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Introduction:

Plasma disruption in tokamaks is a well-known if not well-understood phenomenon, which leads to severe problems in the design of first walls in tokamaks. These disruptions can deposit large fluxes of heat on the surface of first wall components closest to the plasma. This heat flux is in the form of energetic ions, electrons and x-rays, though the total amount of energy impinging on the first wall components and the duration of the disruption are uncertain. In any case, disruptions may occur hundreds of times in the lifetime of a tokamak reactor. If the energy deposited on the first wall is large enough, melting and even vaporization can occur [1,2]. Even if the energy density is not high enough to lead to melting, large thermal stresses may cause unacceptable damage to the first wall.

In this paper, we examine the thermomechanical response of the wall to a tokamak disruption in this latter case, where the energy density on the first wall is low enough that excessive melting does not occur. We have chosen a case where the disruption energy is sufficiently high that the first wall temperature reaches a maximum value close to the melting temperature. In this case, only thermal creep and plastic deformation produced by large thermal stresses remain an important issue when considering first wall design and lifetime. The combined effects of large thermal creep rates and plastic deformation can lead to residual tensile stresses which may cause the growth

of surface cracks in the wall. Such surface cracks have been observed in the first wall and in limiters of present tokamak devices [3,4,5].

In analyzing the evolution of the thermal and residual stresses, temperature and thermal stress profiles as well as their rate of change must be followed simultaneously and throughout the wall thickness. The stress analysis was carried out with a recently developed [6] transient stress code TSTRESS. Relaxation of the stresses was assumed to occur by thermal creep only. Considering the high temperatures in a first wall component when exposed to a plasma disruption, creep deformation and plastic flow become in fact indistinguishable. It is therefore expected that creep relaxes the stresses at such a fast rate that it resembles instantaneous plastic deformation. The results presented below have confirmed this.

Method of Analysis:

The evolution of transient stresses in a tokamak first wall during and after a tokamak disruption is analyzed with two coupled computer codes. The first is a simple finite difference temperature diffusion code which provides wall temperature profiles versus time. These profiles are written into a data file at various times. This data file serves as input for the transient stress finite difference code, TSTRESS. This code solves the stress rate equations for the stresses σ_x and σ_y according to the equation

$$\dot{\sigma}_x(z) = \frac{1}{h} \int_0^h 2\mu(\frac{1 + \nu}{1 - \nu})\alpha\dot{T}dz - 2\mu(\frac{1 + \nu}{1 - \nu})\alpha\dot{T} + \frac{1}{h} \int_0^h \frac{\mu\psi}{1 - \nu} [(2 - \nu)\sigma_x$$

$$\tag{1}$$

$$- (1 - 2\nu)\sigma_y]dz - \frac{\mu\psi}{1 - \nu} [(2 - \nu)\sigma_x - (1 - 2\nu)\sigma_y] ,$$

and similarly for $\dot{\sigma}_y(z)$. Here, the wall is in the x-y plane and is assumed to be a solid slab of thickness h with edges that are not constrained from expanding. μ is the shear modulus, ν is Poisson's ratio, α is the coefficient of thermal expansion, and ψ is the thermal creep compliance.

Considerable effort [7] has been devoted to the determination of a proper expression for the thermal creep compliance for 316 stainless steel, the first wall material chosen for the INTOR tokamak reactor study design [8]. The expression we have used for the creep compliance is

$$\psi = \frac{A_0}{\sigma_{eq}} \left[\sinh(\alpha\sigma_{eq}) \right]^n \exp(-Q/RT) \qquad (MPa\text{-}sec)^{-1} , \qquad (2)$$

where: $A_0 = 3.29 \exp(14633/T)$,

$$\alpha = \frac{-3.603 + 6.010 \times 10^{-4} \, T}{23.55 - 0.01796 \, T} \qquad (MPa)^{-1},$$

$n = 24.608 - 0.01923 \, T$,

$Q = 268 \text{ kJ/mole}$

and T is the material temperature in K. σ_{eq} is the equivalent stress, $\sigma_{eq} = [\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y]^{1/2}$. Equation (2) is strictly applicable only for 811 K < T < 1033 K [9], but we have extended it up to 2000 K based on the assumption that as long as the creep compliance is large near the melting point, the actual value is not very important.

We have also investigated deformation laws other than Eq. (2) which account simultaneously for plastic deformation and thermal creep. The Hart mechanical equation of state [10] gives creep compliances close to those resulting from Eq. (2) when σ_{eq} is less than the yield stress. However, when

σ_{eq} approaches the so-called hardness parameter, the creep compliance rises dramatically. To date, this behavior of the creep compliance has caused severe numerical problems in TSTRESS. TSTRESS uses an automatic time step determination which keeps the creep compliance from changing too much during a time step. Thus, as σ_{eq} approaches the yield stress, the time steps become very small. We expect that this problem will be solved soon but in this paper we will only present results using Eq. (2) as a creep compliance law.

Results:

The analysis described in the preceding section has been used to calculate the evolution of stresses in a tokamak first wall during a plasma disruption. As stated in the introduction, we are interested in the case where the disruption energy is sufficiently low that excessive melting does not occur. We have selected a case which is relevant to the INTOR study and have used the parameters shown in Table I. The heat flux on the surface as a function of time is shown in Fig. 1.

Also shown in Fig. 1 is the surface temperature of the wall versus time. Notice that the wall reaches a maximum temperature of 2000 K, slightly above the melting temperature, and that it cools rapidly to a much lower temperature.

The transient stress profiles are shown in Fig. 2, where the usual convention is followed that compressive stresses are negative. During the rapid heating of the surface layer, the compressive thermal stresses are quickly relaxed by creep. As the heat is conducted farther into the material, the transient thermal stresses penetrate deeper into the material leading to more creep deformation. After the heat flux ceases and the surface temperature drops, residual tensile stresses develop. Since the temperature drops rapid-

Table I. Disruption Parameters

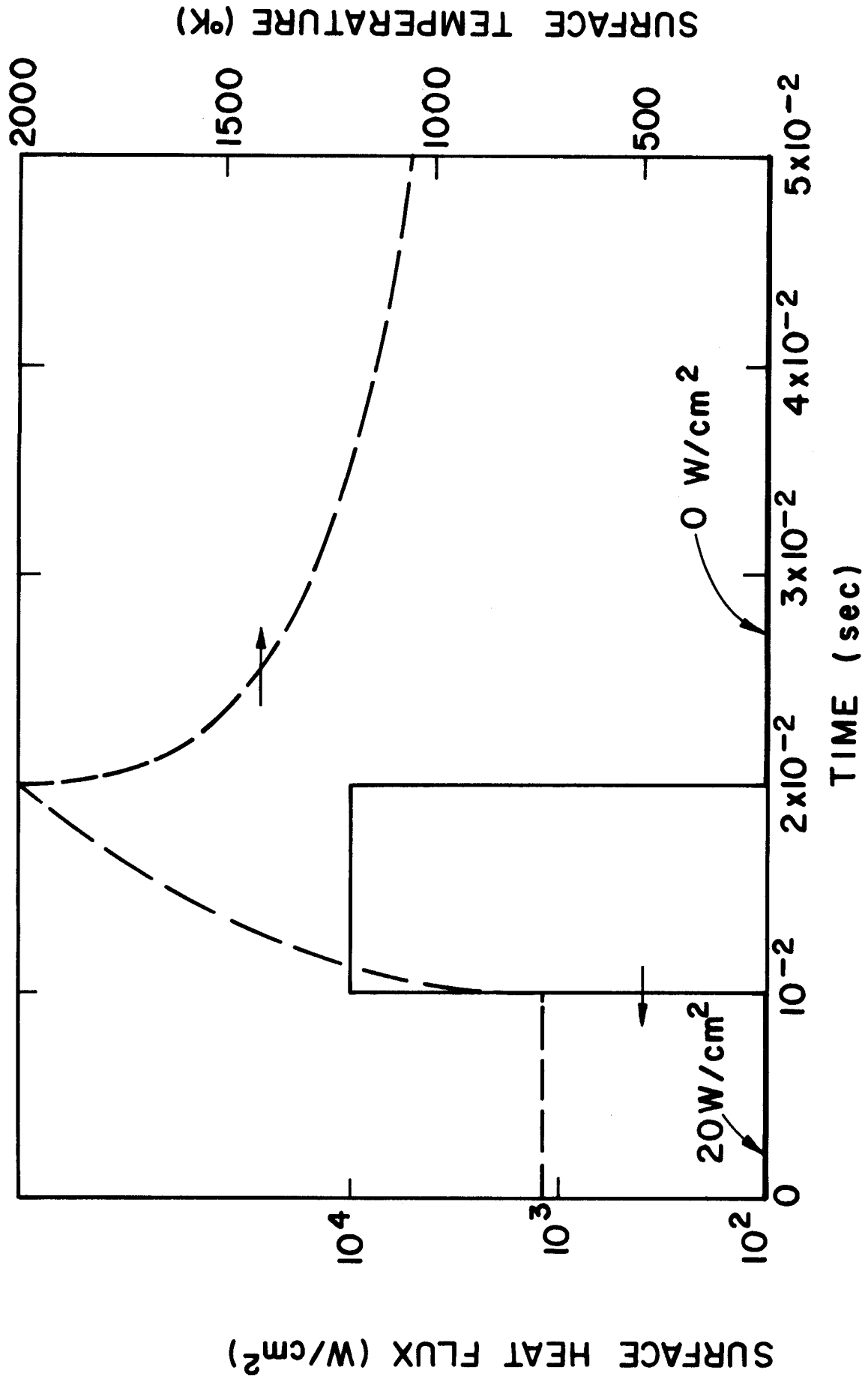|	
Disruption energy density (J/cm^2)	100
Duration of disruption (ms)	10
First wall material	316 SS
Thickness of first wall (cm)	0.5
Wall coolant temp. (K)	680
Yield stress of 316 SS (MPa) (@ 773 K)	525

Figure 1. Surface heat flux and wall surface temperature versus time.

ly, little creep relaxation occurs, and the residual stresses build up to large values, until either plastic deformation or surface cracking occurs. Since it is not known what the yield stress will be of the severely heated and deformed surface layer, plastic instantaneous deformation has not been included in the present calculations. The high residual tensile stresses computed indicate, however, that plastic deformation will occur and that the actual residual stress on the surface is equal to the yield stress.

Figure 3 shows in more detail the evolution of the stress on the surface facing the plasma. The stress at the plasma side surface of the wall versus time is shown in Fig. 3. The very rapid creep of the material while under compression is clearly evident between 10 and 20 milliseconds. In the interval between 30 and 40 milliseconds the temperature is still high enough for rapid creep to occur but the stress is tensile so that the stress relaxation is in the compressive direction. From 40 to 200 milliseconds, there is an equilibrium between thermal creep and the relaxation of the temperature gradient while from 200 to 400 milliseconds the temperature is low enough that thermal creep is no longer important and relaxation of the temperature gradient causes a large increase in the tensile residual stress. Beyond 400 milliseconds the temperature gradient slowly relaxes, leading to a gradual rise in the tensile stress.

Discussion:

We have presented a model for the analysis of transient stresses in a tokamak first wall during a plasma disruption. By completing a representative calculation where excessive melting does not occur and stress relaxation by creep is dominant during the heating phase, we have found that large tensile stresses and plastic deformation should be present in the first wall. In the
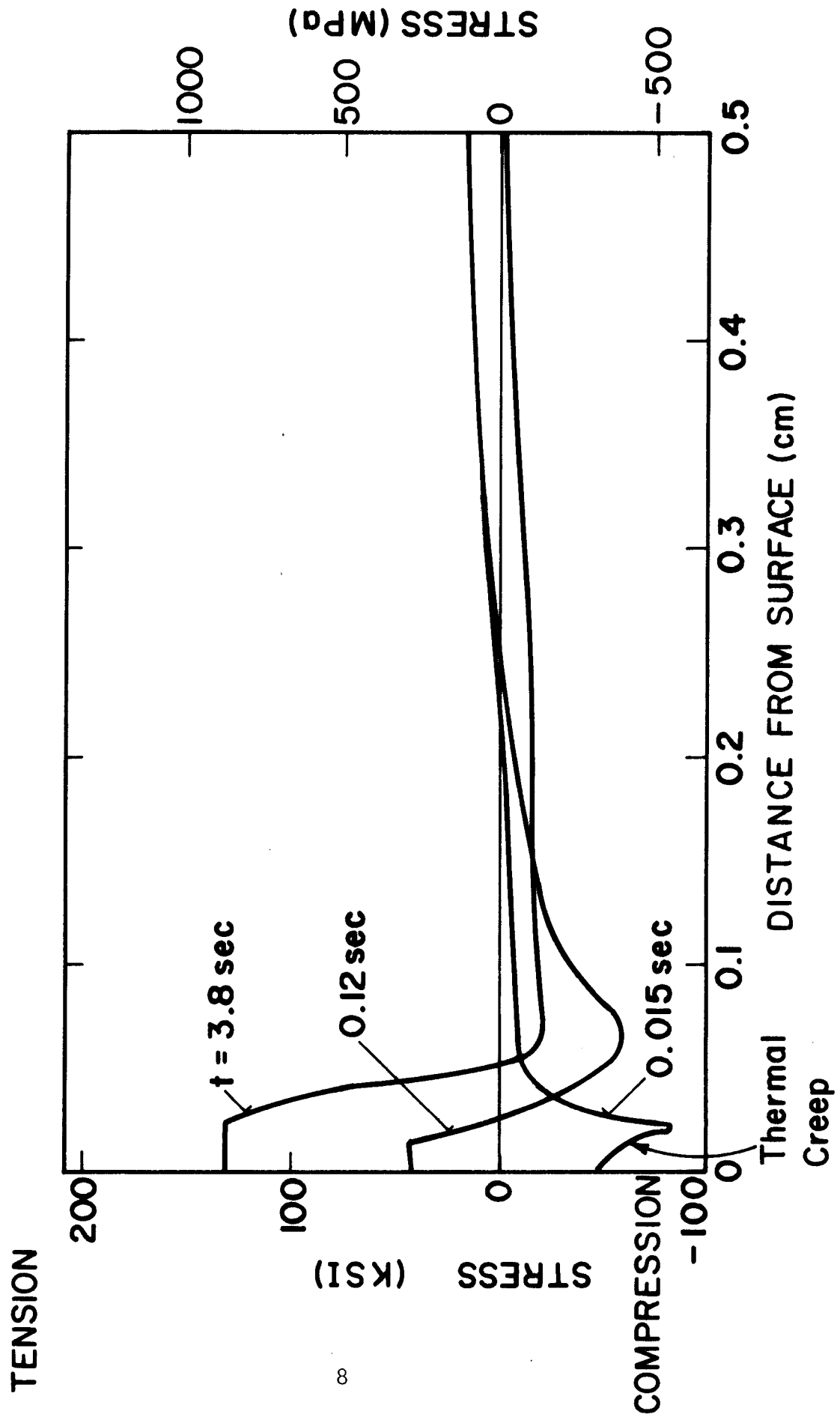
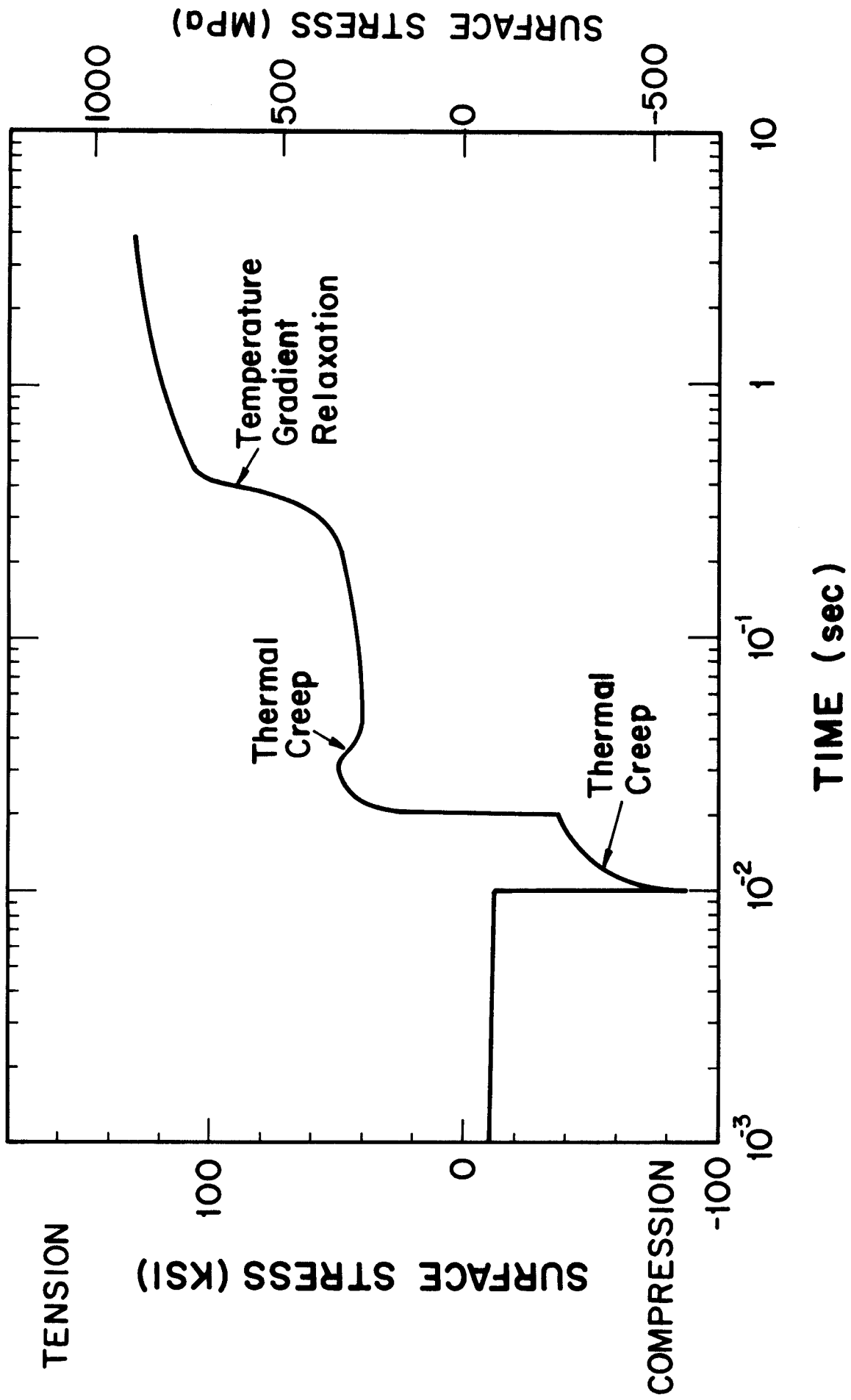Figure 2. Stress versus distance from surface and time.

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Figure 3. Surface stress versus time.

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future, the model will be improved to incorporate a deformation law which includes both creep, plastic deformation, and history-dependent yield stress.

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