μ-structure based models can be used outside of the existing experimental envelope, as they capture the underlying behavior governing evolution.

(11) μ-structure is what can be seen at about 25X magnification. This includes grain size/shape, pores, and phases, etc. Heat treating is a processing technique where a material is held at an elevated temperature to induce μ-structural changes. Diffusion at elevated T allows for point defect/dislocation mobility and annihilation, as well as grain growth. This typically softens the material or increases ductility.

(12) - Soluble oxides act as phonon scatterers.
- Insoluble oxides precipitate + act as phonon scatterers.
- Noble metals form precipitates which increase $K_{th}$.
- Volatile + noble gases form bubbles which act as phonon scatterers.

(13) HBS is a late stage microstructure that develops on the outer rim of the fuel pellet. It is nanograined and has a high porosity and has local burnup much higher than that of the average fuel pellet.

It forms due to U-238 neutron absorption leading to Pu production, as a result of self-shielding and proximity to the moderator.

HBS retains a large amount of fission gas, which beneficially limits the cladding stresses due to plenum pressure.

HBS also increases the thermal conductivity due to the recrystallization process, which removes defects from the grain interiors.

HBS also reduces PCMI, but we didn't talk about this.