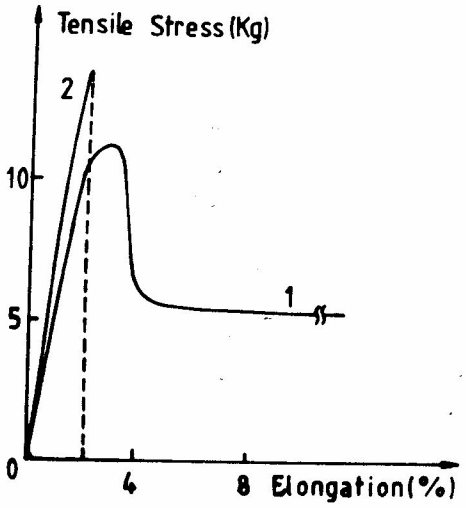

Fig. 7 The tensile stress-elongation curves of amorphous PET. annealing time: 1-before 50h; 2-after 50h.

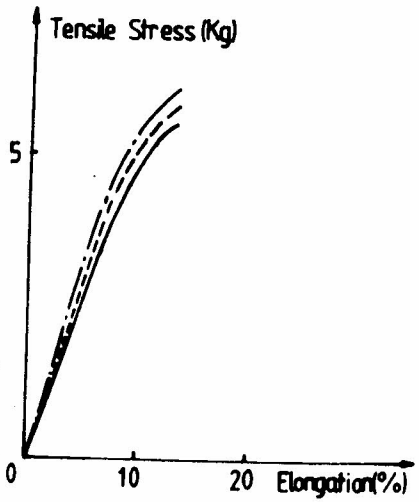

Fig. 8 The tensile stress-elongation curves of semi-crystalline PET. annealing time: ——0h; -·-·-30h; ---120h.

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INJECTED CHARGE FROM SURFACE TRAPS INTO FILMS WITH DEEP BULK TRAPS

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ABSTRACT

In many cases the profile of an open circuit TSC in Teflon FEP shows two well defined peaks. The first is usually interpreted as due to charge injection from thermally activated surface traps into bulk traps and the second one, occurring at higher temperatures, as charge emission from these volume traps. Extending a calculation done by Kanazawa and Batra [1] a theoretical analysis for the first peak is carried out relating the surface voltage and the total charge in the sample as a function of two parameters: the initial Schubweg and the fraction of charge injected into the sample. The heat pulse technique, giving both, the surface potential and the charge in the sample is suitable to verify experimentally the theory.

1. INTRODUCTION

When a negative corona discharge is applied on Teflon FEP films, the deposited charge remains at the surface and it is necessary to produce a thermal activation in order to inject the charge into the bulk of the sample. If an "open circuit" Thermo Stimulated Current (TSC) [2] experiment is carried out, and the "open circuit current", I=CdV/dt [2,3], measured (C is the series capacitance of the sample and the air gap, V is the open circuit voltage), it shows in general two well defined peaks. The first peak is usually interpreted as due to charge injection from thermally activated surface traps into the traps of the bulk and the second peak, occurring at higher temperatures, as charge emission from the volume deep traps.

Usually the heating rate during the TSC is made slow, about $2^{o}C/min.$, to avoid thermal gradients and to insure a good approximation to the thermal equilibrium at the different stages of the process. In this conditions, if the carrier mobility is not too small and if no detrapping occurs, it may be supposed that the injected free charges reach quickly their final trapped state and therefore their density is always negligible as compared with that of the trapped charge. Such an assumption have already been made by Kanazawa and Batra [1] who, besides this, have shown that the fraction of charge injected into the sample contributing to the residual voltage is independent of the mechanism of injection.

This special behavior will allow us to construct a family of curves relating the open circuit voltage at each stage of the process with the electric field at the rear electrode (that is, the total charge inside the sample, which may be accessed experimentally by means, for instance, of the heat pulse technique [4]). These curves permit to infere, in an experimental problem: a) if the process indeed corresponds to deep traps with a field dependent Schubweg, b) the kinetics of the surface charges, c) the value of the product of the trapping time and mobility. The curves will be parametrized by the initial Schubweg $\mu\tau' E_o'$ and the fraction of injected charge,

2. THEORY

The ideas outlined before can be developped supposing that the approximation of open circuit holds. At this point references [1] will be closely followed. The

equation for the total current in open circuit is:

$$0 = \mu\rho'(x',t')E'(x',t') + \varepsilon\frac{\partial E'(x',t')}{\partial t'} \tag{1}$$

The kinematics of deep traps is:

$$\frac{\partial \rho_t'(x',t')}{\partial t'} = \frac{\rho'(x',t')}{\tau'} \tag{2}$$

The Poisson's equation considering negligible the free charge density is:

$$\varepsilon\frac{\partial E'(x',t')}{\partial x'} = \rho_t'(x',t') \tag{3}$$

where the mobility, μ, and the trapping time, τ', are constants. $\rho'(x', t')$ is the free density of charge, $\rho_t(x', t')$ is the density of trapped charge and $E'(x',t')$ is the electric field. The position $x'=0$ corresponds to the free surface and the position $x'=L$ to the earthed rear electrode. The initial conditions of the problem are:

$$\rho_t'(x',0) = 0 \quad \text{and} \quad E'(x',0) = E_o' = \frac{\sigma_o'}{\varepsilon} = \frac{V_o'}{L} \tag{4}$$

where σ_o' is the initial surface charge density deposited on the surface by a corona discharge.
Introducing the dimensionless quantities

$$x = x'/L,\ t = t'/t_o,\ \tau = \tau'/t_o = \mu\tau' E_o'/L,\ v = v'/V_o,\ E = E'L/V_o$$

$$\rho = \rho' L/CV_o,\ \rho_t = \rho_t' L/CV_o \quad \text{and} \quad \sigma = \sigma'/CV_o$$

where $C = \varepsilon/L$ is the capacitance per unit area and $t_o = L^2/\mu V_o$ is the transit time of the leading front. Eqs. (1-3) may be expressed in the following form

$$0 = \rho(x,t)E(x,t) + \frac{\partial E(x,t)}{\partial t} \tag{5}$$

$$\frac{\partial E(x,t)}{\partial x} = \rho_t(x,t) \tag{6}$$

$$\frac{\partial \rho_t(x,t)}{\partial t} = \frac{\rho(x,t)}{\tau} \tag{7}$$

and the initial conditions are reduced to

$$\rho_t(x,0) = 0 \quad \text{and} \quad E(x,0) = 1 \tag{8}$$

From Eqs. (5) and (7) and integrating for a fixed position with conditions (8) one obtains

$$0 = \tau\rho_t(x,t) + \ell n\, E(x,t) \tag{9}$$

now using Eq. (6) and integrating for a fixed time

$$\int_{E(0,t)}^{E(1,t)} \frac{d\,E}{\ell n E(x,t)} = -\frac{1}{\tau} \tag{10}$$

Here $E(0,t) = (1 - \beta)$ where β is the fraction of surface charge already injected. An expression involving the surface voltage is obtained using $dV = -Edx$ with Eqs. (6) and (9). One obtains

$$\int_{E(0,t)}^{E(1,t)} \frac{E\,d\,E}{\ell nE} = -\frac{V(t)}{\tau} \tag{11}$$

The relations (10) and (11) define $E(1,t)$ and $V(t)$ as function of β and τ. Taking the derivative of (10) and (11) relative to β, the following system is obtained:

$$\frac{\partial V}{\partial \beta} = \tau\frac{E(1,t) + \beta - 1}{\ell n(1-\beta)} \tag{12}$$

$$\frac{\partial E(1,t)}{\partial \beta} = -\frac{\ell nE(1,t)}{\ell n(1-\beta)} \tag{13}$$

This coupled system represents the dependence of the open circuit voltage and the electric field at the rear electrode as a function of the fraction of the surface charge injected having τ as parameter.
Now taking the derivative of (10) and (11) relative to τ the following system is obtained:

$$\frac{\partial V}{\partial \tau} = \frac{V}{\tau} - \frac{E(1,t)}{\tau} \tag{14}$$

$$\frac{\partial E(1,t)}{\partial \tau} = \frac{1}{\tau^2}\,\ell nE(1,t) \tag{15}$$

representing the dependence of the open circuit voltage and the electric field at the rear electrode with τ having β as parameter.
Mathematically these systems represent a succession of equilibrium final states and physically they represent a good approximation to the equilibrium provided the rate of charge injection from the surface is slow enough to allow the injected charge to reach almost their final state. These systems are to be solved numerically. The results of these integrations are shown in figure 1.
The curves for τ constant describes the relation between the open voltage and the field at the rear electrode during the different steps of the injection process. For samples with a small initial Schubweg there are not major changes in the value of the rear electric field, meaning that the injected charge is almost all captured by the bulk traps. The samples with a high value of the initial Schubweg presents proeminent changes of the voltage and the electric field evidencing the leakage of the injected charge at the different stages of the injection process.
The curves for β constant give the voltage of similar samples, heated at the same rate, initially charged at different potentials (leading to different τ)

at the same temperature (which means the same stage of the injection process, if one assumes that β depends only on the temperature). The changes in the voltage and the electric field are, again, more significants for the samples with high values of the initial Schubweg.

3. CONCLUSION

The theory here developed treats the surface charge injection as a succession of equilibrium final states, a condition that is approximatelly reached in the laboratory during a TSC measurement on Teflon FEP films. If one have a single level of surface traps it is possible to fit experimental points over one of the β constant curves for similar samples as described in the preceding paragraph. The measured values, V and E(1), in samples heated to the end of the first peak will fit the $\beta = 1$ curve and to each experimental point corresponds a value of τ easily read from the graphic. Since E' and L are known before the TSC process the value of the product $\mu\tau' = \tau L/E'_o$ for each sample is determined in function of V_o or the surface charge deposited on its surface. In this way it is theoretically possible to study the kinematics of the surface injection. To do this one must stop the TSC process before reaching the end of the peak and the values of V and E(1), obtained in the sequence of stops, must fit the correspondent τ constant curve. The values of β will give the injected charge. The experimental points plotted [5] were obtained for 25μm Teflon FEP samples submited to severe thermal treatment of 230°C during two hours previously to the TSC record. Each point corresponds to the mean value of four samples in the same conditions. The initial surface voltages were 150,300,400,500 and 700 volts of negative corona. The mean value of $\mu\tau'$ obtained was $8.3 \times 10^{-9} cm^2/V$.

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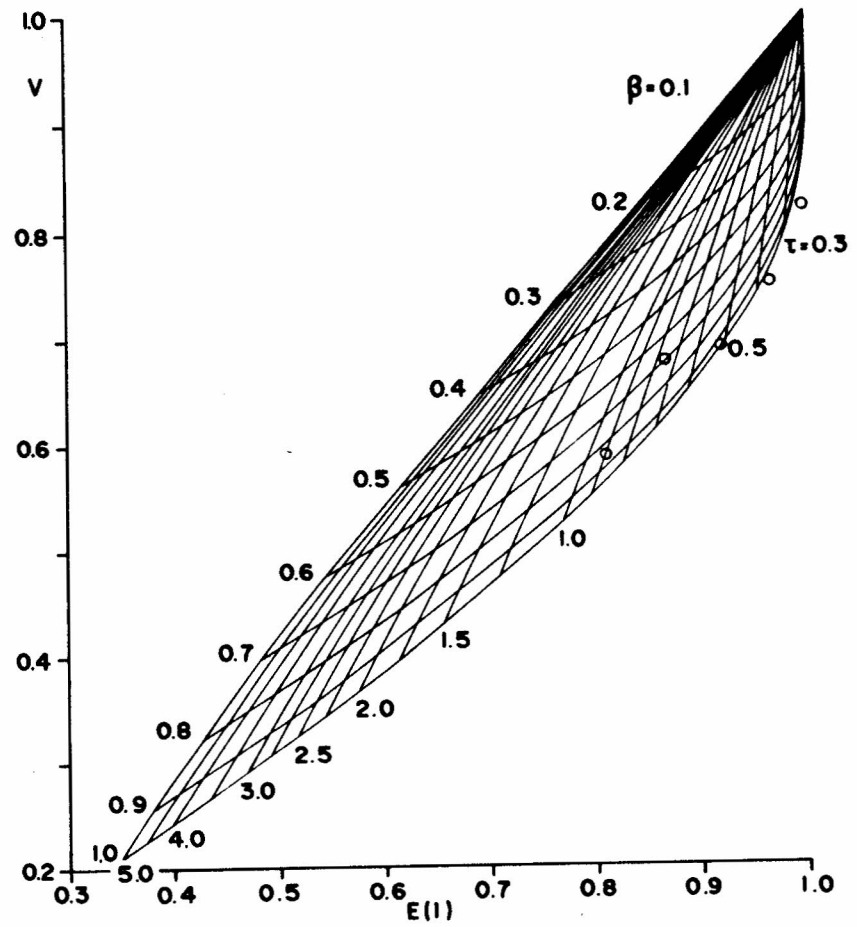

FIG.1 - Final open-voltage vs. electric field at the rear electrode (or total charge inside the sample) in dimensionless units. Parametrized by $\tau = \mu\tau' E'_o / L$ and β, the fraction of injected surface charge. The experimental points shown were obtained from different similar samples of Teflon FEP charged with negative corona to 150,300,400,500 and 700 volts before the TSC.

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