

Cable Rejuvenation Mechanisms

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Abstract: Recent advances in cable life extension technology have demonstrated a greater than three-fold life improvement over earlier generations. While simply supplying an adequate amount of fluid explains a portion of these performance gains, this paper addresses several other important factors required to understand long-term post injection reliability. The chemistry of oligomerization, which determines how long a treatment persists in the cable, and the mechanisms of cable failure, which are addressed by the injection technology are described.

INTRODUCTION

In [1] the authors of this paper demonstrated a significant mismatch between the fluid required to adequately rejuvenate typical URD cables and the fluid supplied by the previous generation of technology. The previous generation of technology described in [2], [3], and [4] was conceived, reduced to practice, and commercialized by the authors and their colleagues and is referred to as '841. In [1] the authors introduced a new injection technology which eliminates the inadequate fluid supply issue and provided data demonstrating short-term performance gains 87 times superior to their previous technology. In a two-part paper, [5] and [6] the authors provide data and a model which focused on the long term performance of their earlier technology and the new developments referred to as 732. In experiments with matched protocols and where each identifiable deviation from matching favored their older technology the new technology provided over three times the post-injection longevity.

The greater than three-times improved performance cannot be explained entirely by the undersupply of fluid common with the '841 technology. The published performance of the '841 technology was for a 20kV, 240 mm² round strand cable. As shown in [1] and [4], 240 mm² round strand cable happens to be the optimum case for the '841 approach and fluid supply was not an issue in its three times shorter life.

This paper provides a theoretical framework and supporting data for the observed three-fold performance difference.

CABLE FAILURE

Figure 1 provides an overview of cable aging and failure mechanisms (square rectangles) and the mechanisms by which cable rejuvenation (rounded rectangles) interferes with aging and failure.

It is not the purpose of this paper to recite the work of countless others to explain the mechanisms of water treeing and how those water trees ultimately lead to failure. Instead, we briefly review the process described by Figure 1.

Manufacturing Defects – while not absolutely required for water tree growth, defects from manufacturing or installation certainly accelerate the growth and propagation of water trees and hence the longest water trees in any section of cable are quite likely to involve some imperfection.

AC stress, Ions, and Water – are generally recognized as the three requirements for the growth of **water trees**. In general, reductions in any of these three elements will retard water tree growth.

Local high-density: space charge and electrical fields – are the inevitable consequence of large water trees and are exacerbated by transient over-voltage events such as switching, failure, lightning, and most cable testing.

UV emission – is a consequence of space charges returning to their ground state. Ultraviolet photons are emitted which have sufficient energy to destroy polyethylene bonds.

Hot electron acceleration – is a consequence of very high local fields created around some dielectric imperfections including space charges. Hot electrons can break polyethylene bonds.

Thermo-mechanical stress – causes the halo visible in most aged cables that are exposed to water and a 24-hour temperature cycle. As the cable warms the solubility of water in polyethylene increases substantially and more water rapidly diffuses into the cable from the surrounding soil. As the temperature of the cable falls, the solubility of water decreases and water cannot permeate out of the cable quickly enough to avoid supersaturation. Driven by thermodynamic forces, the supersaturated water seeks its liquid state and condenses to the micro-voids of the halo.

Void formation – is caused by UV photons and hot electrons created primarily through the water tree process and by the thermo-mechanical stress caused by supersaturation and condensation of water in the halo.

PD (partial discharges) – are the manifestation of voids which are large enough for the gas within the voids to be ionized by the electrical field. The PD inception voltage is greater than the extinction voltage, because once the gas within the void becomes ionized, the PD is more easily sustained.

Failure – results as partial discharges erode the wall of the void in which they occur. The erosion of each discharge in a PE void increases the size of the void and hence decreases the partial discharge inception and extinction voltages for that void. This self-acceleration means that any PD occurring at operating voltages in polyethylene is likely to lead to rapid failure.

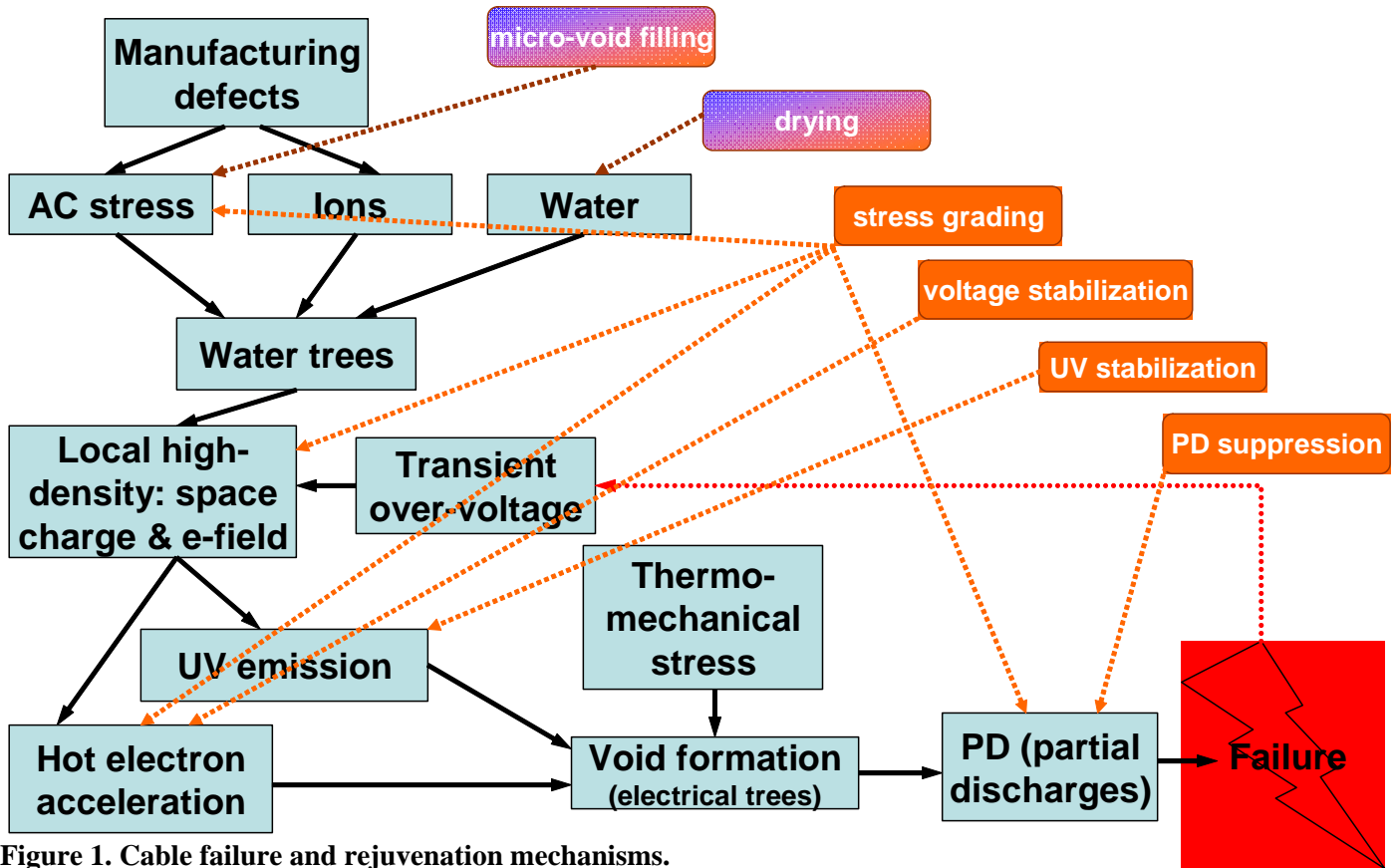


Figure 1. Cable failure and rejuvenation mechanisms.

REJUVENATION DIMENSIONS

To assess the post-injection performance of a rejuvenation technology, it is necessary to consider two dimensions. The first dimension includes consideration of the functional mechanisms by which the treatment fluid interferes with the aging and failure processes. The second dimension is the persistence of those functions with time and will be discussed after the six mechanisms of the first dimension are described.

Figure 1 shows six rejuvenation mechanisms (as rounded rectangles) along with arrows which indicate the step(s) of the aging and failure process which is (are) interfered with by each rejuvenation mechanism. The next 6 sections of this paper will examine each of the first dimension mechanisms in some detail. The older '841 injection technology provides only the first two mechanisms, namely micro-void filling and drying while 732 technology benefits from all six mechanisms.

Table 1 provides a summary of the three ingredients utilized by the older '841 approach alongside the analogous ingredients of the 732 technology. There are five ingredients in the 732 technology which have no analog in the '841 formulation – these absent functions are represented by grey. In Table 1 and throughout this paper, Me_3SiOMe is short for

trimethylmethoxysilane, PhMeSi(OMe)_2 is short for phenylmethyldimethoxysilane, and TIPT is short for titanium(IV) isopropoxide.

'841 Ingredient	732 Ingredient	Comment/Purpose
Me_3SiOMe	acetophenone	short term
PhMeSi(OMe)_2	silane 1	medium term
	silane 2	long term; stress grading
	organic O	UV stabilizer
	organic MA	UV stabilizer
	1,3-diketone	voltage stabilizer; UV stabilizer
	organometallic F	PD suppression; UV stabilizer
TIPT	proprietary catalyst	catalyst

Table 1. Ingredient comparison of '841 & 732 technologies.

MICRO-VOID FILLING

Not to be confused with voids, which can be imaged with an optical microscope, micro-voids are on a much smaller scale. These micro-voids are usually chemical imperfections in the polyethylene and are characterized by the presence of bonded oxygen, often carboxyl-groups which have an affinity for water relative to non-treed PE. The silicones used by both the

'841 and 732 technologies react with and displace (see Drying) water at oxidized PE sites within the water trees. The replacement of conducting ionic water with a silicone dielectric increases the dielectric strength of the insulation. This effect is easily demonstrated with standard water tree staining techniques. Thick samples of treated cable do not easily stain with methylene blue. Only after prolonged boiling is the silicone driven off and the methylene blue is free to react with the oxidized polyethylene. While both the '841 and 732 technologies work similarly here, the analogous silane 1 of 732 was designed to have a higher affinity for polyethylene. In fact, silane 1 has the same molecular structure and functionality as the $\text{PhMeSi}(\text{OMe})_2$ except that it contains three more methylene ($-\text{CH}_2-$) units strategically arrayed about the aromatic phenyl group to mask its aromatic structure from the polyethylene. This masking increases the affinity of silane 1 and its oligomers for polyethylene. The aliphatic methylene is more soluble in aliphatic PE than the aromatic phenyl group. (i.e. Like dissolves like.) For example at 22°C silane 1 is 12% more soluble in PE than $\text{PhMeSi}(\text{OMe})_2$.

DRYING

There are two drying effects. The first, the chemical reaction of methoxy silanes with water yielding methanol as a by-product, is the most widely reported in past literature, but is the least important. As has been demonstrated in [6] and [7] the methoxy water-reactive functionality is very short-lived. Even in the most favorable circumstances the methoxy functionality is all but gone in less than two years. At higher temperatures water reactivity may be depleted in two months.

Much more important than the transient chemical drying is the ability of the treatment to reduce the reentry of water. To this end, materials which have an improved affinity for polyethylene, such as silane 1 and its oligomers, provide superior water repellent capability. The molecular thermodynamics of this phenomenon are discussed in [6].

If high affinity for PE were all that were required, a chemist would choose an aliphatic organic. However, the second dimension, treatment persistence, discussed later in this paper, trumps the first dimension. The high affinity material must also stay in the cable for the desired post-injection lifetime in sufficient concentration to preclude significant water reentry.

STRESS GRADING

The inclusion of high dielectric constant layers to grade the electric field within cables and components is widely practiced and well understood. As modeled in Figure 2, cable rejuvenation with 732 allows for the introduction of carefully chosen high dielectric materials which provide stress grading on a micro-scale where highly divergent electrical fields create strong dielectrophoresis effects. Materials such as water are drawn to such locations because of the great difference

between the dielectric constants of water and PE as predicted by the Clausius-Clapeyron equation.

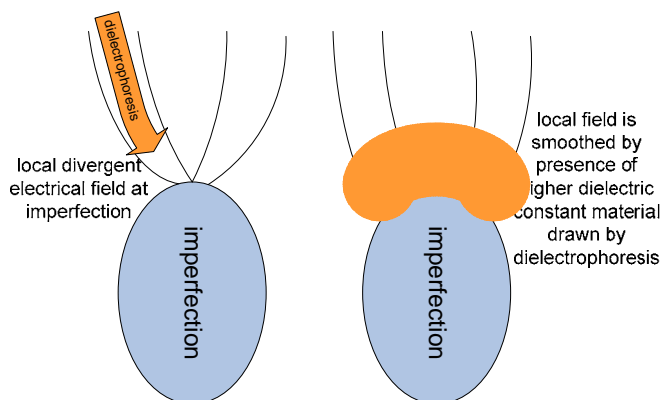


Figure 2. Model imperfection with divergent electrical fields, dielectrophoresis, and the resulting local concentration of high dielectric constant material.

Table 2 provides dielectric constants for selected materials. The difference between the dielectric constants of $\text{PhMeSi}(\text{OMe})_2$ or silane 1 and their respective oligomers with that of PE is not sufficiently high to provide a significant dielectrophoresis effect or a stress grading effect.

Material	Dielectric Constant
air	1.0
water	78.0
PE	2.3
$\text{PhMeSi}(\text{OMe})_2$ & silane 1 and their oligomers	3.2
silane 2 and its oligomers	>20.0
acetophenone	17.3

Table 2. Approximate dielectric constants of selected materials at 60Hz

On the other hand silane 2, its oligomers, and acetophenone enjoy the strong dielectrophoresis effect. This effect draws them to precisely the locations where they are needed. Once at the locally high stress region, these high dielectric constant materials grade the highly divergent electrical fields. Referring to Figure 1, localized stress grading interferes with at least four portions of the failure mechanism.

1. The local AC stress is reduced and water trees grow more slowly.
2. The high electrical fields around space charges are reduced, which reduces the likelihood of UV photon creation and the inception of free electrons.
3. Any free electrons will not be accelerated to the same energy as they would have been in a greater field.
4. The reduced local field increases both the partial discharge inception and extinction voltages.

This functionality is absent from the '841 technology.

VOLTAGE STABILIZATION

The voltage stabilizing effects of 1,3-diketones is due to keto-enol-tautomerism and was first demonstrated by [8]. Tautomers provide a stable receptor for hot electrons.

Because of the electronic stability resulting from the conjugated double bonds of the enol form, the enol form of the tautomer is favored. The dominant enol form absorbs much of the energy of hot electrons and converts to the transition form and free proton shown in Figure 3. The two resonant transition forms in Figure 3 delocalize the excess negative charge. Before the transition forms relinquish the captured electron the excess energy is converted to heat as the electrons resonate between the two transition forms. Finally, the free proton recombines at the central carbon to regenerate the keto form of the tautomer and releases the thermalized electron. 1,3-diketones also show preferential solubility in water treed portions of the insulation due the presence of similar carboxyl functionality in the trees. The 732 technology includes a 1,3-diketone tailored to intercept and thermalize hot electrons.

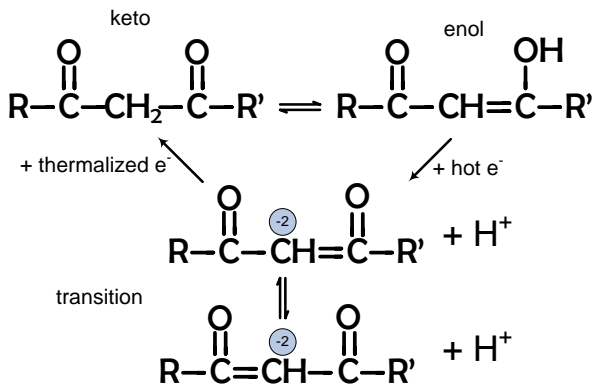


Figure 3. 1,3-diketone keto-enol tautomerism and electron thermalization. R and R' represent the balance of the diketone.

It has been informally suggested that the toroidal cloud of π -electrons surrounding the aromatic phenyl ring present in both the '841 and 732 technologies may provide some voltage stabilization. The theory is that a hot electron is first captured, then thermalized and finally released by the toroidal cloud. While there is no experimental evidence to prove or disprove this theory, both the '841 and 732 technologies include the same functionality. For a unit length of treated cable at any post-injection time there is more of this phenyl functionality delivered by the 732 technology compared to '841. As already established, more fluid is provided and as will shown in the forthcoming Treatment Persistence section of this paper this greater quantity is less fugitive with 732 than '841.

UV STABILIZATION

Figure 4 shows the spectra of visible and UV light emitted from charge recombination near defects as reported by [9] at three different local electrical stress levels. The UV spectrum encompasses wavelengths of 10 to 400 nm. A portion of the UV spectrum (10 to 250 nm) is not displayed in Figure 4. As demonstrated by [9] there are no significant emissions of UV light at wavelengths shorter than 275 nm. While the phenyl groups of $\text{PhMeSi}(\text{OMe})_2$ and silane 1 do absorb within the UV range, that absorption is outside the range of relevant UV emissions, 275 to 400 nm. The $\text{PhMeSi}(\text{OMe})_2$ component of the '841 material plotted in Figure 4 is essentially transparent to UV in the relevant range. The Me_3SiOMe component of the '841 material, lacking any conjugated double bonds is entirely transparent and dilutes the already weak UV absorption of the conjugated component. In contrast, 732 technology includes several components which absorb photons in the 275 to 400 nm range. Over the range of UV photons emitted by water trees the 732 technology absorbs from 31 to 181 times more UV than the '841 material at the same concentration.

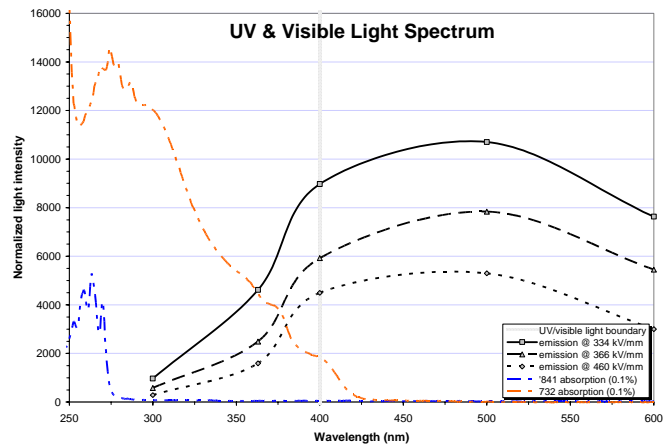


Figure 4. UV and visible light emitted (0=background) from charge recombination near defects and absorbed (0=transparent) by treatment fluids at 0.1%_w concentration in PE.

PD SUPPRESSION

There are several mechanism involved in the suppression of PDs. First as described previously, local stress reduction though stress grading increases the partial discharge inception and extinction voltages. As described in [16], a free electron, sometimes from cosmic rays, is a necessary precursor to the initiation of a PD. Therefore a second suppression mechanism is provided by the electron affinity of the previously described 1,3-diketone and the electron accepting organometallic F. Third and fourth mechanisms are also provided by the organometallic F compound included in the 732 technology. Organometallic F is designed to prevent the inception of partial discharges as illustrated by Figure 5. This is accomplished by rendering the walls of large voids partially

conductive when voltages exceed a threshold well below typical inception voltages in a manner analogous to the electronic activation of a transistor. Once the walls are partially conductive the e-field all but disappears. In the event that a PD does occur a small portion of the compound is consumed and simultaneously raises the pressure in the void and releases an oxygen scavenger. These effects act to quickly snuff out incipient partial discharges and mitigate the damage normally incurred when a discharge occurs. The '841 technology does not include any material to directly address PD activity.

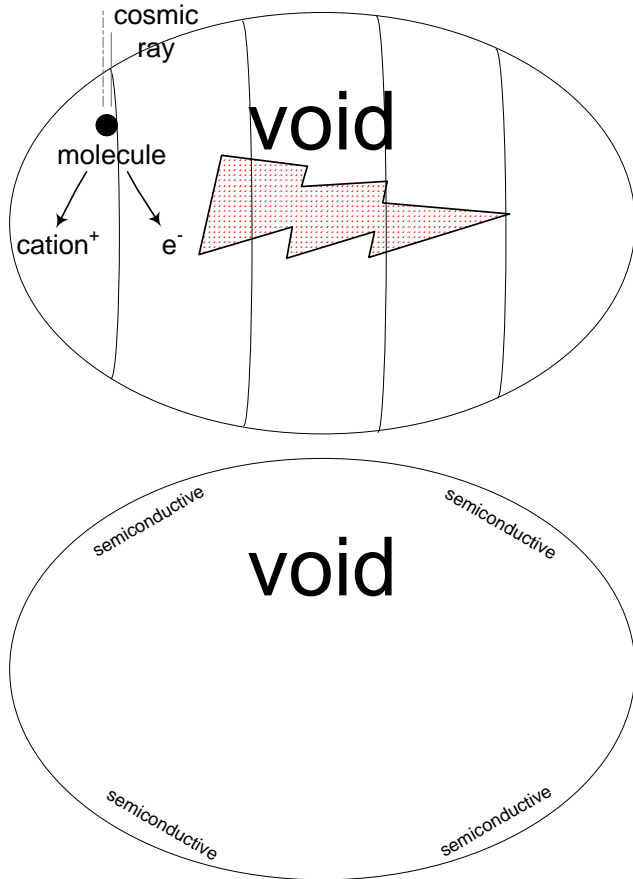


Figure 5. An elliptical void is illustrated, but the void may be of any shape; the principles remain the same. Top shows gas filled void with equipotential voltage lines and a free electron initiating a PD. In this example, the source of the free electron is the collision of a cosmic ray with a molecule in the void, but free electrons are available from other sources. Bottom illustrates the entire void at the same potential when coating on void wall is semi-conductive. No PD is possible.

TREATMENT PERSISTENCE

None of the six mechanisms described above have much practical value, unless the effect can be sustained over the desired post-injection lifetime of the cable. The post-treatment performance persistence is the most challenging requirement

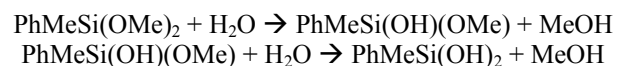
of a rejuvenation technology that extends the reliable life of a 25 to 40 year old cable for another 40 years. The accelerated testing and modeling of rejuvenation technologies was covered in detail in [5] and [6]. The '841 technology includes two components. The first component is Me_3SiOMe . Me_3SiOMe represented about 30%_w [3] of the composition from the introduction of the '841 technology in 1994 until 2005 when the concentration was reduced to between 5 and 10%_w according to the MSDS [10] provided by the supplier. Me_3SiOMe is a highly soluble and quick to diffuse component, which at least at the higher historical concentration provided the short-term (i.e. 3-24 months after injection) performance boost reported in the literature [3]. The higher concentration of Me_3SiOMe component also assured adequate symmetric penetration. The optimum concentration for '841 is explained in [3]:

“... the amount of water-reactive compound [Me_3SiOMe] that is included in the fluid mixture is the least amount needed to reduce the asymmetric penetration front of the antiretreat agent [$\text{PhMeSi}(\text{OMe})_2$] and the appropriate range [is typically greater than 10%_w and preferably about 30%_w.]”

Based upon the data and discussions of [3], the 2005 '841 formulation change will hamper the short-term performance and lead to asymmetric penetration profiles reducing the treatment efficacy. This formulation change was implemented to reduce the likelihood of corrosion of aluminum strands [11] experienced by the '841 chemistry discussed in [12] and [13].

The second '841 component, $\text{PhMeSi}(\text{OMe})_2$ represents the bulk (about 70%_w to 95%_w) of the formulation and for less demanding (i.e. low-load and cool-soil) applications can potentially provide acceptable medium term (i.e. 1-10 years) performance as demonstrated by [6] and could be extended beyond 10 years with previously described improved injection methods and with proper catalysis as explained below. The 732 technology adds entire functional elements not found in the '841 technology, but the over three-fold increase in longevity requires one more dimension to clarify the profound performance difference.

Alkoxysilanes (i.e. both the '841 silanes and the 732 silanes) undergo two types of chemical reactions, both of which typically are accelerated with catalysis. The first reaction type is hydrolysis. For example, $\text{PhMeSi}(\text{OMe})_2$ hydrolyzes in two steps as follows:



An example of the second reaction type, condensation, is:



This second kind of reaction, the condensation of two monomers to a dimer *in the presence of a catalyst*, is one example of dozens of the condensation reactions which actually occur. For example, a dimer and a monomer can condense to a trimer, two dimers can condense to a tetramer or a trimer and a monomer can condense to a tetramer. In theory these condensations can continue indefinitely to create larger and larger oligomers. In practice, the maximum size of the oligomers is limited by a slowing reaction rate as reacting molecules grow. Further slowing the practical reaction rate are the steric encumbrances created by the polyethylene matrix in which the siloxanes are diluted. A third limitation in the condensation process is the required presence of catalyst in sufficient concentration to allow the condensation to proceed at a meaningful rate. For example, Vincent demonstrated in [2] that without catalyst there was no measurable condensation of $\text{PhMeSi}(\text{OME})_2$ in 2108 hours in a test tube at 25°C.

In other words, if there is an inadequate quantity of catalyst permeating along with the silanes and siloxanes of a treatment fluid, there can be no condensation and the monomers will exit the cable in months. The fugitive nature of these uncatalyzed monomers means that any performance benefit is short-lived when compared to a desired life extension of 20 to 40 years. This effect was demonstrated in [5] and [6] and is consistent with the data presented by Kleyer and Chatterton in [14]. The data and analysis demonstrate that in excess of 25% of all monomer supplied permeates into the soil without undergoing any condensation.

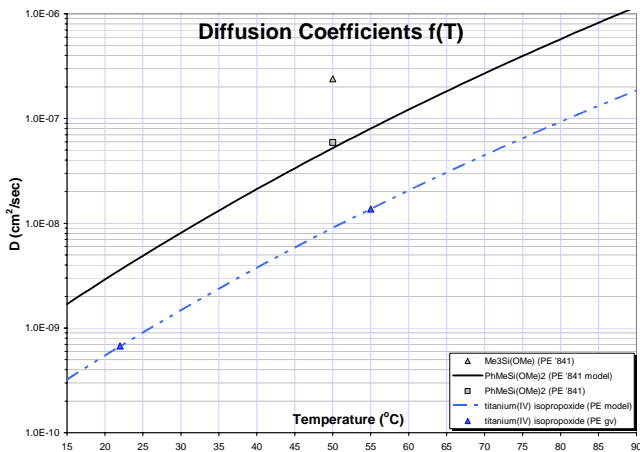


Figure 6. Mismatch of diffusion coefficients in '841 technology

Figure 6 presents diffusion data and models as functions of temperature for Me_3SiOMe and $\text{PhMeSi}(\text{OME})_2$ from [3] along with diffusion data and a model of the catalyst (titanium(IV) isopropoxide or TIPT), which is the preferred catalyst of the previous three incarnations of injection described by [2] and [3]. TIPT remains in use today [10]. At 50°C $\text{PhMeSi}(\text{OME})_2$ monomer diffuses about 5.8 times faster than the catalyst required for it to condense. At that same

temperature Me_3SiOMe monomer diffuses about 26 times faster than the TIPT and is effectively precluded from any condensation reaction. Even if Me_3SiOMe did condense, it would condense to hexamethyldisiloxane, which is itself fast to diffuse and fugitive. With the Me_3SiOMe component representing between 5 and 30%_w of the formulation (depending upon the vintage of the injection) essentially leaving the cable without condensation and about 25% of the $\text{PhMeSi}(\text{OME})_2$ monomer doing the same, between one-third and one-half of the '841 treatment fluid has no influence on the medium-term or long-term post-injection performance.

The retention efficiency may be expressed as a percentage of any monomer-catalyst combination as X_o/X_t . X_o is the mass fraction of the monomer that is not lost from the system before condensation, less the hydrolysis by-products (typically methanol or MeOH) and X_t is the mass fraction of the fully oligomerized monomer less the hydrolysis by-products. The hydrolysis by-product for pure $\text{PhMeSi}(\text{OME})_2$, for example, calculated from stoichiometry is 25.3% methanol. Thus a perfect system, which loses no uncondensed monomer, would enjoy 100% retention efficiency.

Retention efficiency can be measured in full-size cables as in [14], but considerable time is required to obtain the data. Miniature or model cables can be utilized to obtain results in a more timely fashion. The model cable is filled with fluid and catalyst combinations in the same proportion as with actual cable and the weight of the sealed assembly is monitored with time as fluid exudes from the cable. The model cable is temperature controlled in either in a water bath to simulate buried cable or in a bed of diatomaceous earth to simulate a dry environment.

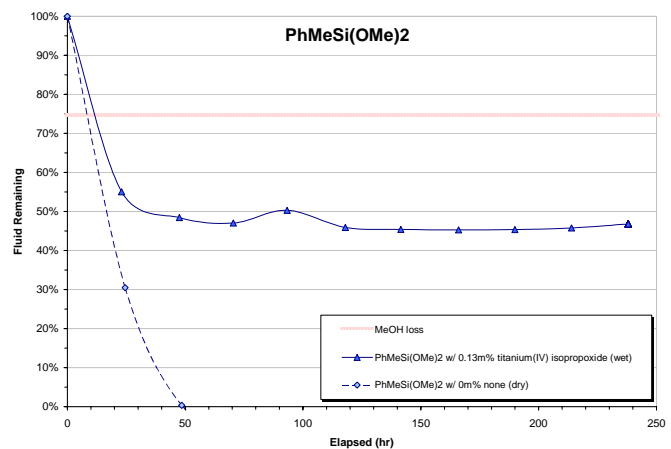


Figure 7. Siloxane retention experimental data for '841 system at 55°C.

Figure 7 presents data collected to measure retention efficiency from a 1/6th scale model of a 15kV cable with 100% insulation and a 53.4 mm² (1/0 AWG) conductor for the

PhMeSi(OMe)₂/TIPT system in historically widespread commercial use.

The dotted line at 74.7% shows the best possible retention after accounting for the unavoidable loss of methanol as silane hydrolyzes. The dashed line delineated with diamonds shows how the monomer quickly exudes if there is no water available to allow hydrolysis to occur, the hydrolysis being a necessary precursor to condensation. Finally, the smoothed line with triangles shows the performance when catalyst is added and the model is submerged in 55°C water. The point at which the silane/catalyst system plateaus is 45.6%. The retention efficiency for this system is 61% (i.e. 45.6/74.7). The retention inefficiency or portion of the treatment fluid that leaves the cable very quickly and does not provide any medium or long-term benefit is 39%.

In contrast to the 61% retention efficiency of the ‘841 technology, the 732 technology enjoys an 87% retention efficiency. The data is provided in Figure 8 with each line being analogous to the lines described in Figure 7.

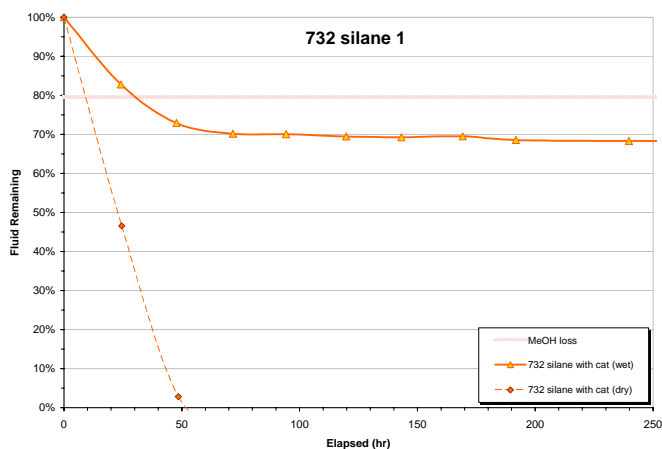


Figure 8. Siloxane retention experimental data for silane 1 of the 732 technology at 55°C.

As described in [1] the ‘841 technology undersupplies fluid for URD-sized cables (round conductors less than 125 mm² or 4/0 AWG). For example a 15kV, 19-strand, 53.4 mm² (1/0 AWG) cable suffers from an undersupply of fluid by about a factor of 2 before dilution of the medium term treatment fluid with the fugitive Me₃SiOMe. The entire Me₃SiOMe portion of the ‘841, which is between 5 and 30% of the formulation is fugitive and has no impact on medium or long-term performance. The technology practiced between 1989 and 1993 described by U.S. patent 4,766,011 [2] did not have its medium term performance diluted. In Table 3 the ‘011 column indicates for item 1 that 50% of the required fluid is supplied. As the ‘841 technology was introduced and changed the medium term component was diluted first by 30% and since 2005 by between 5 and 10%. These dilutions are reflected in

lower supplies of medium term fluid of 35% (1994-2004) and 46% (2005 to the present).

As described in [15], these same cables treated with ‘841 technology lose 5 to 15% of the supplied fluid to the EPDM components through which the fluid is injected. If there are any splices in the cable there is an additional loss not reflected in Table 3. No such losses occur with 732 technology as impermeable injection adaptors are utilized [15]. Item 2 of Table 3 shows component efficiency which is 100% minus the EPDM component loss, about 90% for ‘841 and 100% for 732. Item 3 of Table 3 reflects the 61% retention efficiency of ‘841 and the 87% retention efficiency of 732. For each column in Table 3, items 1, 2, and 3 of are multiplied to yield the total medium-term fluid supplied relative to the requirement to fully treat the cable.

15kV, 53 mm ² (1/0) cable	‘011 1989- 1993	‘841 1994- 2004	‘841 2005- now	732
Medium-term Fluid Supply Effect				
1. Supply relative to requirement	50%	35%	46%	115%
2. Component efficiency	~90%	~90%	~90%	100%
3. Retention efficiency	61%	61%	61%	87%
Cumulative supply	27%	19%	25%	100%

Table 3. Fluid supply summary for ‘841 variations and 732 technology. Cumulative supply = row 1 • row 2 • row 3.

Because of the 732 supply flexibility described by [1], precisely the required amount of fluid can be supplied to almost any cable to achieve the desired post-injection performance. For the 53.4 mm² (1/0 AWG) cable provided as an example in Table 3, the total supply difference between 732 and ‘841 is about four-fold. For smaller cables such as those with 7-strand, 33.6 mm² (No.2 AWG) conductors or cables with thicker insulations such as 25 and 35kV cables or for cables with compressed or compact conductors, the total supply difference becomes greater. For larger cables the difference diminishes, but the medium term component difference never drops below the difference in retention efficiencies.

The 732 technology also includes several long-term performance ingredients which have no analog in the ‘841 approach. For both the ‘841 fluid and the silane 1 component of the 732 formulation a point in time is reached when the oligomer concentration declines below a threshold performance level. Performance above the threshold level is sustained by the medium-term component of 732, silane 1, for considerably longer than that of ‘841. Ultimately silane 1 and its oligomers decline in concentration and if there were no long-term components, the formulation would experience dielectric enhancement efficacy approaching the reliability threshold. It is at this point when the long-term components of 732 (i.e. silane 2, 1,3-diketone, organic O, organic MA, and

organo-metallic F) begin to engage and sustain reliability above the required threshold. These long-term components are absent from the '841 technology. These components and their very long-term effects will be discussed in future papers.

SUMMARY

The greater than three-fold performance improvement of 732 technologies over the previous generation of rejuvenation approaches requires more than the benefits of providing an adequate volume of fluid and adjusting the formulation to the geometry and anticipated cable operating temperature profile as was demonstrated in previous papers [1], [5], and [6]. As important as those advances were, this paper demonstrates a theoretical framework and provides data, which provide new insight into the observed performance improvements in excess of a factor of three. The 732 technology performance advantage is explained by ...

- tailored volume and tailored formulations for each cable geometry and operating temperature compared to the historical method where the amount of fluid supplied is what conveniently fits in the cable and a one-size-fits-all chemistry is applied to disparate applications;
- superior functionality for ...
 - micro-void filling
 - drying;
- completely new functionality for ...
 - stress grading
 - voltage stabilization
 - UV stabilization, and
 - PD suppression;
- long-term treatment persistence provided by catalyst-silane systems which retain the required quantity of dielectric enhancement fluid in the cable at the required concentration for the required time.

Additional advances beyond the scope of this paper will be discussed in future papers.

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