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A SIMPLIFIED MODEL OF CORE THERMAL DILATION

by

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A simple analytical model is developed of core radial expansion for a fast reactor using a limited-free-bow core restraint design. The model is restricted to those bowing regimes where the plane of above core load pads (ACLP) is compacted to the point where the outermost driver assemblies are restrained at the ACLP from further compaction by a continuous network of contacting load pads, and where the top load pads (TLP) of the outer driver assemblies are restrained from further radial expansion by continuous load paths to the TLP restraint ring.

Essentially elementary beam theory is used to calculate the elastic bow of a driver assembly at the core periphery subject to temperature dependent boundary conditions at the nozzle support, ACLP and TLP and subject to thermal and inelastic bowing deformations. The following design parameters are considered: grid plate temperature, core temperature rise, restraint ring temperature, grid plate and restraint ring thermal expansion coefficients, duct material properties (thermal expansion, swelling and creep), nozzle support condition, core radius, core axial location, core height, driver assembly radial thermal gr[illegible], ACLP location and compressibility, and gaps at the ACLP and TLP elevations.

The model, see Fig. 1, gives the core dilation at the outer driver assemblies using a dimensionless core radius in the form

$$\rho = C_1\tau_1 + C_2\tau_2 + C_3\tau_3 + C_0$$

where the core dilation temperature coefficients, C_i, are algebraic functions of the design parameters for both pinned and cantilever support conditions at the inlet nozzle. The τ_i are dimensionless temperatures of the grid plate, core temperature rise and restraint ring respectively. The physical radius is ρL where L is the distance from the nozzle support to the TLP. Changes in reactivity, R, are given by

$$\Delta R = WL\Delta\rho = WL(C_1\Delta\tau_1 + C_2\Delta\tau_2 + C_3\Delta\tau_3)$$

where W is the uniform dilation reactivity worth. In this manner the model predicts reactivity changes as a function of changes in the grid plate temperature, the core temperature rise and the restraint ring temperature.

Parameter Values

The algebraic dependence of the core dilation temperature coefficients, C_i, on the design parameters is quite complex and will not be presented here. Rather we illustrate the implications of this model by examining the magnitude of the various terms for a typical small LMR design. For this example the axial distance from the nozzle support to the TLP is $L = 4.17$ m. The grid plate is assumed to be an austenitic stainless steel with coefficient of thermal expansion of about $\alpha_1 = 2.0 \times 10^{-5}$ °C^{-1} while the duct, load pad, and restraint rings are assumed to be ferritic with a thermal expansion of $\alpha_2 = 1.4 \times 10^{-5}$ °C^{-1}. The average core temperature rise is 122°C for a driver assembly and the average radial temperature gradient in the outer row of drivers is 1.18°C/cm. Uniform dilation reactivity worth for the full core is $W = -2.285$ $/cm.

The model gives the rate of reactivity change due to grid plate temperature rise to be

$$\frac{\partial R}{\partial T_i} = WL \frac{\partial \rho}{\partial T_i} \doteq WL\, C_1\, \alpha_1$$

$$= -0.00254 \text{ \$/°C for a pinned core.}$$

Similarly the rate of reactivity change due to temperature rise across the core is

$$\frac{\partial R}{\partial \Delta T} = WL\, C_2\, \alpha_2 = -0.00209 \text{ \$/°C},$$

and the effect of increasing restraint ring temperature is

$$\frac{\partial R}{\partial T_y} = WL\, C_3\, \alpha_3 = 0.00024 \text{ \$/°C}.$$

We note that for this core design increasing the inlet temperature and increasing the core temperature rise have comparable negative reactivity effects. Increasing the restraint ring temperature has a positive reactivity but is an order of magnitude smaller.

Parameter Dependence

The coefficients of thermal expansion of the grid plate, assembly, and restraint ring play a central role in core dilation. The dilation due to core temperature rise is directly proportional to the coefficient of thermal expansion of the duct material. The inlet temperature dilation is directly proportional to the grid plate thermal expansion coefficient but is also linearly proportional to both μ_2 and μ_3 where:

$$\mu_2 = \frac{\text{assembly thermal expansion coefficient}}{\text{grid plate thermal expansion coefficient}}$$

$$\mu_3 = \frac{\text{restraint ring thermal expansion coefficient}}{\text{grid plate thermal expansion coefficient}},$$

The core location also plays a strong role. Figure 2 shows the dependence of the temperature coefficients on the location of the core within the assembly, β, assuming that the ACLP is not moved relative to the core. Location of the ACLP relative to the core, $\gamma-\beta$, is a less sensitive design parameter.

The load pad stiffness, K_3, appears in the temperature coefficients through the parameter $\lambda = EI/Kl^3$. Figure 3 shows the dependence of the temperature dilation coefficients on $1/\lambda$ which is proportional to K. 1/K represents the compliance of the ACLP plane interior to the core boundary driver assemblies due to the bowing forces of the boundary drivers and assemblies exterior to them. Since smaller values of K may lead to a negative value for C_2, and this implies increasing reactivity with increasing ΔT, a sufficiently stiff above core load pad should be considered a design requirement.

Core Lockup

By examining the core lockup condition for the pinned case, several observations can be made. If the gap at the ACLP is negative (usual) and $\mu_2 \leq 1$ then the inlet temperature lockup coefficient is always negative; i.e. increasing the inlet temperature tends to unlock the core. For an austenitic support plate and ferritic core materials the dominate term is the relative expansion of the grid plate over the core. If the materials are the same ($\mu_2 = 1$) then the phenomena can be controlled by the proper selection of the gaps.

The dominate term in causing lockup is thermal bow at the TLP. Lowering the core will facilitate lockup as will raising the load pad and increasing the transverse thermal gradient. For initially straight assemblies the thermal components of lockup are balanced against the difference in gaps at the ACLP and TLP. Later in life the inelastic bow terms will tend to control lockup.

The Bowing Component

The model allows us to address the issue of the importance of bow relative to ACLP expansion in the fast thermal response of the core. Creep and swelling bow only effect the lockup state. Thermal bow affects both lockup and C_2.

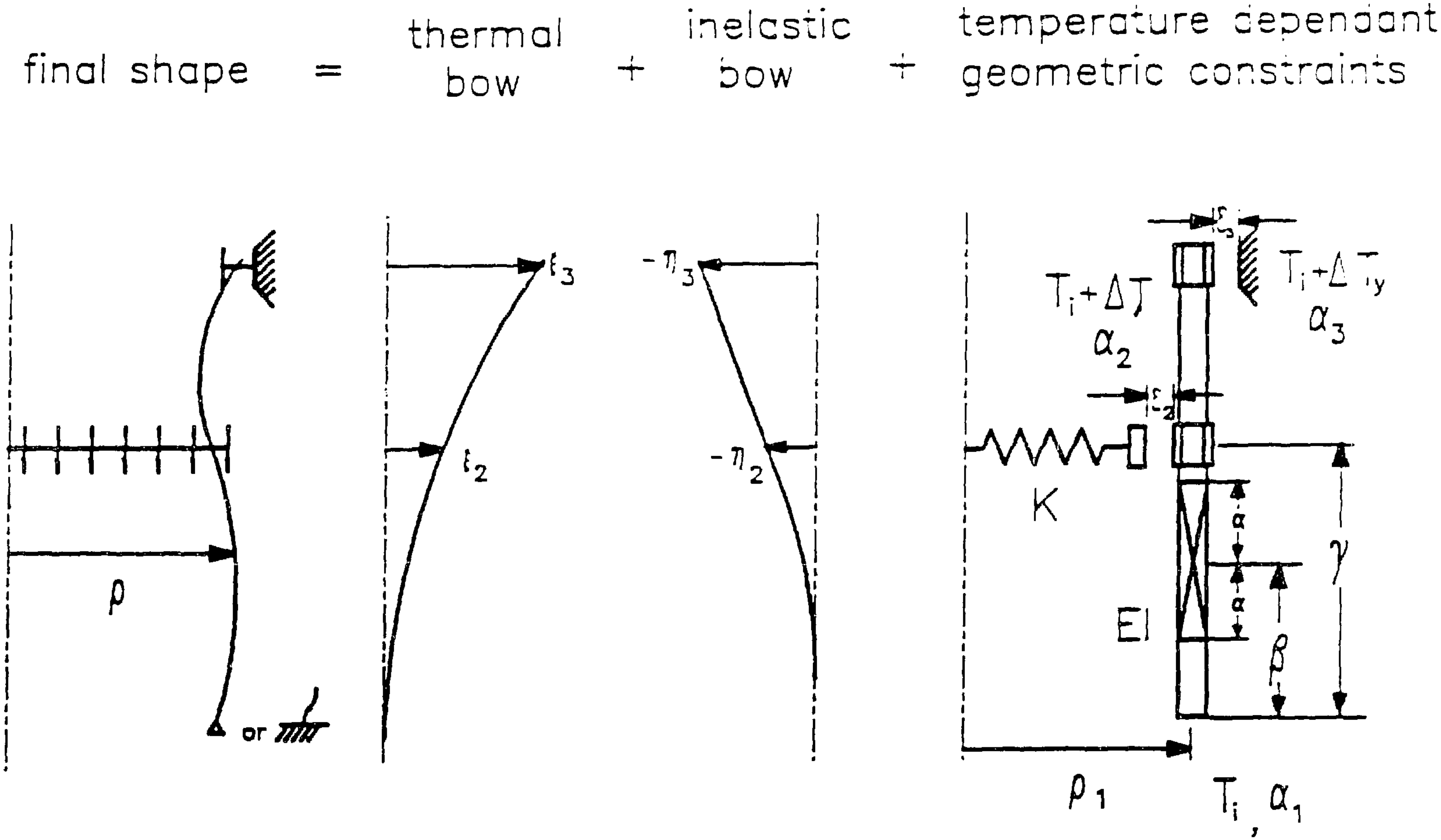
In addition, even without thermal bow, the assembly must bow elasticity to account for the interference of a thermally expanding ACLP relative to the nozzle and TLP supports. Figure 4 shows the percent of the total fast coefficient, C_2, due to thermal bow alone and the percent due to total bow (i.e. the thermal bow plus the additional elastic bow) as a function of location of the core within the assembly, β.

Core Restraint Design for Specific Transients

The relative importance of the inlet temperature dilation coefficient, C_1, the fast coefficient, C_2, and the restraint ring coefficient, C_3, will in general depend on other plant characteristics. If, for a given plant, the critical transient and the critical times during those transients are known, this model will give guidance on how the design might be modified to increase inherent safety margins. It may be prudent, for example, to lower the core somewhat giving a larger value for C_1 at the expense of a smaller value of C_2 if the critical time in the critical transient occurs when the grid plate is heating up. Or it may be that ΔT is decreasing at the critical time so that a smaller value of C_2 is beneficial.

Validation

Limited validation of this model has been performed using the core restraint code NUBOW-3D. Excellent agreement was found with the detailed 3-D calculations both in the magnitude of the coefficient C_2 and in the parametric dependence on design parameters. This is a gratifying result in that it shows that the spatial distribution of bowing induced porosity inside the core is not very important and an average porosity represented by a uniform radial dilation is sufficient to provide an accurate reactivity feedback treatment in plant transient codes.



$$\rho = C_1\alpha_1 T_i + C_2\alpha_2\Delta T + C_3\alpha_3 T_Y + C_0$$

core radius	grid plate expansion	core ΔT expansion	restraint ring expansion	initial radius + inelastic expansion

Fig. 1. Core Thermal Dilation Analysis

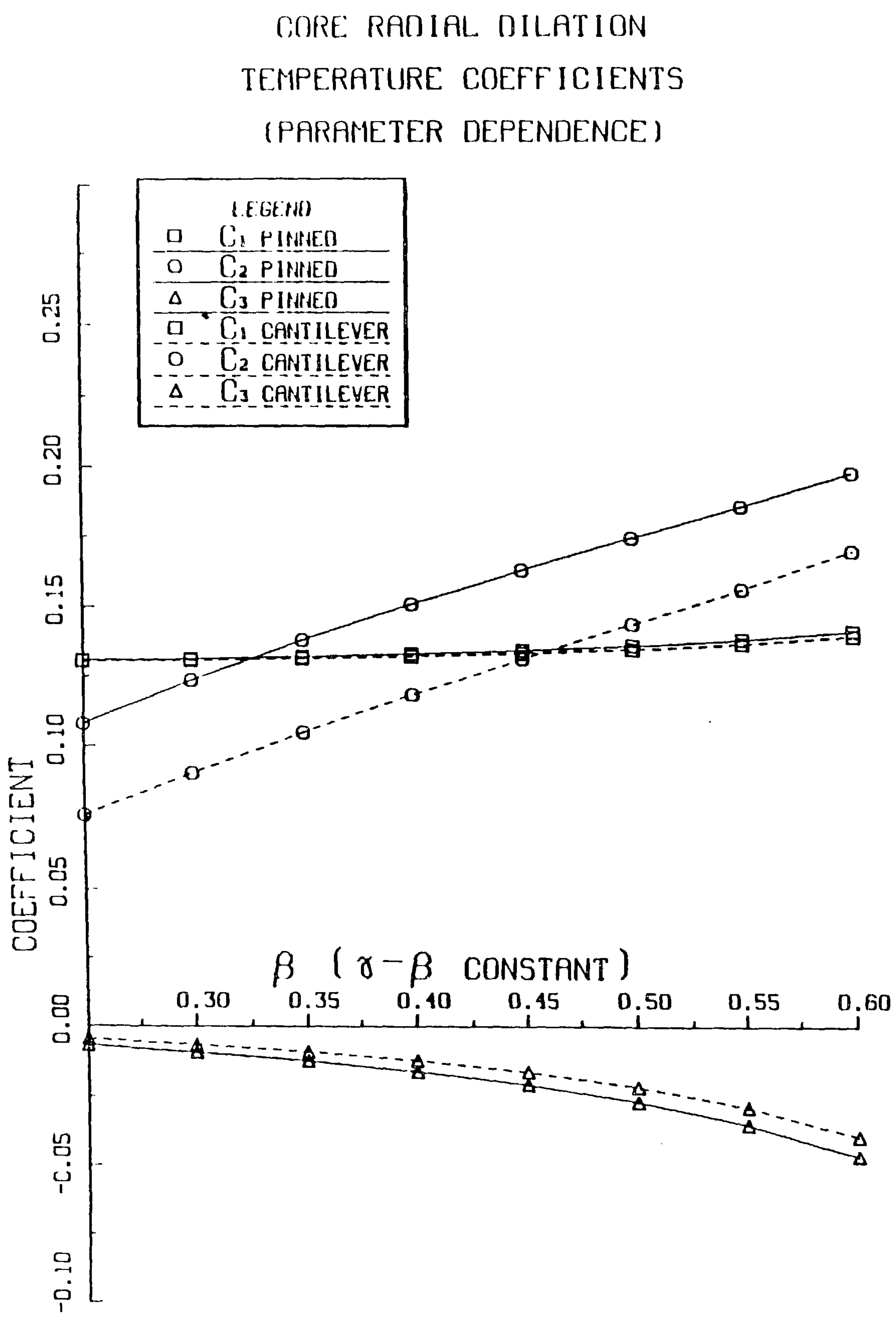


Fig. 2. Dilation Coefficient Dependence on Core Axial Location

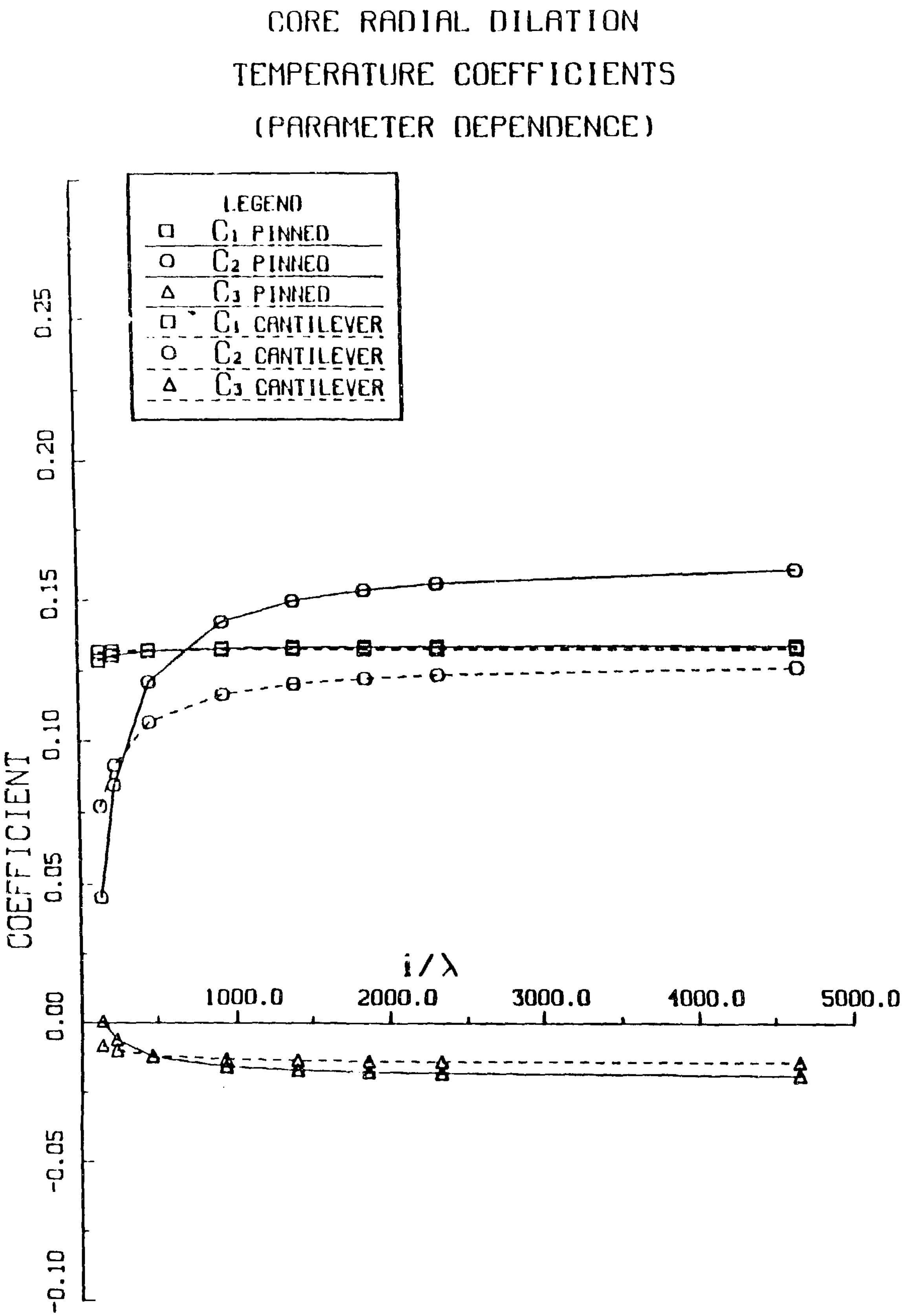


Fig. 3. Dilation Coefficient Dependence on ACLP Stiffness to Bending Stiffness Ratio

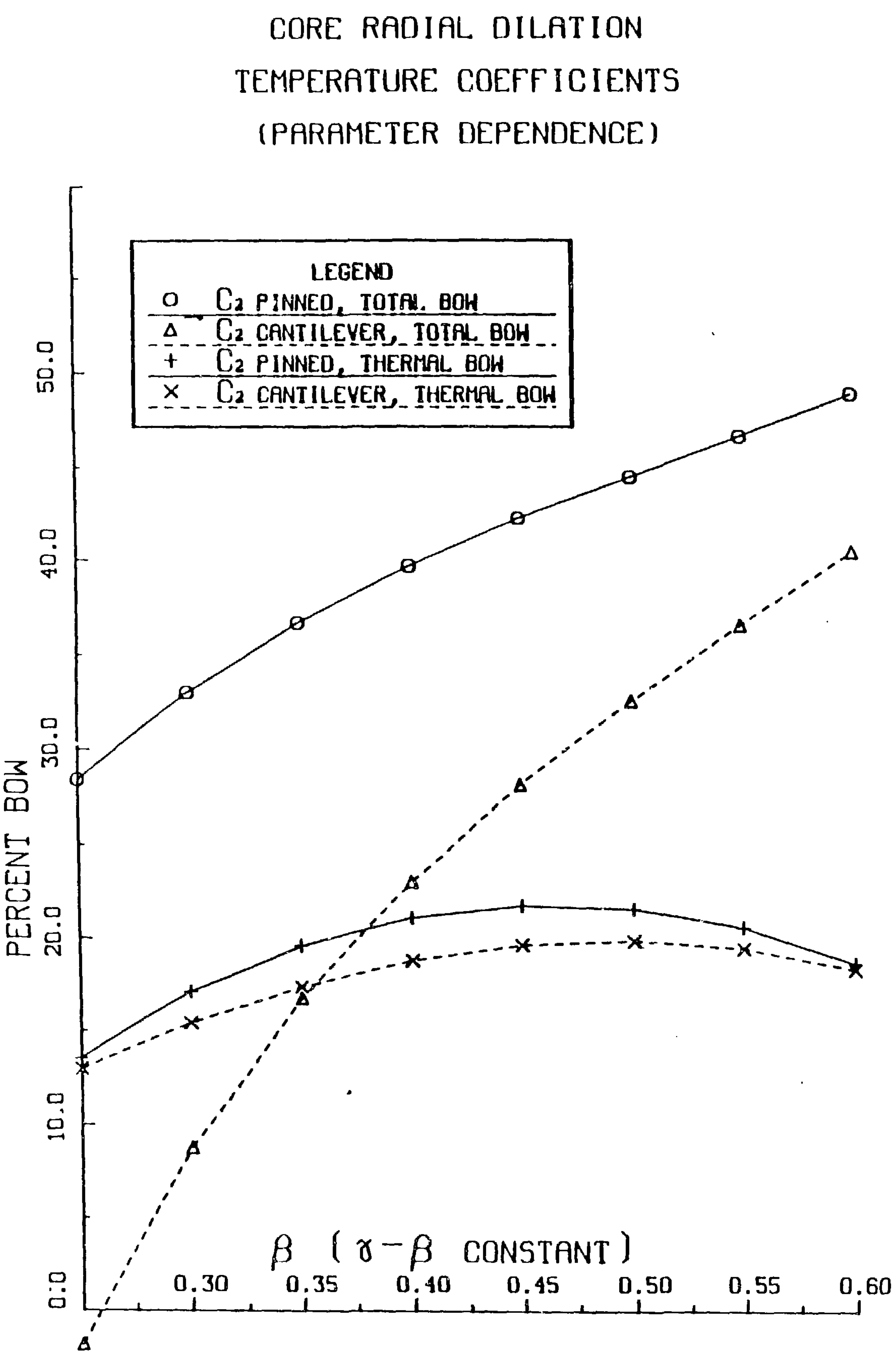


Fig. 4. Bowing Contributions to the Fast Temperature Dilation Coefficient