

# Return voltage as a dielectric characterization tool

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**Abstract**— An insulator charged during a long time cannot be neutralized through an instantaneous short circuit. This return voltage is used as a routine characterization tool in some areas of electrical engineering. Different physical causes may be involved in this phenomenon and are analyzed here: slow dipolar relaxation processes, interfacial polarization, heterogeneous conductivity and injected space charge.

Several recent experimental results are detailed here supporting the interest of this electrostatic technique as a simple and largely underestimated laboratory characterization tool. For instance, the sensitivity of this technique has been demonstrated to follow the ageing of cables for the aircraft industry. It has allowed quantifying interfacial polarization build-up at high temperature on polarized alumina plates. It has also been used to demonstrate a photoelectret effect on polyimide films, which is described.

## I. INTRODUCTION

Reporting his pioneering 1837 experiments, Faraday mentioned: “*if after having been charged for some time, as fifteen or twenty minutes, it [a spherical capacitor filled with a dielectric substance] was suddenly and perfectly discharged(...), then the apparatus being left to itself, would gradually recover a charge*” [1]. This observation, among others, of the residual voltage, was the first report on the memory effect of the insulators. Forty years later, its mathematical description was established by Hopkinson [2] by assuming a delayed dielectric response following the superposition principle.

The “return voltage method” is nowadays in common use in industry to monitor the ageing of HV transformers and cables [3][4]. It is a simple and quite sensitive tool to detect water uptake and degradation of impregnated insulations. Return voltage is also a laboratory tool, used as a complement to classical surface potential decay measurements for dielectric material characterization (fig.1). Recording the evolution of the potential after a fast surface neutralization provides useful information to understand the processes involved in the decay [5-7]. Charge, neutralization and measurement may here be performed without any contact with the surface, through corona discharge and electrostatic probes.

The return voltage phenomenon is due to the existence of internal constraints in the dielectric which cannot be removed by short-time neutralization. Most of the phenomena involved in this process have been described a long time ago, but, to our knowledge, no exhaustive review has ever been written on this topic. This paper is an attempt to fill this gap.

## II. LINEAR RESPONSE

Most disordered insulating materials exhibit a slow component of their dielectric relaxation response, which may have several physical causes, as long-range molecular motions in polymers. Assuming these to be linear with the electric field, the insulator response may be described by a dielectric function [8]. For instance, the voltage at the upper surface of an insulating slab of thickness  $L$  (assuming a zero field boundary condition outside the insulator, which will be granted by the use of an electrostatic probe) will depend on the total amount of charge deposited on its surface with time  $q(t)$  as follows :

$$V(t) = \frac{L}{\epsilon} \int_{-\infty}^t q(\tau) \phi_E(t - \tau) d\tau \quad (1)$$

The dielectric function  $\phi_E(t)$  may in principle be derived easily from the surface potential decay rate after an instantaneous charge deposit  $q_0$  at  $t=0$ . In this case:

$$\frac{dV(t)}{dt} = \frac{Lq_0}{\epsilon} \phi_E(t) = V_0 \phi_E(t) \quad (2)$$

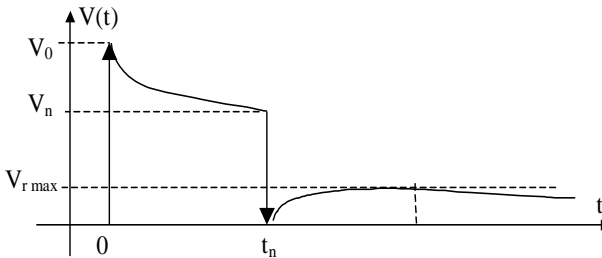


Fig. 1. Potential decay and return experiment.

Neutralizing at  $t=t_n$  the insulator surface at the potential  $V_n$ , the insulator return voltage will be, using the superposition principle:

$$\frac{dV(t)}{dt} = V_0 \phi_E(t) - V_n \phi_E(t - t_n) \quad (3)$$

Considering a homogeneous insulator described by a constant permittivity  $\epsilon$  and a non-zero conductivity  $\sigma$ , it will behave as a simple parallel RC circuit and no return voltage will be observed. In this case  $\phi_E$  is a decreasing exponential function, and from (3) it may also be deduced that  $dV/dt=0$ . However on most disordered materials, dielectric functions are following time power laws:

$$\frac{\phi_E(t)}{\phi_E(t_0)} = \left(\frac{t}{t_0}\right)^{-n} \text{ for } t \neq 0 \quad (4)$$

In this case,  $\phi_E(t)$  is decreasing faster than an exponential at short times, and hence the second term of equation (3) will predominate for small values of  $t-t_n$ , thus leading to a voltage return of the same sign than the initial potential.

The assumption of linearity may be quite easily verified, since from the dielectric function deduced from the voltage decay measurement, it is easy to use equation (3) to predict the shape of the return voltage that should be obtained.

It has to be underlined that the return voltage, after a maximum value reached for  $\frac{\phi_E(t)}{\phi_E(t-t_n)} = \frac{V_n}{V_0}$ , will slowly decrease to zero. For large time values, the voltage decay will be the same than for an initial charge deposit inducing the potential  $V_0 - V_n$ .

For a dielectric function following equation (4), the time to reach the maximum voltage may be computed, it is:

$$t_m = \frac{t_n}{1 - \left(\frac{V_n}{V_0}\right)^{\frac{1}{n}}} \quad (5)$$

Many experiments at moderate fields on polar or composite insulating materials may be described by this linear model (see for instance [9]). Among the physical causes of slow relaxation, interfacial polarization is one of the most common. It may often be described using a relaxation function; however, this phenomenon is not necessarily linear. For this reason, it will be treated in a separate section.

### III. INTERFACIAL POLARIZATION

Most insulating materials commonly used in modern systems are not homogeneous. Many types of composites have been designed to optimize mechanical, electrical, thermal properties. They may be organized as multilayered systems or as a dispersion of fillers in the material bulk. Even a homogeneous material (at the macro scale) made of a single constituting molecule, as pure polyethylene or polypropylene, may be organized at the microscale in domains, with different levels of crystallinity. Different values of conductivity may thus be found in these different phases. As a result, the capacitive potential distribution (involved at short times or high frequencies) may be different from the resistive one. In this case a return voltage will appear.

A simple two-cell RC model may illustrate this situation (fig. 2).

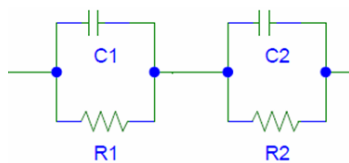


Fig. 2. Two-cell RC model.

It may be easily shown that, for a short-time neutralization after a long DC poling time at  $V_0$ , a voltage return will appear, with always the same sign that the poling voltage:

$$\frac{V(t)}{V_0} = \frac{R_2 C_2 - R_1 C_1}{(R_1 + R_2)(C_1 + C_2)} \left( e^{-\frac{t}{R_2 C_2}} - e^{-\frac{t}{R_1 C_1}} \right) \quad (6)$$

If the time constant of one cell is much higher than the other, for instance  $R_2 C_2 \gg R_1 C_1$ , the return voltage will be high, and its maximum value is obtained assuming at the same time  $R_2 \gg R_1$  and  $C_2 \gg C_1$ . In this case, it may even reach the poling value.

This kind of modelling has been in use for a long time by several teams to assess the ageing of power transformers or cables [10]. According to them, what has proven to be a useful practical indicator is the “p-factor”, which is the ratio of the maximum return voltage to the voltage that would have been reached at the same moment if the initial slope of the return voltage has been maintained.

There are many cases where a simple model such as described in fig. 2 may be sufficient to describe a qualitative behavior. For instance, we have shown that it can provide a good qualitative model for the important return voltage appearing on polycrystalline alumina that we studied at temperatures above 100°C (fig. 3).

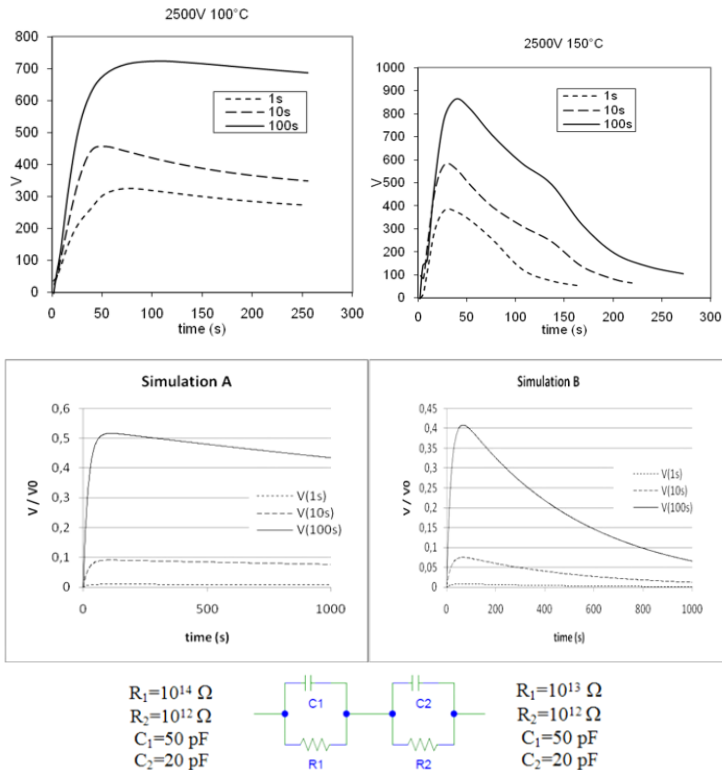


Fig. 3. Return voltage on Imm-thick polycrystalline Al<sub>2</sub>O<sub>3</sub> slabs polarized at 2500V (during 1s, 10s, 100s). Experiment and simulation with a RC circuit [11].

Experiments performed in our laboratory on aircraft cables, insulated with a polyimide/PFA/PTFE wrapped tape, have also shown that it was possible to use return voltage measurements with an electrostatic probe as a laboratory experiment to characterize short (10cm) cable samples therefore allowing to monitor the cable ageing in various contexts [12]. An example of the return voltage for a new and aged cable is given fig. 4. A strong activation by the electric field is observed, but no polarity dependence. For aged samples, the magnitude of the return may be attributed to interfacial polarization. In this case, a model based on a RC circuit proved to be useful as a starting point, by accounting qualitatively for the observed behavior. A complete model should however incorporate field non-linearity as well as the power law character of the dielectric response, which appears when the time dependence of the decay/return is analyzed. This complexity is a quite common behavior of insulators, due to non-linear activation mechanisms, as Schottky or Poole-Frenkel, and to dynamical charge trapping and detrapping phenomena.

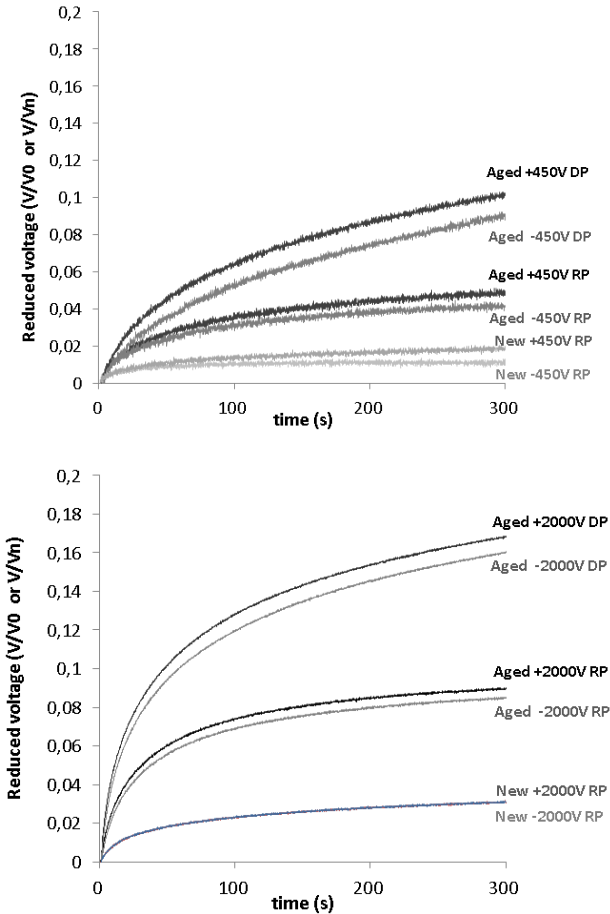


Fig. 4. Voltage decay (DP) and return (RP) on new and aged aircraft cables after charging at  $\pm 450\text{V}$  and  $\pm 2000\text{V}$  and 300s potential decay [12].

## IV. HETEROGENEOUS CONDUCTIVITY

A homogeneous insulator may be subjected to a gradient of temperature, light, humidity, or any other parameter able to activate charge carriers motion and thus lead to a heterogeneous conductivity in the bulk of the material. As a result, an inner space charge distribution may build up, which will not be neutralized instantly when the insulator is short-circuited.

This phenomenon has been studied in the past [13][14], with a special focus on HVDC cables, where the inner conductor may be heated at a much higher temperature than the ambient. A strong temperature gradient appears in high field areas of the cable, which produces a high conductivity gradient.

A gradient of light intensity may also easily be produced in polymer films. Considering a photoconductive material and the appropriate wavelength, an inner space charge may be induced by this gradient. Removing the light activation, the charge of this photoelectret may be stable during a long time.

However, to our knowledge, the link between this space charge buildup due to heterogeneous conductivity and voltage return has not been reported elsewhere than in a conference paper that we issued recently [15]. Subjecting corona-charged polyimide films, which are slightly photoconductive, to white or blue light, we created an inner charge distribution whose profile is depending on the exposure time and the wavelength (fig. 5). After a surface neutralization, the surface potential of the films remains at a stable zero in the dark, the photoelectret charge distribution being steadily trapped. Then a second exposure to light induces a large return potential (fig. 6-7).

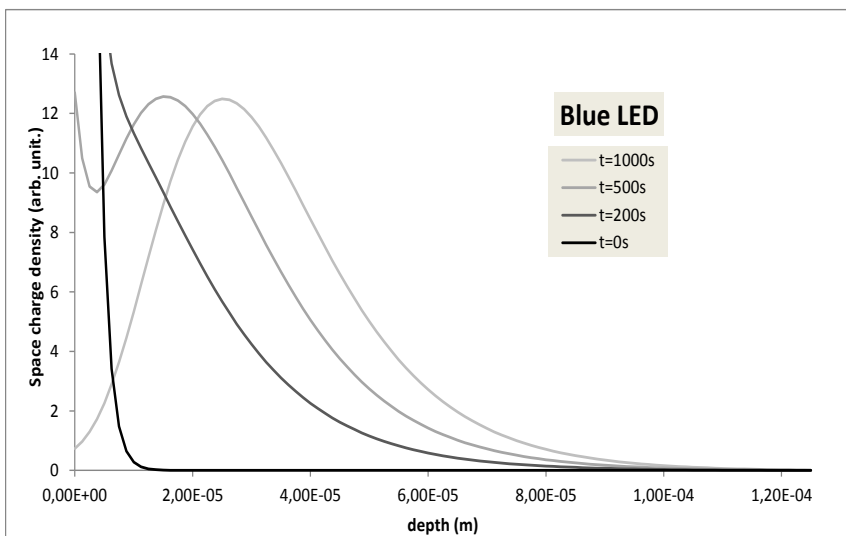


Fig. 5. Computation of the charge distribution induced by light absorption on a charged photoconductive film [15]

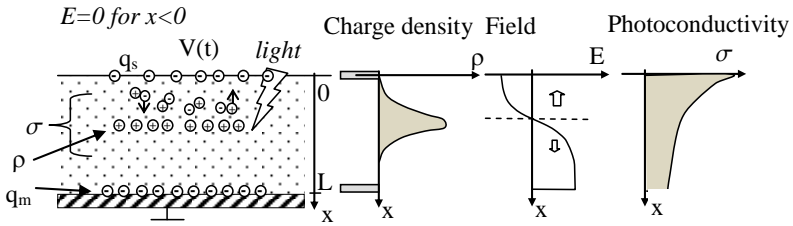


Fig. 6. Return voltage under illumination

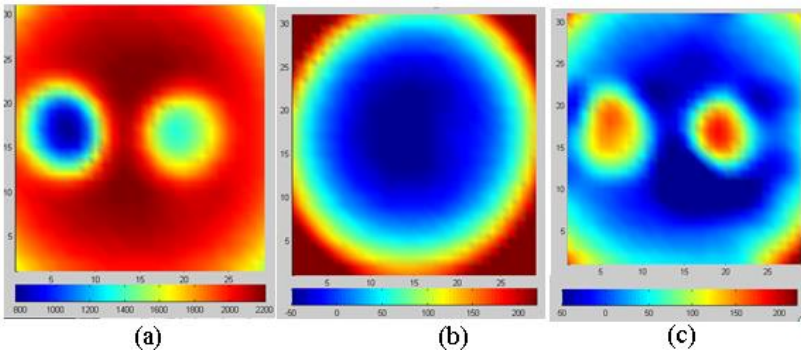


Fig. 7. Experimental voltage mappings showing light-induced decay and return voltages [15].

- (a) 120s exposure to white (left) and blue (right) LED light after 2000V charging.
- (b) Quasi neutralization
- (c) Return voltage after additional 1h lamp illumination

## V. CHARGE INJECTION

Calculations of the voltage decay and return due to the motion of an injected space charge have been performed by Coelho in several works [5][16]. This section provides an extended view of these models, which has never been published before.

### A. General theory

The voltage decay due to the injection of a charge deposited on an insulating surface has been extensively studied. Various hypotheses may be done on the injection process, charge mobility and trapping in the material [7][16]. Assuming a zero field at the upper surface, using the Poisson equation, the surface potential due to a charge  $q_0$  distributed inside the sample may be written:

$$V_0 = \frac{1}{\epsilon} \int_0^L x \rho(x) dx = \frac{q_0 \bar{x}}{\epsilon} \quad (7)$$

The surface potential is proportional to the mean distance  $\bar{x}$  of the charge to the ground.

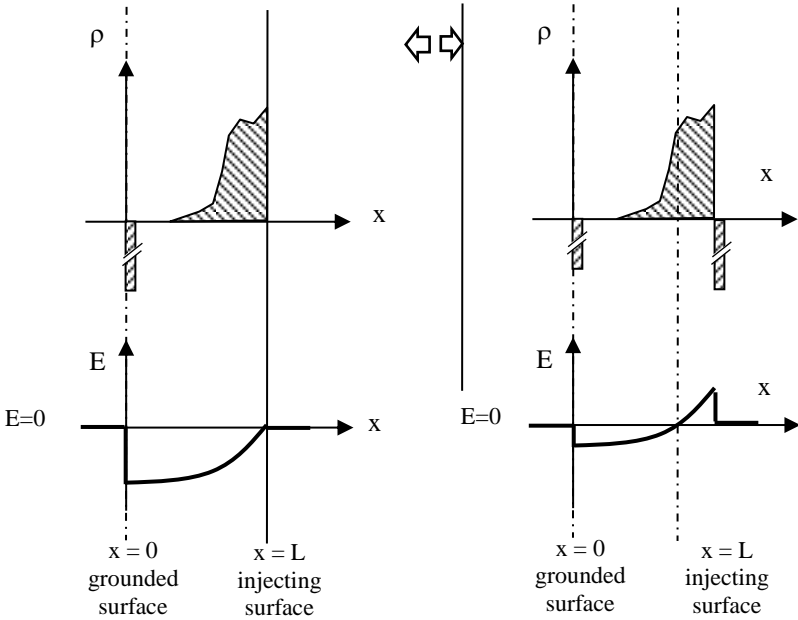


Fig. 8. Charge distribution and field in the insulator before (left) and after (right) surface neutralization.

When the insulator surface is neutralized, the average field inside becomes zero. A zero field plane appears in the bulk (shown as a dotted line in fig. 8). The charge injected beyond this plane continues its drift, whereas the rest comes back to the injecting electrode.

The neutralization surface charge is  $q_n = -q_0 \frac{\bar{x}}{L}$ . Using Gauss theorem between the zero field plane and the upper surface, the surface density of the charge located in the inversed field region is  $-q_n$ , while the charge located beyond the zero field plane (including the charge already neutralized at the ground electrode) has a density  $q_0 \left(1 - \frac{\bar{x}}{L}\right)$ .

We may describe the charge motion by a mobility value  $\mu$ , which may be depending on field and time (to take into account progressive trapping and dispersive transport phenomena). Then the charge transport on both sides of the zero field plane may be described as the motion of charged sheets, each of them having the same charge density (fig. 9). For each of them, the amount of charge separating it from the zero field plane is constant, and thus its driving field, and its drift speed is then also constant. However, the speed of the sheets increases with their initial distance to the zero field plane, as illustrated below.



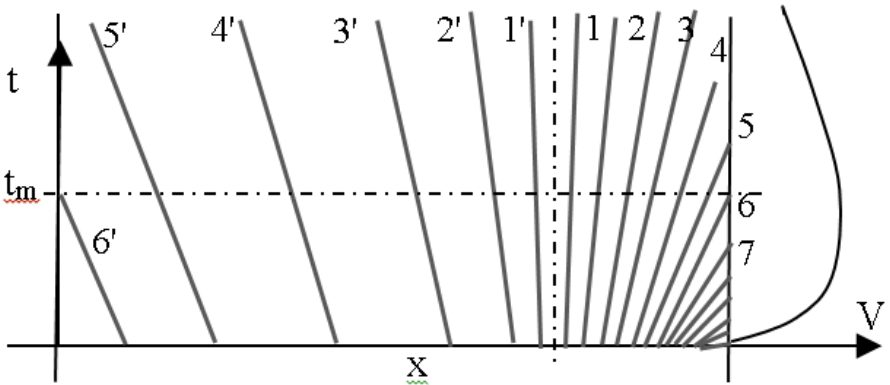


Fig. 9. Charge sheets motion on both sides of the zero-field plane (left and center of the figure) during the voltage return experiment (voltage shown on the right).

If the insulator is homogeneous, two charged sheets driven by the same field on both sides of the zero field plane (N and N' on fig. 9) will have exact opposite influences on the surface voltage. If  $\frac{\bar{x}}{L} > 0,5$ , the charge density will be higher on the right side of the zero field plane, and the return voltage will be due to the motion of the sheets with no counterpart on the other side only (here  $N > 6$ ). The maximum of the return voltage will be reached, at a time  $t_m$ , when the field immediately below the right surface has decreased enough to reach the value of the field at the ground electrode. Then the surface voltage decreases, the charge moving towards the ground being larger.

From this we can divide the space charge into three components. It can be considered that all the charge remaining in the volume at  $t_m$  (located between 6 and 6' sheets on fig. 9) has not contributed to the return voltage buildup, since the motion before  $t_m$  of each sheet has been compensated by the motion of another one on the other side. The return voltage is then equal to the voltage return due to the motion of the charge  $q_r$  returned to the right surface at  $t_m$ , minus the voltage drop due to the motion of the charge  $q_g$  returned to the ground. The maximum return voltage is therefore  $V_{max} = \frac{q_r L - x_r}{\epsilon} - \frac{q_g \bar{x}_g}{\epsilon}$ . The charge distributed in the middle is equally distributed on each side of the zero field plane, thus:

$$q_0 \frac{\bar{x}}{L} - q_r = q_0 \left( 1 - \frac{\bar{x}}{L} \right) - q_g \tag{8}$$

$$q_r = q_0 \left( \frac{2\bar{x}}{L} - 1 \right) - q_g \tag{9}$$

For a small mean injection depth, we may assume that the amount of charge having reached the ground at the maximum is negligible.

An anomalous voltage return (with a sign opposed to the initial voltage) may be observed if the charge has been deeply injected, so that  $\frac{\bar{x}}{L} < 0,5$ . The description of the return process is the same.

It has to be underlined that this return voltage due to space charge motion has quite different features than what has been described in the previous sections. This phenomenon is strongly nonlinear, the possibility of an anomalous voltage being one feature of this non-linearity. However the competition between both sides of the zero field plane will reduce the maximum possible return voltage. This will be shown in next section for a particular charge distribution.

### B. Exact calculation for a SCLC distribution

We assume here a constant mobility  $\mu$ , independent of time and field, and that the insulator has been polarized using conditions allowing the maximum possible charge injection (space charge limited current of density  $j$ ). That means that space charge will reach its maximum value reducing to zero the field at the injecting electrode. Then it can be shown from  $j = \mu\rho E$  and from Poisson equation that:

$$\rho = \left( \frac{2\mu}{j\epsilon} (x - L) \right)^{-\frac{1}{2}} \quad (10)$$

$$\text{and } V_0 = \left( -\frac{8j}{9\mu\epsilon} \right)^{\frac{1}{2}} L^{\frac{3}{2}} \quad (11)$$

The charge density may be written as a function of V:

$$\rho = \frac{3\epsilon}{4L^2} V_0 \left( 1 - \frac{x}{L} \right)^{-\frac{1}{2}} \quad (12)$$

The calculation of the field inside the insulator immediately after neutralization by a charge  $q_s = -\frac{\epsilon V_0}{L}$  gives:

$$E = -\frac{V_0}{L} \left[ \frac{3}{2} \left( 1 - \frac{x}{L} \right)^{\frac{1}{2}} - 1 \right] \quad (13)$$

The abscissa of the zero field plane is:  $x = \frac{5}{9}L$

The initial field at the injecting electrode is  $\frac{V_0}{L}$ , twice the value of the field at the ground electrode ( $-\frac{V_0}{2L}$ ). At  $t_m$ , the field on both electrodes will be equal, to a particular value  $E_t$ . At this time, the field at the ground electrode is the field that was immediately after neutralization at  $x_t = E_t \mu t$ , and the field at the injecting electrode is equal to the field immediately after neutralization at  $x = L - x_t$ . Combining this with the relationship between  $E$  and  $x$  we find quadratic equations and in the end:

$$E_t = \frac{V_0}{2L\sqrt{2}} \quad (14)$$

$$\text{and } x_{t_m} = E_t \mu t = \frac{L}{2} \left( 1 - \frac{8}{9\sqrt{2}} \right) \approx 0,18573 L \quad (15)$$

From this we computed the voltage return due to the charges having reached the surface and the voltage drop due to the charges having reached the ground at  $t_m$ , and by subtracting:

$$V_{RP} = \frac{3}{2} \frac{x_{tm}}{L} \left[ \left( 1 - \frac{x_{tm}}{L} \right)^{\frac{1}{2}} - \left( \frac{x_{tm}}{L} \right)^{\frac{1}{2}} \right] V_0 \quad (16)$$

$$V_{RP} = \frac{3}{2} \left( \frac{1}{2} - \frac{4}{9\sqrt{2}} \right) \left[ \left( \frac{1}{2} + \frac{4}{9\sqrt{2}} \right)^{\frac{1}{2}} - \left( \frac{1}{2} - \frac{4}{9\sqrt{2}} \right)^{\frac{1}{2}} \right] V_0 \quad (17)$$

$$V_{RP} \approx 0,13133 V_0 \quad (18)$$

The interest of this result is to show that the typical return voltage value is quite low, even for the maximum possible injected charge in an insulator, compared to what is possible to obtain in a heterogeneous insulator by interfacial polarization, or by heterogeneous conductivity. Concerning neutralization after a surface potential decay experiment, the return voltage will be less important, because the space charge density will tend towards a larger uniformity during the decay than the SCLC profile.

That may explain why it is very difficult to present experimental results showing clear evidence of a return voltage due to an injected space charge only. The signal due to this component is usually quite faint, and often appears at high field as a transient and irregular phenomenon. Some interesting results of anomalous voltage return on polyethylene films were presented by Coelho a long time ago [5], but not reported elsewhere since (fig. 10).

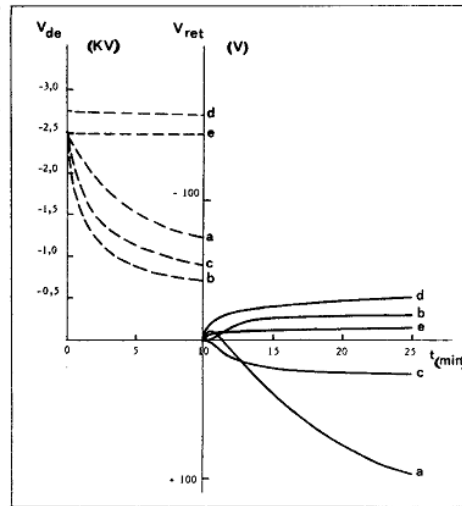


Fig. 10. Anomalous return voltage on polyethylene [5].

## VI. CONCLUSION

Return voltage measurements provide an interesting complement to surface potential decay experiments. Combining both of them offers a broader view of the mechanisms involved in the insulator. However, a large set of experiments with various experimental conditions and a careful analysis of the data have to be implemented to reveal all the possibilities of this technique. We hope that this review may help its readers to reach this goal.

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