

The Role of Degassing in XLPE Power Cable Manufacture

Key Words: XLPE cables, crosslinking byproducts, degassing, extrusion linespeeds, weight loss, HPLC, GCMS, electric breakdown strength

Background

The undergrounding of energy transmission cables is widely recognized as a good means to provide reliable supplies of power at a low total cost [1], [2]. As utilities increasingly acknowledge this and install many more high voltage (HV) and extra high voltage (EHV) cables, they will face a major challenge: namely, sourcing the increased amount of high quality power cable with the cable manufacturing infrastructure that exists today. Analysis [3] shows that it is practically possible to reduce the effect of all of today's constraints to productivity and boost output. At the highest cable voltages, the output and the response time are often determined by the byproduct removal (degassing) procedures. Ensuring that the most appropriate procedures are used enables manufacturers to deliver the amounts of cable needed, without recourse to extra capital investment.

Yet safe and productive changes require that the degassing problem and its potential solutions be fully understood. This article focuses on a range of elements critical to this process; from the fundamental chemistry, through computational and measurement techniques to the solutions that are in use today.

However, before commencing the discussion, it is useful to be clear on terminology. The process whereby the byproducts of the crosslinking reaction are removed is almost universally termed degassing. Although there is no doubt that gaseous byproducts (primarily methane) are removed during this procedure, this is not the only effect. Within the process all byproducts are redistributed and the solid/waxy byproducts (acetophenone and cumyl alcohol) are reduced in level. Therefore, when the term degassing is used in this paper, we use it to refer to the reduction and redistribution of all crosslinking byproducts, whether they are gaseous or solid.

Crosslinking of XLPE

Polyethylene (PE) is a long chain polymer manufactured through the polymerization of ethylene gas [4]. At its introduc-

T. Andrews, R. N. Hampton

NEETRAC, Georgia Tech, USA

A. Smedberg, D. Wald

Borealis AB, Sweden

V. Waschk

NKT Cables, Germany

W. Weissenberg

Brugg Cable, Switzerland

Degassing contributes greatly to the quality of power cables by improving the certainty in electrical testing and improving the dielectric properties.

tion, thermoplastic PE was very popular, compared to paper insulation, as insulation for cables because of its low cost, electrical properties, processability, moisture and chemical resistance, and low temperature flexibility. A significant design issue with PE [5], in its thermoplastic state, was that its temperature of operation was limited to 70°C. Consequently, it could not match the temperature rating of paper-oil insulated cables. This problem was solved with the advent of crosslinked polyethylene (XLPE), which had the ability to match the thermal rating of paper-oil insulated cables and provide the freedom from the

hydraulic problems of oil-filled cables. When using XLPE as cable insulation, it is possible to achieve a rated maximum conductor temperature of 90°C and a 250°C short circuit rating.

The polymers used in XLPE compounds for medium voltage (MV) to EHV cables are produced by high-pressure tubular reactors. This reactor technology has been proven over a long time to provide an optimum balance of electrical, physical, extrusion, and crosslinking properties. The crosslinking of LDPE with DiCumylPeroxide (DCP) to form XLPE was first accomplished by Gilbert and Precopio in 1955 at the GE Research Laboratory located in Niskayuna, NY [4].

The long chain molecules become linked during the curing or vulcanizing (named after Vulcan the god of heat) process to form a material that is mechanically stronger, with similar electrical properties and capable of operating at higher temperatures than LDPE. The basics of the thermally activated crosslinking mechanism are shown in Figure 1 for one of the less complex approaches to crosslinking. A more complete discussion of the physical/chemical aspects of XLPE crosslinking will be the subject of a complementary paper by many of the same authors at a later date.

Some of the characteristics of the commonly used insulation materials that can be crosslinked in this manner are given in Table 1.

The data presented in Table 1 were generated in a Göttfert™ Elastograph at 180°C. Hot set is the elongation resulting from a 20N/cm² load, attached on a crosslinked sample at 200°C.

Figure 1 shows a number of important points with respect to peroxide crosslinking. First, it can be seen that one –O–O– bond (generally one per peroxide molecule) could at a maximum give rise to one chemical crosslink in the network structure. Second, every decomposed molecule of peroxide, whether it provides a crosslink or not, gives at least two byproduct molecules. These byproducts are contained within the structure. If they are not constrained by a high external pressure (most usually hot nitrogen), the byproducts form bubbles in the molten insulation, thereby leading to partial discharges and electrical failures. Table 2 shows typical properties of these main byproducts. The exact proportion of the byproducts will depend upon the exact proportions of routes (a) and (b) in Figure 1, followed by the peroxide during its decomposition. Thus, the exact time/temperature profile insulation experiences is of vital importance.

Table 1. Characteristics of the materials discussed.			
Polymer Type	Usage	Material characteristics	
		Typical hot set (%)	Typical torque when crosslinked (Nm)
Low density polyethylene	MV to EHV	50 – 60	0.62 – 0.67

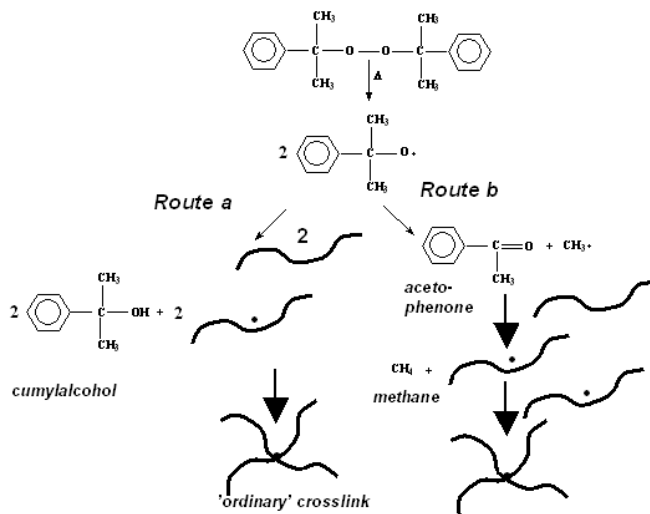


Figure 1. Peroxide initiated crosslinking of PE.

Degassing XLPE cables

The external applied pressure ensures that byproducts do not form voids while the cable insulation is being crosslinked in the continuous vulcanization (CV) tube. This pressure is maintained until the insulation is sufficiently cooled for the byproducts to remain incorporated within the solid. When the crosslinking is completed, the insulation will have an approximately constant level of byproducts throughout its thickness as expected from the uniform distribution of peroxide at extrusion. This distribution will change with time after crosslinking as these byproducts will diffuse out of the cable, depleting the exposed layers first then the inner layers. This process starts within the hot section of the CV tube, but most of the loss is accomplished outside of the CV tube. Consequently, all cables that are crosslinked using organic peroxides will retain some of the decomposition byproducts within their structure [3]. The precise distribution and level of the byproducts will depend upon the cable type, production technology, and process conditions. Figure 2 shows the distribution of byproducts throughout the insulation thickness for cables of selected voltage classes produced using the same insulation material.

A number of features are clear from Figure 2:

- Prior to the start of the degassing procedure, some level of byproducts are lost from the inner and outer surfaces into the CV tube gases or liquids or the conductor.
- The rate of loss of byproducts is not the same from the inner and the outer surface of the cable — generally most losses occur from the outer surface.
- The byproduct levels are inherently different, see midpoint concentrations, for different voltage classes (even when the same insulation material is used). The reason for this is two-fold. First, crosslinking is completed in different parts of the CV tube for MV and HV cables (complete within 45% and 60% of the tube length for MV and HV, respectively), allow-

Table 2. Properties and concentration of different XLPE byproducts (LDPE data provided for comparison).

Component	Reagent grade				XLPE cable	
	Boiling point (°C)	Melting point (°C)	Permittivity	Electrical Conductivity at 80°C ($\Omega^{-1}\text{cm}^{-1}$)	Proportion of total byproducts (Wt %)	Proportion of total byproducts (Vol %)
Methane	-162	—	—	—	0.08	0.084
Acetophenone	202	19 – 20	17	$5 \cdot 10^{-9}$	0.6	0.44
Cumylalcohol	215 – 220	28 – 32	8	$1 \cdot 10^{-10}$	1.2	0.84
Water	100	0	80	—	0.08	
LDPE	—	80 – 105	2.3	$< 1 \cdot 10^{-16}$	98.1	98.6

ing different opportunities for the insulations to lose byproducts. Second the time/temperature profiles experienced by the insulations are different, leading to different ratios of the reaction routes (a) and (b) from Figure 1.

These byproducts will, to some degree, affect the performance of cables and their associated accessories. The issues associated with these byproducts often include the following:

A. Mechanical considerations

Methane usually is removed because it constitutes a health and safety issue due to its flammability during the jointing/installation procedures. However, the gas also can lead to issues in service [5], [6]. As the cable operates, the gases are liberated. If they are constrained by a metal barrier (universal in HV and EHV cables and increasingly common at MV), the gases can travel along the cable to the accessories (joints or terminations). Once in this region they build up underneath exerting a pres-

sure. Most modern accessories use elastomeric components to exert a high mechanical pressure on the interface to the insulation and thereby suppress partial discharges. The gas pressure will work against the compression of the component and make partial discharges more likely. In the worse case, this would lead to failure. Figure 3 shows the relationship between the residual methane content of the cable and the pressure that can be exerted at different temperatures. Experience has shown [6] that a gas pressure of 1 bar gives very acceptable service and test performance. In this case, the cable must be thermally treated to reduce the methane content, at jointing, to below 30–50 ppm.

Until fairly recently, most workers have considered the case in which the strong metal sheath retains the liberated gases. There are cable designs that increasingly use thin and, consequently, mechanically weaker, compared to lead and corrugated aluminium, aluminium foils as the moisture barrier. In this situation the gas pressure may be sufficient to distort the foil/jacket combination itself. This distortion can affect both the foil and

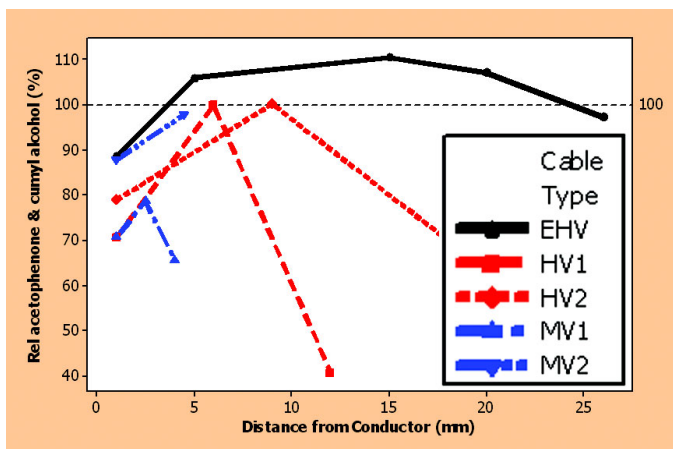


Figure 2. Spatial distribution of byproducts in cables of selected voltage classes produced using the same insulation material. No degassing procedure has been used for these cables. Data normalized to 100 at the HV midpoint level.

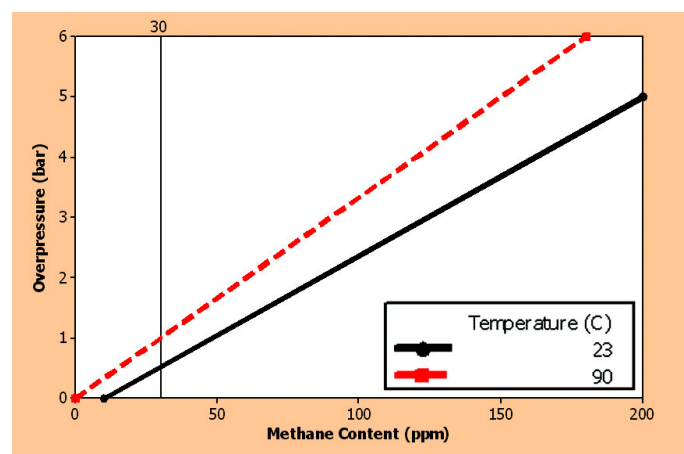


Figure 3. Effect of residual gas content on pressure under accessories [6].

	Tan δ Insulation (10^{-4})	DC resistance semicon (Ωm)
Initial	3.5	0.1
Impregnated with 2.3 wt% acetophenone (approximately four times larger than real life)	141	
Impregnated with 2.3 wt% cumyl alcohol (approximately two times larger than real life)	299	10

the foil overlap joint. Thus degassing is important to ensure that there is no deformation when the cable sees elevated temperature in operation. In addition to the proper level of degassing, the strength of the combination can be increased through the use of a high-density polyethylene (HDPE) jacket; a hardness level of Shore D > 59 has been found to be particularly effective.

B. Dielectric Considerations

The byproduct components such as cumylalcohol, water, and acetophenone are polar in nature. This means they will modify the dielectric and conduction properties of the material that includes them. The level of this modification will depend upon the concentration (volume fraction), the dielectric properties of the components, and the manner in which they are incorporated into the media. The effect is most often discussed for insulation materials, however, these polar species also effect the semiconducting materials (Table 3) for which they could increase the electrical resistance. Semiconductive materials are themselves

crosslinkable and will have their own similar byproduct load. However as they are on the outside and experience some of the highest temperatures, these levels are depleted very rapidly in the CV production process. In this case, subsequent degassing from the insulation could re-establish the byproduct levels, although the largest effect is likely within experiments that reintroduce byproducts into structures.

Table 3 shows quite noticeable dielectric effects when byproducts are reintroduced into a crosslinked matrix. However, the concentrations involved are very much higher than seen in practice, and there is a real issue associated with chemical changes (degradation) of the impregnants during the impregnation at high temperatures. When they become degraded (increased water content [7]), the reagent grade byproducts become much more conductive, and thus the loss performance could become anomalously high. In addition, the location of the byproducts in the polymer will have a significant effect. One group [8] found that there was a difference of three orders of magnitude in the dielectric loss ($\tan \delta$) between the same level of byproducts when they had been incorporated into the bulk or just applied to the surface. It was seen that application of the byproducts just to the surface causes the larger increase.

Initial inspection of Table 2 would suggest that the water component might have the largest effect on the dielectric properties due to the high permittivity. However, this would not allow for the effect of different byproduct concentrations. It is possible to better understand the combined effects through calculation of the permittivity of each added component using many existing, elegant semiempirical and theoretical treatments [9]. However, the simple weighted mixture approach Equation (1) is sufficient to understand the concepts. The calculations (Figure 4) show that acetophenone has the largest effect, as it has an intermediate permittivity and volume concentration within the matrix. This approach has taken the basic case of a single byproduct species within an LDPE matrix; however, it would

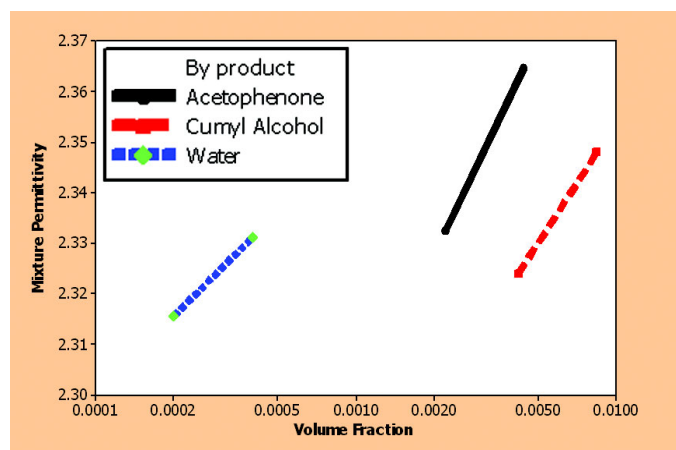


Figure 4. Effect of selected single byproduct concentrations on the calculated (1) mixture permittivity with LDPE as the matrix. The upper volume fractions are those estimated in Table 2 for freshly manufactured XLPE; the lower values represent the case in which the byproducts have been reduced to 50% of their original values.

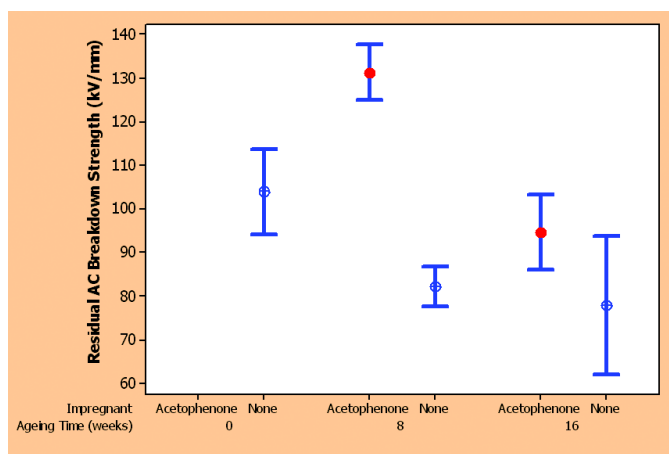


Figure 5. Effect of wet aging time (10 kV/mm 20°C) and impregnation on the AC electrical breakdown strength of Rogowski-shaped test objects [10].

be interesting to compute the effect of sequentially adding the full mixture of byproducts.

$$\epsilon_{composite} = (1 - \Phi)\epsilon_{matrix} + \Phi\epsilon_{byproduct} \quad (1)$$

Where ϵ is the permittivity and Φ is the volume fraction.

C. Electrical Test and Performance Considerations

The crosslinking byproducts are polar in nature and thus affect the dielectric properties of the XLPE. In addition, they also affect the high-field breakdown performance in both wet (Figure 5) and dry (Figure 6) conditions, generally resulting in a temporary improvement in breakdown strength.

Figure 5 shows the range of breakdown data for Rogowski-shaped test objects, which were impregnated with pure acetophenone then aged in accelerating wet conditions. The data show that the improvement is very impressive at short times, with almost a 75% improvement over the untreated case. However, it is equally clear that by week 16 the improvement has largely disappeared, though some benefit remains.

Figure 5 also shows the effect under the conditions of interest (wet) for MV applications [10]. The case relevant to a high voltage insulation, installed in dry conditions, is shown in Figure 6. The experiments start with the true mixture of byproducts after crosslinking, which are gradually removed by treatment at high temperatures. This experiment is different from that represented in Figure 5, which describes impregnation of the matrix with a single chemical. In this experiment, tree inception has been determined using an opposed double-needle (Ogura type) configuration. A slowly rising AC voltage is applied to the samples. The test is terminated once an electrical tree starts to grow and partial discharges have been detected. The data show

Added cumene content (Wt %)	Added acetophenone content (Wt %)	AC		Impulse	
		Weibull scale (kV/mm)	Weibull shape	Weibull scale (kV/mm)	Weibull shape
0	0	220	10.4	674	6.9
0.32	0	—	—	665	7.9
1	0	—	—	606	10.5
0	1.15	291	6.5	—	—

that stability is achieved after about 72 hours, and the true electrical tree inception voltage can be determined as approximately 10–14 kV. The initial (or untreated) value is markedly higher at 22 kV than the final 10–14kV. The 0 hour samples did not initiate an electrical tree at the maximum voltage available, even when very sharp needles were used to provide the defects. The data in Figures 5 and 6 show that the crosslinking byproducts improve the breakdown strength. However this improvement is not universal. Studies [11] on both AC and impulse performance of press moulded plaques showed different effects. The tests were conducted by adding different byproducts (Table 4) to highly degassed XLPE. The results show that the additions decrease the breakdown strength (Weibull scale) and the scatter in the data (increase in Weibull shape) for impulse whereas AC results show an increase in breakdown strength (Weibull scale).

These results (Figures 5, 6, and Table 4) clearly show that, unless the cable insulation is degassed, it is not possible to determine the true threshold for tree initiation. This is a significant experimental issue for anyone wanting to carry out electrical or water treeing studies on XLPE or ethylene propylene rubber (EPR) materials. The effect is recognized when testing full-sized cables for water tree resistance; CENELEC Std HD605 has introduced a pre conditioning protocol and IEEE Std 1407-1998 cautions users on these issues.

It generally is believed that the temporary improvement in performance seen in Figures 5 and 6 comes from two possible sources: filling of voids and stress modification around defects. In the first case, gaseous byproducts will, if any voids are present, tend to increase the electrical tree inception stress by raising the pressure within the void. Waxy byproducts also will tend to diffuse to any void surface and deposit on the inner surface where their effects could be twofold: decreasing the size of the void and affecting the conduction and emission from the wall surface. In either event, the breakdown strength of the void is increased.

Even in the absence of a void and partial discharge, the byproducts have an influence when stress enhancing contaminants are present. Calculations [12] show that the conductivity, which will be effected by the polar byproducts, at high stresses is sufficient to reduce the local stress in the defect vicinity. The effect will be that the breakdown strength is improved over the field that would be calculated theoretically.

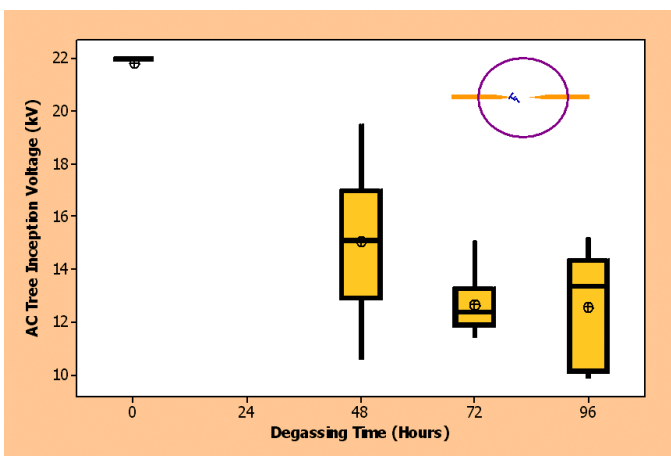


Figure 6. Effect of degassing on the AC electrical tree inception voltage (in an opposed double-needle test) for HV/EHV insulation material. The samples were 3-mm thick plaques and were degassed at 90°C to remove the byproducts. Inset, top right, shows the experimental arrangement of the two opposed metal needles and the electrical tree growing between them.

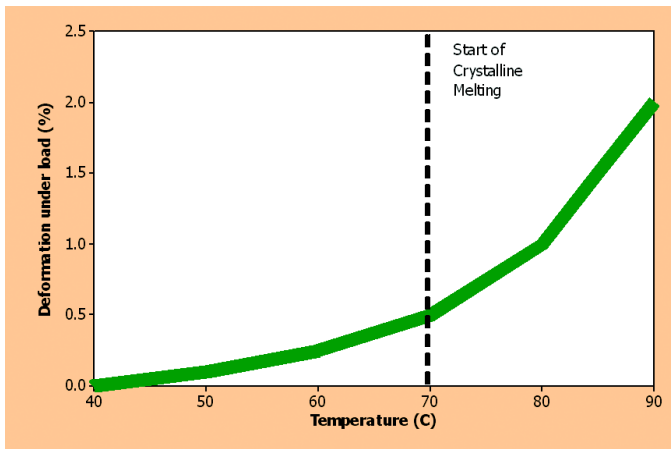


Figure 7. Effect of temperature on the expansion, and thus softening, of XLPE cable insulation (MV to EHV).

When in operation, the insulation of XLPE cables will be at temperatures between 50°C and 90°C, resulting, unfortunately, in the loss of these byproducts in service. Thus any apparent positive effects from filled voids or shielded defects will be dissipated (see the effects at longer times in Figures 5 and 6). Clearly the presence of voids or defects within an insulation that cannot be detected by partial discharge or voltage tests is a real and practical concern. Consequently, there is an advantage for all of the byproduct components (gaseous and waxy) to be reduced to a low and stable level to be certain that truly reliable and representative electrical results are obtained during routine testing.

The Degassing Process

To ensure that the cables have the correct dielectric properties and that any voids are free of gas, cable manufacturers ensure that sufficient degassing (sometimes termed vaporization or conditioning) has occurred during the production process [3], [5]–[7]. This means that, when finally tested before release, all parties can be assured that the true properties of the complete cable are measured. The increased thickness of transmission-class cables and the high boiling points of the byproducts (Table 2) imply that any natural degassing processes must be augmented by high temperature treatments. Such treatments are used before the metallic sheath is applied as its presence dramatically reduces the rate of degassing. It is worth noting that for many MV cable designs (thicknesses and operating stresses) and process flows, it has long been assumed that sufficient degassing may occur in the cable manufacturing processes. It is interesting to note that the importance of degassing is recognized in the ICEA specification, which requires a minimum time of 5 days between testing and the finishing of the cable.

Degassing for large cables is almost universally accomplished in large, heated chambers. These devices can consume considerable amounts of energy and factory space. The chambers are well ventilated to avoid the build-up of flammable methane and ethane, for obvious safety reasons. Sometimes, to assist the cable

in attaining the required temperature quickly, the heated chambers are augmented by conductor heating. However, experience has shown that conductor heating on its own is rather ineffective as a method of degassing; in this situation, desorption is limited by the lower temperature on the outer surface of the cable.

The temperatures used for practical degassing can range between 50°C and 80°C, with 60°C to 70°C being the most preferred range. The range between 70°C and 80°C has been shown to work reliably only for smaller MV cables. However, when degassing a cable (especially at high temperatures), very considerable care must be exercised not to damage the core. The attendant thermal expansion and softening of the insulation (Figure 7) have been shown to lead to undue deformation of the core (causing flats or destroying the outer semiconducting layer). This deformation can lead directly to failures during routine electrical test, thereby negating any benefits of degassing. Additionally, a set of inappropriate degassing times and temperatures can result in damage (from too high a temperature) which is not detected during the routine test due to incomplete degassing (defects are masked). Therefore, it is very common for the degassing temperature to be decreased as the cable weight is increased, this is particularly important for HV and EHV cables.

Measurement of Byproducts in XLPE

One of the most crucial steps in understanding degassing is the measurement of the initial state of the cables and how any treatments proceed with time. The progress of degassing can be conveniently followed on full-sized cables by weight change ([7] provides a particularly good discussion), Fourier transform infrared spectroscopy (FTIR) and high pressure liquid chromatography (HPLC) or gas chromatography mass spectrometer (GCMS) methods. Table 5 gives most of the important issues associated with the different test methods.

Experience with a large number of analyses for many different cable designs has shown that:

- Weight loss on a full cable is the most practical and simplest way of determining the byproduct level within XLPE insulations for a range of conditions.
- HPLC is the best method for determining the level of individual solid byproduct components.

Degassing Calculation

Direct measurements of degassing are extremely useful and essential. As discussed earlier (Figure 2), the details depend upon cable material, cable design, production line, process conditions and temperature experienced by the cable (Figure 8). However, it is not practical to conduct such measurements for all different cable designs or potential treatment temperatures. Thus, it is a very common and useful practice to use computational methods to extend the fundamental understanding derived from degassing experiments.

The desorption of the byproducts (i.e., the change of concentration C at time t and position x) of the crosslinking reac-

Table 5. Experimental methods for determining byproduct concentrations.		
Method	Advantages	Concerns
Weight loss – thermo gravimetric analyzer (TGA) GENELEC HD632	Fast Able to provide data for different parts of the insulation	Requires special equipment – thermo gravimetric analyzer Considers small insulation samples – 100 mg Uses non-practical temperatures Not possible to separate different byproduct species Loss of byproducts during sample preparation
Weight loss – cable weight	Simple Looks at a whole cable Uses practical degassing temperatures Figures 8 and 12	Not possible to separate different byproduct species Takes considerable time to reach equilibrium Loss of byproducts during sample preparation
Extraction high pressure liquid chromatography (HPLC)	Looks at different byproduct species Good for non-gaseous byproducts Fast Able to provide data for different parts of the insulation Figures 2 and 9	Requires special equipment – HPLC Considers small insulation samples – 1 g Calibration can be tricky Affected by variations in extraction yield Loss of byproducts during sample preparation Not possible to measure gas simultaneously
Volatalization – gas chromatography mass spectrometry (GCMS)	Looks at different byproduct species Good for gaseous byproducts Fast Able to provide data for different parts of the insulation	Requires special equipment – GCMS Considers small insulation samples – 1 g Difficult to calibrate for all species at the same time Uses nonpractical temperatures Effected by variations in extraction yield Loss of byproducts during sample preparation
Gas Volume estimation after volatalization	Simple Looks at a whole cable Directly relevant if practical temperatures are used	Difficult to interpret — gas losses and condensation effects Often uses nonpractical temperatures Species decompose/mutate during measurement Loss of byproducts during sample preparation
Fourier transform infrared spectroscopy (FTIR)	Can look at many byproducts (spectral peaks) at the same time Minimal propagation Cross-sectional scans easy to acquire	Large effect from surface concentrations Qualitative calibration can be difficult

tion can be simply described mathematically using Fick’s Law.

$$\frac{\partial C}{\partial t} = \rho D \nabla^2 C \quad D = D_0 \exp\left(\frac{-E_D}{RT}\right) \quad (2)$$

Here D represents the diffusion constant at temperature T , E_D is the temperature dependent activation energy, ρ is the ma-

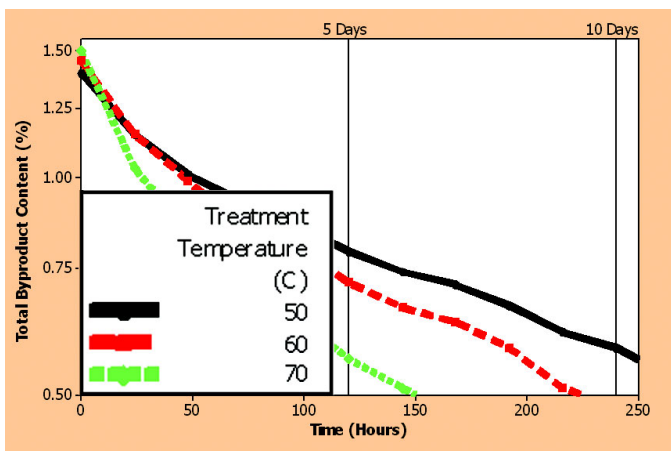


Figure 8. Effect of temperature on the change in weight with time of a MV (5.5-mm insulation) XLPE cable.

terial density, and R is the Universal Gas Constant. D_0 is a prefactor that relates the measured diffusion data at different temperatures. Elevating the treatment temperature (T) speeds the diffusion, thereby reducing the degassing times. The various byproduct species (gasses, liquids, waxes) of interest each

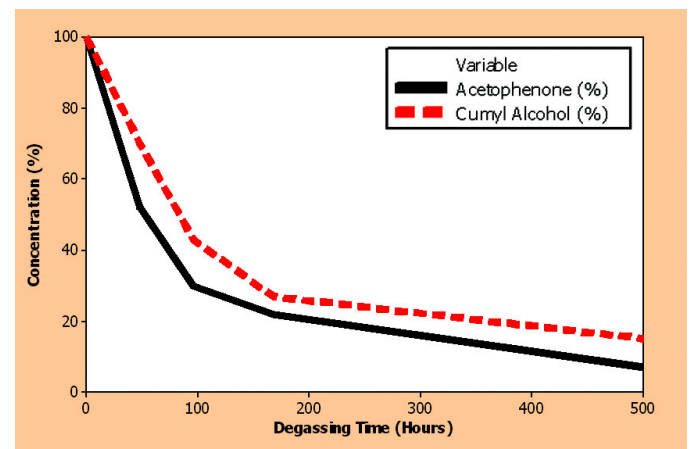


Figure 9. Effect of time of degassing on the total acetophenone and cumyl alcohol content as measured by HPLC – average level for MV cable.

have different activation energies and prefactors, resulting in different rates of diffusion for each byproduct component.

The differential equations are normally solved using either analytical solutions for simple geometries (infinite flat plane) or numerical methods for a prescribed set of boundary conditions. The most common solution method uses straightforward finite-element modeling (FEM), either for the steady-state case or for the more complex transient case and coupled electrical and thermal effects. The standard FEM approach has been used by the authors, who found that a one-dimensional model with axial symmetry is particularly suitable for investigation of the transient degassing case in cable structures. A number of calculations have been performed to examine the effect on degassing time due to different cable designs (voltage class and conductor size), static temperature gradients, and multilayer structures. It has been found that these all can be conveniently modeled using the FEM approach for a variety of diffusing byproducts.

One critical aspect, as noted above, of calculating the distribution of byproducts is the selection of correct boundary conditions for the FEM model. In principle, three types can be used:

- Degassing occurs freely from both the outer and inner surfaces.
- Degassing occurs freely from the outer surface, but it is completely blocked from the inner surface due to the presence of the conductor and any strand-blocking materials.
- Degassing occurs freely from the outer surface, but it occurs in a very constrained manner from the inner surface.

Experimental data in Figure 2 shows that in real cables more byproducts are lost from the outer surface than into the conductor. Thus, the third case is most applicable for numerical solutions. However, it can be very difficult to determine the precise condition for the inner surface as this will depend upon the na-

ture of the conductor and any tapes or water blocking used. Thus, the authors prefer to adopt the second type of boundary condition. This has the advantages of computational simplicity and the fact that the predictions will inherently be slightly conservative.

In this study, it was noted that byproducts diffuse through the semicon screen materials faster than through the insulation. Thus, considering this thickness as a layer with a separate material yields slightly shorter times than would have been calculated if the insulation parameters had been used for the whole polymer thickness.

As typical output from FEM calculations, Figure 10 shows the concentrations of various diffusing species at 80% of the way through the thickness of the insulation as a function of time at room temperature. Figure 11 shows the case for a multilayer (semicon – insulation – semicon) structure when two different time/temperature protocols are used.

The simulations in Figure 10 show a number of well-known features:

- the times involved are rather long, even for a small cable;
- the different species diffuse through the insulation at different rates.

It should be noted that the data in Figure 10 was calculated at 80% of the distance through the insulation. Points nearer the conductor will diffuse much more slowly. Additionally, these calculations were performed assuming sufficient air flow around the cable undergoing degassing so that the byproducts are removed from the core surface. Multiple layers of cable on a reel, for example, could impede air circulation, resulting in longer degassing times.

Many of the effects reduced by degassing are related to the absolute level of byproducts in the insulation (Figure 12 and Table 6). Thus, in most practical cases, we are interested in the time to reach a prescribed level. The level required will depend upon the details of use (MV, HV, and EHV) and the cable system. Within the study reported here, we find that a useful end point can be taken to be the point at which 50% of the original byproduct levels remain in the middle of the insulation. Table 6 shows how FEM can be used to calculate the time for degassing. The simulations enable the engineer to study the effects on degassing of temperature, the initial byproduct concentration, and the cable design. The levels of 100% and 75% have been chosen for the initial byproduct concentrations as these appropriately model the situation for power cable compounds in use today. Inspection of Table 6 shows a number of interesting points:

- Temperature has a significant effect: increasing the temperature of degassing by 40°C decreases the length of time required to reach a given concentration level by an order of magnitude.
- The final level of byproducts (the end point) has a significant effect on the time required. If an endpoint of 75% of the initial concentration had been chosen, then the times required would be shorter (Figures 10 and 11).

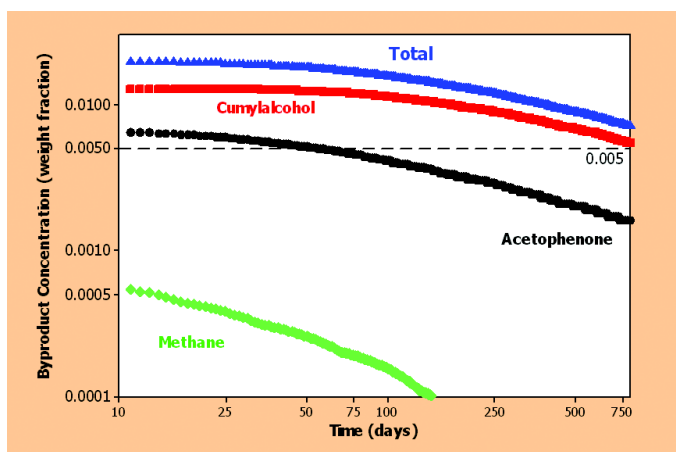


Figure 10. Calculated effect of time for the main crosslinking byproducts located 80% of the distance from the conductor in a MV Cable (20 kV – 5.5 mm wall), log-log scales. The simulation has been conducted at 20°C and has assumed that there is no loss of byproducts from the inner conductor.

- The conductor size does have an influence on the degassing time; however, this likely can be safely neglected for all except the largest EHV cables.
- The initial level of byproducts within the cable insulation once it exits the CV tube has a very profound effect on the degassing requirement; e.g., a 25% reduction in initial level reduces the time by approximately 50%. The initial level of byproducts will depend upon the insulating material chosen, the production line, and the line operating conditions (temperatures and line speeds).
- The degassing times used for degassing HV cables cannot be simply scaled then applied to MV or EHV constructions. This issue can be visualized by considering the HV calculations at 60°C (Table 6), with an initial byproduct concentration of 100%. We see that the time requirement then could be expressed as 2.4 – 2.6 days/mm of polymer. If this requirement then were to be applied to the MV cable of Table 6, it would need 14 days instead of the 5 days calculated by the FEM. In practice this effect is recognized within cable manufacturing with longer degassing requirements (days/mm) as the insulation thickness increases. This finding is confirmed by the analysis reported in Figure 11, which shows the spatial change in byproducts with time.

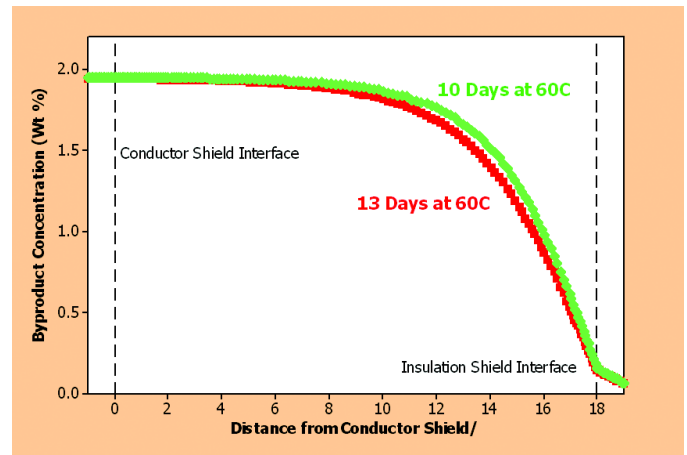


Figure 11. Spatial distribution of byproducts in a HV XLPE power cable (18 mm XLPE, 1 mm semicons) calculated using FEM, including the semicon layers. The simulation has assumed that there is no loss of byproducts from the inner conductor.

Practical Significance and Solutions

A. Effect of Ambient Conditions

It was noted earlier that any beneficial effects of crosslinking byproducts would be transient in nature as the byproducts diffuse out of the insulations over time. Thus, it is interesting to examine the effect of storage at ambient conditions on the remanant byproducts. This effect has been studied using the weight-loss technique on full-sized MV cables. In this study, the major interest was in the ultimate magnitude of byproduct loss, rather than the rate. Thus, to shorten the experimental time, the conductor was removed and degassing was permitted from

both the inner and outer surfaces. Figure 12 shows how the cable insulations lose byproducts under such circumstances as a function of time at 70°C. The data are presented as a percentage loss of the original cable insulation weight. The study has looked at recently manufactured cables, cables taken from long-term storage, and cables that have been stored with and without a jacket.

Inspection of the final levels of the weigh (Figure 12) shows that there has been some loss of byproducts with time under ambient conditions. However, even on MV systems, measurable levels of byproducts remain after many years of storage at ambient conditions. In addition, it is clear that the time to stabilization is reduced as the ultimate level reduces.

Figure 13 shows how the byproduct levels (based on the ultimate weight loss) depend upon the time at ambient conditions

Table 6. Simulation of the time for the acetophenone concentration to fall to 50% of the reference level in the middle of the insulation for two HV cables and one MV cable with selected temperatures and initial Acetophenone concentrations.

Temperature (°C)	Selected concentration (% of ref)	Time required to degas (Days)			Time required per mm of insulation (Days/mm)	
		Case A HV 400mm ² 18mm	Case B HV 1000mm ² 18mm	Case C MV 240mm ² 5.5mm	HV	MV
20	100	540	570	65	31	12
20	75	279	288	33	16	6
60	100	43	47	5	2.5	1
60	75	23	23	3	1.3	0.5

The simulation has assumed that there is no loss of byproducts from the inner conductor. 100% is set as the byproduct level normally found in XLPE insulations.

(time since cable manufacture). This analysis shows a number of interesting features:

- The presence of a polymeric cable oversheath has a significant effect and retards the rate at which byproducts are lost. The cable examined in this study had only a polymeric oversheath. If a metallic foil or sheath were included, an even lower rate of loss would be expected. This result demonstrates the importance of performing the degassing process before the application of any outer coatings. It identifies issues concerning the effectiveness of specifications that require a certain resting time between cable completion (potentially with jackets) and routine testing. The presence of oversheaths within the waiting time could reduce the expected benefits.
- The byproduct concentration reduces with storage time and this modifies the electrical performance. Thus, it should not be unexpected that cable performance changes even if no voltage or temperature stresses are applied. This indicates that care needs to be taken when conducting studies [retained breakdown strength or endurance (ACLT)] on notionally unaged cables as the results can be perturbed by the changing byproduct levels. Some experimental studies deal with this issue by intentionally degassing test samples to ensure that these effects do not confound the analysis [13], [14].
- Weight loss is known to be a good technique to measure degassing. However (Figure 13), some adjustment needs to be made when comparing different insulation technologies, as is clearly shown with the EPR data in Figures 12 and 13. Adjustment is necessary because the density of EPR is significantly higher than that of PE due to the filled nature of EPR. Thus, comparison on an original weight basis can give an incomplete picture of the byproduct levels. A more complete overview can be gained by making a density adjustment to give a volume-based comparison, thereby enabling,

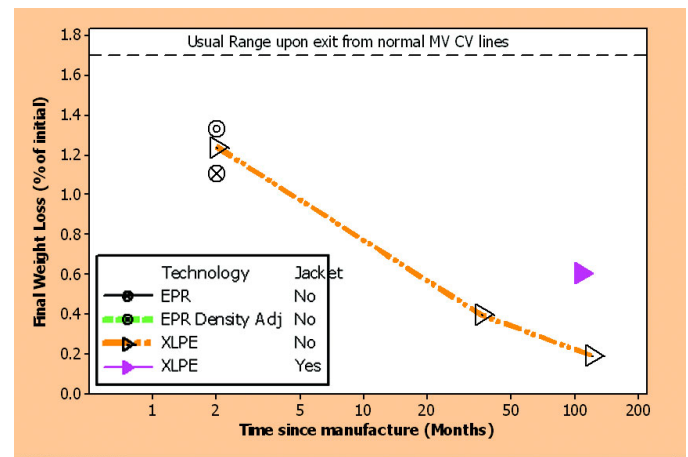


Figure 13. Effect of time since manufacture on the amount of byproducts retained within MV cables. Data from Figure 12.

if desired, examination of filled and unfilled cases. Such adjustments are clearly not required when all of the insulations being considered are of the same type.

B. Degassing Times and Temperatures

It was discussed previously that degassing is an important process to ensure the stability of electrical properties and the effectiveness of many test procedures. Equally, the times for degassing at ambient temperatures are prohibitively long. Thus, it is virtually universal to use high temperature treatments to achieve practical degassing times. The precise time/temperature conditions depend upon the details of the cable design. Figures 14 and 15 show the practical implications of cable designs on the times and temperatures. These practical features fit very well with the finite element simulations discussed earlier. Figure 15 confirms the findings, from the finite-element analysis, on the times required for specific thicknesses. The practical measurements and simulation work confirm that the approach to use a selected time per thickness is applicable only over a relatively small range of thicknesses. When determining the

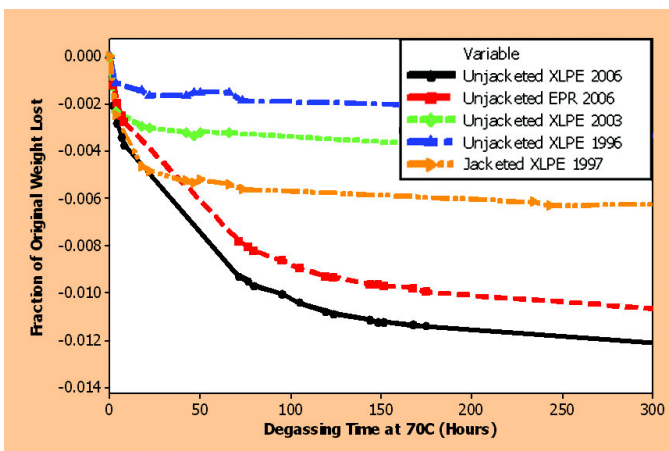


Figure 12. Weight lost from MV cable cores (excl. conductor) after degassing at 70C for different cable insulations and designs of selected ages. The years represent the date of manufacture, none of the cables had been in service.

Table 7. Acetophenone, measured by FTIR peak heights, at selected CV linespeeds; directly after production for two positions within two MV cables.

	Sampling position	100% of normal linespeed	120% of normal linespeed
Design χ	Middle	100%	114%
	Outer	54%	82%
Design η	Middle	100%	132%
	Outer	60%	77%

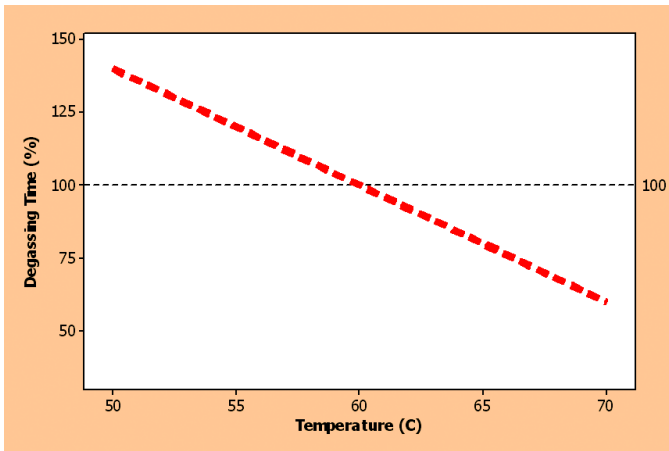


Figure 14. Effect of temperature on degassing times at for XLPE cables (MV to EHV) at selected initial temperatures (100% set at 60 °C).

practical conditions, it is useful to recognize that issues associated with the degassing process—reels (open or closed) and oven (ventilated or circulated)—can have significant influences. These are sufficient for process upgrades to be verified as a matter of good practice.

C. Effect of Extrusion Conditions and Insulation Technologies

Both weight loss and HPLC studies show that some byproducts are lost from the cable insulation while it is still within the CV tube during the production of the core (Figure 2, Table 7). This loss is almost certainly limited to the curing section as the surface temperature falls very rapidly on entering the cooling section. Thus, one consequence is that as line speeds increase and/or the length of the cure sections decreases (both can happen when productivity is raised), less byproducts are lost in the CV tube (Table 7). However, this is not simply a residence time problem as the temperature and the amount of

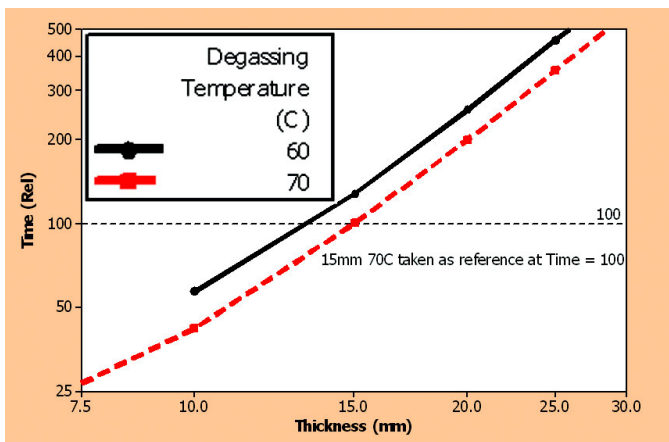


Figure 15. Effect of insulation thickness and temperature on degassing requirements.

crosslinking that occurs before the core surface enters the cooling zone will depend very much on the cable design. As an example, in a MV cable, 83% of the crosslinking can be completed in the curing section and an average insulation temperature of ~225°C is attained. However, these values fall to 55% crosslinking complete in the curing section and an average temperature of 170°C attained for an EHV cable. The residual crosslinking occurs in the depth of the insulation when the core is being cooled.

This feature of reduced degassing in the CV tube has two main consequences. First, if less byproducts are expelled during production, their accumulation within the production system is reduced. This makes maintenance of the CV line considerably simpler. However, in principle, this positive effect for core production raises the second issues, namely that more degassing must be accomplished after production to ensure that the ultimate, delivered byproduct levels remain at the low levels that manufacturers and users are accustomed to. Also, unexpected issues can occur as different conductor sizes and increased line speeds are used so as to perturb the balance of curing and cooling within the whole core extrusion process.

Conclusions

Degassing is an important process with cable manufacturing. It contributes greatly to the quality of power cables by improving the certainty in electrical testing and improving the dielectric properties. To ensure that the degassing process delivers the expected benefits, it is important to measure and model the process by which the crosslinking byproducts are desorbed from the cable polymers. Weight loss and HPLC have shown themselves to be the most effective and practical measurement techniques. Diffusion data derived from such measurements can, with FEM, be conveniently used to make predictions concerning the time needed for degassing on a range of cable sizes and constructions. Improved efficiencies (lower times or lower temperatures) within the degassing process lead directly to either improved throughput or improved electrical performance.

Acknowledgements

The authors gratefully acknowledge the assistance of and valuable discussions with Dr. Pekka Huotari, Gustaf Linderoth of Maileffer Oy, Finland; Prof. Len Dissado of University of Leicester, UK; and Rick Hartlein of NEETRAC, United States.

References

- [1.] Gorham and Partners, "Undergrounding — A success story already in Europe - Potentially Worldwide," *Report to International Cablemakers Federation Congress, 1995*.
- [2.] H. Brakelmann, "Studie "Netzverstärkungs-Trassen zur Übertragung von Windenergie: Freileitung oder Kabel?" *Bundesverband WindEnergie e.V.* Oct. 2004.
- [3.] H. Faremo, N. Hampton, J. Lepanen, J.-P. Lonquist, C. Philippczyk, K. V. Poulsen, A. Smedberg, W. Weissenberg, and J. Ahman, "Improved productivity for power cable manufacture," *CIGRE 2006*, Paper B1-109.

- [4.] F. M. Precopio and A. R. Gilbert, U.S. Patent 3,079370, 1955.
- [5.] E. Peschke and R. von Olhausen, *Cable Systems for High and Extra-High Voltage*, Verlag 1999.
- [6.] D Wald and W Weissenberg, "Enntgasen von VPE-Kabeln – ein notwendiges Übel?" *EW 11*, pp. 26–29, May 2005.
- [7.] S. T. Hagen, "AC breakdown strength of XLPE cable insulation," Ph.D. Thesis, Norwegian Institute of Technology, Trondheim, Norway, 1993.
- [8.] F. Aida, G. Tanimoto, M. Aihara and E. Hoshokawa,; "Influence of curing byproducts on dielectric loss of XLPE insulation," pp. 465–473, *CEIDP*, 1990.
- [9.] T. Hanai, *Emulsion Science*, P. Sherman, Ed. Academic Press, New York: 1958, Chap. 5, p. 353.
- [10.] H. Faremo and E. Ildstad, "Rehabilitation of Water Tree Aged XLPE Cable Insulation," *ISEI*, pp. 188–192, 1994.
- [11.] D. Damon, "Breakdown statistics for XLPE containing the volatile by-products of the crosslinking reaction," *ICSD*, pp. 513–517, 1992.
- [12.] Z. Zheng and S. Boggs, "Defect Tolerance of Solid Dielectric Transmission Class Cable," *Elect. Insulation Mag.*, vol. 21, no. 1, pp. 35–41, 2005.
- [13.] CENELEC Standard HD 620, *Distribution Cables with Extruded Insulation for Rated Voltages from 3,6/6 (7,2) kV to 20,8/36 (42) kV*.
- [14.] ANSI/ICEA Standard S-94-649-2004. *Standard for Concentric Neutral Cables Rated 5 through 46 kV*.

Tim Andrews is a research engineer at the National Electric Energy Testing, Research, and Applications Center (NEETRAC). Tim holds bachelor's and master's degrees in electrical engineering from the Georgia Institute of Technology and is a professional engineer. His research interests include underground cable diagnostics, operational safety, and the application of finite element modeling to power distribution systems.

Nigel Hampton is the Chief Materials Scientist at the National Electrical Energy Testing Research and Applications Centre of Georgia Tech in Atlanta, Georgia. Nigel has B.Sc. and Ph.D. degrees in physics from the University of Bath in the UK and holds an M.Sc. in polymer engineering. He has spent more than 15 years working in the power cable arena, holding posi-

tions within BICC, Pirelli, Borealis, and NEETRAC. Dr Hampton is active within CIGRE and the IEEE Insulated Conductors Committee.

Annika Smedberg is an experienced and respected development engineer within the Wire and Cable Business Unit of Borealis AB. She holds a masters degree in chemical engineering and a Ph.D. in materials science/polymer technology both from Chalmers University of Technology in Goteborg, Sweden. Dr. Smedberg's area of expertise is in the fields of extrusion and crosslinking technologies.

V. Waschk is Manager of Development and Technology at NKT Cables GmbH in Koln, Germany. He has worked at NKT Cables GmbH since 1984. Dr. Waschk has contributed to various national and international committees/conferences (CEPSI, CIGRE, VDEW Kabeltagung, IMEMME, IWMA VDE, Europacable).

Detlef Wald is Technical Service Manager Wire and Cable at Borealis Polymers N.V. in Belgium. Detlef has a diploma from the Technical University of Aachen, Germany. He has spent more than 15 years working on the development and technical service of wire and cable products for various parts of the world.

W. Weissenberg has been working in the area of research and development of high voltage cables and accessories since 1986. He started his career at the Kabelwerk Meissen and has worked since 1992 in the Kabelwerk Berlin of Siemens AG, later Pirelli Cables and Systems. He was responsible for the product development, test engineering and the test benches for high voltage cables and accessories up to 500 kV. In 2001 he joined Brugg Cables as Technology Manager for high-voltage products. Dr. Weissenberg studied electrical engineering at the Technische Universität, Dresden, where he also earned his doctorate in high-voltage technology. Dr. Weissenberg is an active member in different national and international bodies such as VDE-ETG Q2 and IEC TC20 WG 16.

