THE BOWING OF SOLID BREEDER RODS
IN A PIN-TYPE FUSION REACTOR

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ABSTRACT

The bowing of circular solid breeder pins is studied using standard beam theory. Deformations caused by thermal gradients, swelling gradients, and gravitational forces are included in the investigation and swelling is found to cause the most severe pin bowing. The bowing of Be multiplier rods is found to be insignificant when swelling is not considered. In all cases it is found that adding internal supports can reduce the rod deflections to acceptable levels without increasing the stresses beyond design limits.

INTRODUCTION

Recent studies in France[1] and at UCLA[2] feature long breeder and/or multiplier rods encased in a thin steel cladding. Because of thermal and swelling gradients, these rods will tend to bow, constrained only by internal or end supports. If neighboring rods bow at different rates, they may contact each other, leading to restricted flow or hot spots. Prudent design can prevent these difficulties by making use of theoretical estimates of the rod deflections.

The bowing of fuel rods in fission reactors has been studied extensively for many years. Olander[3] gives a general discussion of this work, while the transactions of the eight SMIRT conferences contain more detailed papers on the subject. These analyses are helpful to the fusion community, but there are basic differences between fission and fusion reactors that necessitate some changes:

1) The coolant in fission reactors flows parallel to the fuel rods, while fusion blankets may be designed for cross-flow as well.

2) The flux source in a fission reactor is the fuel rod itself, while the fusion plasma acts as an external heat source. As a result the damage gradient over the cross section of a solid breeder rod may be more severe than in a fission fuel rod.

Taking these factors into account, this paper develops a model applicable to breeder rods in fusion blankets using Euler beam theory.

ANALYSIS

Beam Theory

Because the rods are very long compared to their diameter and are assumed to be loosely connected at each end, they behave like simply supported Euler beams. A support is added at the center to reduce the rod deflections. The thermal and radiation damage fields are assumed to be constant along the rod, while they vary arbitrarily over the cross-section. This leads to symmetry about the central support, allowing analysis of only half the rod length as shown in figure 1. The applied force per unit length q represents the weight of the breeder pellets. For an Euler beam under axial and transverse loadings, the axial strain ϵ_z is given by Lin[4] as

$$\epsilon_z = \epsilon_o - \frac{d^2v}{d\xi} \qquad (1)$$

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

$$\epsilon_z = \sigma_z / E + \alpha T + \epsilon^s + \epsilon^c \qquad (2)$$

where αT, ϵ^s and ϵ^c represent the thermal, swelling and creep strains, respectively.

Combining equations (1) and (2), multiplying by x and integrating over the cross section leads to the following second order equation for the rod displacement:

$$-EI \frac{d^2v}{d\xi^2} = M + M_T + M_s + M_c \qquad (3)$$

where I is the moment of inertia of the cladding, E is its elastic modulus and

$$
\begin{aligned}
M &= \int x\sigma_z \, dA \\
M_T &= \int xE\alpha T \, dA \\
M_s &= \int xE\epsilon^s \, dA \\
M_c &= \int xE\epsilon^c \, dA
\end{aligned}
\qquad (4)
$$

Using equilibrium, the moment M can be related to q:

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

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

$$M = C_1 (\xi - L/2) - .5q (\xi^2 - L^2/4) \qquad (6)$$

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

$$
\begin{aligned}
-EIv = {} & C_2\xi + C_3 + .5\xi^2(\xi/3 - L/2)C_1 \\
& - .125\xi_2(\xi_2/3 - L_2/2)q \\
& + .5\xi^2(M_T + M_s) + \int_0^\xi \int_0^\lambda M_c \, d\Phi \, d\lambda
\end{aligned}
\qquad (7)
$$

Using the displacement boundary conditions $v(0)=v'(0)=v(L/2)=0$, eq. (7) yields our final result:

$$
\begin{aligned}
EIv = {} & .25\xi^2 (1 - 2\xi/L) (M_T + M_s) \\
& + (1/64)\xi^2L^2(1 - 4\xi/3L)(1 - 2\xi/L)q \\
& + 6\xi^2/L^2(1 - 2\xi/3L) \int_0^{L/2} (L/2 - \lambda)M_c \, d\lambda \\
& - \int_0^\xi (\xi - \lambda)M_c \, d\lambda .
\end{aligned}
\qquad (8)
$$

Stresses

The axial stress is determined by returning to eq. (2). Substituting eq. (1) for ϵ_z and integrating over the cross section, ϵ_o is found in terms of the axial force F on a cross section and the inelastic strains:

$$\epsilon_o = \frac{F + F_T + F_s + F_c}{EA} \qquad (9)$$

where A is the cross sectional area and

$$
\begin{aligned}
F &= \int \sigma \, dA \\
F_T &= \int E\alpha T \, dA \\
F_s &= \int E\epsilon^s \, dA \\
F_c &= \int E\epsilon^c \, dA ,
\end{aligned}
\qquad (10)
$$

Inserting these equations into eq. (1) and using eqs. (2) and (3) yields the final result:

$$
\begin{aligned}
\sigma = {} & \frac{F + F_T + F_s + F_c}{A} - E(\alpha T + \epsilon^s + \epsilon^c) \\
& - \frac{(M_T + M_s)}{2I} (1 - 6\xi/L)x + M_c x/I \\
& - (qL^2x/32I)(1 - 2\xi/L)(1 - 8\xi/L) \\
& - (12x/IL^2)(1 - 2\xi/L) \int_0^{L/2} (L/2 - \lambda)M_c \, d\lambda
\end{aligned}
\qquad (11)
$$

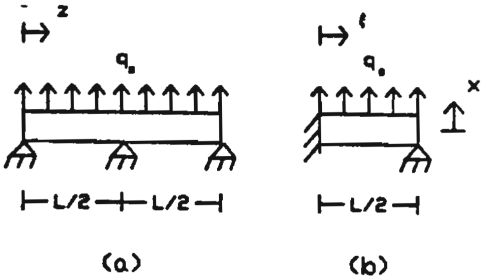

Figure 1: Beam model: a) full model, b) half-length model using symmetry.

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 equations (4) and (10) 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 is assumed to conform to the following general relation[5]:

$$\frac{\Delta V}{V}(\%) = S (\delta - \delta_I) \exp\left[- \left[\frac{T - 425^\circ C}{59} \right]^2 \right] \qquad (12)$$

where S is the swelling rate (%/dpa), δ is the dose rate (dpa) and T is the cladding temperature (°C). If δ is less than δ_I the swelling is assumed to be zero. Using data on 2 1/4Cr-1Mo gathered by Gelles and Puigh[6], S and δ_I are chosen to be .025 %/dpa and 90 dpa,respectively. A 30 dpa incubation dose will also be considered.

Again using the work of Gelles and Puigh, irradiation creep is modeled according to:

$$\frac{d\epsilon^c}{d\delta} \ (\mathrm{dpa}^{-1}) = C\,\sigma^{1.5} \qquad (13)$$

where C is found to be 8.511×10^{-8} dpa^{-1} $\mathrm{MPa}^{-1.5}$.

THE UCLA BLANKET

Configuration

The blanket studied features a lobular module that also acts as a first wall and is filled with solid breeder and multiplier rods of circular cross-section to form the blanket. Gaseous He coolant flows through first wall channels in either side of the module until it reaches the point where it is nearest the plasma, ie. the point of the lobe. It then enters the blanket, flowing away from the plasma as it cools the multiplier and breeder rods. The multiplier zone consists of solid Be rods with a diameter of 1.70 cm. The next zone contains breeder rods, which are made up of many $LiAlO_2$ pellets in an HT-9 tube. The pellet radius of 0.61 cm is chosen to keep the peak temperature below the limits of the breeder. The last zone is identical to the middle zone except the radius is increased to 1.70 cm because the volumetric heating rate is lower. In this paper the transverse deflections (bowing) of the rods in all three zones are estimated using standard Euler beam theory.

Temperature Distributions for Cross-Flow Cooling

The temperature distributions in the multiplier and breeder rods are calculated using finite elements[7]. They vary markedly from zone to zone because of the different materials, flow conditions and volumetric heating rates. In general the heat transfer coefficient is highest in the back of the rod and the coolant picks up heat as it flows over the rod, so the temperature is highest in the back. On the other hand the heating rate is highest at the front, which tends to make the front hotter. The resulting thermal fields are a combination of these effects.

The first row of breeder rods is hotter at the front because of the very steep gradient in the heating rate. Hence pins in this zone will tend to bow towards the plasma. The distribution in the second zone of breeder rods is dominated by the variation of the heat transfer coefficient, so the thermal gradient is reversed and the pins will bow away from the plasma.

Although the same effects occur in the multiplier rods, the high thermal conductivity of Beryllium substantially reduces the front-to-back temperature difference. The bowing of these rods will be driven by the swelling gradient, which is caused by the gradient in the displacement rate.

RESULTS

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 are by far the most severe. The bowing caused by the pellet weight is inconsequential due to the low density of the breeder and the thermal deflections are also very small, even for a 2 meter long rod with only one internal support. In all cases presented here, the stresses are well below accepted limits for HT-9.

Initial Deflections

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

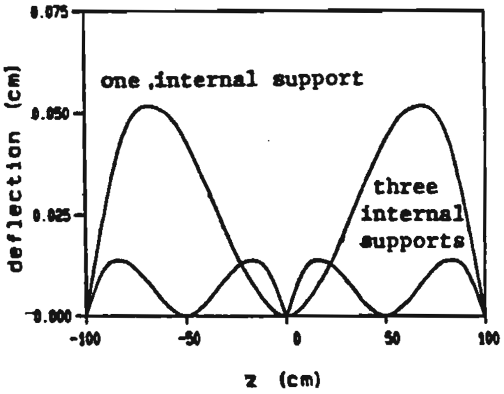

Figure 2: Initial Deflected Shape of rods in first row of first zone.

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 using an effective rod length of 100 cm. The deficiency in this approach is seen in the second curve of figure 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.

Time-Dependent Behavior

Because the void swelling of HT-9 has a temperature variation that is approximated by a gaussian (eq. 12), the thermal gradient over the rod's cross section leads to an even harsher swelling gradient. Hence, the swelling deformations are expected to be quite severe. As shown in figure 3 the peak deflection after 4 full-power-years overwhelmed the initial deflections, which are essentially zero on this scale. Further swelling causes very large deflections, but a four year life is very reasonable.

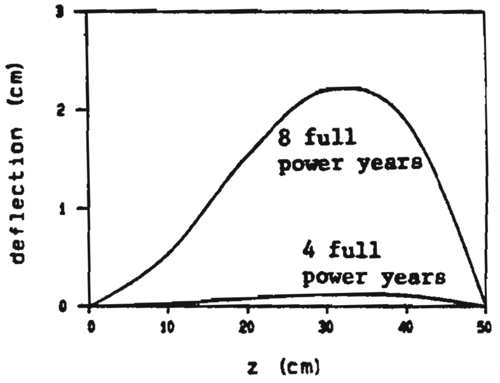

Figure 3: Deflected shapes of rods including swelling and creep.

The effect of the support spacing is shown in figure 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 one cm after 6 years. Considering that the model overestimates the rod deflections this should be an adequate choice for the design.

Relative Bowing in Different Breeding Zones

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

1) The second zone contains stiffer rods due to the larger diameter.

2) The thermal gradients are different, as described previously.

3) The damage rate decreases with distance from the plasma.

All these factors lead to reduced deflections ir the back zone.

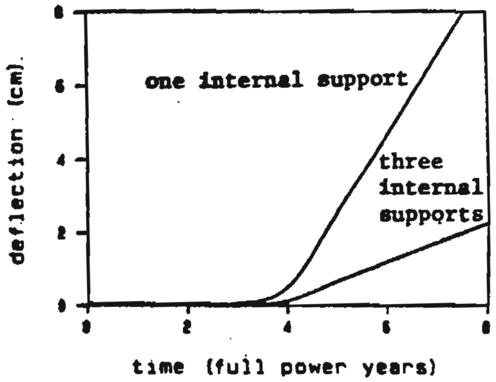

Figure 4: Reduction of peak deflection for added internal supports.

In figure 5 the peak deflections are shown for the first row of each zone. Due to the 90 dpa incubation dose, there is no significant bowing for more than three years. The first rod then deflects towards the plasma at a peak rate of about 0.5 cm/yr, whereas the second rod shows no bowing through 5 years. The deflections here are quite small, leading to no interaction over 5 full-power-years.

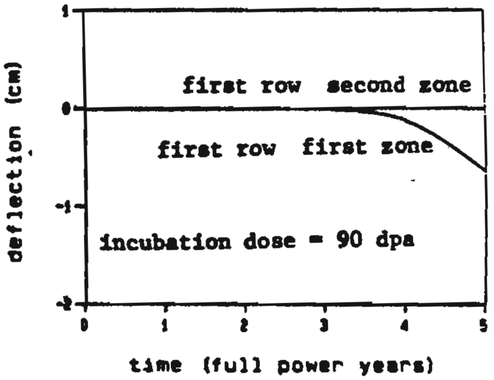

Figure 5: Comparison of peak deflections in different breeder zones.

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. As shown in figure 6, the bowing of the first zone begins after about a year and the second zone begins after about 2 years, when the incubation dose is 30 dpa. Because the two rods are bowing in opposite directions, the most important rod interaction will be between the last Be multiplier rod and the first breeder rod, rather than between neighboring breeder rods.

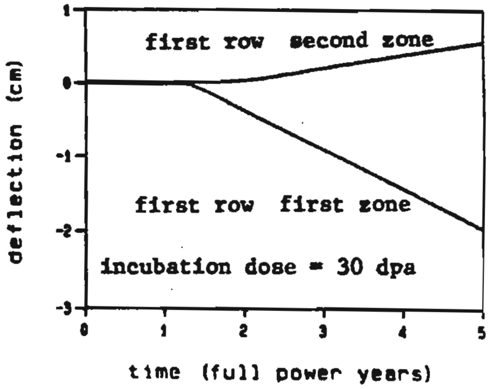

Figure 6: Comparison of peak deflections in different breeder zones.

SUMMARY

The most significant outcome of this bowing analysis is the determination that three internal breeder rod supports should be sufficient to keep the deflections to reasonable levels without significantly raising the breeder-to-structure ratio or stress levels. Although many effects are considered, swelling deformations are the most restrictive in terms of the peak deflections. Additional supports could be added to reduce the deflections to conform to arbitrarily small limits, but the corresponding increase in stresses and reduction in tritium breeding must be closely monitored.

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