Accelerated Aging of Rejuvenated Cables – Part II

Glen J. Bertini
Novinium, Inc.

***Abstract*: This paper provides part II of a framework for the prediction of the effective life extension of cables treated with rejuvenating chemicals under accelerated aging conditions. Utilizing the principles of molecular thermodynamics and a cable's soil regime, soil thermal conductivity, and load profile, it is possible to make accurate estimations of life extension for legacy fluids and methods as well as for methods that tailor the chemistry to the circuit performance requirements. Part II of this two-part paper introduces an improved model which includes and integrates all of the refinements introduced by Part I, plus: all cable layers; not just the insulation, dynamics of fluctuating temperature, molecular thermodynamics of component interactions, and reaction kinetics.**

INTRODUCTION

Part I of this paper [1] highlighted some of the shortcomings of earlier attempts at estimating post-treatment life extension of chemically rejuvenated cable. The identified shortcomings included:

- Neglecting the entire temperature profile of the cable not just the conductor temperature and particularly the outermost insulation layer temperature on the accelerated experiment when utilized for acceleration calculations.
- Failing to use an accurate estimation of soil temperature and cable loading to calculate the flux-weighted temperature of in-service cable.
- Neglecting differences in cable geometry especially where less than the optimum fluid supply is utilized.

In Part II of this two-part paper an improved model is introduced which includes and integrates all of the previously neglected elements listed above, plus modeling:

- finite volumes which include all cable layers; not just the insulation,
- the dynamics of fluctuating temperature,
- the molecular thermodynamics of component interactions,
- the reaction kinetics, and
- AC breakdown performance as a function of concentration profile.

With the introduction of these refinements the model becomes a predictor of performance instead of an estimation of life extension. The predictive capacity of the model is demonstrated by comparing measured and predicted results.

ICC, Subcommittee A, November 1, 2005
glen.bertini@novinium.com

As in Part I, it is not within the scope of this paper to discuss the protocols of accelerated electrical cable aging which are widely discussed by others. Instead, this paper and its Part I companion are aimed entirely at the correlation of molecular thermodynamic and chemical reaction aging parameters with the anticipated life under varying field operating conditions. When choosing a protocol for acceleration of the permeation and reactions of rejuvenation fluids in a power cable, those acceleration factors should be chosen to correspond with accepted accelerations for the electrical dimension of the experiment.

FINITE VOLUMES

Before dielectric enhancement fluid can even reach water trees in the insulation it must travel through the conductor screen or shield. The permeation properties of the conductor screen vary greatly from the insulation. In addition to the loading of carbon black which greatly affects solubility and diffusivity and the relationships of those parameters to temperature, the conductor screen has two other impacts which cannot be ignored if accurate predictive modeling is desired.

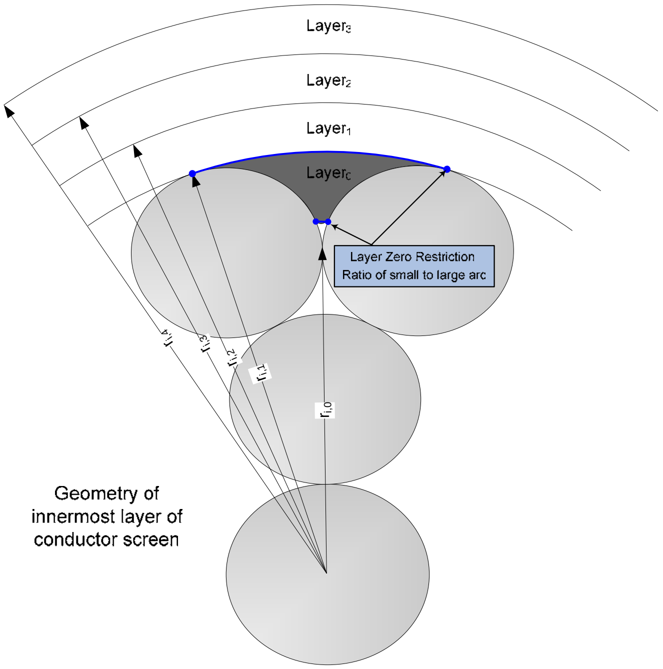

Figure 1. For a 1/0 cable treated without the benefit of sustained-pressure, the mass flux restriction created by the extruded non-cylindrical Layer$_0$ results in a 20-fold reduction in fluid penetration during the early portion of the injection.

First the conductor screen is the first layer of thermal insulation that reduces the temperature of the surrounding insulation layer.

Second, in the most common case the innermost layer of the conductor shield, labeled Layer$_0$ in Figure 1, is a non-cylindrical layer extruded between adjacent outer strands of the conductor strand bundle.

Within the insulation properties are not homogenous. Most importantly, on any loaded cable there is a temperature gradient declining from the inside of the cable to the outside. Additionally there are morphological changes in the insulation which affect permeability – most notably, the presence of a halo. The micro-voids of halos provide an enhancement to solubility which has a significant effect on mass flux.

Outside the insulation, another layer of carbon black filled material, namely the insulation screen or shield, slows exudation from the cable and greatly affects the flux of water into the cable from the surrounding soil. Where a jacket is present, its impact on the flux of materials into and out of the cable is analogous to that of the insulation shield with wide variations in performance for PVC or PE jackets and semi-conducting or insulating fillers. Again each of these macro-layers provides a thermally resistive element which affects the thermal profile of the cable which in turn has a profound influence on the performance of treatment fluids.

The predictive model described by this paper provides at least 5 and as many as 35 finite volume elements (hereafter layers) for each of these macro-layers. The properties of each layer are defined first on an aggregate level by the material(s) which makes up the macro-layer. These macro-layer properties are then refined within each layer by models which account for the morphological and temperature changes across the macro-layers.

DYNAMIC TEMPERATURE

The profound influence of temperature on mass flux was demonstrated by the Part I companion [1] of this paper. There are an infinite number of possible dynamic temperature profiles a cable might experience after treatment, so a framework of *typical* cases is required to analyze *typical* performance. Of course, once armed with a predictive model any of the myriad of cases can be simulated to provide guidance on specific cases. For the purposes of this paper we consider two typical cases meant to bracket the majority of real-world cases. Figure 2 is a graphical representation of one of those cases, namely a heavily loaded cable in hyperthermic soil. For this assumed case the seasonal fluctuation of the bulk soil temperature is shown by the lower dashed sinusoidal curve as a function of time in months (ranging from 0 to 12 months). The upper 12 sinusoidal curves indicate the daily (0 - 24 hours on the x-axis) average fluctuations in conductor temperature for each of the 12 months of the year. The solid monotonically declining line describes the radial temperature profile across the cable conductor shield, insulation, and insulation shield at a particular simulated moment (e.g., 3:45 PM on August 31, 2010), the corresponding abscissa being scaled such that zero represents the innermost radius of the conductor shield and 24 represents the outermost radius of the insulation shield on a jacketless 1/0 cable.

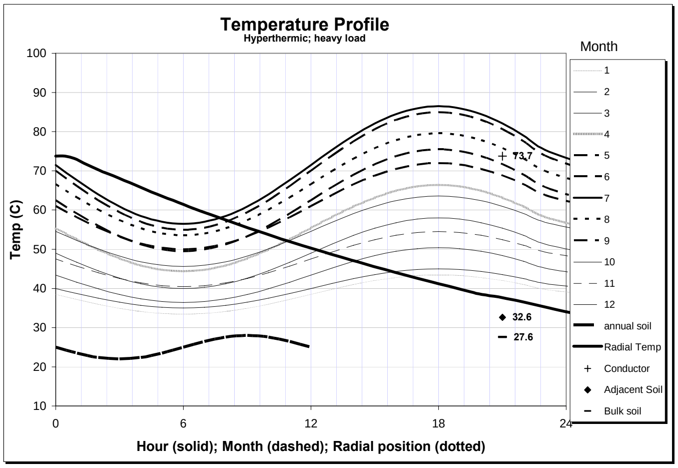

Figure 2. Temperature fluctuations typical of a heavily loaded cable in hyperthermic soil.

This first case represents generally higher flux weighted temperatures. The second case is mesic soils with light loading which represent a cooler flux-weighted temperature.

COMPONENT INTERACTIONS

The technology widely employed for the last decade [2] (referred hereinafter as '841) which was conceived, reduced to practice and commercialized by the author and others includes three components injected into the strands, namely phenylmethyl-dimethoxysilane (70%$_w$; i.e. PhMe-1.0), trimethylmethoxy-silane (28.8%$_w$), and titanium(IV) isopropoxide (0.2%$_w$), the later as a hydrolysis and condensation catalyst. Also present in the cable in addition to these three feed components are water which reacts with some of the supplied silanes and methanol which is a by-product of the hydrolysis of the silanes with water. To this mixture of 5 components one must also add each of the significant hydrolysis and condensation products. While all possible combinations would exceed 25 the most significant combinations include the following seven compounds: PhMe-1.1, PhMe-1.2, PhMe-2.0, PhMe-2.1, PhMe-2.2, PhMe-3.2, and PhMe-4.2, where the number to the left of decimal point is the degree of oligomerization from 1 to 4 and the number to the right of the decimal point is the extent of hydrolysis wherein 0 indicates no hydrolyzed groups (i.e. 2 methoxy ligands), 1 is one hydrolyzed group (i.e. 1 methoxy ligand and one hydroxyl ligand) and 2 is two hydrolyzed groups (i.e. two hydroxyl ligands).

Thus there are a total of 13 significant components which are all present in the cable. These 13 species interact particularly with regard to their equilibrium concentrations. These interactions must be measured or estimated.

REACTION KINETICS

Alkoxysilanes undergo two types of reactions, both of which typically require catalysis. The first reaction type is hydrolysis. For example phenylmethyldimethoxysilane or PhMe-1.0 in the shorthand introduced in the last section hydrolyzes as follows:

$$\text{PhMe-1.0} + H_2O \rightarrow \text{PhMe-1.1} + \text{MeOH}$$

An example of the second condensation reaction is:

$$\text{PhMe-1.1} + \text{PhMe-1.1} \rightarrow \text{PhMe-2.0} + H_2O$$

While there are dozens of theoretically possible hydrolysis and condensation reactions, in practice a much smaller number are required to account for the bulk of the chemical reactions. For the phenylmethyldimethoxysilane systems defined by [2], [3], [4] and [5] a minimum of 10 reactions must be modeled.

Reaction rates can be obtained by measuring the disappearance of reactants or the appearance of reaction products as a function of time at various temperatures. For reactions which take place in a sterically hindered environment, such as between the intermolecular spaces between polyethylene molecules, it is best to measure these reactions within that environment.

Consider the cable described by Kleyer and Chatterton [3]. The cable and the experiment were described as:

> *"… a 1/0 AWG, 15 kV rated cable … cut into segments, filled with phenylmethyldimethoxysilane and the ends sealed before immediate immersion in a 60°C constant temperature water bath. At various time intervals (7, 17, 27, 54, 67 and 248 days) a segment was removed from the bath, sectioned and the insulation was profiled by microscopic infrared spectroscopy for treatment distribution.*"

The results of that experiment, which are plotted in Figure 4 in the Kleyer & Chatterton paper, were refined and re-plotted as Figure 15 in "Dielectric Enhancement Technology" by Bertini & Chatteron [5]. The latter data were digitized and are re-plotted in Figure 3.

The total amount of fluid in the insulation of the cable for each curve in Figure 3 can be obtained by numerically integrating the concentration profile across the cylindrical geometry of the cable. The results of this calculation are shown as triangles in Figure 4 and reveal the total concentration of silane and siloxane components in the insulation for the following times: 7, 17, 27, 54, 67 and 248 days. Plotted along with the above data in Figure 4, is a simulation utilizing the methods described by Part I and Part II of this paper. The values predicted by the simulation are within 10% of the measured values.

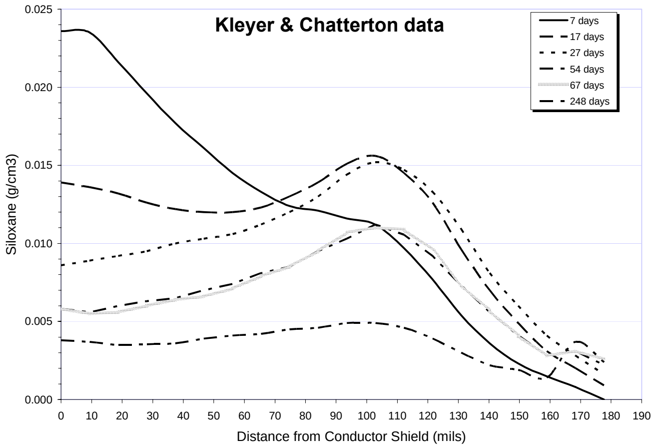

Figure 3. Data of Kleyer & Chatterton digitized and re-plotted showing silane and siloxane concentration profile across the insulation of a treated 1/0 cable in a 60°C water bath.

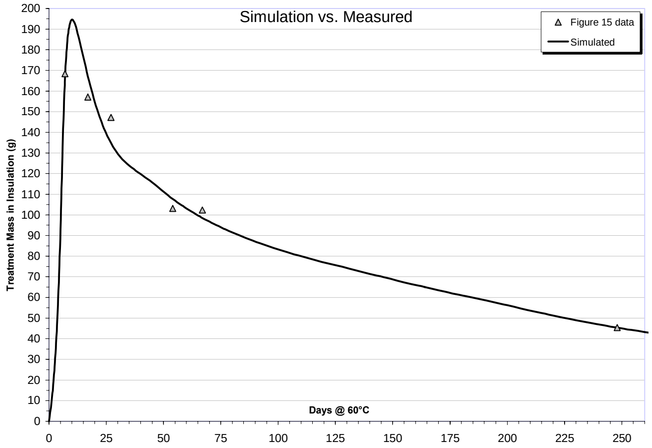

Figure 4. Integrated quantity of silane and siloxane in the 1/0 cable of Figure 4 normalized to a 220 foot length measured by Kleyer & Chatterton versus simulated.

A second test of the simulation was supplied by the previously cited paper [3], when the authors wrote:

> *"The presence of the water reactive functionality of phenylmethyldimethoxysilane within the insulation was confirmed by microscopic infrared spectroscopy (SiOMe band at 1190 cm-1) through 54 days."*

In other words, methoxy groups were still observable by micro-IR at 54 days, but were no longer observed at 67 days.

All IR-measurable quantities of methoxy functionality must disappear in the 13 days between 54 and 67 days. That observation is confirmed when the SiOMe band concentration predicted by the simulation is plotted in Figure 5 as a function of time and the concentration passes the threshold that could be measured with the technology available a decade ago and described by the authors.

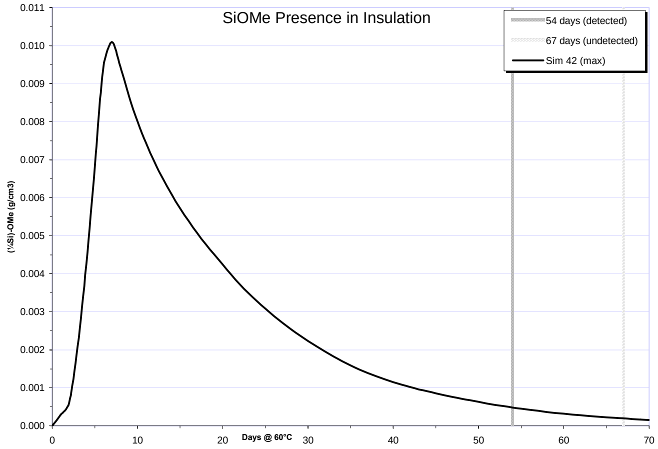

Figure 5. The simulation predicted concentration of SiOMe functionality conforms to the observation of Kleyer.

PREDICTED AC BREAKDOWN

A dynamic concentration profile does not directly satisfy the desire of the circuit owner to predict the future reliability of a treated circuit. To accomplish that goal a correlation is required which converts stress weighted concentration profiles into AC breakdown performance. There are two published data sources [6] and [7] which provide three AC breakdown performance measurements and fluid concentration profiles for ‘841 treatment technology. These data allow just such a correlation (labeled the SiLDK model in Figure 6) to be discerned.

In addition to the three cited data points [10] and [11] briefly describe the point where an excess of fluid becomes counterproductive. While a complete discussion of that phenomenon is beyond the scope of this paper, the flattening and decline in ACBD recovery suggested by the SiLDK model in Figure 6 is due to over-saturation. With a simulation tool that predicts the concentration of rejuvenation ingredients in the dielectric and a correlation such as that shown in Figure 7 it is possible to predict AC breakdown performance for almost any circumstance within the bounds of the measured molecular thermodynamic properties and hence correlate available accelerated lab data with anticipated field performance.

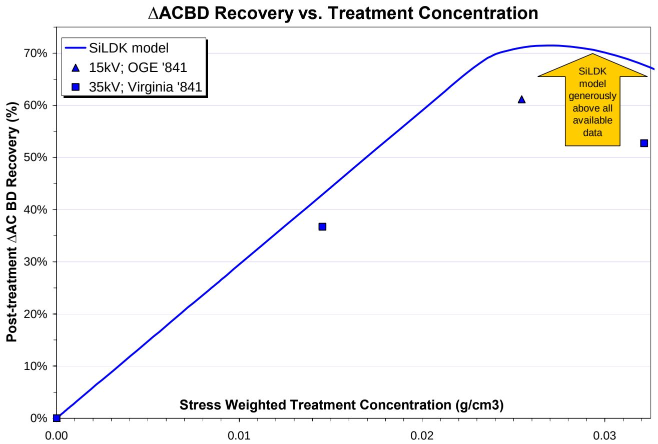

Figure 6. Correlation of stress weighted concentration of phenylmethyl-silanes and siloxanes in insulation to AC breakdown recovery expressed as a percent of recovery to an estimate (i.e. 40 kV/mm) of pre-installation value.

Figure 7 provides a schematic representation of the old acceleration model and the new model proposed by this paper. In the old model a very complex system with dozens of variables condenses the extrapolation to a single-factor based on the permeation of a single component. The model ignores the geometry of the cable, the operating temperature and temperature fluctuations of the cable, every chemical species present except the single chosen component, and the chemical reactions which make the mix of components change with time. The model proposed by this paper considers all of these important variables. Laboratory testing remains critical to establish the relationship between concentration and reliability performance and to validate the chemistry and molecular thermodynamics of the mass flux simulation.

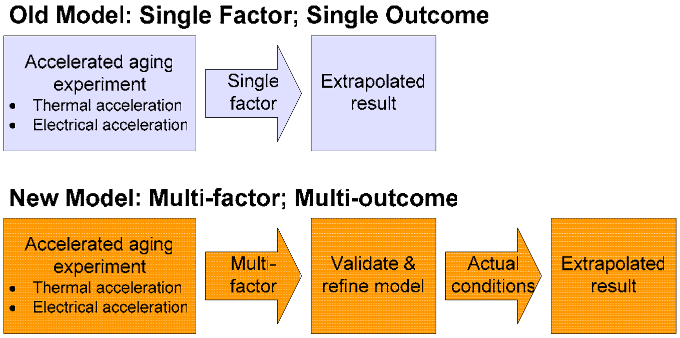

Figure 7. Comparison of single factor; single outcome model with multi-factor; multi-outcome model.

Figures 8 and 9 demonstrate the application of the multi-factor, multi-outcome model for a 19-strand, 53.4 mm^2 (1/0), 4.45 mm (175 mil) polyethylene insulated cable for two thermal cases – “mesic soil; lightly loaded” and “hyperthermic soil; heavily loaded” respectively. Within Figures 8 and 9 two injection approaches are plotted side-by-side – the ‘841 treatment and the technology described by [8] and [9], referred to herein as 732.

While AC breakdown performance above 16 kV/mm (the line labeled reliability threshold in Figures 8 and 9) is not necessarily required for reliable cable performance, Steennis [12] demonstrated that a 16 kV/mm (about 400 v/mil) level of AC breakdown performance virtually assures failure-free performance in field conditions.

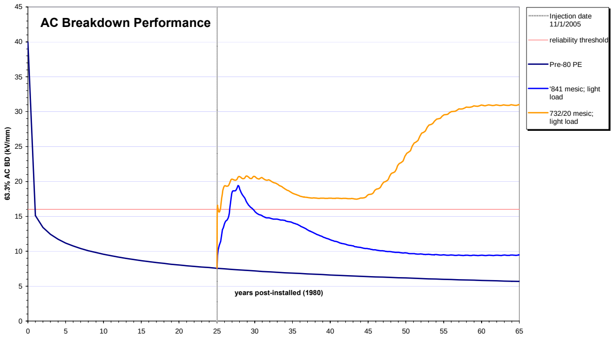

Figure 8. Predicted post-injection AC breakdown performance of ‘841 and 732 for a typical lightly loaded cable in mesic soil.

For lightly loaded cables in cool mesic soils the ‘841 treated cable takes approximately two years to pass the reliability threshold and stays above the threshold for about three years. Over the next decades the performance declines below the threshold, but remains above the performance of the cable before it was treated. In contrast, the 732 technology boosts the AC breakdown performance above the threshold within a week of treatment and stays above the threshold in excess of 40 years.

These results are consistent with available accelerated laboratory data. The accelerated aging data used to support an extrapolation of 20-year life for the ‘841 approach involved a 240 mm^2, 20kV, jacketed cable submerged in water maintained at 50°C and a conductor maintained at 60°C and 2.5 times rated voltage (U_0) for 1000 hours in [5]. By comparison, the 732 technology underwent aging at 2.5 U_0 for 3000 hours at 50°C and an additional 2000 hours at 60°C. The flux weighted temperature for the ‘841 experiment is approximately 57.5°C. 3000 hours at 50°C plus 2000 hours at 60°C together are approximately 3.5 times “longer” on a flux weighted basis than 1000 hours at 57.5°C. Not only was the flux-weighted time approximately 3.5 times longer for the 732 experiment, the cable was a 19-strand, 53.4 mm^2 (1/0), 4.45 mm (175 mil) unjacketed cable. The ‘841 experiment enjoyed a larger available interstitial volume in the strands, thicker insulation (20 kV versus 15kV), and an outer jacket. Each of these differences prolong the availability of fluid in the insulation and hence the AC breakdown performance. With at least a factor of 3.5 longer equivalent time and geometry favorable to ‘841 described in [5], the 732 accelerated experiment yielded a 63.3% AC breakdown performance of 19.9 kV/mm (505 v/mil) versus 17.2 kV/mm (436 v/mil) for the ‘841 approach.

The small fluctuations in performance within a calendar year are anticipated and are caused by seasonal fluctuations in temperature.

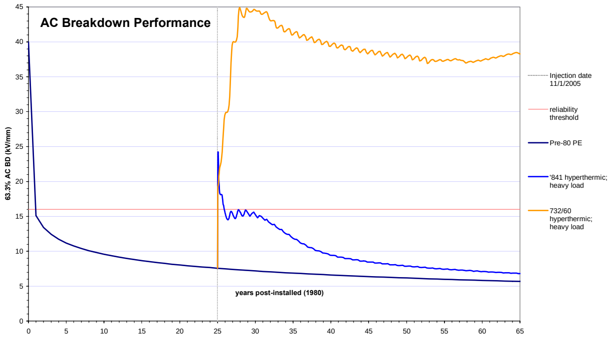

Figure 9. Predicted post-injection AC breakdown performance of ‘841 and 732 for a typical heavily loaded cable in hyperthermic soil.

SUMMARY

With a simulation model verified with multiple data sets over a wide range of conditions that includes consideration for:

- the geometry of the cable,
- all cable layers; not just the insulation,
- dynamics of fluctuating temperature,
- molecular thermodynamics of component inter-actions, and
- reaction kinetics,

… it is possible to predict the concentration profile of active ingredients as a function of time for laboratory or field conditions. These concentrations when combined with a correlation between species concentration and reliability performance can be used to predict life extension for virtually any field circumstance. The model thus described is used to compare two alternative approaches to treatment at two different thermal conditions that bracket the population of typical field temperature conditions. In all cases a typical 19-strand, 53.4 mm^2 (1/0), 15kV-rated cable is modeled. The ‘841 approach provides greater than 16 kV/mm performance for 3 years in lightly loaded cables in mesic soil and 0.9 years for a heavily loaded cable in hyperthermic soil. The 732 technology package provides greater than 16 kV/mm performance for more than 40 years for both lightly loaded cable in mesic soil and heavily loaded cable in hyperthermic soil.

The multi-factor – multi-outcome model proposed by this paper and validated with published laboratory results demonstrates long-term reliability for the 732 technology package at least 3.5 times longer than the ‘841 approach conceived and commercialized by the author and others about 15 years ago.

REFERENCES

1. Bertini, “Accelerated Aging of Rejuvenated Cables – Part I”, ICC, Sub. A, April 19, 2005.

2. Bertini, "Method for enhancing the dielectrical strength of a cable using a fluid mixture", U.S. Patent 5,372,841.

3. Kleyer & Chatterton, “The Importance of Diffusion and Water Scavenging in Dielectric Enhancement of Aged Medium Voltage Underground Cables”, Proceedings of the IEEE/PES Conference April 1994.

4 Vincent & Meyer, “Restoring Stranded Conductor Electrical Cable”, U.S. Patent 4,766,011.

5. Bertini & Chatterton, “Dielectric Enhancement Technology”, IEEE Electrical Insulation Magazine, 03/04-1994, V10, N2.

6. Mokry et al, "Cable fault prevention using dielectric enhancement technology", Jicable 1995.

7. Jenkins & Bertini, "Fourth Generation Dielectric Enhancement Technology", Jicable 1998.

8. Bertini, “New Developments in Solid Dielectric Life Extension Technology”, IEEE ISEI, Sept. 2004.

9. Bertini, “Further Improvements in Rejuvenation Technology”, ICC – C26D, April 18, 2005.

10. Bertini, "Injection Supersaturation in Underground Electrical Cables", U.S. Patent 6,162,491.

11. Bertini, "Injection Supersaturation", Minutes of the ICC, Fall 1998, p. 117.

12. Steennis, “Water Treeing: The behavior of water trees in extruded cable insulation”, Ph.D. Thesis, 1989, published by KEMA.