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ABSTRACT

In this paper we model and analyze cyclic thermal loads and stresses in two critical components of inertial and magnetic confinement fusion reactors (including fusion-fission hybrids); namely, in the solid wall adjacent to the fusion plasma ("first wall") and in the fuel elements located in the high power density region of the blanket. We derive explicit expressions for the parametric dependencies of thermal stresses to provide a quantitative basis for design and comparative assessment studies of different fusion reactors.

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1. INTRODUCTION

A number of potential applications of fusion reactors have been identified and investigated; several examples that appear technically and economically feasible are production of (a) electricity, (b) process heat, (c) synthetic fuels, and (d) fissile fuels. Realization of these applications requires solution of many outstanding and challenging scientific and engineering problems. One of the outstanding problems for most fusion systems is modeling and analysis of cyclic thermal stresses with the view toward reducing their effects on component availability, reliability, and lifetime.

From the mechanical engineering point of view, one fundamental difference between the fusion and fission reactors (including advanced fuel breeders) is the type of operation: fission reactors operate in a steady state while fusion reactors, in general, are expected to operate cyclically. The cycle time or period may range from tens of minutes to small fractions of a second and the fraction of the cycle during which fusion energy is released may range from near unity to 10^{-6}, therefore, both the energy pulse duration and the cycle length may be less than, equal to, or greater than the characteristic thermal response times of different structural components.

In this paper we model and analyze cyclic thermal loads and stresses in the complete range of potential operating conditions. We examine two critical components of fusion reactors (including fusion-fission hybrids): namely, the solid wall adjacent to the fusion plasma ("first wall") and the fuel elements located in the high power density region of the blanket. These two components exemplify two limiting cases of thermal loading: the first wall loads are generated by predominantly shallow energy deposition that may be approximated with a flux across the surface and the fuel element loads are generated by predominantly volume energy deposition or volumetric heating. For these two types of loading we derive approximate closed form expressions for temperature increases and thermal stresses that may be evaluated conveniently and rapidly for comparison of different systems. The results are analyzed to identify parameter ranges where different phenomena dominate (and therefore where different approximations are valid) and to determine parametric dependencies and trends in the different parameter ranges.

The explicit expressions for the parametric dependencies of thermal stresses are used to identify critical stress areas, to derive comparisons between the relative merits of fusion reactor operations in different parameter regimes, and to estimate benefits that may obtain from changes in operating characteristics. The results provide a quantitative basis for tradeoff studies and assessments of different fusion core systems.

2. TEMPERATURE DISTRIBUTIONS AND EXCURSIONS

Thermal stresses in reactor components are induced by nonuniform and/or unsteady temperature distributions. The first step in their analysis is the derivation of the expressions for the mean steady state and fluctuating temperature excursions; results are used in the next section to calculate the corresponding stresses.

2.1 Problem formulation

The problem of the determination of cyclic temperature variations in the fusion reactor first wall and fuel elements is formulated as follows. We assume that the radius of curvature of the first wall is so large relative to its thickness that the wall can be approximated with a flat plate and that power production in the plasma is so symmetric that the energy flow parallel to the surface can be neglected. We also postulate that fuel elements in the hybrid blanket are in the form of thin plates that can be approximated, as the first wall, with one-dimensional slabs. In a one-dimensional slab of material x-cm thick, thermal energy is generated in a layer δ-cm thick ($\delta < x$) as shown in Fig. 1a. This formulation allows a uniform treatment of surface energy flux and volume energy deposition cases. The heat generation because of the absorption of x rays, ions, or neutrons occurs periodically with the period t_p s and lasts for τ s with $\tau/t_p < 1$ as shown in Fig. 1b. The temperature variation $T(x,t)$ at the point x inside the material and at the time t is given by the solution of the inhomogeneous heat conduction equation

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} + \frac{s}{\rho c} \qquad (1)$$

where the source function (rate of energy deposition) $s(x,t)$ erg/cm^3 s, shown in Fig. 1b, is given by $s(x,t) = s_0$; $0 \le x \le \epsilon$; $nt_p \le t \le nt_p + \tau$; $n = 0, 1, 2, 3, \ldots$; $s(x,t) = 0$ otherwise; and κ is the thermal diffusivity equal to $k/\rho c$, k being the heat conductivity, ρ the density, and c the heat capacity of the material; all are assumed to remain constant. The postulate of uniform intensity during the pulse duration τ is made only to simplify the computations.

The boundary conditions are specified at the surface facing the plasma (or the centerline of the fuel element), $x = 0$, and at the surface facing the coolant, $x = \ell$; they are

$$\frac{\partial T}{\partial x} = 0 \text{ at } x = 0 \text{ and } T = 0 \text{ at } x = \ell \quad . \tag{2}$$

The first condition expresses the assumption that no heat is transferred to the interior of the reactor cavity or across the symmetry plane of the fuel element and the second condition expresses the assumption that the face of the material contiguous to the coolant remains at the constant coolant temperature. Because we are interested in cyclic stresses, we seek a periodic solution $T(x,t + t_p) = T(x,t)$ and not a solution of the initial value problem with an arbitrary initial temperature distribution.

Under certain conditions, in particular when $\varepsilon/\ell \ll 1$, the above formulated problem may be approximated with the homogeneous heat conduction equation and the boundary condition that prescribes a specified energy flux across the surface $x = 0$. However, the solution of this problem breaks down ($T \to \infty$) when $\tau \to 0$ while the amount of energy deposited remains constant.[1] The solution of the problem formulated in this paper remains valid for all values of τ/t_p [1] and we use it for that reason.

The periodicity condition on the solution of Eq. (1) suggests the use of Fourier series for the determination of cyclic temperature fluctuations. Toward this end we expand the source $s(x,t)$ in Eq. (1) into a Fourier series as an even function of x and t over the intervals $-2\ell \le x \le 2\ell$ and $-0.5\, t_p \le t \le 0.5\, t_p$. The use of even functions as the expansion basis improves the accuracy significantly[2] and the double length interval in x is necessary to satisfy both boundary conditions, Eq. (2), exactly.

2.2 Approximate temperature distribution.

We have calculated complete Fourier series solution of the above formulated problem and the details will be published elsewhere. Here we use an approximate expression for the temperature distribution denoted by $T_1(x,t)$, consisting of the first approximation to the steady state (mean) temperature distribution, T_s, and the fundamental harmonic component of the temporal fluctuation T_f:

$$T_1(x,t) = T_s + T_f \quad . \tag{3}$$

After tedious but elementary computations, we obtain for the mean temperature

$$T_s = \frac{S_0 \tau}{k t_p}\left[\text{[illegible]} \left(\text{[illegible]}^2 - x^2 \right) + \frac{8\,\text{[illegible]}}{\text{[illegible]}^3} \sin(\text{[illegible]}) \cos\left(\frac{\pi x}{2\,\text{[illegible]}}\right) \right] \tag{4}$$

and for the fundamental harmonic

$$T_f = A_1 \sin\left(\frac{2\pi t}{t_p}\right) + B_1 \cos\left(\frac{2\pi t}{t_p}\right) \quad , \tag{5}$$

where

$$A_1 = \frac{2 s_o t_p \sin\left(\frac{\pi\tau}{t_p}\right)\left[\frac{\delta}{\ell} + \sin\left(\frac{\pi\delta}{2\ell}\right)\right]}{\pi^3 \rho c \left(1 + \frac{\pi^2}{64}\frac{t_p^2}{t_c^2}\right)} \cos\left(\frac{\pi x}{2\ell}\right) \quad ,$$

$$B_1 = \frac{s_o t_p^2 \sin\left(\frac{\pi\tau}{t_p}\right)\left[\frac{\delta}{\ell} + \sin\left(\frac{\pi\delta}{2\ell}\right)\right]}{4\pi^2 \rho c t_c \left(1 + \frac{\pi^2}{64}\frac{t_p^2}{t_c^2}\right)} \cos\left(\frac{\pi x}{2\ell}\right) \quad ,$$

and the characteristic thermal diffusion time, t_c, is $t_c = \ell^2/\kappa$.

The amplitude of the harmonic fluctuation, $A = \sqrt{A_1^2 + B_1^2}$, is

$$A = \frac{2 s_o t_p \sin\left(\frac{\pi\tau}{t_p}\right)\left[\frac{\delta}{\ell} + \sin\left(\frac{\pi\delta}{2\ell}\right)\right]}{\pi^3 \rho c \left(1 + \frac{\pi^2}{64}\frac{t_p^2}{t_c^2}\right)^{1/2}} \left|\cos\left(\frac{\pi x}{2\ell}\right)\right| \quad . \qquad (6)$$

The approximate solution represented by Eqs. (3)--(6) simplifies considerably when specialized to particular cases of the reactor first wall and fuel elements; the detailed analysis will be published elsewhere.

3. THERMAL STRESSES

Thermal stresses arise when temperature distributions induce incompatible thermal expansions in different parts of structural elements. Because the compatibility of the distortion distribution depends not only on the material stiffness but also on the element stiffness that may be provided by its shape, the same temperature distribution may induce different stresses in a cylinder than in a flat plate, even though the ratio of the wall thickness to cylinder radius may be very small. We calculate the thermal stresses by postulating that the first wall of the reactor vessel is a cylinder and that the fuel elements in the hybrid are flat plates.

3.1 The First Wall

Examination of the general expressions for the thermal stress distribution in a hollow cylinder induced by the temperature distribution $T(x,t)$ shows [3] that the tangential stress σ_t equals the axial stress and exceeds the radial stress by the factor R/ℓ where R is the radius of the cylinder. Therefore, and because of the space constraint, we limit our presentation to the tangential stress.

An approximate expression for σ_t valid for $\ell/R \ll 1$ is

$$\sigma_t = [illegible]\,[T_{av} - T(x,t)] \qquad ([illegible])$$

where

$$T_{av} = \frac{1}{\ell} \int_0^{\ell} T(x,t)dx$$

and $\beta = \alpha E/(1 - \nu)$ with α being the coefficient of linear thermal expansion, E the Young's modulus, and ν the Poisson's ratio.

Using Eqs. (4)--(6) in Eq. (7), we determine that the steady state component of the stress, $\sigma_{\theta s}$, is

$$\sigma_{\theta s} = \frac{s_o \tau \delta t_c}{\rho c \lambda t_p} \beta F_1(\frac{x}{\ell}) \quad , \qquad (8)$$

where

$$F_1(\frac{x}{\ell}) = \frac{1}{6} + \frac{8}{\pi^3} - \frac{1}{4}(1 - \frac{x^2}{\ell^2}) - \frac{4}{\pi^2}\cos(\frac{\pi x}{2\ell}) \quad .$$

Similarly, the amplitude of the fluctuating stress component, $\sigma_{\theta fa}$, is

$$\sigma_{\theta fa} = \beta A_m F_2(x/\ell) \quad , \qquad (9)$$

where A_m is the maximum amplitude of the temperature fluctuation given by Eq. (6) for x = 0 and

$$F_2(\frac{x}{\ell}) = \frac{2}{\pi} - \cos(\frac{\pi x}{2\ell}) \quad .$$

The functions F_1 and F_2 are plotted in Fig. 2; the plots show that both stresses change from tensile to compressive at points that are very close together. The amplitude of the fluctuating component vanishes at $x/\ell = 0.560$.

In the analysis of fluctuating stresses and the associated fatigue failure of interest is the ratio of the peak to steady state stresses, $(\sigma_{\theta s} + \sigma_{\theta fa})/\sigma_{\theta s}$. This ratio, R_s, is given by

$$R_s = 1 + \frac{\sigma_{\theta fa}}{\sigma_{\theta s}} \quad , \tag{10}$$

where

$$\frac{\sigma_{\theta fa}}{\sigma_{\theta s}} = \frac{2 + \pi}{\pi^2} \frac{\sin(\pi\tau/t_p)}{\pi\tau/t_p} G(t_p/t_c) \frac{F_2(x/\ell)}{F_1(x/\ell)} \tag{11}$$

and the function $G(t_p/t_c)$ is

$$G = \frac{t_p/t_c}{\left(1 + \frac{\pi^2}{64} \frac{t_p^2}{t_c^2}\right)^{1/2}} \quad .$$

Because the ratio t_c/t_p is a nondimensional frequency expressed in cycles per characteristic thermal time, $G(t_p/t_c)$ may be called the frequency function.

The three functions that appear in Eq. (11) are plotted in Figs. 3--5. The plot in Fig. 3 indicates that the stress ratio decreases as the pulse length τ approaches the cycle period t_p and becomes unity at $\tau = t_p$, as expected in the case of steady state operation. The plot of the frequency function in Fig. (4) shows that the stress ratio decreases monotonically as the frequency increases (t_p/t_c decreases). This is an expected behavior: when the load on the wall is pulsed rapidly relative to the thermal response time ($t_p/t_c \ll 1$), the wall cannot respond to individual pulses and their magnitude is small. The plot of the ratio F_2/F_1, shown in Fig. 5, indicates that its value is 1.576 at the inner ($x = 0$) and 1.499 at the outer ($x = \ell$) faces of the first wall. The values of this ratio in the range of x/ℓ from 0.5 to 0.6 are not meaningful because both stress components vanish there as shown in Fig. 2.

[illegible] The Fuel Element

A symmetric temperature distribution [illegible] between the faces of a thin flat plate with free edges induces a thermal stress in the plane of the plate given by [illegible]:

$$\sigma_p = [illegible]\,\beta(T_{av} - T) \qquad ([illegible])$$

where

$$T_{av} = \frac{1}{[illegible]} \int [illegible]\, T(x,t)\,dx \; .$$

Using Eqs. [illegible] with the characterization of the fuel element, which is [illegible], we obtain:

$$\sigma_s = [illegible]\, \frac{S_0 [illegible] t_c}{[illegible]\, t_p}\, F_3([illegible]) \qquad ([illegible])$$

where

$$F_3(\frac{x}{\ell}) = \frac{1}{6} + \frac{16}{\pi^4} - \frac{1}{4}\left(1 - \frac{x^2}{\ell^2}\right) - \frac{8}{\pi^3}\cos\left(\frac{\pi x}{2\ell}\right)$$

and

$$\sigma_{pfa} = \alpha A_m F_2(x/\ell) \quad . \qquad (14)$$

The function F_3 is plotted with F_2 in Fig. 6.

The stress ratio for the fuel element is given by Eq. (10) with

$$[illegible] \qquad (15)$$

Equation (15) indicates that the behavior of the stress ratio for the fuel element is the same as for the first wall, except that in this case the value of the ratio F_3/F_2 is [illegible] at the center [illegible] and [illegible] at the face [illegible] as shown in Fig. 6.

6. CONCLUDING REMARKS

We have outlined the approach, analysis, and results of the modeling of cyclic thermal stresses in fusion reactors. The model is idealized and the analysis is approximate.

however it covers the complete range of potential operating conditions and thus provides quantitative basis for tradeoff studies of different fusion core types.

Because of space limitations, the presentation is sketchy; in particular, it contains neither the validity and accuracy estimates nor the discussion of special cases when the validity of the general solution breaks down (for example, when t_p/t_c is large). A complete description of the work, including comparisons with previously obtained special results will be submitted for publication in the near future.

5. REFERENCES

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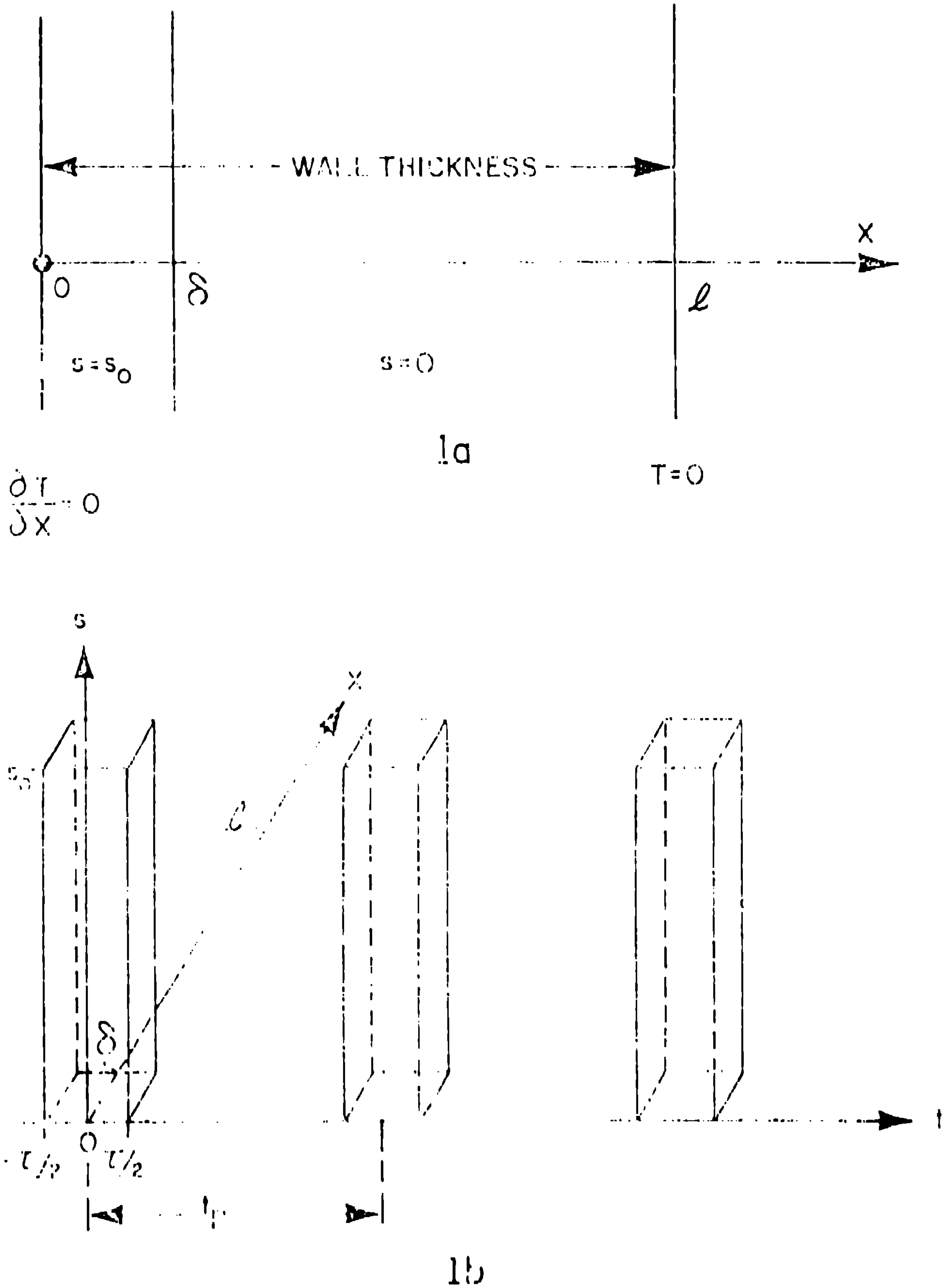
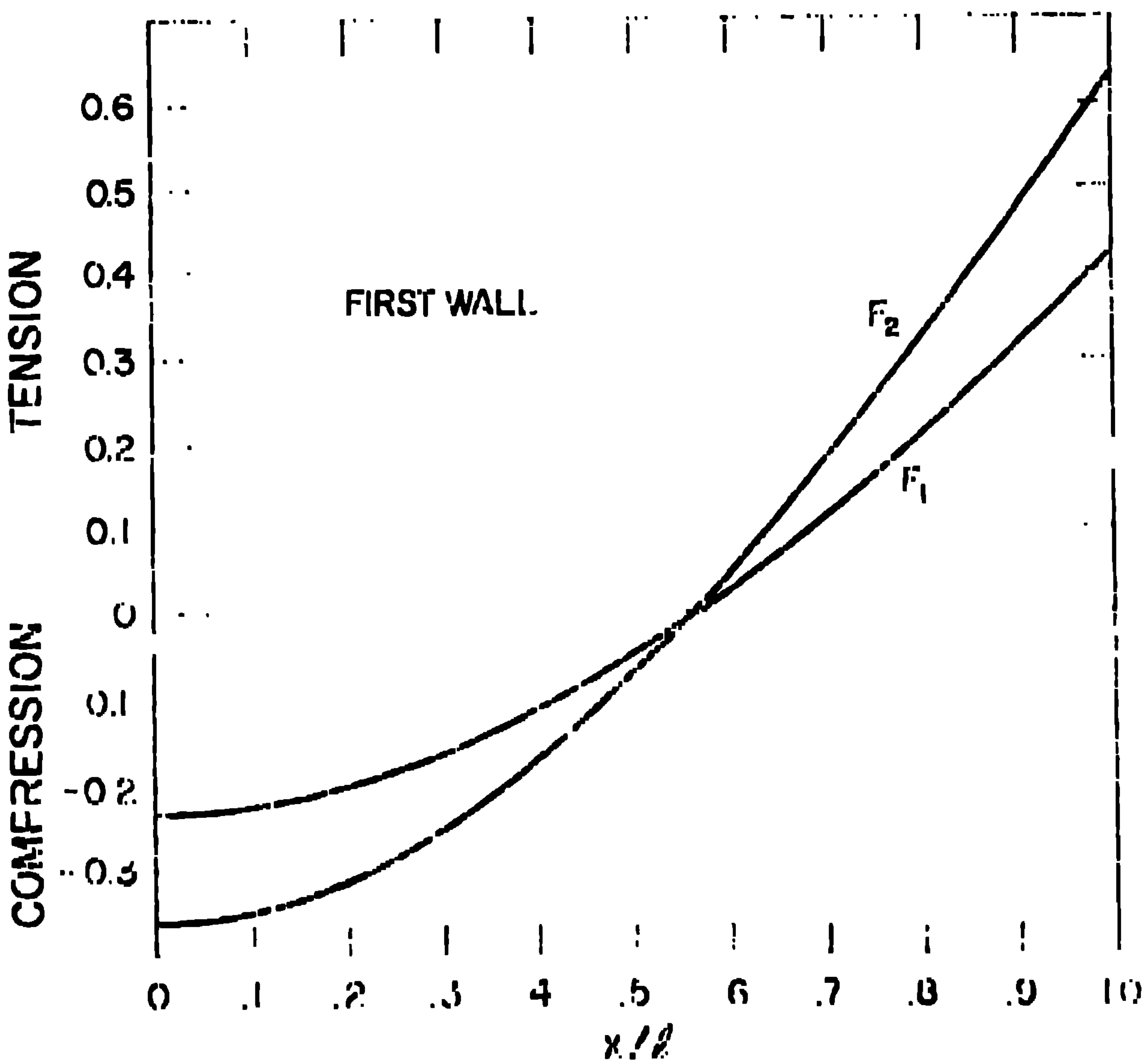
[2] MILLER, K.S., Partial Differential Equations in Engineering Problems, Prentice Hall, NY (1953) 67.

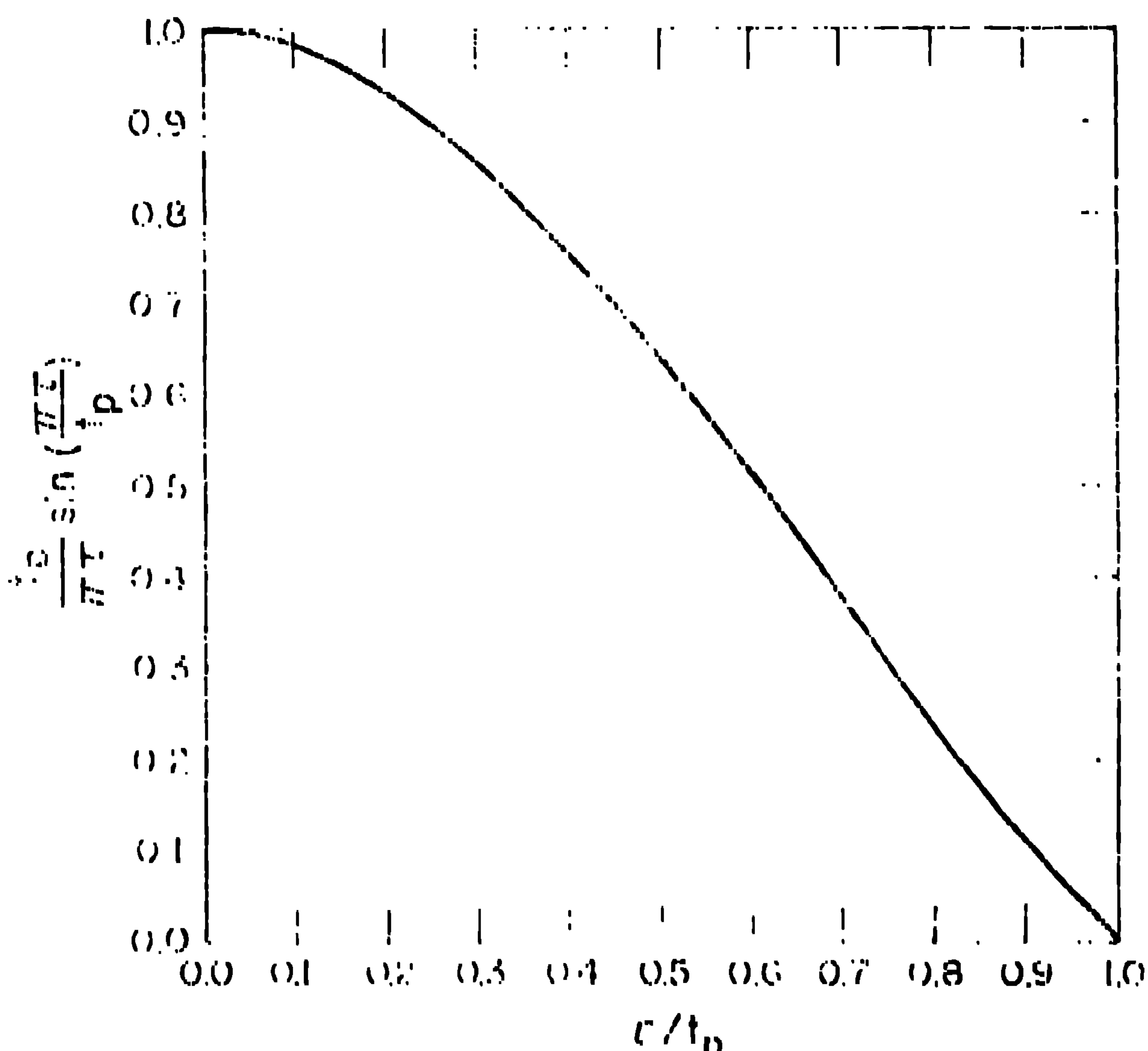
[3] TIMOSHENKO, S. P., GOODIER, J. N., Theory of Elasticity, 3rd ed., McGraw Hill, NY (1970) Chapter 14.



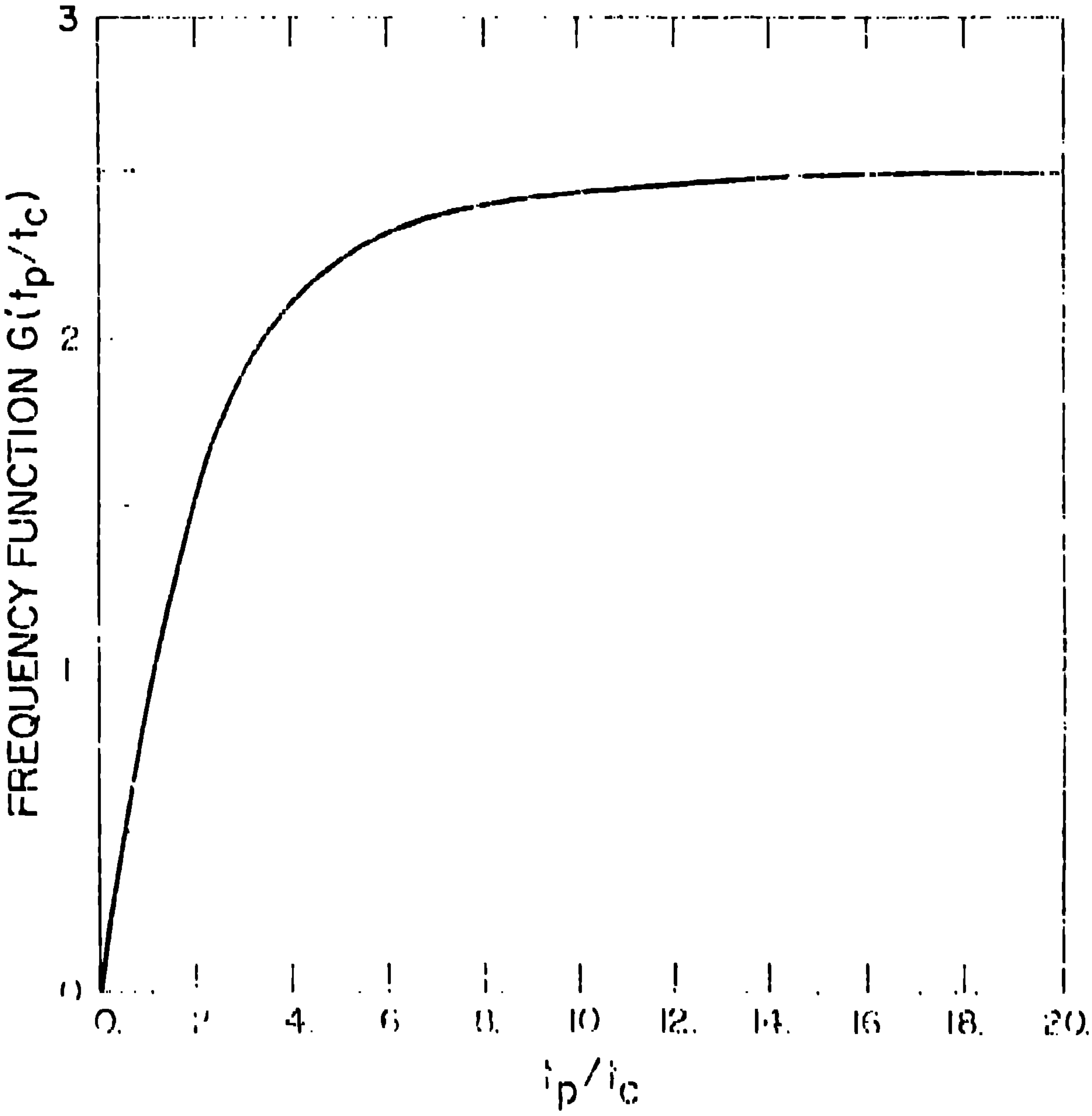
1. Problem formulation: (1a) Geometry and boundary conditions; (1b) The source function.



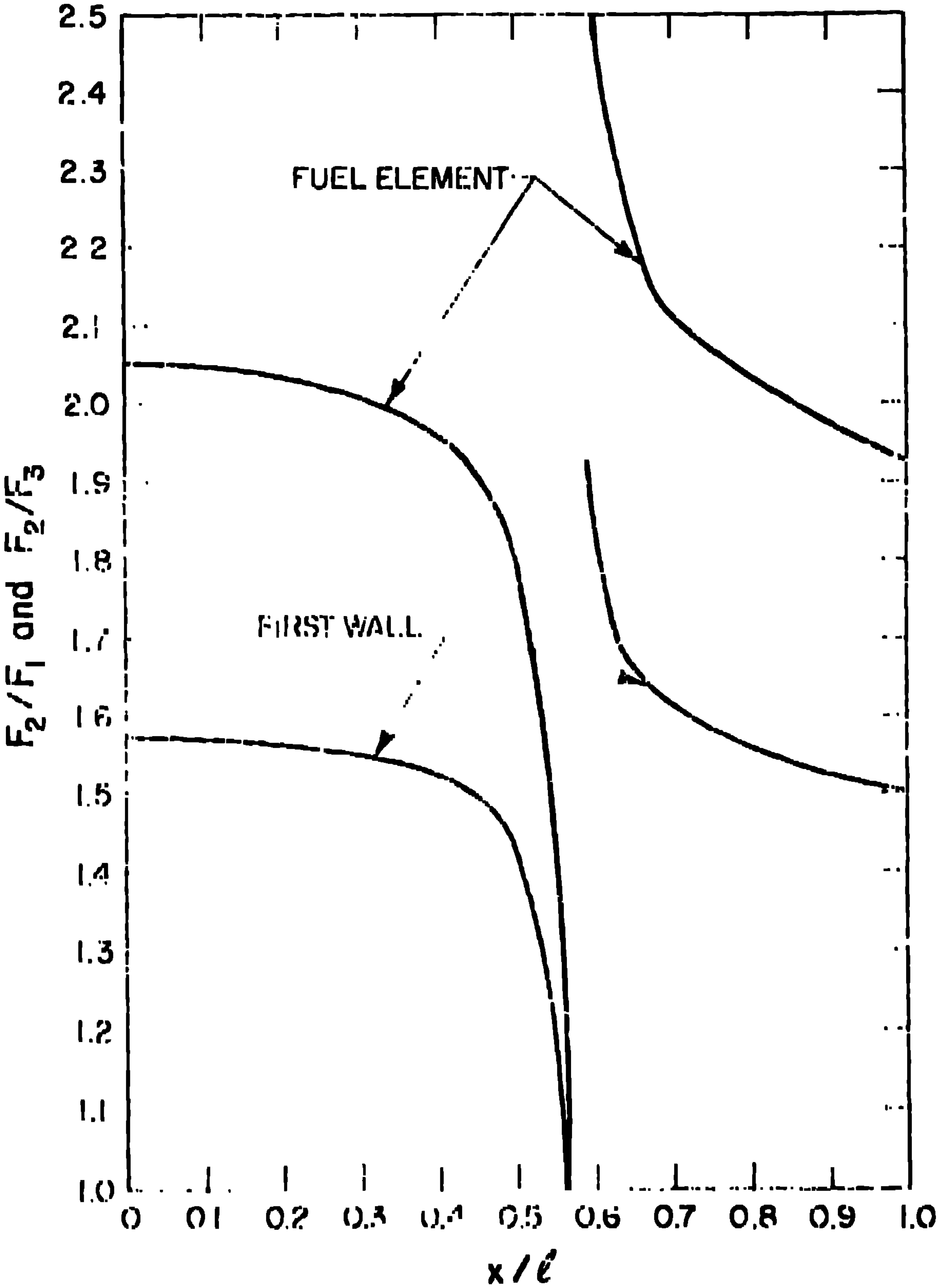
2. Stress distributions inside the first wall.



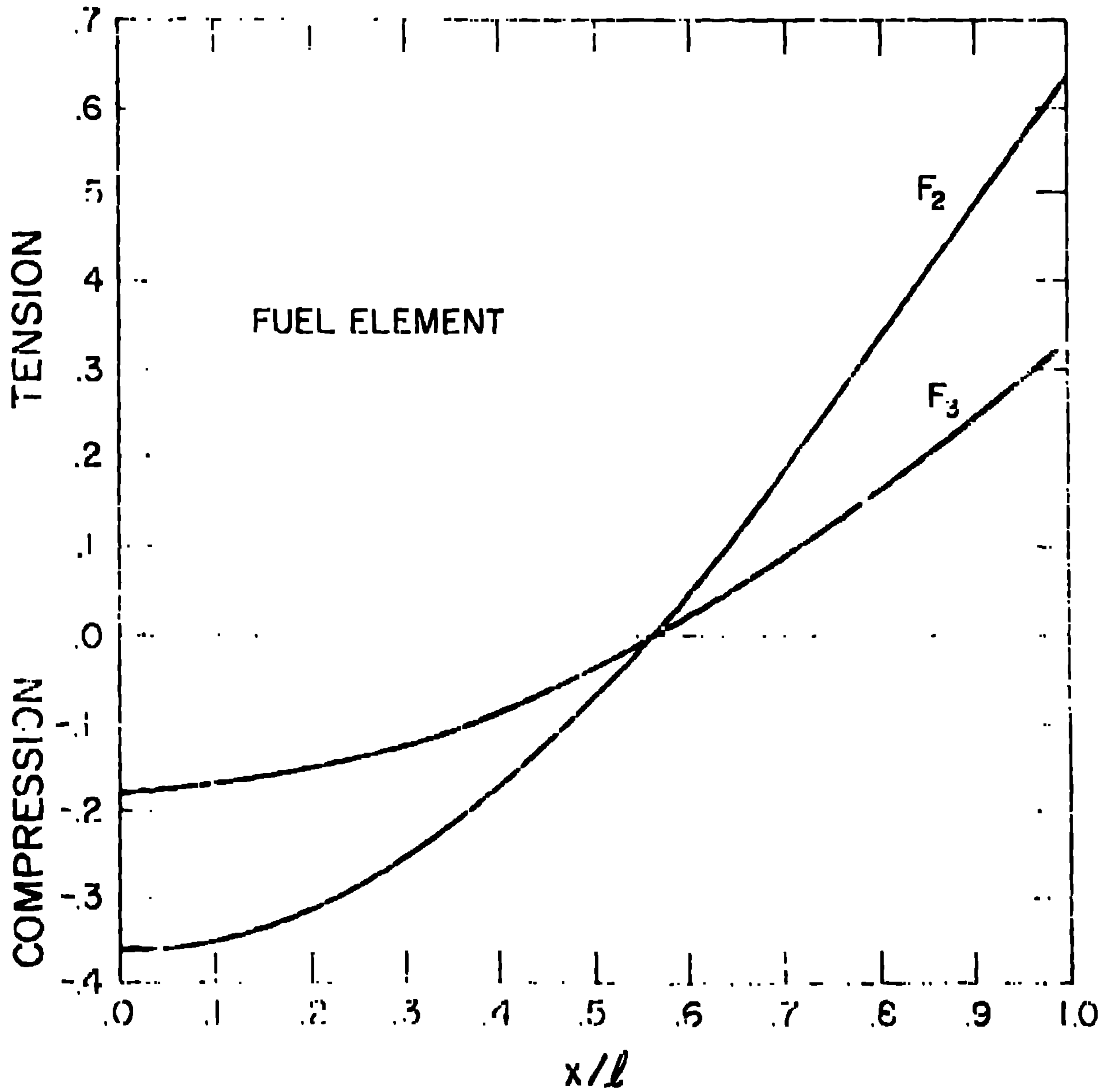
3. Dependence on pulse duration.



4. Frequency function.



5. Stress distribution ratios.



6. Stress distribution inside the fuel elements.