# Accelerated Aging of Rejuvenated Cables – Part I

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***Abstract*****: This paper provides part I 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 technologies and for new advanced technologies.**

## INTRODUCTION

In 1999, the author presented [1] the first good faith attempt at predicting the post treatment life of chemically rejuvenated cable using the best technology which was available at that time. The 1999 prediction was 20 years for the most widely used technology at the time which is described thoroughly in [2], [3] and [4]. New technology and a more robust understanding of the mechanisms of life extension by rejuvenation have led to an improved method of predicting actual life extension results based upon accelerated life testing.

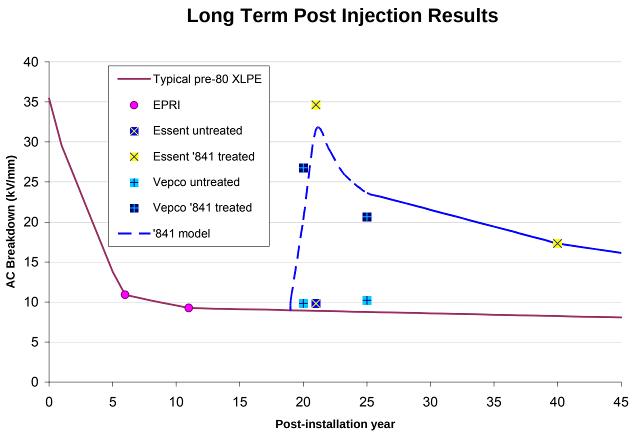

**Figure 1.** Early projections suggest 20 years of post treatment life extension of the most widely used pre-2005 technology.

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 II companion are aimed entirely at the correlation of molecular thermodynamic aging parameters with the anticipated life under varying field conditions. When choosing a protocol for acceleration of the permeation and reactions of rejuvenation fluids in a power cable, the acceleration factors should be chosen to correspond with accepted accelerations for the electrical portion of the experiment. For example if the electrical acceleration factor is estimated to be 10, an experiment where the molecular thermodynamics and chemical reaction rates were accelerated by a factor of 100 may not yield test results that are easy to correlate with field results.

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The basis for the post-treatment 20 year life prediction shown in Figure 1 can be found in [5] and [6]. In 1996 this author wrote [5]:

> "The concept of accelerated time for cables was described by Kleyer and Chatterton and is based on a mathematical model of permeation of the treatment fluid …"

Kleyer and Chatterton [6] in turn revealed the model and provide the permeation parameters to do the calculation:

> "… the elapsed time after bath immersion and the calculated elapsed time for the same cable insulation at *ground temperature (assumed to be 15°C)* is [calculated with] a temperature acceleration factor of 170 [using] Permeability$_{60C}$/Permeability$_{15C}$."

Significant assumptions which limit the accuracy of this approach are:

- In-service cable uniformly at 15°C
- Indifference to the cable geometry
- Use of the difference in permeability for a single component of a multi-component and chemically reactive system

In this Part I, we will examine refinements of the first two of these three assumptions providing a much better estimation of life extension. An even better estimation is possible when improvements are adopted to accommodate the multi-component and chemically reactive systems. These improvements will be discussed in the Part II companion to this paper.

## TEMPERATURE

Fick's first law is the fundamental law of diffusion. It states that the flux in the r-direction ($F_r$) is proportional to the concentration gradient ($\delta c/\delta r$):

$$F_r = -D(\delta c/\delta r) \tag{1}$$

The solubility and hence the equilibrium concentration of any material in PE or EPR is a function of temperature. The higher the temperature is; the higher the equilibrium concentration is.

The diffusion coefficient is also a function of temperature and like solubility, the higher the temperature the greater the diffusion. Hence both terms of Fick's first law increase with increasing temperature and likewise the mass flux $F_r$ also increases with increasing temperature. Multiplying the diffusion coefficient and solubility over the range of temperatures provides an estimate for the maximum flux of material exuding from the cable. This relationship is plotted in Figure 2 using the data of Kleyer and Chatterton [6].

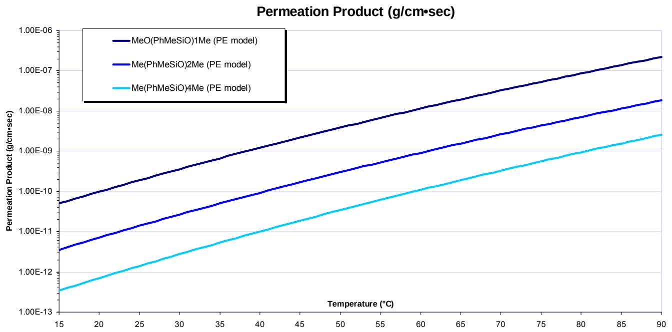

**Figure 2.** Product of Diffusion and solubility for '011 monomer, dimer and tetramer as reported by Kleyer & Chatterton [6].

Note that the y-axis of Figure 2 is logarithmic and even modest changes in temperature have a profound effect of the maximum possible permeation rate.

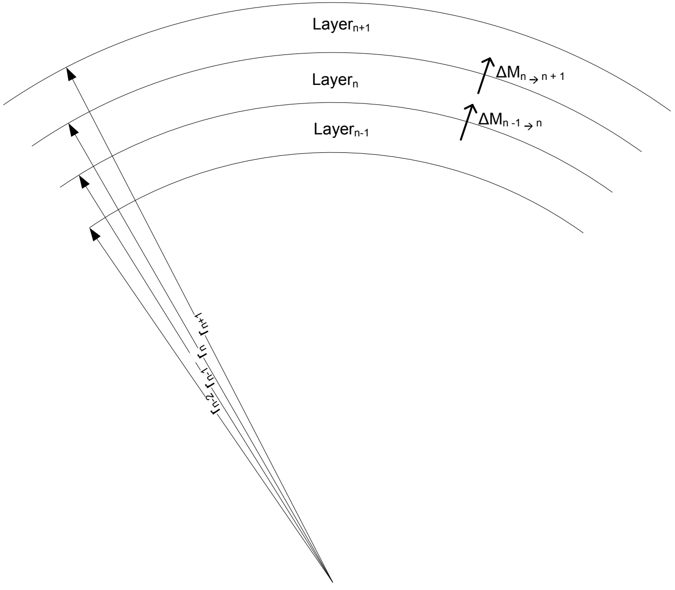

**Figure 3.** Radial permeation through multiple layers.

Figure 3 demonstrates the general situation for a cable where there are layers of plastic or rubber between the strand interstices, near the center of the cable through which fluid will diffuse until it is ultimately exuded into the surrounding environment. There are three kinds of layer boundaries. The first kind of layer boundary is delineated by obvious changes in material such as the change from the strand shield to the insulation. The second kind of layer boundary is delineated by subtle changes in material morphology such as the change from a lightly haloed layer to a heavily haloed layer. The third kind of layer is a mathematical construct of some arbitrary thickness $r_n - r_{n+1}$ as defined in Figure 3. Since a real cable in field conditions carries some load, the cable has a temperature gradient decreasing from a high temperature at the layers adjacent to the conductor to a lower temperature at the outermost layer of the cable. The layer which has the slowest diffusion is almost certainly the outermost layer. The exceptions to this general pronouncement are the cases where the load is negligibly small; for those cases the cable is at the same temperature as the soil.

In the aging experiment cited to generate the 20-year life extension estimate of Figure 1, the temperature of the water bath was 50°C. While the conductor temperature was 60°C, the outermost layer would have been very close to the water temperature. The permeation ratio between for 50°C and 15°C is 77X. The permeation ratio between 57.5°C[1] and 15°C is 175X. This refinement of 7.5°C results in a decrease of about 2.3X, shortening the anticipated life from 2 decades to less than 1 decade.

For cases where the soil temperature at cable depth is not 15°C, or where cable loadings cause the outer cable temperature to exceed 15°C the assumption of uniform 15°C cable temperature should be refined. Because of the sensitivity of performance to temperature demonstrated by Figure 2, just a few degrees Celsius can make a significant difference.

There are many papers, tables and computer programs to calculate the temperature profile of cables, so this paper will not attempt to provide guidance in this area. To calculate the outermost insulation layer temperature the cable owner is advised to calculate the permeation-time-weighted average temperature of the outermost layer of insulation accounting for both loading and varying soil temperature over a typical year.

The temperature at burial depth is quite easily estimated in a variety of ways. As a first rough approximation the circuit owner can consult the global soil temperature regime map [7] published by the U.S. Department of Agriculture (USDA) and reprinted here with permission as Figure 4.

Globally, the majority of the buried cables are in three soil temperature regimes:

| | |
|---|---|
| • Mesic | 8-15°C |
| • Thermic | 12-22°C |
| • Hyperthermic | 22-28°C |

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[1] While the author cannot recall why he chose 57.5°C in 1996; that is the temperature which is consistent with the reported acceleration factor.

Only lightly loaded cables in mesic regimes are likely to have outer temperatures near 15°C. In areas of the globe outside mesic areas in Figure 4, a different temperature should generally be utilized.

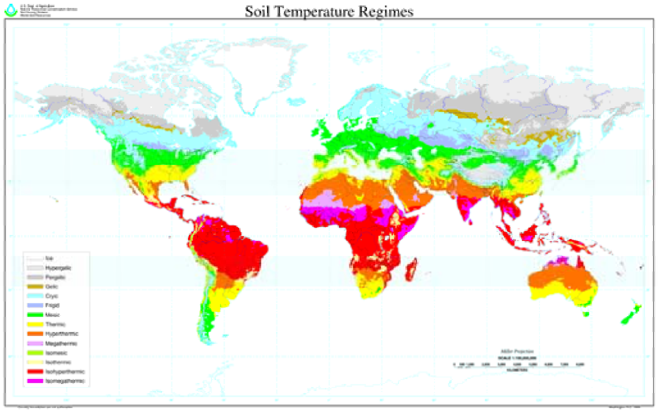

**Figure 4.** Global soil temperature regimes.

The soil temperature regimes are reported at 0.5 meters of depth, so a small correction may be necessary to adjust these temperatures to a more typical cable depth of 1 meter.

In Figure 5, the data of Schultz [8] is compared to the USDA soil regime map. The bar at 0.5 meters shows the range of temperatures reported by the USDA and measured data of Schulz along with linear interpolations are displayed at 0.5 feet, 2 feet, 4 feet and 6 feet for both soil and blacktop. In this example, the annual average soil temperature difference between 0.5 meters and 1.0 meters is approximately 1°C for both soil and blacktop.

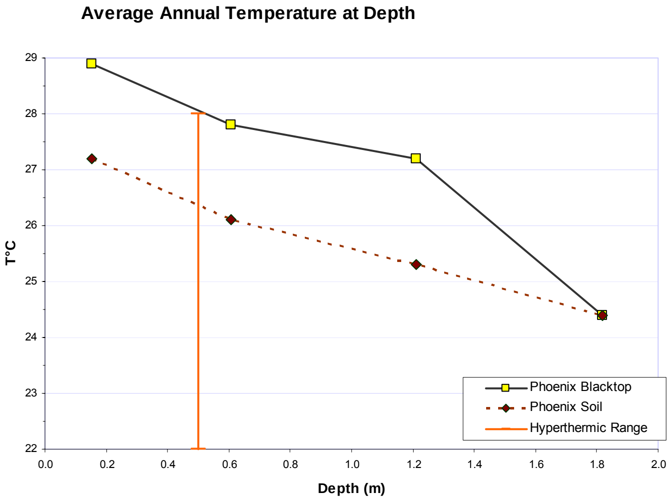

**Figure 5.** Soil Regime map comparison to measured data in Phoenix Arizona.

The other important conclusion of Figure 5 is that blacktop adds about 2°C to the soil temperature at 1 meter in Phoenix Arizona. Since a cable is likely to fail at the weakest portion of the circuit's length, a worst case perspective of temperature is appropriate and the technology choice for treating the cables should be optimized to handle the range of temperatures expected for the geography and the circuit.

Other good sources for temperature data at depth are available online. For example at www.wcc.nrcs.usda.gov/scan/, real time and historical data for sites around the United States are available. Circuit owners in other parts of the world can pick a U.S. location with a similar soil regime and climate to estimate their own soil temperature values. Given ambient air temperatures and knowledge of the thermal diffusivity of the soil a simple calculation can be performed at: http://soilphysics.okstate.edu/toolkit/temperature/index0.html

Once the temperature of the outermost layer of insulation is established it is possible to refine the estimation of life further. That refinement is plotted in Figure 6 showing the estimated life extension as a function of the reference temperature and showing the midpoints of the ranges for the soil temperature regimes of most interest.

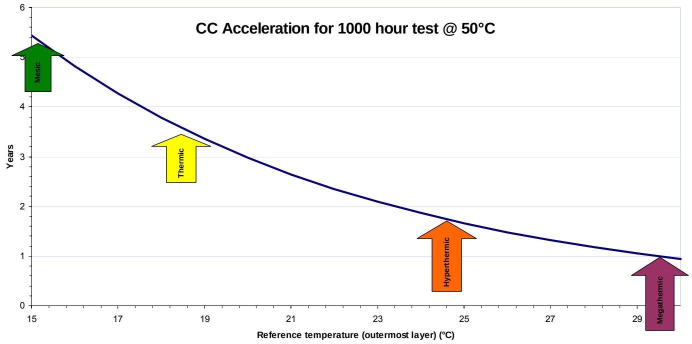

**Figure 6.** Acceleration factors for major soil temperature regimes.

The originally estimated life extension of 20 years varies from 6 years for lower temperature soils to 1 year for higher temperature soils or cables with loads that warm the adjacent soil above the ambient.

Using these temperature refinements to more accurately predict life extension acceleration factors it is now possible to redraw Figure 1. This is done in Figure 7. Along with the data for the fluids and techniques described by [2], [3] and [4] data for a new generation of process and materials are also included from [9] as updated in [10].

In each case the estimated 2-year and 20-year accelerated life data points must be reduced (moved to the left on the graph) to values consistent with Figure 6. "Not" symbols (🚫) are drawn over the less accurate estimations and arrows show the required leftward shifts to refine the location of the data points. Three new data points are added to the figure for each previously estimated 20-year data point for typical (from left to right) hyperthermic, thermic and mesic soil temperature regimes. New lines to interpolate and extrapolate are drawn as dotted lines to indicate the likely decay in AC breakdown performance. In Part II of this series, the method for interpolation and extrapolation will be further described.

There is considerable debate about whether AC breakdown performance is a viable predictor of field failure and this author wishes to avoid that controversy here. It has been shown by Steennis [11] however that the opposite proposition is reasonable. Namely that if the AC breakdown performance is above 16 kV/mm (400 v/mil) the cable is unlikely to fail in service.

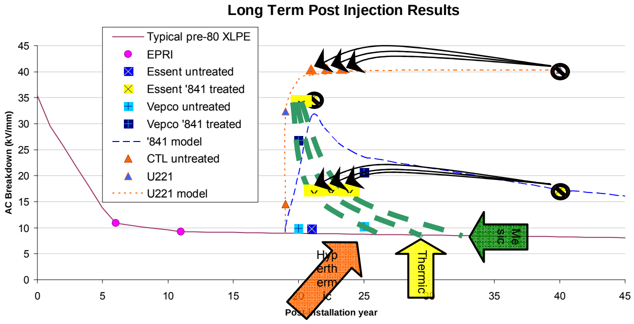

**Figure 7.** Figure 1 annotated to show more likely results at different soil temperature regimes.

The low AC breakdown strengths of the '841 treated cables after just several years of service aging does not necessarily mean that the cable will become unreliable in service. On the other hand, the AC breakdown value of approximately 40 kV/mm of the U221 treated cable eliminates all doubt about service reliability. Additional longer term data for the U221 technology will be published later in 2005.

## CABLE GEOMETRY

One key to providing long-term performance is providing just the right amount of fluid so that the fluid quantity and amount of solid dielectric to be treated is optimally balanced. U.S. Patent 6,162,491 [4] teaches how to calculate the fluid requirement and U.S. Patent 5,279,147 [12] teaches how to calculate the interstitial volume. The traditional injection approach where the cable interstices are filled to their capacity and some nominal additional fluid is fed for 2 to 3 months generally fails to supply this optimum for small conductor cables. In a previous paper [13], the author wrote:

> "On cables less than 4/0 (120 mm2) in size there is never sufficient volume in the cable strands to hold enough fluid to adequately treat the cable."

In the same paper [13] the author added:

> "Since most of the $Me_3$ [trimethylmethoxysilane] diffuses rapidly out of the cable, about 30% excess fluid is desirable."

Figure 8 which was explained in more detail in [9] provides a graphic representation for the mismatch of the fluid supplied to the fluid requirement encountered with the previous injection method. In short, for round (or concentric) conductor cables there is simply not enough fluid to optimally treat the cable with older generations of injection technology until the conductor size is in excess of 110 $mm^2$, for compressed conductors the conductor must be larger than 175 $mm^2$ and for compact conductors the conductor must be over 550 $mm^2$.

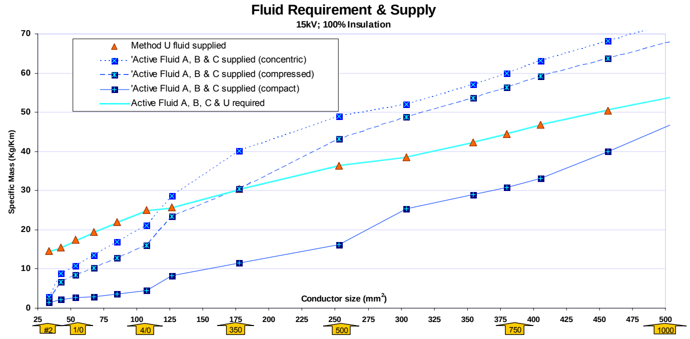

**Figure 8.** Historical mismatch between fluid supply (squares) to the fluid requirement (triangles).

For the single data point referenced in Figures 1 and 7 as "Essent '841 treated" the cable was a 240 $mm^2$ round conductor. This size conductor is unfortunate to use as an example from which to extrapolate to other cable geometries, because it happens to be the optimum geometry for the historical approach. The ratio of total fluid supplied to optimum fluid required is 1.3 (i.e. 1 quantity of active medium term ingredient plus 0.3 extra for the quick to exude trimethylmethoxysilane drying agent.)

For a 19-strand 53.4 $mm^2$ (1/0) round conductor cable which is most commonly rejuvenated, the ratio of total fluid supplied to optimum fluid required is 0.6. This is over a factor of 2 lower than used in the single published accelerated life experiment which has been used to suggest 20 years of extended life. For 7-strand or more compact conductors the fluid supplied is even less and all cases where the fluid supplied is less than 1.3 times the fluid required, the probable life extension needs to be factored downward appropriately.

## ANECDOTAL FIELD DATA

While injection was first utilized over two decades ago, the anecdotal experience provides little insight. The global historical injection rates were first reported in [9] and are provided in Figure 9. The first and most important observation is that the majority (50% of the "reverse cumulative" line) of field injection experience is three years or less. Similarly, 90% of the total experience is 7 years or less. The remaining 10% of the available samples prior to 1997 have several confounding events. First the data from 1984 to 1987 is for acetophenone and is not relevant to the performance of silicone treatments not only because of the difference in chemistry, but because a feed bottle was left attached for as much as a decade after the original treatment – a method never since employed. Second, when phenylmethyldimethoxysilane supplanted acetophenone in field applications in 1988, there were no warranties to provide an incentive for the utility to report post-treatment failures. Even more important, there were no warranty tags attached to cables until the middle of 1992. The warranty tags provide instructions to field personnel requesting their cooperation in the reporting of failures. About two years later, in 1984 the phenylmethyldimethoxysilane was replaced by a new mixture described in [3] of 70%$_w$ phenylmethyldimethoxysilane and 30%$_w$ trimethylmethoxysilane. As described previously, this change dilutes the active ingredient and reduces the effective post-treatment cable life. Finally, even when warranty tags are attached and in the event of a post-treatment failure, there is no way to know if they remain in place, are found, or are reported.

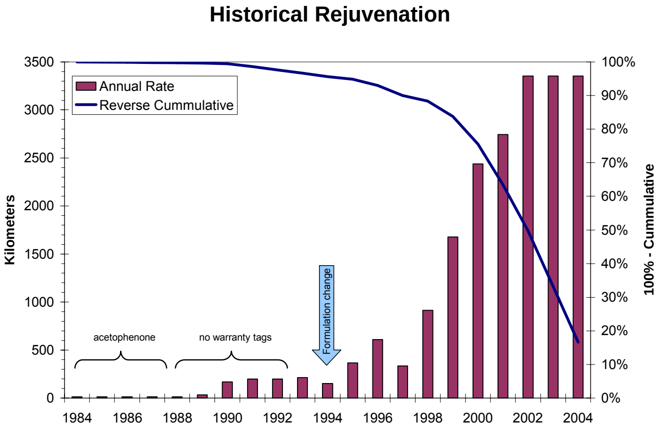

**Figure 9.** Rejuvenation history provides little insight into field performance.

Typical of the available anecdotal data is that of [14] where the authors wrote in 2000:

> "Salt River Project (SRP) has been using cable injection technology to treat crosslinked polyethylene (XLPE) cables since 1998, during which time more than 2.5 million ft (762 km) of underground residential distribution (URD) cable has been successfully treated. Nearly 99% of the treated cable has remained in service and failure free."

An approximate 1% failure rate in Phoenix after just two years cannot be readily extrapolated to future years. In short, it is not possible with the available data to confirm life extension expectations.

## SUMMARY

It is desirable to refine the method propose by Kleyer and Chatterton to get a first approximation of acceleration factors to estimate rejuvenation life extension. First, the outermost insulation layer temperature on the accelerated experiment should be utilized for acceleration calculations. Second, an accurate estimation of soil temperature and cable loading should be utilized to calculate the outer insulation layer permeation-time-weighted temperature of in-service cable. These two temperatures should be used to calculate the acceleration factor based on the Kleyer and Chatterton permeation equation. Third, where less than the optimum fluid supply is utilized; factor downward appropriately.

In Part II of this two-part paper we will introduce an improved model which includes and integrates all of the above refinements, plus:

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

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