INSULATION AGING TESTING

Much work has been done over the years on predicting the lifespan of electrical insulation (1–7). However, there are very few theories or empirical tests that are yet able to fully and accurately describe in-service aging–and, hence, the practical lifespan—of most dielectric polymers. Insulation life under normal conditions is often so long that testing under service conditions is completely out of the question; time and money can therefore be saved through accelerated aging tests. To simulate the in-service conditions, it is customary to perform accelerated aging tests by submitting samples to stresses (electrical, thermal, or mechanical) more severe than those encountered in the field, which will eventually induce early failures. It is hoped that the results obtained under a compressed aging could then be extrapolated to the normal service conditions in order to obtain an estimated service life for the material or product tested.

Developing an accelerated aging test is never a simple thing because it involves several parameters. These should contain all deterioration factors encountered under service but they should not introduce mechanisms that do not occur in service. Therefore, it is important to have clear objectives and to have some understanding of the major factors involved before starting an accelerated aging test. Two main questions are associated with the overall planning process (a rough diagram of which appears in Fig. 1): (1) what do you wish to learn from this test and (2) how do you expect to achieve it? The main objective of this article is to address these two basic questions. We begin with a brief review of the techniques most commonly used to characterize and evaluate the electrical properties of new materials. Then we discuss the limits and capabilities of some well-known single stress tests. For the examples, we used some of the results obtained in electrical treeing and in the aging of rotating machinery to demonstrate the complexities of aging tests involving multiple stresses.

The development of reliable dielectric-aging tests is a matter of great concern for the electrical industry since the present accelerated aging tests are known to give ambiguous and occasionally inaccurate life predictions. Following the tradition established long ago by mechanicians who plot the aging results on a log stress versus log number of cycles graph (the so-called S–N plot), dielectricians have also plotted for years (8) their electrical aging results on a log field versus log time graph, as shown in Figure 2. By using the power law, which often describes the accelerated aging results obtained under high stress in less than one year, an extrapolation for life under service condition then can be made. Yet, even after many years of extensive use, there is no formal (and reliable) theory supporting this power law relationship between field and time of aging. In fact, many experimental results have shown that the power law describes only relatively short (i.e., less than 1–2 years) aging time (9). Years ago, Dakin had proposed an aging model where electrical aging of dielectrics obeys an exponential relation between field and time (1,10). This model has been considerably improved by several authors (5–7), and the exponential relation appears to lay on firmer theoretical grounds than the empirical power law. It is obvious that the major weakness of most accelerated aging tests is that the aging mechanisms under consideration are still poorly understood. A brief review of a physical model describing all aging results for extruded cables (7,11) is presented and the application of this model to other insulated systems is also analyzed.

Selecting an aging model that best describes the aging processes under study is an important step in the determination of an accelerated aging test, but the selection of the appropriate parameters, measurements technique, and method of data analysis are also of the utmost importance. In practice, they make the difference between a successful approach and an expensive failure. The complex phenomenon known as water treeing was chosen to show how difficult it could be to select the appropriate experimental conditions when synergistic effects are present. In this specific case, it appears that in addition to a need for a comprehensive model, there is also a need for a comprehensive test, that is, one that would take all major parameters into account at the same time. This is a most formidable task.

After having chosen an aging model and experimental conditions, the collected data need to be interpreted, which is always a complex problem because dielectric aging is never

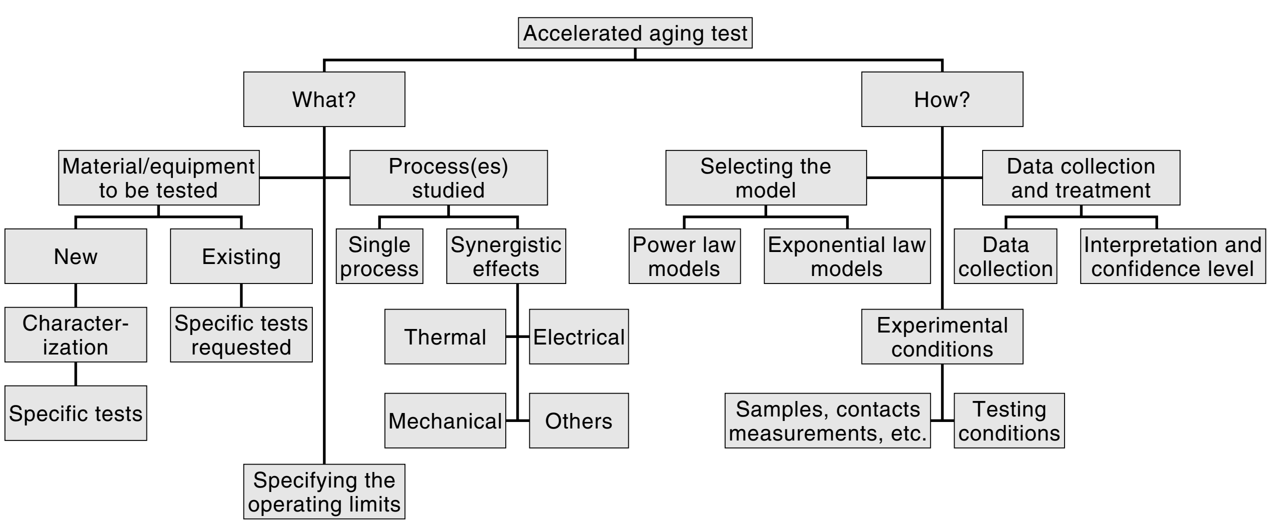

Figure 1. The various steps in the planning and realization of accelerated aging tests.

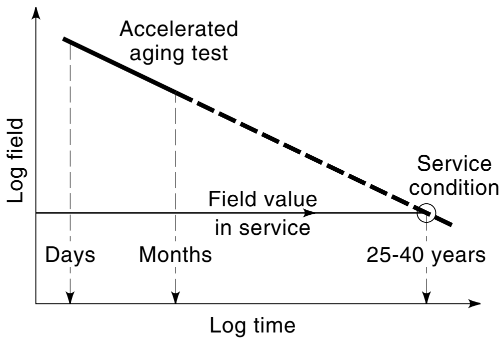

Figure 2. Life prediction from a log *F*/log *t* graph. Accelerated aging results obtained at high fields and short time are extrapolated (dashed line) to low-field service conditions. Note the huge differences in the time scale.

associated with a single parameter. The use of Weibull statistics as a tool to establish some sort of confidence limit for data interpretation is reviewed. Finally, the difficulties and learning associated with accelerated aging tests for solid polymers are summarized.

EVALUATION OF NEW MATERIALS

Before evaluating the aging behavior of a new material, it is essential to characterize the basic properties most related to electrical aging, that is the morphology, resistance to oxidation, charge injection limits (including partial discharges), and electrical strength of the unaged material. Note that several of these properties can be determined according to standard procedures; the most commonly used ASTM tests for polymers have been listed (12).

Morphology

The techniques used to characterize the morphology of polymers (e.g., density, amorphous vs. crystalline content, additives content, melting temperature) are well known and are described in detail in many textbooks (13,14). We would like to stress the fact that aging (electrical, thermal, or mechanical) is almost always associated with some modifications of the polymer's morphology (11). Therefore, knowing the nature and scope of the morphology change allows better evaluation of the cause and degree of degradation. Although this may seems obvious, it remains that many aging tests were conducted on many insulating materials or equipment without any morphology measurements reported (e.g., 7). The measurement of the key morphological properties of the polymer before and after accelerated aging should not be neglected, because it may be more informative than only the measurement of its electrical properties.

Oxidation Resistance and Thermal Life

Usually polymers are easily oxidized, and therefore their resistance to oxidation is a fundamental property to evaluate before the onset of any accelerated aging test, especially if it is performed at relatively high temperatures. The thermal classification and evaluation of insulating materials have been described (15). The onset of oxidation is usually determined from the oxidation induction time (OIT), which can be evaluated using either IR spectroscopy (16) or differential scanning calorimetry (DSC) (16–18). In the first case, samples are aged around the melting temperature (T_m) in air, whereas in the second case they are directly heated under an atmosphere of pure oxygen at temperatures well above T_m. The advantage of using DSC is that results are obtained in a few hours, whereas aging in an oven followed by spectroscopy measurements could take weeks or even months. Note that it is difficult to obtain reproducible and reliable results with the DSC technique unless great care is taken during preparation of the samples (17). The interpretation of OIT results for polybutadiene and polyethylene has been discussed in detail (16). Great care must be exercized when the time comes to extrapolate thermal lifetime at service conditions from accelerated aging results obtained under very high temperatures. According to the rate theory, the thermal life t is (16)

$$t \approx (h/kT)\exp(\Delta G/kT) \tag{1}$$

where h and k are the Planck and Boltzmann constants, respectively, T is the temperature in degrees Kelvin, and ΔG is the activation energy of the process given by

$$\Delta G = \Delta H - T\Delta S \tag{2}$$

where ΔH and ΔS are the activation enthalpy and entropy, respectively. The value of ΔH is approximately equal to those of the so-called activation energy E usually deduced from Arrhenius plots. As discussed elsewhere (16), Eq. (1) gives access to much more information than can be afforded by the Arrhenius equation. As an example, let us consider the accelerated thermal aging of Schwarz et al. (18) who have studied antioxidant (Irganox 1330) diffusion in isotactic polypropylene (PP) below and above the melting temperature, $T_m =$ 436 K. According to Eq.(1), results plotted as $\ln tT$ versus $1/T$ should yield straight lines, whose slope and intercept give ΔH and ΔS, respectively. The results of Schwarz et al. obtained for various antioxidant contents and different temperatures replotted as $\ln tT$ versus $1/T$ do in fact give straight lines from which it is easy to calculate ΔH, ΔS, and then ΔG. The ΔG values at 413 K and 443 K (i.e., below and above T_m) are plotted in Fig. 3 as a function of antioxidant content. As

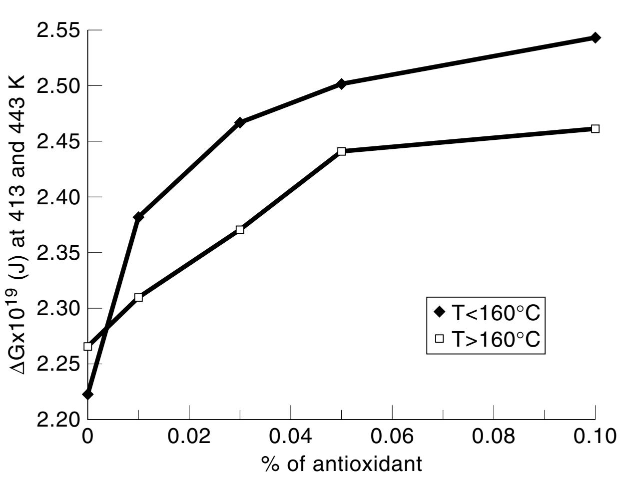

Figure 3. Activation energy for antioxidant diffusion (i.e., oxidation resistance) in isotactic polypropylene near the melting temperature as a function of antioxidant (Irganox 1330) concentration.

expected, the ΔG value (and thus, the resistance to oxidation) increases with the antioxidant concentration. It is also obvious that ΔG does not significantly increase above a concentration of 0.05% of Irganox 1330; in other words, adding more antioxidant is useless. Note that this conclusion could not be so easily deduced if the original data (18) were not treated with Eq. (1).

Charge Injection and Space Charges

A good dielectric is characterized by a very limited charge injection and space charge content, even under high electric fields. This is often evaluated by the following techniques, which are classified in order of increasing experimental complexity.

Dielectric Relaxations. The polarization and dielectric behavior of polymers change in the presence of space charges and aging in general (4,19,20). Dielectric relaxation measurements on unaged materials give access to basic properties such as the dielectric constant and losses (20). The evolution of dielectric relaxations with aging time and temperature between 10^{-5} Hz and 10^{6} Hz may provide some information on charge injection and space charges associated with the aging phenomena under study. Recently, XLPE samples that were aged in a humid environment under high ac fields have been shown to exhibit a different behavior at low frequencies than unaged samples (19). They concluded that aging leads to space charges formation, thus making XLPE more conductive. Although such measurements are relatively easy to perform, their interpretation is rarely simple and straightforward. Most of the time, they must be complemented by results obtained by another technique.

Conductivity and Thermal Transient Current. The measurement of steady-state current as a function of the applied voltage is one of the oldest electrical measurements performed by electrical engineers to characterize new materials. Any deviation from Ohm's law at high fields tends to suggest space charge formation and it is usually recommended to operate the dielectric under lower electric fields. Albeit very simple, this measurement is plagued with many difficulties with good insulators, because a steady state is rarely, if ever, achieved. Thus, one cannot expect to learn much from this measure. Thermal transient current (TTC) is a method that takes advantage of the long transient current flowing in a dielectric subjected to a high-voltage step. The TTC is similar to a pyroelectric response (possibly due to dipoles or space charges), which occurs when electrodes are shorted after the voltage step. It is a simple experiment but results are once again not easy to interpret. Das-Gupta and Scarpa (19) used this technique to complement their dielectric relaxation measurements on aged XLPE, cited above.

Thermally Stimulated Current. Thermally stimulated current (TSC, also called thermally stimulated discharge current–TSDC) is a well-known method used to investigate the nature of polarization in dielectrics (4,19). Dipoles (or space charge formation) is induced by applying a high electric field, sometimes above room temperature. The polarization is then rapidly frozen at low temperature (around or below the glass transition) to be finally released by heating with the measuring electrodes short-circuited. The charge decay thus measured as a function of temperature may evolve with aging (19,21) or with many other experimental parameters (22). In fact, we have shown that TSC results can be interpreted by a simple model based on rate theory (22), and there is no need for complex equations, as in the Navriliak-Negami or Vogel-Tammann-Fulcher models, to describe existing data. When our model is applied, it appears that the activation energy, ΔG, of the process is often related to some physical property. For example, it has been shown (22) that the ΔG values for the α and γ relaxations of PE depend on the sample's crystallinity. Thus, this is another often-used simple technique but care is required before any firm conclusion can be drawn from the results.

Direct Space Charges Measurements. Over the last 15 years, at least four different techniques have been developed to directly measure space charges in polymers: the thermal wave (23), the pressure wave (24), the pulsed electroacoustic (25), and the mirror effect (26) methods. In the first two methods, the trapped charges are set in motion by either a thermal wave (in fact, an abrupt increase of temperature) or a pressure wave (induced by a powerful laser). In the pulsed electroacoustic method, the induced pressure wave is detected by a piezoelectric transducer that generates a voltage. In these three cases, the determination of the charges spatial distribution is made by Fourier transform deconvolution. In the mirror method, a given quantity of electrons is injected (without contact) in a dielectric by the electron beam of a scanning electron microscope. A space charge builds up in the sample, and, when the field of the residual trapped charges is high enough, it deflects the low-energy beam of the microscope. The image thus formed can be analyzed to yield the density of trapped charges and the voltage above which the mirror effect disappears; the two parameters give information on the trapping and detrapping characteristics of the material. The thermal wave method is particularly adapted to relatively large samples, such as extruded high-voltage cables. The pressure wave and the electroacoustic are well fitted for thin and plane samples with the latter technique requiring a much less complex experimental set-up. The mirror effect has been used more often with ceramics than with polymers, although some limited measurements on PE samples have been published recently (26). Use of one of these four techniques to characterize the charging behavior of new materials prior to and after aging is highly recommended.

Breakdown Strength

The evaluation of the breakdown strength of new insulating material or equipment is absolutely required and always it is useful to measure it over a relatively large temperature range. As is well known, the breakdown strength of polymers abruptly decreases around the glass transition (4,27). In addition, their mechanical and thermal stability are significantly reduced in the more viscous state above T_g. Breakdown strength is measured under ac, dc, or impulse conditions and the three different measurements give different values and different information on the material behavior. The lowest value is always obtained at power frequency with a sharp decrease with increasing frequency (4,27). We have suggested that fatigue associated with the field cycles is responsible for this phenomenon (28). Impulse breakdown measurements are made to simulate some specific operating (either lightning or switching) conditions and they give much higher values. It is often considered that the intrinsic breakdown strength value is obtained under dc condition. In fact, most reported values for the so-called breakdown strength of polymers are the dc values. A broad rule of thumb is that the ac value at 22°C is approximately half the dc value. The measurement should be made with the sample immersed in oil (or under an SF_6 pressure) to avoid flashovers and to reduce the influence of humidity.

SINGLE STRESS AGING TESTS

Voltage Endurance Tests: Constant or Progressive Stress

There are basically two types of voltage endurance tests: the progressive (or stepped) stress test and the constant stress test. The later test consists of applying constant voltages and temperatures, higher than those encountered in service, to a group of specimens until all fail. By repeating the same test under various stresses and temperatures, it is possible to establish life curves, which allow an estimation of the probable lifetime at service conditions to be made. The AEIC Accelerated Water Tree Test CS-5 often used by cable manufacturers is one type of constant stress test (29). Results are difficult to interpret when breakdown occurs during the initial voltage rise or when there is no breakdown, even after a very long aging time. The experiment should be repeated with different voltage values. The major advantage of the constant-stress test is that it has some similitudes with the usually constant-stress conditions used in service.

In the progressive stress test, voltage is increased stepwise up to breakdown from zero or from about 50% of its expected failure value. The major practical advantage of this test is that it is much shorter than the constant stress test. It yields higher failure voltage values (30), and its time-to-breakdown, t_p, can be related to the time-to-breakdown in constant stress, t_s, by two equations depending on whether the power law or the exponential law applies (discussed previously) (31). For the power law,

$$t_s = t_p/(n+1) \tag{3}$$

where n is the exponent of the power law (i.e., the slope in a log field vs. log time plot). For the exponential law,

$$t_s = t_p/bV \tag{4}$$

where b is the slope of the exponential relationship between field and log time and V is the voltage.

The results given by the progressive test should be used with care, because the influence of space charges building during the voltage rise in the case of a continuously varying field is not well understood. Also, the breakdown mechanism may be different as the voltage increases, which implies that samples may not be tested under the same conditions as those encountered in service. Note that the well-known AEIC High Voltage-Time Test is a progressive test, although it is not necessarily thought of this way. Its validity and the validity of AEIC CS-5 have been often questioned in view of the inherently large variability of the breakdown data and some apparent inconsistencies in the aging test results (29). To conclude, progressive tests could possibly be used to make a rapid comparison between results obtained (under the same conditions) with different samples but they cannot be used to establish life curves.

Constant Temperature or Temperature Cycles

Most electrical equipment is not used in the field under constant temperature conditions and this suggests that accelerated aging should be done under similar conditions. Therefore, several types of temperature cycles are used depending on the type of equipment tested. Cables, for example, are often tested under cycles of 8 hr heating (up to a given temperature) and 16 hr cooling (down to room temperature). However, most accelerated aging tests are performed under constant temperatures for at least two reasons:

1. It is simpler and cheaper.
2. There is no reliable aging model taking temperature cycles into account and, thus, able to predict their influence on the material or equipment lifetime.

Although it is not well understood, testing under temperature cycles often yields a longer lifetime than does testing under constant temperature (7). Another well-known experimental fact that is poorly understood is that breakdown very often occurs not during the temperature rise but at the beginning of the cooling regime (32). One tentative explanation is that during the cooling, the polymer contracts rapidly because of its relatively large expansion coefficient and this contraction could be faster than the contraction of surrounding materials, potentially leading to the formation of small defects that could eventually become discharge initiation sites. Nevertheless accelerated aging under temperature cycles should be performed whenever possible. However, duration of the cycles and the maximum temperature should be as close as possible to the service conditions.

Uniform or Nonuniform Field

Many aging tests (electrical treeing for instance) are performed under highly divergent electric fields. The use of a needle electrode (among other things) allows very high fields at the tip without having to rely on a very high voltage source. It is also argued that the interface between a conductor and a dielectric is never perfectly smooth and, therefore the smallest protrusion is a field enhancement artifact that could be simulated in the laboratory by a needle electrode. Although these arguments cannot be disputed, the unnecessary use of nonuniform fields often leads to beautiful but hard-to-analyze results. It is true that fields can be calculated at the tip and away from a point electrode, but these calculation may not always be reliable. As an example of our scepticism, let us consider the electroluminescence of polyethylene. It has been customary for years to generate electroluminescence at the tip of small metal electrodes inserted in polymers (33) for the reasons already given. The fields calculated from the shape of the needle and from the applied voltage were fairly high, in fact in the hundreds of kilovolts per millimeter for most polymers. When finally some years ago a group of scientists measured the same phenomenon under parallel-plane electrodes (where the average geometric field is simply equal to the voltage/distance ratio), they discovered that electroluminescence in polyethylene occurred not in the 100 kV/mm range but only at 15 to 18 kV/mm (34). More recent results obtained by another group of scientists have confirmed that the electroluminescence of various polymers occurs at much lower fields than expected when they are measured under relatively uniform conditions (35). Of course, this does not mean that the electric field in a dielectric is constant between the electrodes but, when the field is reasonably uniform (especially for thin films), this allows the experimental results to be compared against the prediction of models that mostly rely on the average field value. Another distortion induced by nonuniform fields is a localized overheating at the tip of a needle electrode subjected to voltage impulses, as recently shown by Kuang and Boggs (36).

SOME MULTIPLE STRESS AGING TESTS

Many insulation systems of electrical equipment are exposed to multiple stresses, including electrical, thermal, mechanical, and environmental. In most cases, there will be synergistic effects where the byproducts of one aging process will influence another, making life predictions extremely difficult. In this section, we consider the synergistic effects in the aging tests for electrical treeing and for rotating machinery.

Electrical Treeing Tests

When a polymeric insulator such as polyethylene is subjected under dry conditions to high nonuniform electrical fields, a partial breakdown of the dielectric occurs along tracks that tend to resemble trees. To accelerate that phenomenon, it is customary to apply very high voltages to the tip of metallic electrodes embedded in polyethylene samples. The monitoring of electrical treeing tests can be done by recording the electroluminescence or the partial discharge activity associated with the growth of the tree channels (4,27). It is observed that tree growth is associated with charge injection from the metal electrodes, partial discharges, and electroluminescence (4,27, 33). We have shown that the injected charge density depends on the oxide layer on the metal electrode (37). In fact, easily oxidized metals such as aluminum or iron require higher tree inception voltage than noble metals, such as gold and silver. Therefore, if the voltage source is limited, it is recommended to use gold or nickel electrodes rather than steel electrodes.

Other experimental factors that greatly influence electrical treeing are the voltage frequency and the number of voltage applications (4,27,28). This strongly suggests that mechanical fatigue affects the phenomenon and, in fact, several studies have shown that mechanical stresses enhance tree growth (38,39). Electrical treeing tests are a nice example of the complexity that can be brought by just a limited number of synergistic effects. Although the phenomenon has been extensively studied for the last 20 years, there is not yet a comprehensive model able to take into account the different parameters briefly described above.

Aging of Rotating Machinery

Generator winding insulation is exposed to thermal, mechanical, vibrational, environmental, and electrical stresses. Predicting the insulation lifespan is made even more complicated by the mode of machine operation: some are operated under constant load, whereas others are started or stopped abruptly, which induces totally different failure processes. The insulating materials used (mica tape, epoxy, etc.) are another parameter. The number and complexity of synergistic effects is so great that even after several decades of extensive research there is not yet a reliable and general model able to predict the lifetime of rotating machinery. Obviously, such a model would be helpful and warmly greeted considering the cost of these machines and the revenues lost when they are out of order. For the last 50 years, partial discharge (PD) testing has been used as an attempt to measure the condition of the winding insulation (40). Some years ago, PD signals were recorded on limited bandwidth oscilloscopes and RIV meters, which implied that the tester needed a great expertise to distinguish PD signals from the surrounding electromagnetic noise. The interpretation of the signal also required skill, making even more difficult the correlation between the measurement and the condition of the insulation. With the advent of new (and very fast) electronic instrumentation, with recent signal-processing techniques, and with the help of computers, there are now several commercially available systems that can reliably detect PD on machines in operation or under testing. There is not yet a complete agreement on the interpretation of the signals but the staggering number of publications published in this area over the last few years is an indication that great progress is currently being made (e.g., 40).

Several standards were issued by the IEC and IEEE on the multistress aging of rotating machinery. The Thermal Class of motor windings can be determined from the procedure described elsewhere (15). IEEE Standard 275 (41) provides detailed testing procedures based on sequential exposure to high temperature, mechanical vibration, high humidity, and voltages. In fact, there is no evidence whatsoever that sequential testing yields similar results to simultaneous testing, but of course, the latter is much more complex to perform. Ramu (42) and Kimura et al. (43) tried to age winding bars in setups by simultaneously applying mechanical, thermal, and electrical stresses. The degradation of the insulation was estimated from the variation-of-loss tangent, change of capacitance, and breakdown strength as a function of time (number of cycles) and temperature. PD activity measured in accelerated aging tests under very high temperature or very high field may not be representative of what happens under less stringent service conditions. To avoid this problem, Sheehy et al. (44) have accelerated thermal, mechanical, and electrical aging using a variable frequency power electronic converter operated at 500 Hz. Although great progress has been made to accelerate aging in the laboratory, it is nevertheless obvious that there is still a long way to go before one will be able to apply all (and not only three) stresses simultaneously. An understanding of the results thus obtained is even more remote.

DESIGNING ACCELERATED AGING TESTS

Selecting the Appropriate Aging Model

Electrical and Thermal Aging. Electrical aging is rarely performed under only one temperature, which implies that the aging model must be able to describe the phenomenon under study for various temperatures. Our own model of aging of

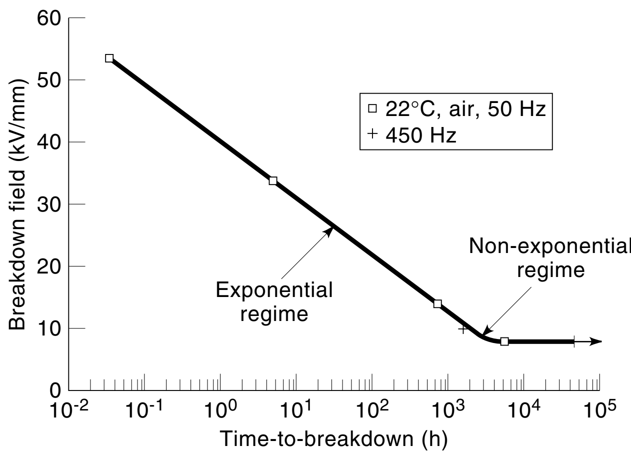

Figure 4. Accelerated electrical aging results for XLPE cables plotted on a semilog graph according to Eq. (5). Physical parameters describing the aging process (see text) can be deduced from the exponential regime.

solid dielectrics is described in detail elsewhere (7,11), and here we summarize only the basic features that distinguish it from others (3,5,6):

1. It relies on the rate theory and does not include arbitrary adjustable constants.
2. It was shown to describe all electrical aging data for extruded cables very well.
3. It can take into account the influence of mechanical stresses.
4. It is based on simple physical concepts and phenomena.

The model predicts that the lifetime t of a polymeric dielectric under thermal and electrical stresses is (7,11)

$$t \approx (h/2kT)\exp(\Delta G/kT)\,\mathrm{csch}(e\lambda F/kT) \tag{5}$$

where ΔG is the activation energy of the process and λ is equivalent to a scattering length. We have shown that λ is also equal to the amorphous phase thickness for PE or XLPE insulation (11). Our speculation is that during aging tiny submicrocavities are formed with a maximum size equal to λ (i.e., in the 5 nm to 40 nm range for most polymers). Electrons injected into these empty spaces can gain kinetic energy and therefore can induce more localized damage. Eventually, they may gain enough energy to break intermolecular bonds, which is the final step before the final breakdown. At high fields, Eq. (5) reduces to

$$t \approx \frac{h}{2kT}\exp\frac{\Delta G - e\lambda F}{kT} \tag{6}$$

The exponential relation between field and time was indeed proposed years ago by Dakin (1) and it has been observed by many authors (1,4–8). Thus, results of combined electrical and thermal aging should be plotted on a field versus log time graph, as in Fig. 4. The values of λ and ΔG are directly given by the slope and the intercept, respectively, of the straight line in this graph. Knowing ΔG at various temperatures yields the ΔH and ΔS values of the process. Note that λ is constant in the high field regime but decreases with field in the ⟨tail⟩ (i.e., in the nonexponential) regime (7,11). This model was applied to extruded cables aging (7,11), to epoxy aging (45), and to aging data of several polymers used in space insulation (46).

Mechanical Aging and Combined Electrical-Mechanical Aging. The time-to-breakdown of a polymer under a mechanical stress σ is sometimes given by the Zhurkov equation (47)

$$t = B\exp\frac{E - \gamma\sigma}{kT} \tag{7}$$

where E is the activation energy, B is an empirical factor, and γ is a parameter, the units of which are those of an activation volume. Equation (7) is verified when the results of $\log t/\sigma$ yield a straight line (at constant T). Although Eq. (7) is widely used, it has some rather severe limitations, that is:

1. The physical origin of the preexponential factor B is unknown and hence its value is difficult to assess.
2. There is usually no relation among the value of E, the polymer nature, and the process being studied.
3. More important, the linear relation predicted by Eq. 7 between the log time and $1/T$ is not always respected, especially when results are obtained over a wide range of temperatures.

Our own model of aging can describe mechanical aging with some minor adjustments (16). Under a stress σ, the energy barrier controlling the mechanical strength of the material is then deformed by an amount equal to $\Delta V\sigma$. The time to breakdown becomes

$$t \approx \frac{h}{2kT}\exp\frac{\Delta G}{kT}\,\mathrm{csch}\,\frac{\Delta V\sigma}{kT} \tag{8}$$

where ΔV is the activation volume of the process. At high stresses, Eq. (8) is reduced to

$$t \approx \frac{h}{2kT}\exp\frac{\Delta G - \Delta V\sigma}{kT} \tag{9}$$

Thus, Eqs. (8) and (9) are verified when the results, plotted on a $\log t/\sigma$ graph, yield straight lines for constant temperatures at high stress and a nonexponential regime at low stress (Fig. 5). In our model, the lowest stress of the exponen-

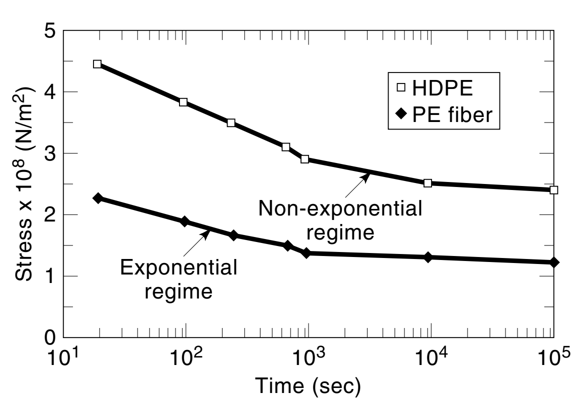

Figure 5. Accelerated mechanical aging results for different PE samples plotted on a semilog graph according to Eq. (8). Note the two different regimes.

tial regime is called the critical stress; it is the stress above which damage is irreversible. The slope and the intercept of the exponential regime yield the values of ΔV and ΔG, respectively. Obviously, Eqs. (7) and (9) are highly similar although E should not be confused with ΔG, and B is not equal to (h/kT). But the most significant difference is that Eq. (9) describes the time dependence of the mechanical process over the entire stress range, whereas Zhurkov's equation is restricted to the high-stress regime. Obviously, Eqs. (6) and (9) describing electrical and mechanical aging have a lot of similitudes. At high fields and high mechanical stress, it is easy to deduce the lifetime under combined stresses:

$$t \approx \frac{h}{2kT} \exp \frac{\Delta G - e\lambda F - \Delta V \sigma}{kT} \tag{10}$$

However, at low field and/or low mechanical stress, the equation would be far more complex, but accelerated aging is usually performed under severe conditions, which should allow the use of a simple equation, Eq. (10). Now that a model has been obtained that is able to describe many aging phenomenon, the experimental conditions that would yield useful data still need to be selected.

SELECTING EXPERIMENTAL CONDITIONS: WATER TREEING AS AN EXAMPLE OF A COMPLEX PHENOMENON

When selecting the experimental conditions of an accelerated aging test, the foremost question that one should keep in mind is: What do I want to learn from this test? There are several typical answers to this question, such as setting the operating limits of the tested object (temperature, field, etc.), evaluating the impact of one or two variables on the behavior of the insulation, performing a comparison against a somewhat similar system, and understanding the mechanisms at work. The test would be entirely different depending on the answer and it is nearly impossible to provide all the answers with a single test. The next question is: What to accelerate? For example, if one is conducting a water tree experiment in which the growth rate of trees is to be measured, the test will be entirely different from one in which the initiation rate (i.e., the density of trees/surface unit) would be studied. The following question is then: How to do it? The answer is related to the number and type of samples, the type of experimental cell, the voltage and temperature range, and so on. Amazingly enough, we tend to spend more time on the *how* than on the *what*. This may possibly explain why many tests yield inconclusive and confusing results. To show that answering these apparently simple questions is sometime far from a trivial matter, let us consider water-tree testing as an example of a poorly understood and complex phenomenon for which there is not yet a comprehensive test.

Existing Water-Tree Tests

Water trees are a type of detrimental degradation composed of tiny (micron sized) channels evolving in extruded cable insulation (48). Those growing from the semiconductive shield of the cables with shapes similar to trees or bushes are often called *vented trees*. Those growing from impurities and/or voids in the middle of the insulation are called *bow-tie trees* because of their typical shape. The former variety is by far the most detrimental because they may bridge the insulation or serve as an initiation site for electrical trees (i.e., to the final arc). The basic mechanisms responsible for the initiation and growth of water trees are not yet known, although some experimental facts are well established and undisputed:

1. Water is absolutely needed and adding some type of impurities may help.
2. The electric field must be ac (no water trees under dc voltage) and the growth rate increases with frequency.

Many other parameters (as seen later) influence water treeing, but there is no consensus as to their role, and sometimes different experiments yield contradictory results. In addition, there are clear synergistic effects among these variables (48). This unexpected degradation process has, in the last 30 years, induced many underground cable failures, resulting in heavy losses for electric utilities throughout the world. This led AEIC to develop the Accelerated Water Tree Test (AWTT) CS-5, the main purpose of which is to give comparative results on different full-size cables. The test is performed on ten cable samples, 3.7 m long, installed inside water-filled conduits subjected to three-times rated voltage and to temperature cycles. Each week, the cables experience five consecutive 24 h load cycle periods (8 h heating up to 90°C, 16 h cooling) followed by two consecutive no-load periods. One sample is a dummy used to monitor temperature and voltage. Three samples are aged 120 days and then subjected to a series of tests, including tree counts on wafers cut in the aged insulation and high-voltage tests. If these tests are passed successfully, the cable has met the requirements for AEIC AWTT. However, the manufacturer is required to obtain data for 180 and 360 days of aging, for engineering information only. Three samples are aged for 180 days and then subjected to a high-voltage test. The remaining three are aged for 360 days and then subjected to a high-voltage test. The test has several limits: in service, the conduits may contain water but they are not continuously filled, and the temperature gradient is very different from the AWTT test. The tank-type test is an alternative test where cable loops are aged in water-filled tanks under temperature cycles and three-times rated voltage. The test is currently being standardized by the IEEE (49) and present results suggest that the conditions of this aging test are closer to service conditions than are those in the AEIC AWTT. These two tests may be useful to compare different batches of cables but they are of no help in clarifying or understanding the water treeing mechanisms.

Several ad hoc tests have been developed for such fundamental studies, and three major types of experimental cells are used (Fig. 6). Let us call them A, B, and C cells, although they are not usually referred to by these names (50). In cell A, also known as an Ashcraft-type cell or a Cigré-type A cell, a molded PE or XLPE plaque with impressed conic cavities filled with a water solution (usually 0.1 M NaCl) is subjected at room temperature to an inhomogeneous high electric field applied by a metal wire soaked in water (see Fig. 6). Trees grow rapidly at the tip of the depressions and this type of cell is particularly useful for statistical studies requiring a lot of data. This is an interesting cell to compare the behavior of different materials, but it is far from obvious that it simulates cable operation. In cell B, also known as a Cigré-type B cell, attempts were made to have a more homogeneous field and

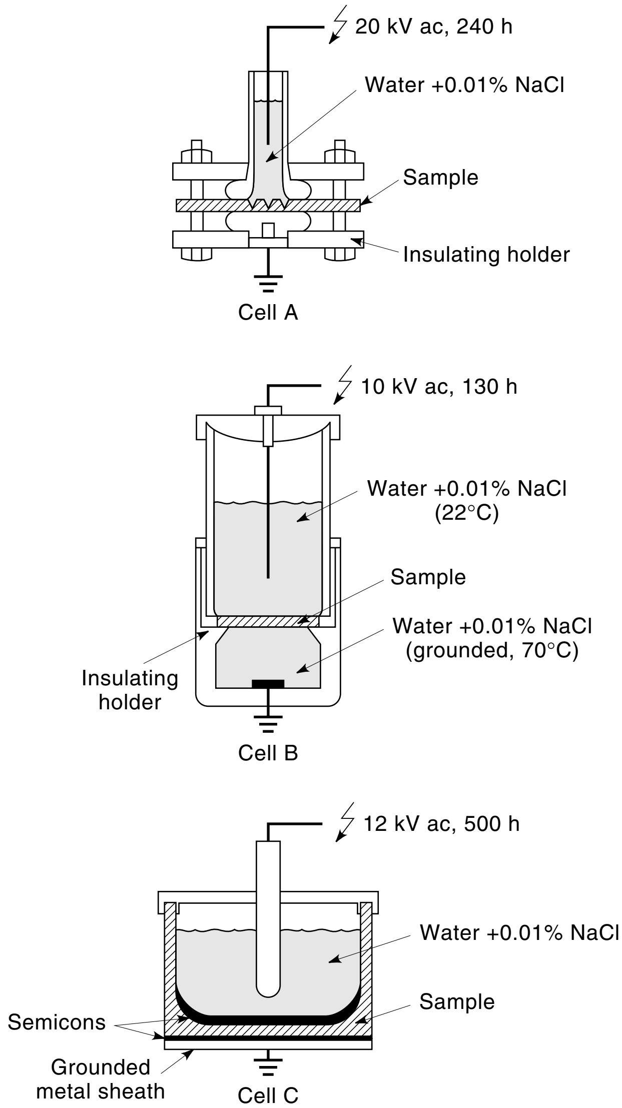

Figure 6. Three main types of cells standardized by CIGRÉ for water treeing tests.

conditions closer to cable operations in service by using a PE container and with a water solution on both sides of the sample. The grounded side is maintained at 70 °C, which is perhaps high compared to the actual temperature of operation of most cables. In addition, the temperature induced in the sample is more or less easy to control. The molded PE or XLPE sample is normally flat, although some studies were made with scratched surfaces to increase the water-tree initiation rate. The influence of ionic contamination by the metal HV electrode can be eliminated by using a carbon electrode, and the problem of trapped air under the sample can be solved by using the modified design proposed by Fothergill et al. (51). This cell may also be used to investigate the initiation and growth of bow-tie trees, which is almost impossible with cell A. Finally, cell C, also known as Cigré-type C, has a design similar to a Rogowski electrode, which insures a nearly homogenous field. It is also the only one that allows the study of the influence of semiconductive shields on water treeing and the ability to perform breakdown measurements directly in the cell. One main drawback is the fact that the sample is exposed to water only on one side, whereas in actual cables, the insulation is often soaked in water. The fabrication of the cell is much more complex than in the case of cell B, which is itself more expensive and more time consuming to prepare than cell A. Although cell C seems to be used more and more, it is widely acknowledged that any of these cells (and their numerous variations) can give reproducible results. This is particularly true when results obtained with identical materials by various laboratories are compared (50). This suggests that the choice of test parameters and conditions is not appropriate. This is not surprising when all the experimental factors affecting water trees are considered.

Synergistic Effects in Water Treeing

Among the many parameters affecting water tree initiation and growth, the following are generally considered as the most detrimental (4,48,51): oxidation, nature and concentration of ions, material morphology and additives, electric field value and frequency, temperature and mechanical stress and strains. Table 1 summarizes the relative impact of each of the above parameters according to the three main schools of thought (i.e., the chemical, dielectric, in a very broad sense, and mechanical models). In many cases, there are synergistic effects between them, which makes the evaluation of the impact of each parameter even more difficult.

Oxidation and Ions. According to Ross et al. (52), the initiation and growth of water trees is fostered by the local oxidation of the insulation. However, experiments performed with nitrogen have shown that three growth in NaCl or $CuSO_4$ solutions is reduced by 50% and 20%, respectively, compared to tree growth in air (53). On the other hand, the density of trees was not affected by the absence of oxygen. Thus, the main detrimental factor is not oxidation but synergistic effects between oxygen and some ions.

Oxidation and Material Morphology. In the same study (53), it was shown that XLPE samples preoxidized before water-tree tests grew much less and much shorter trees than nonoxidized samples. This is another evidence that oxidation is not the culprit. Heating XLPE several hours over the melting temperature in air will induce many morphological changes in the material. The synergistic effects between morphology, temperature, and oxidation are not yet well understood, but are nevertheless present.

Water and Temperature. Among test cells, only type B maintain water contact on the two sides of the samples, and this considerably affects tree growth at high temperature as shown by Matey et al. (54). Tests performed for the same time duration with a type-A cell (water on one side) indicated that water trees grown at 70°C were longer than at 22°C. On the other hand, exactly the inverse relation was observed when trees were grown in a type-B cell (water on 2 sides). Another difference between the two setups is the fact that the solution on one side of a type-B cell is maintained continuously at 70°C.

Temperature Gradient and Saturated Ionic Solution. Since there happens to be a synergistic effect between water and temperature, Patsch and Paximadakis (55) have gone a step

Table 1. Major Parameters Affecting Water Treeing and Their Impact According to the Three Main Types of Models

	Oxygen		Solution		Material		Voltage		Frequency		Temperature		Mechanical Stress	
Parameters	Air	N_2	Water	Ions	PE	Modif.[a]	≈5 kV	≥5 kV	60 Hz	>1 kHz	20°C	70°C	No	Yes
Chemical models	++			++		+						+		
Dielectric[b] models	?		+	+		+		++		?		+		+
Mechanical models				?		+		+		++		?		++

[a]Modified morphology, including annealing, different crystallinity, special additives, etc.
[b]Includes dielectric heating, dielectrophoresis, etc.
++ Strong influence; + moderate influence; ? may have some influence.

further; they aged cable samples soaked in water under temperature gradients. A saturated solution of sodium chloride maintained on the outside of the cable led to a reduction in the number and size of water trees compared to the situation where tap water was used. These results contradict those obtained at constant temperature and with a smaller concentration of ions. Patsch advocates that water treeing is due to a combination of dielectrophoresis and water precipitation enhanced by the presence of salt impurities.

Electrical Field Value and Frequency. In type-A cells, the local electric field depends on the radius of the tip of the voids impressed in the samples. Filippini and Meyer (56) have shown that tree growth varies with this radius and also with the frequency of the field. In other words, it is difficult to evaluate the impact of each parameter precisely. The observed exponential relationship between the number of field cycles and the length (and density) of water trees (28) suggests that frequency acts as a mechanical fatigue parameter. High values of the electric field may also induce some local overheating (36), which combined with mechanical fatigue may cause microcracks to form, eventually leading to water trees.

Additive and Mechanical Strength of the Material. Sletbak and Ilstadt (57), Patsch (55), and Filippini (56) suggested that water treeing is associated with the mechanical properties of polymers, and its growth rate is increased by tension. Auckland et al. (58) have shown that an increase of plasticizer content results in a decrease of the initiation time because it modifies the mechanical properties of the polymer. Recently, Asano et al. (59) have shown that very-low-density PE (i.e., a polymer with mechanical properties significantly different from those of PE) containing a neutralizing agent generates very few water trees. This suggests synergistic effects between some additives, the polymer's morphology, and its mechanical properties. A comprehensive model should include all these parameters and their occasionally contradictory effects. Obviously, a single stress test does not represent field conditions and cannot lead to a full understanding of such a complex phenomenon. The question is: How does one obtain more pertinent data and more effectively use the enormous amount of data that already exists? The statistical technique, alternately known as *design of experiment, fractional-factorial design,* and the *Taguchi method,* could possibly be of help for the development of a performing and reliable water treeing test.

Design of Experiment and Water Tree Tests

If one intends to perform a complete test with the seven parameters listed in Table 1 (with the possibility of others being added) for at least two different conditions for each, there is a minimum of $2^7 = 128$ combinations. When at least five samples are needed by combination for statistical credibility, this becomes financially intolerable and extremely time-consuming. Statisticians have developed more efficient test plans known as fractional-factorial experiments (60). The various factors are arranged in orthogonal matrices, and it is then possible to reduce the number of tests. For example, the 128 combinations could be reduced to only 16, and, in addition, the interactions between the various parameters could be statistically evaluated. In fact, it is possible to even further reduce the number of experiments by eliminating variables of secondary importance or by not evaluating the interactions between the main parameters. In the latter case, it could be possible to study the seven parameters in water treeing in the only eight experiments depicted by the empty boxes in Table 2. Note that this approach is considered to have lower reliability than a full 16 experiments for seven parameters. The purpose of this article is not to give a full description of the advantages and limits of this technique (for more details, see 60). Among other things, parameters and conditions should not be distributed randomly, and the data interpretation must follow strict statistical procedures. Note that Taguchi matrices are based on the same approach and the only difference is in the signal-to-noise ratio typical of this author (60). The important point here is that although performing only the eight experiments (instead of 128) suggested by Table 2 may appear limiting, there are still several testing combinations that have not yet been attempted.

To give an example of the kind of information on synergistic effects that can be gained from the design of experiments, let us consider a simple case for which we have enough data. Noirhomme et al. (53) reported values for the length of water trees grown at 22°C after 500 h in sodium chloride solutions in oxidized and nonoxidized XLPE cable ribbons subjected to various fields and frequencies. The results shown in the left-hand column in Table 3 is the average value measured in many similar samples. The average tree length value for these eight experiments is then 558.75 μm. The average values for each condition in all columns were also calculated, and they allow us to determine the relative influence of the parameters and of their interactions. A large spread in the

Table 2. Simplest fractional-factorial experiment for the seven parameters (A to G) affecting water treeing. Note that with only eight different experiments, it is not possible to evaluate the interactions between the parameters.

	A: Frequency		B: Oxygen		C: Ions		D: Field		E: Temperature		F: Material[a]		G: Mechanical Stress	
Results	60 Hz	1000 Hz	Yes	No	NaCl	Other	Low	High	22¡C	70¡C	1	2	None	Tension
1		■		■		■	■		■		■			■
2		■		■	■		■			■		■	■	
3		■	■			■		■	■			■	■	
4		■	■		■			■		■	■			■
5	■			■		■		■		■	■		■	
6	■			■	■			■	■			■		■
7	■		■			■	■			■		■		■
8	■		■		■		■		■		■		■	

[a] Material morphology (e.g., crosslinking, annealing, etc.) or additives (tree retardant, plasticizer, etc.)

Table 3. Water tree length obtained under different frequencies (A), levels of oxidation (B), and electrical fields (C) in XLPE ribbons aged 500 hr in 0.05 M NaCl solution at 22°C. Note that with eight experiments, it is also possible to evaluate the interactions (AB, AC, BC, and ABC) between the three main parameters.

	A: Frequency		B: Oxidation		C: Field		AB		AC		BC		ABC	
Length, μm	60 Hz	1000 Hz	No	Yes[a]	1.5 kV /mm	5 kV /mm	1	2	1	2	1	2	1	2
300	300		300		300			300		300		300	300	
400	400		400			400		400	400		400			400
320	320			320	320		320			320	320			320
340	340			340		340	340		340			340	340	
600		600	600		600		600		600			600		600
950		950	950			950	950			950	950		950	
520		520		520	520			520	520		520		520	
1000		1000		1000		1000		1000		1000		1000		1000
Mean 558.75	350	767.5	562.5	555	455	682.5	562.5	555	475	642.5	547.5	570	537.5	580

[a] Preoxidized for 800 h in air at 130°C prior to testing.

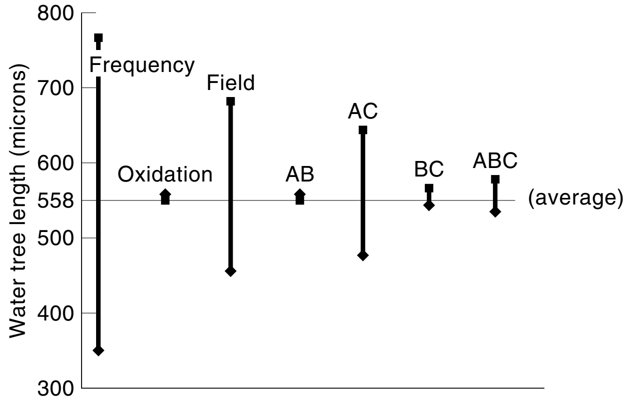

Figure 7. Graph of the estimated effects (from Table 3) for frequency, field, and oxidation on the length of water trees grown in XLPE cable ribbons.

mean values of the two conditions for one given case (parameter or interaction) suggests that it significantly affects the phenomenon under study. This is sometimes more evident when it is represented graphically, as in Fig. 7. Obviously, the main parameter affecting water tree growth in these tests, that is, the one with the largest spread between the mean values of the two conditions, was the frequency (column A). The electrical field had a smaller influence but the combination of frequency and field (column AC) was almost as great as the field effect (column C). Interestingly, when the influence of field is correctly isolated (as in Fig. 7), it appears to be much more significant than it is usually assumed. On the other hand, Fig. 7 shows in clear statistical terms that oxidation (column B) had a negligible influence on water treeing, contrary to what is often claimed. Note that the same approach could be used to evaluate the influence of the parameters involved in the water tree initiation process. It is our belief that the technique of design of experiments could be extremely useful, not only for water-treeing tests, but for all types of tests involving many parameters. It is not only useful to interpret data but it is especially useful for planning efficient and reliable experiments.

DATA ANALYSIS

Data collection and treatment has been completely changed by personal computers and modern commercial data acquisition systems. One important modification they brought is that it is now possible to store a large database continuously, which is potentially useful for statistical purposes. Another positive change is the possibility of rapidly treating very noisy signals to retain significant data only. This is particularly useful for partial discharge measurements, which are often buried in electromagnetic noise; this explains the huge amount of research being done in this area (61). Regardless of the type of acquisition technique, the experimental data still has to be interpreted.

Statistical Distributions

One objective of any accelerated aging test is to verify whether repeated testing of many identical specimens will generate identical or nearly identical, results. The difference, if any, should reflect sample inhomogeneities induced during processing or inherent in the material tested. Thus, a statistical interpretation of the results may be helpful for determining the tolerance bounds of acceptability or rejection.

There are many probabilistic distributions for evaluating reliability, but they could be classified in two broad categories: the extreme value distributions (often using asymptotic functions) and the smallest value distributions, such as the Weibull distribution below which the γ estimator has been set to 0 (62). In the latter case, the probability $P(t,V)$ of failure at time t under constant voltage V is

$$P(t,V) = 1 - \exp[-(t/\alpha)^{\beta}] \tag{11}$$

where α is the scale parameter and β is the shape parameter. There are endless variations of this function, and there are many possibilities of producing estimators of α and β (39,62). One approach is to use the maximum-likelihood method by computing the 90% confidence bounds using the conditional interval procedure of Lawless (62). Another approach was published by Hirose (9). Results should then yield straight lines in ln (probability)/ln t graphs. It is very common to analyze voltage breakdown results obtained at constant time by substituting V instead of t in Eq. (11); results are then plotted as ln (probability)/ln V. Another form of the Weibull function often used is

$$P(L,V) = 1 - \exp[-(L/\alpha)^{\beta}] \tag{12}$$

where L is the length of water trees, for example, grown under constant voltage. In this case, plots of ln (probability)/ln L should yield straight lines. However, straight lines are rarely observed unless a very high amount of data is available (39). It is customary to take the 63.2% probability value as the most representative value when using the Weibull distribution.

Occhini (63) has proposed the modified Weibull distribution to explain cable endurance results

$$P = 1 - \exp[-(ct^{\alpha}V^{\beta})] \tag{13}$$

where c is an adjustable constant. The inverse power law between time and field sometimes observed (8) in aging tests can be deduced from Eq. (13) (63). However, Hirose (9) has shown that Eq. (13) is valid only under some limited circumstances and it should not be considered as a two-dimensional probability function.

Confidence Limits

One very popular method used to check the validity of the mean value deduced from various tests is the Student t-test (60,61), which is based on a symmetrical distribution. Boundaries of the confidence limit and calculated mean values are tabulated in any statistical handbook. Of course, it is always highly recommended to calculate the standard deviation (i.e., the square root of variance) of a series of data points, especially when there is some spread in the values. This can be done with almost any electronic calculator. Another method is the analysis of variance, which breaks down the total variation into its appropriate components. The simplest case is known as no-way analysis of variance, and it includes only two components: the variation of the average and the variation of the individual data points around the average (usually called the experimental error). Other methods can be found in any statistical handbook (e.g., 60,61).

Finally, the signal/noise ratio (SNR) introduced by Taguchi can also be of some interest to determine limits of confidence, especially when using the design of experiment technique. As in the no-way analysis of variance, the SNRs are derived from quadratic functions, and they take into account the amplitude of the variation and its variability around the average value. Taguchi suggests three main types of ratio for three different responses: the minimal, when the response must be as small as possible; the maximal, when the response must be as large as possible; and the nominal, when variability is as small as possible. In the above example on water tree length (Fig. 7), the appropriate SNR would be the maximal response

$$\mathrm{SNR}_{\max} = -10\log[\textstyle\sum(1/y^2)/n] \tag{14}$$

where y is the value measured in each of the n similar tests performed under the same conditions. A large SNR for results in Table 3, column A would add more confidence to our contention that frequency is a main factor in water treeing. Western engineers are reluctant to use some of Taguchi's tools, and generally tend to favor the analysis of variance over the S/N ratios. Since results obtained with the two approaches are almost similar, the important point here is to use the statistical tool with which one feels more comfortable.

CONCLUSION

A very fast overview of some accelerated aging tests has been made with a special emphasis on the importance of adequately planning tests before actually starting them. Aging tests are in fact time-consuming and expensive. Time spent in clarifying needs and attempts is never lost. In that respect, the design of experiments or Taguchi techniques are worth the time invested in understanding them thoroughly.

One major conclusion regarding most electrical aging tests is that there is a very limited number of reliable models. In addition to poorly describing processes of great industrial significance, the lack of dependable models affects standards and accelerated aging tests. As shown by the water treeing example, there are so many parameters affecting these tests and there are such complex synergistic effects that it is not surprising that there are few comprehensive tests yielding nonconfusing results.

Finally, if the time used to plan appropriate tests is well spent, it becomes absolutely essential to spend time organizing and interpreting data in convincing statistical terms. A brief review of the main statistical distributions and of some methods used to establish limits of confidence was made. To conclude, it may seem an easy thing to conduct an accelerated aging test on solid dielectric materials but to obtain conclusive and useful data is a hard, sometimes frustrating and exhilarating task requiring dedication, skills, and above all a lot of common sense. In other words, this is an area that offers some considerable challenges to engineers and scientists.

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