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Bowing of Solid Breeder Fuel Pins and Multiplier Rods in a Pin-Type Fusion Blanket

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1. INTRODUCTION

When a solid breeder is encased in a metal tube, its designer must use analyses of both the deflections and stresses in order to determine the number and type of supports to construct along the rod. For a thorough analysis, one must include such "loads" as thermal expansion, body weight of both the pellets and tube, and swelling. In addition, models for thermal and irradiation creep must be incorporated to model time-dependent response. For this report, analytical methods will be used to allow use of the most general, up-to-date material models.

The breeder rods, as shown in Fig. 1a, are modeled as Euler beams which are simply supported at each end and in the center. The thermal and radiation damage fields are assumed to be constant along the rod, varying only over the cross section. This leads to symmetry about the central support, allowing analysis of only half the length of the model as shown in Fig. 1b. The applied force per unit length q is equivalent to the weight loading, while arbitrary temperature and swelling variations over the cross section are also considered.

2. ANALYSIS

2.1. BEAM THEORY

For a Bernoulli-Euler beam under axial and transverse loadings, the axial strain ϵ_z is given by

$$\epsilon_z = \epsilon_0 - x \frac{d^2 v}{d\xi^2}, \quad (1)$$

where ϵ_0 is the strain at the central axis ($x = 0$) and v is the transverse beam deflection [1]. To relate ϵ_z to the stress σ_z , one requires a constitutive relation, which for a 1-D stress state is

$$\epsilon_z = \frac{\sigma_z}{E} + \alpha T + e^S + e^C, \quad (2)$$

where αT , e^S , and e^C represent the thermal, swelling, and creep strains, respectively.

Combining Eqs. (1) and (2), multiplying by x , and integrating over the cross section, one finds the following second order equation for the displacement:

$$-EI \frac{d^2 v}{d\xi^2} = M + M_T + M_S + M_C, \quad (3)$$

where I is the moment of inertia of the cladding cross section, E is its Young's Modulus and

$$\begin{aligned} M &= \int x \sigma_z dA, \\ M_T &= E \int x \alpha T dA, \\ M_S &= E \int x e^S dA, \\ M_C &= E \int x e^C dA. \end{aligned} \quad (4)$$

Using the standard sign conventions, the moment M can be related to q ; equilibrium requires

$$\frac{d^2 M}{d\xi^2} + q = 0 \quad . \quad (5)$$

Integrating Eq. (5) twice and using the boundary condition $M(L/2) = 0$, yields

$$M = C_1 \left(\xi - \frac{L}{2} \right) - \frac{1}{2} q \left(\xi^2 - \frac{L^2}{4} \right) \quad , \quad (6)$$

where C_1 is an arbitrary constant. Substituting Eq. (6) into Eq. (3) and integrating twice gives

$$\begin{aligned} -EIv = & C_2 \xi + C_3 + \frac{1}{2} \xi^2 C_1 \left(\frac{\xi}{3} - \frac{L}{2} \right) - \frac{1}{8} \xi^2 q \left(\frac{1}{3} \xi^2 - \frac{L^2}{2} \right) \\ & + (M_T + M_S) \frac{1}{2} \xi^2 + \int_0^\xi \int_0^\eta M_C d\psi d\eta \quad . \end{aligned} \quad (7)$$

Using the displacement boundary conditions $v(0) = v'(0) = v(L/2) = 0$, the constants are found to be

$$\begin{aligned} C_2 = C_3 = 0 \quad , \\ C_1 = \frac{5}{16} qL + \frac{3}{L} (M_T + M_S) + \frac{24}{L^3} \int_0^{L/2} \int_0^\eta M_C d\psi d\eta \quad , \end{aligned} \quad (8)$$

and Eq. (7) becomes

$$\begin{aligned}
EIV = & \frac{1}{4} \xi^2 \left(1 - 2 \frac{\xi}{L}\right) (M_T + M_S) + \frac{1}{64} \xi^2 L^2 \left(1 - \frac{4}{3} \frac{\xi}{L}\right) \left(1 - 2 \frac{\xi}{L}\right) q \\
& + 6 \frac{\xi^2}{L^2} \left(1 - \frac{2}{3} \frac{\xi}{L}\right) \int_0^{L/2} \left(\frac{L}{2} - \eta\right) M_C d\eta - \int_0^{\xi} (\xi - \eta) M_C d\eta \quad , \quad (9)
\end{aligned}$$

where Green's theorem has been used to reduce the double integral in Eq. (7) to a single integral, i.e.,

$$\int_0^{\xi} \int_0^{\eta} M_C d\psi d\eta = \int_0^{\xi} (\xi - \eta) M_C d\eta \quad . \quad (10)$$

2.2. STRESSES

To determine the axial stress we return to Eq. (2). Substituting Eq. (1) for ϵ_z and integrating over the cross section, ϵ_0 is found in terms of the axial force on a cross section F , and the inelastic strains:

$$\epsilon_0 = \frac{F + F_T + F_S + F_C}{EA} \quad , \quad (11)$$

where A is the cross-sectional area and

$$\begin{aligned}
F &= \int \sigma dA \quad , \\
F_T &= E \int \alpha T dA \quad , \\
F_S &= E \int e^S dA \quad , \\
F_C &= E \int e^C dA \quad . \quad (12)
\end{aligned}$$

Inserting Eq. (11) into Eq. (2) gives

$$\sigma = \frac{F + F_T + F_S + F_C}{A} - E(\alpha T + e^S + e^C) - xE \frac{d^2 v}{d\xi^2} \quad (13)$$

From Eq. (9), $d^2 v/d\xi^2$ is found to be

$$\begin{aligned} EI \frac{d^2 v}{d\xi^2} = & \frac{1}{2} (1 - 6 \xi/L)(M_T + M_S) \\ & + L^2/32 (1 - 8 \xi/L)(1 - 2 \xi/L)q \\ & + 12/L^2 (1 - 2 \xi/L) \int_0^{L/2} (L/2 - \eta) M_C d\eta - M_C \quad , \end{aligned} \quad (14)$$

and the stress equation [Eq. (13)] becomes

$$\begin{aligned} \sigma = & \frac{F + F_T + F_S + F_C}{A} - E(\alpha T + e^S + e^C) - \left(\frac{M_T + M_S}{2I} \right) x \left(1 - \frac{6\xi}{L} \right) \\ & - qL^2 x / 32I (1 - 2 \xi/L)(1 - 8 \xi/L) \\ & - \frac{12x}{IL^2} (1 - 2 \xi/L) \int_0^{L/2} (L/2 - \eta) M_C d\eta + M_C x / I \quad . \end{aligned} \quad (15)$$

2.3. CONSTITUTIVE EQUATIONS

To solve this rod bowing problem, a time-dependent or steady-state thermal field must be determined. To calculate the equivalent moments and forces of Eqs. (4) and (12) also requires equations for swelling and thermal and irradiation creep in terms of time (or dose) and temperature.

In this study, the swelling of the HT-9 cladding was assumed to conform to the following general relation [2]

$$\frac{\Delta V}{V} (\%) = S(\delta - \delta_I) \exp\left[-\left(\frac{T - 425^\circ\text{C}}{59^\circ\text{C}}\right)^2\right] \quad (16)$$

where S is the swelling rate (%/dpa), δ is the dose (dpa), δ_I is the incubation dose (dpa), and T is the cladding temperature ($^\circ\text{C}$). If δ is less than δ_I , $\Delta V/V$ is taken to be zero. Using data for 2-1/4 Cr-1 Mo gathered by Gelles and Puigh [3], S and δ_I were chosen to be 0.02%/dpa and 90 dpa, respectively. A 30-dpa incubation dose will also be studied.

Again using data from Gelles and Puigh, irradiation creep was modeled according to

$$\frac{de^c}{d\delta} (\text{dpa}^{-1}) = C\sigma^{1.5} \quad (17)$$

where C was found to be $8.511 \times 10^{-8} \text{ dpa}^{-1} \text{ MPa}^{-1.5}$.

The thermal creep correlation for HT-9 takes a different form [4]:

$$\dot{\epsilon}_{th}^c = \frac{2289}{T} (|\sigma| - \sigma_0)^3 \exp\left(-\frac{1.427 \times 10^4}{T}\right) \quad (18)$$

Here $\dot{\epsilon}_{th}^c$ (yr^{-1}) is the thermal creep rate and σ_0 (MPa) represents a temperature dependent back stress given by

$$\sigma_0 = 1366.4 - 1.507 T \quad (19)$$

where T is the temperature (K). This formula predicts no thermal creep for temperatures below 500°C and stresses below 200 MPa, so irradiation creep dominates thermal creep in this analysis.

3. RESULTS

3.1. BREEDER ROD BOWING

Excessive deflections in a bank of solid breeder rods can severely impair reactor performance. Relative displacements of neighboring rods can choke off coolant flow paths, leading to hot spots and premature failure. In extreme cases, the rod cladding may buckle, causing changes in thermal gap conductances, and possibly tube rupture. Therefore, the peak rod deflections due to thermal, gravitational, and swelling effects must be kept small.

For the rod dimensions and reactor parameters analyzed here, the deflections due to swelling were by far the most severe. The bowing caused by the pellet weight was inconsequential because of the low density of the breeder and the thermal deflections were also relatively small, even for a 2-m-long rod with only one internal support. The final support spacing will depend on the peak bowing caused by swelling, as well as by the allowable cladding stresses.

3.2. INITIAL DEFLECTIONS

The rod bowing due to the pellet weight and thermal field is primarily driven by an azimuthal temperature variation over the cladding's cross section. In the first few breeder pins, the temperature gradient is due mostly to a gradient in the volumetric heating, so the front (plasma side) is hotter than the rear. On the other hand, pins near the back of the blanket are hotter at the rear of the tube because the heat transfer coefficient is highest there. This basic difference in the thermal fields causes the front

pins to bow towards the plasma, while the rear pins deflect in the opposite direction.

The initial deflections of a 2-m-long rod with one internal support are shown in Fig. 2. The ends are assumed to be simply supported, while there is no axial restraint. The peak deflection is under 0.5 mm, which is negligible. Unfortunately, the swelling deformation is somewhat larger, so additional internal supports must be added to reduce the peak displacements to an acceptable level.

The model developed previously features only one internal support, so care must be taken if it is used to analyze multiple internal supports. To approximate the deflections of a rod with 50 cm between supports, the existing model can be used by setting L equal to 100 cm. The deficiency in this approach is seen in Fig. 2, which shows that the slope continuity condition at the center of the rod clearly is not met. Fortunately, the model is conservative because the calculated deflections will be greater than those in the actual blanket. The swelling behavior will determine the final choice for the number of internal supports.

3.3. TIME-DEPENDENT BEHAVIOR

Because the void swelling of HT-9 has a temperature variation that is Gaussian [Eq. (16)], the thermal gradient over the rod's cross section leads to an even harsher swelling gradient. Hence, one might expect swelling deformations to be quite severe. As shown in Fig. 3, the peak deflection after eight full power years overwhelmed the initial deflections, which are essentially zero on this scale. These deflections should be small enough to allow a four year life.

The effect of the support spacing is shown in Fig. 4 which shows the peak deflections of rods with 100 and 50 cm between supports. In the case of the smaller spacing, the peak deflection is only about 1 cm after 6 years. Considering that the model over-estimates the rod deflections, this should be an adequate choice for the design.

3.4. RELATIVE BOWING IN DIFFERENT BREEDING ZONES

The deflections in the first breeder zone differ from those in the second zone for three reasons:

1. The second zone contains stiffer rods because of the larger diameter,
2. The thermal gradients are different, as discussed in Section 3.2,
3. The damage rate decreases with distance from the plasma.

All of these factors lead to lower deflections in the back zone.

In Fig. 5, the peak deflections are shown for the first row of each zone. Because of the 90 dpa incubation dose, there is no significant deformation for the first three years. The first rod then begins to deflect towards the plasma at a peak rate of about 0.5 cm/yr, whereas the second rod shows no bowing through five years. The deflections here are quite small, leading to minimal tube contact during five full power years.

This rosy picture is altered by uncertainties in the swelling correlation for HT-9. If the incubation dose is smaller, the rods will begin to bow significantly at a lower dose and the peak deflections will be larger at a given time. In Fig. 6 we see the peak deflections for a 30 dpa incubation dose. The first zone begins bowing after about a year and the second zone begins after about two years. Because the two rods are bowing in opposite

directions, the most important rod interaction will involve the multiplier rods and the first breeder zone.

3.5. Be MULTIPLIER RODS

In terms of bowing, the multiplier rods have two distinct advantages over the breeder rods. First, the multiplier rod is solid, so its moment of inertia is much larger than the breeder rods. Second, the thermal conductivity of Be is much higher than the effective conductivity of the breeder pellet and its cladding, so the temperature gradient over the cross section is much smaller. The resulting deflections are very small.

For a 2-m-long Be rod with one internal support and a linear temperature dependence, Eq. (9) predicts a peak deflection of

$$v_{\text{peak}} = 0.015 \Delta T \quad , \quad (20)$$

where ΔT ($^{\circ}\text{C}$) is the front-to-back temperature difference over the cross section. Thermal calculations similar to those for the breeder rods predict a difference of only 2°C , leading to a deflection of less than 1 mm.

Because the temperature is nearly constant in the Be rods, the swelling gradient will depend only on the damage gradient. The damage gradient is expected to be small in the individual multiplier rods because of their relatively small diameter, so the Be rod deflections should remain low. More detailed neutronics calculations are required before this assumption is validated.

4. CONCLUSIONS

The most important outcome of this bowing analysis is the determination of the number of internal breeder rod supports required for good thermal performance. Although many effects were considered, the swelling deformations were the most restrictive in terms of the peak deflections. It appears that three internal supports should be sufficient to keep the rod bowing below acceptable levels without significantly raising the structure-to-breeder ratio.

The most severe interaction problem involved the last multiplier row and the first breeder row. Because the Be rods deflect very little, this problem can be alleviated by leaving enough space between these two zones. The spacing can be tighter elsewhere. A more detailed analysis of the multiplier rod bowing caused by the damage gradient must be analyzed before this can be verified.

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REFERENCES

1. T. H. Lin, Theory of Inelastic Stresses, (Wiley & Sons, New York, 1968) p. 128.
2. R. W. Conn and N. M. Ghoniem, "Assessment of Ferritic Steels for Steady-State Fusion Reactors," Fusion Reactor Design and Technology, IACA-TC-392/62, (International Atomic Energy Agency, Vienna, 1983) Vol. II, p. 389.
3. D. S. Gelles and R. J. Puigh, "Evaluation of Ferritic Alloy Fe-2-1/4 Cr - 1 Mo After Neutron Irradiation-Irradiation Creep and Swelling," Hanford Engineering Development Laboratory Report HEDL-7405 (1983).
4. R. J. Amodeo and N. M. Ghoniem, "Development of Design Equations for Ferritic Alloys in Fusion Reactors," Nucl. Engrg. and Design/Fusion, 2 (January 1985) pp. 97-110.

(a)

(b)

Fig. 1. Beam models used for bowing analysis.

Fig. 2. Initial (thermal) deflections of a 2-m-long breeder rod.

Fig. 3. Rod deflections over eight full-power years.

Fig. 4. Bowing of rods with different support spacings.

Fig. 5. Comparison of the peak deflections in two different breeder zones

Fig. 6. Peak deflections in two breeder zones with reduced incubation dose.