Insulation aging and life models

Let us consider a solid insulation system subjected to one (or more) stress that causes irreversible changes of material properties with time, thus reducing progressively the attitude of insulation in enduring the stress itself. This process is called aging and ends when the insulation is no more able to withstand the applied stress. The relevant time is the time-to-failure, alternatively called insulation life [1]. Insulation life modeling consists of looking for adequate relationships between insulation life and the values of the stress(es) applied to it. In the case of electrical insulation, the stresses most commonly applied in service are electric field (due to voltage) and temperature, but also other stresses, such as mechanical stresses (bending, vibration) and environmental stresses (such as pollution, humidity) can be present.

The theory of aging and phenomenological life models

The rate of change of material properties with time can constitute a measure of the severity of aging in progress. Then, end-of-life occurrence can be associated with the time required by a chosen diagnostic property (e.g. electric or tensile strength, density, and so on) for reaching a proper limit value. Considering a dielectric subjected to a single stress, S (constant with time), the main requirements that a given property, P, must match in order to be a diagnostic property are that the property is actually correlated to aging and that it changes monotonically with aging time, t. Then, if a suitable function of P, $F(P)$, can be found, that increases with aging time and depends on applied stress, the following relationship holds:

$$F(P) = K(S)t \tag{1}$$

where $K(S)$ is aging rate, constant with time as well as S. Eventually, a situation is reached when the material is no more able to withstand the applied stress, i.e. it does not perform any longer the task for which it has been realized. This point, named end-point, corresponds to a limit value of P, P_L, and the time to its achievement is called time-to-end-point of the material (or system), or life, L [1, 2]. Then, from eq. (1) the L vs S relationship (i.e. the life model) is achieved in implicit form:

$$L = F(P_L) / K(S) \tag{2}$$

Hypotheses on $K(S)$ are needed in order to explain the L vs S relationship. Often, the relationship between life and applied stresses is derived (neglecting the physical phenomena that govern aging) by simply resorting to experimental evidences of the insulation breakdown phenomenon, consisting of failure times obtained by (accelerated) life tests at given stress levels. Then, life models are referred to as phenomenological life models and their parameters have no physical meaning: they can only be derived by processing failure times coming from life tests and cannot be directly measured as material properties. The scopes of phenomenological models are the following:

a) correctly describing the relationship L vs stress(es), as it comes from life test results;
b) achieving parameters useful for the characterization of insulating materials and systems;
c) life inference at service stress levels, by extrapolating times to failure at test stress levels.

For instance, if only voltage is applied, then $S = E$ (electric field). In this case, two alternative phenomenological expressions for $K(E)$ were historically considered in the literature, i.e. [2, 3]:

$$K(E) = K' E^n \tag{3}$$

$$K(E) = K'' \exp(-hE) \tag{4}$$

By means of eqns. (3), (4), the so-called inverse-power (IPM) and exponential (EXP) models, respectively, are derived from eq. (2). By setting $C_0=F(P_L)/K'$, $L_0= F(P_L)/K''$, they can be written as:

$$L = C_0 E^{-n} \quad \textit{(inverse-power model)} \qquad (5)$$

$$L = L_0 \exp(-hE) \quad \textit{(exponential model)} \qquad (6)$$

If two stresses, S_1 and S_2, are applied together, aging rate is $K(S_1, S_2)$. Then, from eq. (2):

$$L = F(P_L) / K(S_1, S_2) \qquad (7)$$

A rather common example of such situation among insulation service conditions is the combination of voltage and temperature ($S_1=E$, $S_2=T_C$ ≡ thermal stress, function of absolute temperature, T). Then, an expression frequently found in literature for aging rate, $K(E, T_C)$, is [3]:

$$K(E, T_c) = K'' \exp(hE + BT_c - bET_c) \qquad (8)$$

from which the exponential electrothermal life model is obtained, in the following form [2,3]:

$$L = L_0 \exp(-hE - BT_c + bET_c) \qquad (9)$$

This model is a combination of the EXP model (eq. (6)) with the well-known Arrhenius thermal life model [2, 3], in which parameter B represents the slope of thermal life line in log L vs T_C coordinates. Parameter b accounts for synergism between stresses. In a similar manner, several different phenomenological life models can be obtained, varying with applied stresses: they are extensively reported in [2, 3].

In several cases, even if the model is conceived in order to describe a specific aging phenomenon, nevertheless the presence of coefficients that cannot be derived directly by measuring physical properties makes the model actually phenomenological. An example of such a situation is the electrical life model developed by Dakin in order to describe the electrical breakdown due to partial discharges (PDs). It can be written as follows [4]:

$$L = C_0 / (E - E_T)^n \qquad (10)$$

Equation (10) is analogous to the IPM (eq. (5)), with the addition of E_T, the so-called electrical threshold (i.e. an electric field value below which no degradation due to a given mechanism takes place). E_T can be measured, at least in principle, as the field value corresponding to PD inception voltage, whereas coefficients C_0 and n can be determined only by accelerated life tests. Thus, model (10) is actually a phenomenological one. Indeed, it has been widely used to describe the behavior of materials that exhibit electrical life line tending to a threshold [3, 5].

An improvement of model (10) is obtained, in exponential form, on the basis of more rigorous phenomenological hypotheses. It has the following expression [2, 3]:

$$L = \frac{L_0 \exp[-h(E - E_0)]}{\left[(E - E_0)/(E_{T0} - E_0) - 1\right]^{\mu}} \qquad (11)$$

where E_0 is the field value below which electrical degradation ceases, E_{T0} is electrical threshold at room (or reference) temperature (T_C=0) and μ accounts for a proper tendency to threshold.

Model (11) holds at room temperature, but can be extended at different temperatures by replacing L_0, E_{T0}, h, with suitable parametric functions of T_C. By properly explaining such functions in terms of T_C, model (11) can be rewritten as (see eq. (9) for a comparison):

$$L = \frac{L_0 \exp[-h(E-E_0) - BT_c + b(E-E_0)T_c]}{\left[(E-E_0)/(E_{T0}-E_0) + T_c / T_{c,T0} - 1\right]^{\mu}} \qquad (12)$$

where $T_{C,T0}$ is thermal threshold at $E=E_0$ and $L_0=L(E=E_0,\ T_C=0)$.

Model (12) is characterized by 6 parameters, i.e. h, B, b, E_{T0}, $T_{C,T0}$, L_0, that make the model rather complex, but also rather flexible. So, it can describe experimental results that lead to electrical life lines with different electrical thresholds at different temperatures, like those shown in Fig. 1 for XLPE minicables (data after [6]).

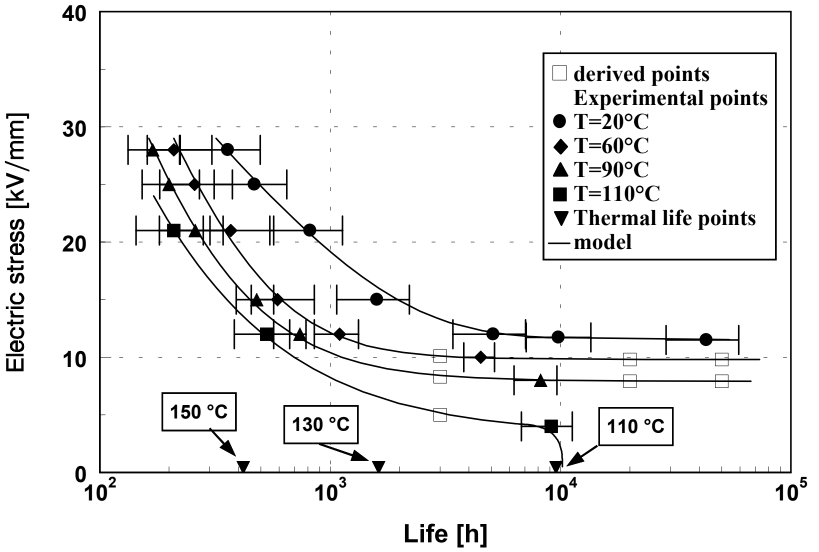

Fig. 1. *Electrical life lines at different temperatures, derived by model (12), fitting experimental failure times at 50% failure probability (confidence intervals at probability 95%) relevant to XLPE minicables (after [6]).*

Failure is a stochastic phenomenon, thus, in order to determine life model parameters, life test results at the various test stress levels must be processed resorting to proper statistical methods and (failure) probability distribution functions. The probability distribution function most-widely used when dealing with solid insulation is the Weibull probability distribution function. The Weibull distribution of failure times of a tested sample can be written as [7]:

$$F(t_F) = 1 - \exp\left[-(t_F/\alpha)^{\beta}\right] \qquad (13)$$

where t_F is failure time, β and α are shape and scale parameter, respectively. By observing that α, life at 63.2% probability, is a function of applied stresses, a proper life model can be substituted into eq.(13) for α (e.g. eq. (5), (6) or (12), depending on the kind of applied stresses). After proper rearrangement, a probabilistic life model is obtained, that enables life percentiles at a chosen probability and at stress levels different from the test ones to be obtained. Thus, a probabilistic life inference that includes a reliability analysis of chosen design stress levels becomes possible [8].

Physical models

The main shortcoming of phenomenological life models is that model parameters can be estimated only after life tests, often lasting for a very long time (even if aging is accelerated by raising stress levels with respect to service conditions). This aspect promoted the search for physical models, based on the description of specific degradation mechanisms assumed as predominant within proper ranges of applied stresses. Such models are characterized by "physical" parameters, that can, at least in principle, be determined by measuring directly physical quantities. Some examples of physical models are the following.

a. Field emission model

This model accounts for the damage produced by charge injection in the material, thus it holds for high electric field values. It is expressed by the following equation [9]:

$$t_I=C'[exp(-B_I\Phi^{3/2}/E)-exp(-B_I\Phi^{3/2}/E_T)]^{-1} \qquad (14)$$

where t_I is electrical treeing inception time (t_I does not always coincide with life, since time to failure is composed by treeing induction and treeing growth time), $C'=C/A_I$ (C is the critical energy level that charges injected into the insulation must exceed to contribute to tree initiation), B_I and A_I are material constants, Φ is the effective work function of the injecting electrode.

b. Treeing growth models

They describe the treeing growth period and, thus, hold only during that period. Some examples are the following:

i) the model by Bahder et al. [10]:

$$t_G = \frac{1}{f b_1 \{\exp[b_2(E-E_T)]-1\}[\exp\ (b_3 E + b_4)]} \qquad (15)$$

where b_1, b_2, b_3, b_4 are constants which depend upon material, temperature and geometry;

ii) the model by Dissado et al. [11]:

$$t_G = S_C\ (1/2f)\ N_C\ \{[exp\ (L_b\ \alpha_T(E))]-1\}^{-1} \qquad (16)$$

where d is fractal dimension of tree, S_C is the number of tree branches at failure, L_b is tree-branch length, $\alpha_T(E)$ is 1st Townsend coefficient (function of E), N_C is a material constant;

iii) the model by Montanari [12]:

$$t_G = \frac{\{\ln[(Q_m/k_1)+1]\}^d}{k_4(E-E_T)} \qquad (17)$$

where $k_4=k_3k_2^{1/d}$, k_1, k_2 and k_3 are coefficients depending on material and tree-growth phenomenology, x_m and Q_m are end-point values for quantities x_i (penetration depth) and Q_i (amount of charge flowing in the channels with penetration depth x_i), respectively.

c. Thermodynamic models

They are based on the concept of thermally-activated degradation reactions that are responsible for material aging. Such reactions carry the moieties that undergo degradation (e.g., polymer chains or monomers) from reactant to product (degraded) state, through a free energy barrier. The energy needed to overcome the barrier height, ΔG, is provided by temperature. The applied electric field plays the role of lowering the barrier in different ways, depending on the approach proposed. Some examples are the following:

i) Crine's model.

According to Crine et al. [13], the field accelerates electrons (of charge e) over the so-called scattering distance, δ, so that they gain a mean energy $e\delta E$ that lowers the barrier. After proper rearrangements, the thermodynamic model becomes:

$$L \propto (h/2kT)\, exp(\Delta G/kT)\, csch(e\delta E/kT) \tag{18}$$

where k and h are Boltzmann and Planck constants. Equation (18) provides electrical life lines at a chosen temperature which are straight at high stresses in semilog plot, tending to infinite life when $E \rightarrow 0$. δ is shown to be a temperature dependent quantity and should be linked to microstructural characteristics of the material (e.g., the dimensions of amorphous regions between crystalline lamellae in Polyethylene) and to the size of submicrocavities that progressively grow in the material due to weak bond-breaking by accelerated electrons [13]. In fact, this involves that the model is not fully explained as a function of temperature and time (submicrocavities increase during aging time). Hence, it can fit electrothermal life test results, but its estimates cannot be extrapolated at temperatures different from the test ones, as can be done by fully-explicit electrothermal life models. In addition, the model postulates that electrons are enough accelerated to gain the energy needed to break weak bonds: this involves either the presence of sufficiently-large microvoids from the very beginning of aging process, or of high electric fields, maybe both [14-16].

ii) Electrokinetic Endurance (EKE) Model.

This model, proposed by Lewis et al. [17], is based on the formation of microvoids by means of chemical bond-breaking processes induced by voltage and temperature. Some of such microvoids can coalesce into larger voids. As soon as sufficiently large voids are formed, from them a crack can start that ultimately breaks insulation. Hence, according to Griffith criterion for crack propagation, the time needed to initiate crack growth, t_C, (which is assumed as predominant during the whole aging time) is obtained as:

$$t_C = \int_{N}^{\eta_C} \left\{ \frac{kT}{h} \left[\exp\left(\frac{-Ur(E)}{kT}\right)(N-\eta) - \exp\left(\frac{-Ub(E)}{kT}\right)\eta \right] \right\}^{-1} d\eta \tag{19}$$

where η is the number of broken bonds, η_C is the critical number of broken bonds, N is the number of breakable bonds, $Ur(E)$ and $Ub(E)$ are the energies needed for bond forming and breaking, respectively.

iii) Space-charge model.

This model, proposed by Dissado, Mazzanti and Montanari [18], assumes that space-charges injected by electrodes and/or impurities and trapped within the insulation are responsible for electromechanical energy storage that, in turn, lowers the energy barrier, thus favoring degradation. The higher the field, the higher the stored charge and energy, hence the lower the life. After some simplifying hypotheses and proper rearrangements, the model is obtained in the following form:

$$L(E,T) = \frac{h}{2kT} exp\left(\frac{\frac{\Delta_H}{k} - \frac{C'E^{2b}}{2}}{T} - \frac{\Delta_S}{k} \right) \left\{ ln\left[\frac{A_{eq}(E)}{A_{eq}(E) - A^*} \right] \right\} \left[cosh\left(\frac{\frac{\Delta}{k} - C'E^{2b}}{2T} \right) \right]^{-1} \quad (20)$$

where $A_{eq}(E)$ is the equilibrium value of A, the conversion rate of moieties from state 1 to 2. Other quantities introduced in eq. (20) are: A^*, the critical limit of A (when exceeded, failure is said to take place); C' and b, material constants; $\Delta_H = H_a - (H_1 + H_2)/2$ and $\Delta_S = S_a - (S_1 + S_2)/2$, enthalpy and entropy contributions of activation free energy per moiety (H and S are enthalpy and entropy per moiety, subscripts 1, a and 2 are relevant to ground, activated and degraded state, respectively). Model (20), holding strictly speaking for dc voltage only, was extended to ac voltage by splitting activation entropy and enthalpy into a dc part plus an ac contribution, the latter proportional to $W_{sl}(\omega)$, the mechanical energy of the polymer lattice that oscillates at a frequency f (angular frequency $\omega=2\pi f$) equal to that of the supply voltage [19]. Then, by proper rearrangements, the ac version of the model is obtained (omitted here for the sake of brevity), similar to the dc one (eq. (20)), but with additional ac terms containing a proper function of frequency, i.e. $f(\omega) = \omega^2 / [(\omega - \omega_0)^2 + \gamma^2]$, where ω_0 is the natural oscillation frequency of the lattice and γ is a damping constant. The model, arranged in this way, provides an explanation for ac degradation at moderate-low fields which involves electromechanical fatigue [19].

Model (20) is fully explained as a function of applied stresses, E and T, thus enabling the derivation of electrical life lines at different temperatures and the extrapolation to stress levels other from the test ones (see Figs. 2.a and 2.b, times to failure after [20]); its parameters, Δ_H, Δ_S, Δ, b, C', A^*, are related to microstructrure, thermodynamic properties and space charge characteristics of the material, thus attainable in principle by short-term analytical measurements. On the other hand, model (20) has some limitations [18], since it holds for homogeneous materials and it estimates time to formation of microcavities, not time to breakdown, thus should be applied to specimens for which this component of time to failure is predominant (e.g. thin specimens). Figure 2 clearly shows that model (20) exhibits an electrical threshold, function of temperature. As previously discussed, threshold inference is usually performed by conventional life tests, but recently new techniques for threshold evaluation by means of short-term tests have been satisfactorily employed, based on high field conductivity measurements (charging current measurements [21], space charge measurements [22]) or electroluminescence [23].

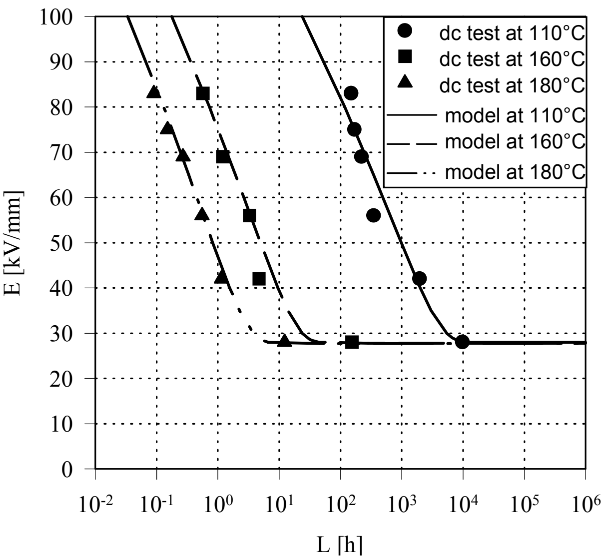

Fig. 2.a. *Model (20) fitting failure times (at 63.2% probability) obtained by dc life tests on PET specimens [20].*

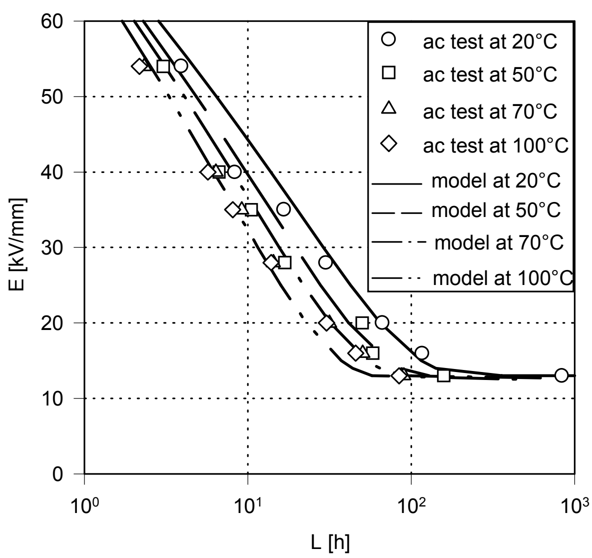

Fig. 2.b. *Model (20) fitting failure times (at 63.2% probability) obtained by ac life tests on PET specimens [20].*

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