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TOOLS FOR UNDERSTANDING THE THERMO-ELECTRICAL BEHAVIOUR OF XLPE INSULATION IN POWER CABLES AND ACCESSORIES

S. LE ROY, LAboratoire PLAsma et Conversion d'Energie, Toulouse (France), severine.leroy@laplace.univ-tlse.fr
F. BAUDOIN, LAboratoire PLAsma et Conversion d'Energie, Toulouse (France), fulbert.baudoin@laplace.univ-tlse.fr
G. TEYSSEDRE, LAboratoire PLAsma et Conversion d'Energie, Toulouse (France), gilbert.teyssedre@laplace.univ-tlse.fr
C. LAURENT, LAboratoire PLAsma et Conversion d'Energie, Toulouse (France), christian.laurent@laplace.univ-tlse.fr
L.A. DISSADO, University of LEICESTER, Engineering Dept, Leicester (U.K.), lad4@le.ac.uk
G.C. MONTANARI, University of Bologna, Bologna (Italy), giancarlo.montanari@mail.ing.unibo.it

ABSTRACT

We have developed numerical models of bipolar charge transport, featuring specific cases and geometries in order to predict the space charge behaviour and improve the knowledge on polymeric insulation under electrical stresses. This communication briefly describes the models, and shows comparisons of the numerical results with experiments, for 3 specific cases: a plan parallel geometry, a cylindrical geometry featuring a cable, and a dielectric-dielectric interface encountered in cable joints.

KEYWORDS

Space charge, cable insulation, joints, modelling, transport, organic insulation

INTRODUCTION

Polyethylene has advantageously replaced oil-impregnated paper as insulation in high voltage (HV) cable for electrical energy transport. However, after some fifty years of use, the drawbacks remain the same. We do not yet know how charges appear inside the insulation properties, how they behave and how they affect the dielectric under long periods of electrical stress. We have to improve our knowledge on this type of materials, and their behaviour once submitted to electrical stresses. Models could help in that way. We have developed a modelling approach, based on a step by step evolution of the models, in order to understand the behaviour of polymers under electrical stress [1, 2]. In this paper, we present a model of bipolar charge transport in polyethylene under DC stress, for three different case studies, i.e. a plane-parallel geometry, a dielectric-dielectric system, featuring the interface encountered in joints and terminations, and a cylindrical geometry, reproducing the cable system. This paper briefly describes the model, equations and their numerical resolution, and shows a comparison between experiments and simulation results for each case.

MODELS DESCRIPTION

Common features

Each model is one dimensional, function of the thickness of the dielectric. Figure 1 shows a schematic representation of each system used for the simulations, i.e. a plane parallel system (1.a), a dielectric-dielectric interface (1.b), featuring cable joints, and a cylindrical geometry (1.c) featuring a cable. Whatever the type of model, it is bi-polar, and features injection of electronic charges at both electrodes, charge trapping in traps distributed exponentially in trap depth, and hopping transport. For sake of simplification, recombination of charges and internal generation are not taken into account.

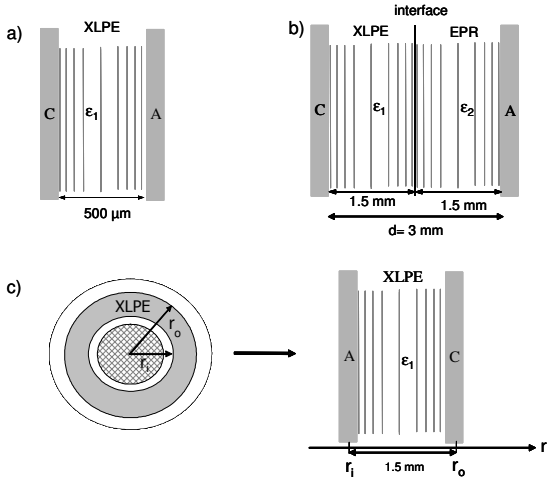

Figure 1: schematic representation of the one-dimensional systems used for the simulation. a) plan-parallel system, b) dielectric-dielectric interface, and c) cylindrical geometry.

Trap distribution: The chemical structure of the material is taken into account by considering an exponential distribution of trap levels (Figure 2), i.e. a large amount of shallow traps corresponding to physical defects, and a smaller amount of deep traps corresponding to impurities. This exponential distribution of traps has a maximum limit in trap depth, and is of the form:

$$N_{t(e,h)} = N'_{(e,h)} \exp\left(\frac{-\Delta_{e,h}}{k_B T_{0(e,h)}}\right) \qquad \Delta_{e,h} \le \Delta_{max(e,h)} \qquad (1)$$

Where $N_{t(e,h)}$ is the trap density distribution and is characterized by the parameters N', T_0 and the maximum limit in trap depth Δ_{max}. This exponential distribution of trap levels holds for each kind of carrier (electrons and holes). In the case of a dielectric-dielectric system, the exponential distribution of traps also holds for each type of material, only the values of the parameters change from one dielectric to the other. Traps are considered to be filled from the deepest level upwards.

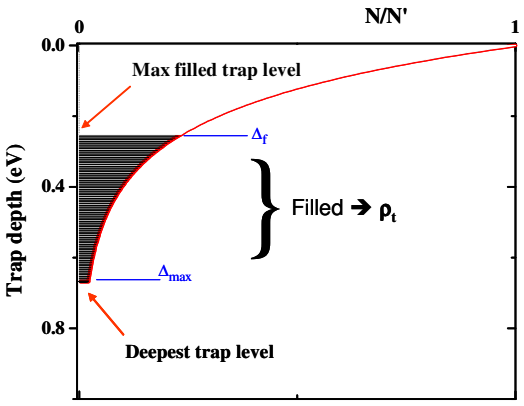

Figure 2: Distribution of trap levels for one kind of carriers. Δ_f defines here the upper filled level, which is variable as a function of time and space.

Cartesian coordinates are used for the plane-parallel and the dielectric-dielectric systems, whereas cylindrical coordinates are used for the cable geometry. However, for sake of simplification, equations in the following will only be given for the planar geometry.

Mobility: Charge transport within insulating polymers is often described by a hopping mechanism in which carriers move from site to site by getting over a potential barrier. In our case the hopping charges essentially come from the highest filled trap state at a depth Δ_f, and the resulting mobility $\mu(x,t)$ is then function of the trapped charge density ρ_t:

$$\mu(x,t) = \frac{2.\upsilon.d}{E(x,t)}.\left(\frac{\rho_t(x,t)}{N'.k_B.T_0} + \exp\left(\frac{-\Delta_{max}}{k_B.T_0}\right)\right)^a \sinh\left(\frac{e.E(x,t).d}{2.k_B.T(x)}\right) \quad (2)$$

$$\text{with } a(x) = \frac{T_0}{T(x)} \rangle 1 \quad (3)$$

$$\text{and } d = \left(N'k_B T_0\right)^{-\frac{1}{3}}\left(1 - \exp\left(-\frac{\Delta_{max}}{k_B T_0}\right)\right)^{-\frac{1}{3}} \quad (4)$$

where ν is the attempt to escape frequency, d is the average distance between traps, E(x,t) is the electric field, and e is the elementary charge. As the model also holds for a cylindrical geometry, there can be a temperature gradient due to the application of a current in the core of the cable, so the temperature T(x) is function of the radius from the core of the dielectric.

If the electric field is small ($e.E.d \langle\langle k_B.T$), equation (2) can be reduced to:

$$\mu(x,t) = \frac{e.\upsilon.d^2}{k_B.T(x)}.\left(\frac{\rho_t(x,t)}{N'.k_B.T_0} + \exp\left(\frac{-\Delta_{max}}{k_B.T_0}\right)\right)^a \quad (5)$$

When $T_0 >> T$, only a fraction of charge ρ_f from the trapped charge ρ_t is available for conduction:

$$\rho_f(x,t) = \frac{\rho_t(x,t)}{1 + a(x)} \quad (6)$$

Generation of carriers: The only source of charge is the injection of electronic carriers at both electrodes. The injection for each kind of carrier follows a modified-Schottky law:

$$j_{e,h}(x,t) = A.T(x)^2.\exp\left(-\frac{e.w_{e,h}}{k_B.T(x)}\right)\left(\exp\left(\frac{e}{k_B.T(x)}\sqrt{\frac{e.E(x,t)}{4.\pi.\varepsilon}}\right) - 1\right) \quad (7)$$

where $j_h(x,t)$ and $j_e(x,t)$ are the injected fluxes of holes and electrons at the anode and cathode respectively, A is the Richardson constant, w_e and w_h are the injection barriers. ε refers to the permittivity of the dielectric.

The time and space dependent equations describing the behaviour of charge carriers are the following, neglecting diffusion, and in Cartesian coordinates:

$$\frac{\partial n(x,t)}{\partial t} + \frac{\partial j(x,t)}{\partial r} = 0 \quad \text{continuity} \quad (8)$$

$$\frac{\partial E(x,t)}{\partial x} = \frac{\rho(x,t)}{\varepsilon} \quad \text{Poisson} \quad (9)$$

$$j(x,t) = \mu(x,t).\rho_f(x,t).E(x,t) \quad \text{transport} \quad (10)$$

Numerical techniques

The thickness d of each system is discretised using a non-uniform grid of elements of size Δx, being tightened next to the electrodes, in order to follow the penetration of charge in the dielectric (See Figure 1). At each time of the simulation, the time step is calculated to be less than the quickest phenomenon occurring in the dielectric. It must also satisfy the Courant-Friedrichs-Lewy condition, for each mobile carrier. It means that the charge displacement within one time step is less that the size of an element Δx.

The time and space dependent electric field and potential are calculated by discretization of the Poisson equation. The numerical method used to resolve steep front problems due to charge penetration in the dielectric is based on a scheme first developed by Leonard [3], avoiding numerical diffusion. To avoid production of negative densities of species, a flux limiter has been also included in the code. Further details of the numerical resolution of the equations in the model can be found in [4].

RESULTS

In this section, simulated results of XLPE systems will be compared with measurements, mainly of space charge distribution using the Pulsed Electro-Acoustic (PEA) method. For each case (plan-parallel, dielectric-dielectric and cylindrical), an optimized set of parameters has been used for the simulation.

Plan-parallel system

For experiments and simulation, a DC voltage of 20 kV has been applied during 10000s on a 500 µm XLPE flat sample (see Figure 1.a), at room temperature. The parameters used for the simulation are given in Table 1. Figure 3 compares the experimental (Figure 3.a) and the simulated (Figure 3.b) space charge profiles at t=5s and t=10000s. It is to note that a Gaussian filter has been applied on the simulated data in order to produce profiles of the same form as the experimental ones. Experimentally, negative charges are detected next to the cathode after 3 hours of polarization, whereas no positive charges are measured.

Table 1: optimized parameters used for the simulation of a XLPE plane-parallel system.

Symbol	Value	unit
N': density of traps per unit energy		
for electrons	5.10^{43}	$1/m^3/J$
for holes	5.10^{45}	$1/m^3/J$
Δ_{max} : maximum trap depth		
for electrons	0.8	eV
for holes	0.83	eV
T_0: shape parameter of the exponential distribution of trap levels		
for electrons	1200	K
for holes	2000	K
Injection barriers (Schottky)		
w_e for electrons	1.12	eV
w_h for holes	1.20	eV

In the simulation, injected negative charges accumulate at the vicinity of the cathode, their quantity being approximately the same as the one observed experimentally. No positive charges are observed.

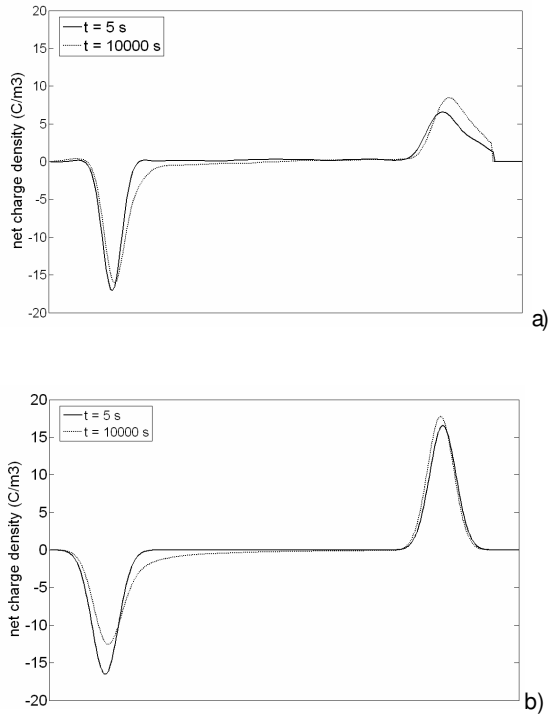

Figure 3: a) experimental and b) simulated space charge profiles in a 500 µm XLPE plan-parallel system, at t=5s and t=10000s. Applied voltage 20 kV, at room temperature.

Conclusion: For a plane-parallel geometry, at room temperature, the model is able to reproduce the space charge profiles obtained experimentally.

Dielectric-dielectric interface

For experiment and simulations, a DC potential of 30 kV is applied at room temperature during 6 hours to an

Table 2: values of the parameters used for the simulation of a XLPE/EPR system.

Symbol	Value	unit
N': density of traps per unit energy		
for electrons in XLPE	1.10^{42}	$1/m^3/J$
for holes in XLPE	3.10^{42}	$1/m^3/J$
for electrons in EPR	1.10^{42}	$1/m^3/J$
for holes in EPR	1.10^{42}	$1/m^3/J$
Δ_{max} : maximum trap depth		
for electrons in XLPE	0.8	eV
for holes in XLPE	0.8	eV
for electrons in EPR	0.8	eV
for holes in EPR	0.8	eV
T_0: shape parameter of the exponential distribution of trap levels		
for electrons in XLPE	1000	K
for holes in XLPE	1000	K
for electrons in EPR	1000	K
for holes in EPR	1000	K
Injection barriers (Schottky)		
w_e for electrons in the XLPE	1.18	eV
w_h for holes in the EPR	1.18	eV

XLPE/EPR system, as presented in Figure 1.b).The thickness of each dielectric is 1.5 mm. The parameters used for the simulations are given in Table 2. Figure 4 represents the experimental space charge at t=0s and t=6 hours obtained by Bodega et al [5] with the help of the Pulsed Electro-Acoustic (PEA) method. Only a small amount of charge accumulates at the interface. On the EPR side, negative charges seem to accumulate next to the anode, whereas positive charges might be observed next to the interface on the XLPE side.

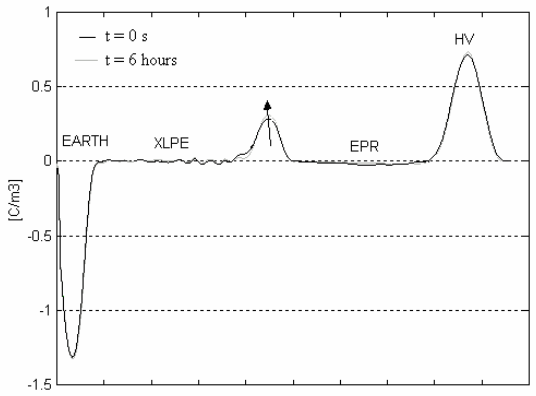

Figure 4: measured space charge profiles in a XLPE/EPR system, at t=0s and t=6 hours. Applied voltage: 30 kV, T=20°C.

Figure 5 shows the simulated space charge profiles obtained at t=0 and t=6 hours, for the same applied voltage. As in the previous case, a Gaussian filter was applied to simulated data in order to produce profiles of the same form as the experimental ones. Positive carriers, injected at the anode, transport through the EPR, and accumulate around the interface on the XLPE side. Negative charges, injected at the cathode, penetrate into the XLPE, transport through

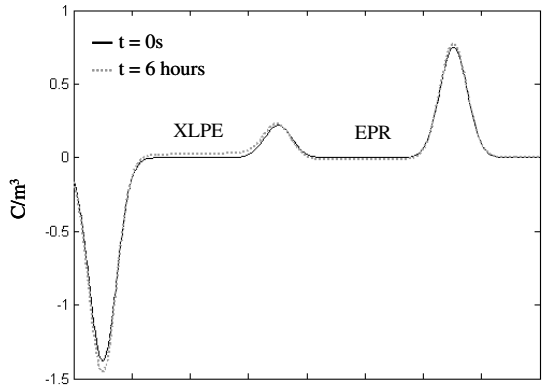

Figure 5: simulated space charge profiles in a XLPE/EPR system, at t=0s and t=6 hours. Applied voltage=30 kV, T=20°C.

the interface, and reach the anode, where they are extracted.The simulated results are in good agreement with the experimental data, as the model is able to reproduce the behaviour of positive and negative carriers in both dielectrics. Positive charges, injected at the anode, seem to penetrate deeper into the XLPE, leading to an increase of the image charge at the cathode, which is not observed experimentally.

The evolution of the accumulation of interfacial charge, calculated from model on one hand, and deduced from PEA experiments on the other hand, is given in Figure 6, for the same experimental protocol. It should be noted that the experimental graph has been redrawn from [5]. The model shows a negative interfacial charge at short time. Due to the difference of permittivities of the two materials, the electric field is higher in the XLPE compared to the field in the EPR. The mobility is then higher for electrons in XLPE, so they reach the interface first. As the time increases, the simulated interfacial charge becomes positive, and in good agreement with the experiment.

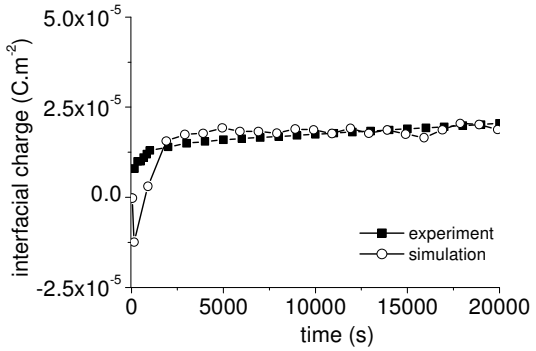

Figure 6: Evolution of the interfacial charge as a function of time. Squares: deduced from the PEA experiment, circles: simulation. The applied voltage is 30kV on the 3mm-thick sandwich.

Cable system

Contrarily to the other cases, the cable system experiences an inhomogeneous temperature inside the insulator. Under service conditions, the current flowing in the core of the cable produces an increase of the temperature at the vicinity of the inner electrode. The temperature in a cable is not uniform anymore, and there is a temperature gradient in the dielectric. In the modelling, we take into account the temperature distribution as a function of the radius of the cylinder:

$$T(r) = T(r_i) - \frac{\ln\left(\frac{r}{r_i}\right)(T(r_i) - T(r_o))}{\ln\left(\frac{r_o}{r_i}\right)} \quad (11)$$

where $T(r_i)$ and $T(r_o)$ are the temperature at the inner and outer electrode respectively. Moreover, in order to reproduce the space charge measurements in a cable, we added an extraction coefficient, featuring a partly blocking electrode. The extraction flux for electrons at the anode is of the form, for a cylindrical system:

$$j_e(A,t) = n_e \mu_e(A,t) C_{ext} E(A,t) \quad (12)$$

Where $j_e(A,t)$ holds for the flux of electrons at the anode, and E(A,t) is the electric field at the anode. The same equation holds for holes at the cathode.

The cable system under study is a 1.5 mm XLPE insulated cable, the radius of the inner electrode being 1.9 mm and the one of the outer electrode is 3.4mm. The temperature at the inner electrode (anode) is 65°C, and it is set to 45°C at the outer electrode (cathode). A DC voltage of 60 kV is applied to the cable system during 10000s (~3 hours). The set of parameters used for this case is given in Table 3.

Table 3: values of the parameters used for the simulation of a XLPE insulated cable system.

Symbol	Value	unit
N': density of traps per unit energy		
for electrons	1.10^{44}	$1/m^3/J$
for holes	2.10^{44}	$1/m^3/J$
Δ_{max} : maximum trap depth		
for electrons	0.85	eV
for holes	0.85	eV
T_0: shape parameter of the exponential distribution of trap levels		
for electrons	1200	K
for holes	2000	K
Injection barriers (Schottky)		
w_e for electrons	1.1	eV
w_h for holes	1.3	eV
C_{ext}: Extraction coefficient		
for electrons at the anode	10^{-4}	
for holes at the cathode	10^{-2}	

Figure 7 presents the temperature and electric field gradient experienced by the insulator for that protocol. Both the electric field and the temperature are higher at the inner electrode, promoting the amount of charge that is injected at that electrode.

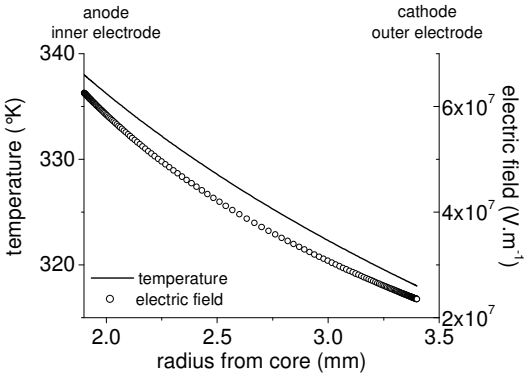

Figure 7: temperature and electric field distribution in a cable insulation, from inner to outer electrode.

Figure 8 compares the experimental (8.a) and the simulated (8.b) space charge profiles at t=0 s and t=10000s. Here also, a Gaussian filter has been applied to the simulated results. Experimentally, after 3 hours of polarization, positives charges accumulate next to the outer electrode. This behaviour is understandable, as both the temperature gradient and the field promote the motion of positive charges from the anode, where they are injected, to the cathode. Negative charges also accumulate at the vicinity of the anode, which is more surprising, as all the variables go against the promotion of electrons inside the cable. In the simulation (Figure 8.b), the profiles only show positive heterocharges occupying the all insulation. An extraction coefficient has been added at the anode in order to slow down the disappearance of the electrons, and a low amount of electrons accumulate next to the anode.

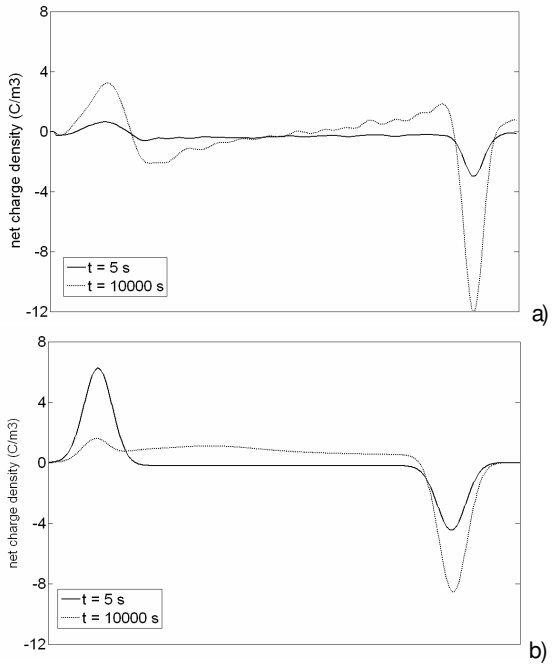

Figure 8: a) experimental and b) simulated space charge profiles in a 1.5 mm thick XLPE insulated cable, at t=0s and t=10000s. Applied voltage= 60

However, with the addition of the influence charges at both electrodes and the Gaussian filter, it is then possible to see any negative charges. It is only possible to observe the decrease of the influence charge at the anode.

Conclusion: In a cable system, the model fails to reproduce the experimental behaviour. A cable is a complex geometry, and the material is not that simple. Our model may forget some physical hypotheses, which play an important role in that case. One could think for example that ions might be present in the dielectric.

Discussion

For each case study, i.e. a plane-parallel system, a dielectric-dielectric system, and a cylindrical one, an optimized set of parameters has been found. It is however each time the same type of material: XLPE. One would think that the set of parameters found for one system would hold for all geometries, as most of the parameters reflect the microstructure of the material (density of traps, depth of the traps, injection barrier…). Simulations have been run for each system for the same set of parameters, with no consistent results when compared to the experimental data. There are many ways to explain the difference of parameters for each geometry. First of all, even if the type of material (XLPE) is the same, its history (implementation, from melting to extrusion…) surely plays a role in the microstructure of the polymer. The interface material (metal, semiconductor…) could also play an important role, as it acts on the injection and extraction of charges. Despite theses comments, it is also interesting to look at the physical model itself. On the physical side, the injection law taken is surely not valid in our cases. The Schottky law, even modified, does not take into account the microstructure of the interface, which plays a considerable role in the generation of charges inside the bulk. Moreover, recombination has not been taken into account. Even if a previous paper [1] stated that recombination did not play an important role in the space charge behaviour when considering a short-time stressing, a recent study [6] shows the contrary when considering steady state solution. It seems however impossible to implement our model with recombination. Last point: The originality of this model is to consider an exponential distribution of traps, and to link this trap distribution to the mobility. The model is however difficult to implement. Although some parameters can be found (trap depth), most of the parameters have to be guessed. Different sets of parameters can lead to the same mobility value (variable that can be extracted from the experiment). So the parameterization is a long lasting game, and the room for manoeuvre for the parameter values is very low.

CONCLUSION

We presented a model of charge transport in cross-linked polyethylene, for three different geometries. In a planar geometry (plane-parallel and dielectric-dielectric system), the model is able to reproduce the space charge profiles obtained with the help of the PEA method, at room temperature. The model fails to reproduce the space charge behaviour when it comes to cable geometry. Hypotheses might have been forgotten, and the next step in the evolution of our modelling is to search for physical

hypotheses that are likely to play a role in the space charge behaviour, in order to understand the way these charges affect the life of the dielectric.

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