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ADVANCES IN CHEMICAL REJUVENATION OF SUBMARINE CABLES

Glen BERTINI, Novinium, Inc., (U.S.A.), glen.bertini@novinium.com

ABSTRACT

Submarine cables spanning two or more kilometers have proven challenging to apply conventional rejuvenation technology. Novel approaches, which include new installation methods and new materials to extend the life of submarine power cables, are described. Theory, experiments, and field results demonstrate that these new approaches address the shortcomings of the earlier technology. The technology described can be tailored to provide: (1) more rapid short-term reliability, (2) longer rejuvenated cable life, (3) an inherently safer installation, (4) a tailored formulation paradigm which adjusts the chemistry to account for significant operational variables, and (5) a process which can address any length of cable.

KEYWORDS

Submarine cable, rejuvenation, injection, life extension, radial exclusion, strand desiccation.

INTRODUCTION

Over twenty years have elapsed since the author and his colleagues introduced the first commercially significant solid dielectric enhancement technology as described in [1]. During those twenty years, this first generation technology has proven itself as an important tool to enhance the reliability of aging infrastructure, saving circuit owners an estimated US$1B of capital, which otherwise would have been spent on replacement. Submarine cables have proven to be an engineering challenge. Since the cables are often very long, the two-decade-old approach is often incapable of fully completing the cable treatment.

This paper describes novel approaches, including new installation methods and new materials, to extend the life of submarine power cables. Theory, experiments, and field results demonstrate that the new approaches address the shortcomings of the first generation technology. The new technology choices can be tailored to provide: (1) more rapid short-term reliability – the post-injection dielectric performance improvement slope is steeper by more than an order of magnitude as shown in [2], (2) longer rejuvenated cable life often exceeding the 40-year expected life for the highest performance modern cable designs as demonstrated in [3] and [4], (3) an inherently safer installation, including lower flammability fluids, which have flash points in excess of 94°C compared to the legacy material, which has a flash point of 0°C as per the supplier's MSDS, which can be found at [5], (4) a tailored formulation paradigm, which adjusts the chemistry of the treatment fluid to account for significant operational variables described in [2], and (5) a novel process, which can address any length of cable. The first four items in this list of advances have been explained elsewhere. The balance of this paper will examine the injection conundrum faced when treating very long cable lengths.

CONDENSATION

From 1984 to 1987 approximately 20 km of medium voltage underground power cable were treated with acetophenone. Acetophenone was a known tree retardant and life extension material. Acetophenone is present in most cross-linked polyethylene (XLPE) as a by-product to the cross-linking process. The beneficial effects of acetophenone were noticed accidentally, since it is present in significant quantities in new XLPE cables as a by-product of the cross-linking process.

There are two problems with acetophenone when it is used alone. First, its freezing point is about 20°C, which makes its injection at temperatures below that temperature problematic. Second, with a rapid diffusivity of 1.3×10^{-7} cm^2/s at 50°C in polyethylene, it is fugitive and would not stay inside the cable insulation for periods beyond a couple of years. The early injections with acetophenone employed permanent bottles attached to the cable to replenish the acetophenone which exuded from the cable. Although failure free and a huge technical success, the safety and maintenance issues associated with this life-time connection drove the development of a water-reactive silicone material PMDMS (phenylmethyldimethoxysilane). The properties and advantages of moderately diffusing ($D=5.73 \times 10^{-8}$ cm^2/sec at 50°C) PMDMS are described in considerable detail in [1]. In short, a silicon atom with two water reactive groups was substituted for the carbon-oxygen double bond of the acetophenone. The two water-reactive portions of the PMDMS are methoxy groups, which readily hydrolyze with water and condense in the presence of an appropriate catalyst, to form siloxane oligomers, generally to an equilibrium mixture with degrees of polymerization between 4 and 7.

Alkoxysilanes undergo two types of chemical reactions, both of which are typically accelerated with catalysis. The first reaction type is hydrolysis. For example, PMDMS or $PhMeSi(OMe)_2$ hydrolyzes in two steps as follows:

$$PhMeSi(OMe)_2 + H_2O \rightarrow PhMeSi(OH)(OMe) + MeOH \quad [1]$$

$$PhMeSi(OH)(OMe) + H_2O \rightarrow PhMeSi(OH)_2 + MeOH \quad [2]$$

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

$$2\ PhMeSi(OH)(OMe) \xrightarrow{\text{catalyst}} PhMe(OMe)Si\text{-}O\text{-}SiPhMe(OMe) + H_2O \quad [3]$$

This second kind of reaction, the condensation of two monomers to a dimer in the presence of a catalyst, is but one example of dozens of condensation reactions which actually occur. The catalyst employed by the over two-decade-old technology is tetraisopropyltitanate (TIPT). For example, with TIPT present 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

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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 [1] that without catalyst there was no measurable condensation of $PhMeSi(OMe)_2$ in the presence of water after 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 [3] and [4] and is consistent with the data presented by Kleyer and Chatterton in [6]. The data and analysis demonstrate that earlier generations of technology suffer a loss of over 25% of all monomer supplied. The uncondensed or under-condensed monomer permeates into the soil.

CONUNDRUM

While condensation of the monomer is desirable within the cable insulation, it is not desirable in the conductor interstices – at least on the very long runs of conductor commonly encountered with submarine applications. As the silane oligomerizes, its permeation rate decreases (desirable), but its viscosity increases (undesirable). In [1], Vincent provided the data of Figure 1.

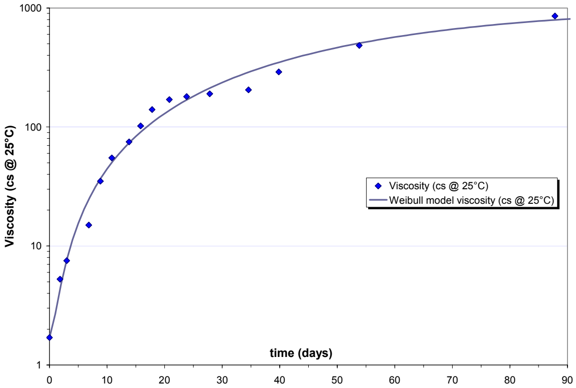

Figure 1. Viscosity increase with time for PMDMS.

An increase in viscosity within the strand interstices during the injection slows the flow of fluid along the conductor length. This slowing provides more time for further condensation and further increases in the viscosity in a counterproductive reinforcing cycle. The injection conundrum: How is it possible to assure adequate condensation in the insulation to promote long post-treatment life while preventing premature condensation in the strand interstices? As described in [7] and in the co-published [8], substantial progress has been made in the catalysis of silane condensation.

POISEUILLE'S LAW

The laminar flow of rejuvenation fluids through the small interstitial areas of power cables is entirely laminar and hence is described by Poiseuille's law.

$$\frac{dV}{dt} = \frac{\pi R^4}{8\eta}\frac{|\Delta P|}{L} \tag{4}$$

dV/dt is the volumetric flow rate, η is the dynamic viscosity, ΔP is the pressure driving force, L is the length of the cable, and R is the hydraulic radius of the cable interstices. The geometry of the submarine cable, its interstitial shape, and its length were determined by the design of a cable, which was installed decades ago. The manufacturer of the cable and the engineer who determined the length of the cable did not make any allowances to facilitate the injection of the cable when it approached the end of its useful life.

To inject a cable one has only two variables over which it is possible to exert some influence – namely, the injection pressure and the viscosity of the fluid. The flow rate for any given length is directly proportional to the pressure drop; hence the maximum allowable pressure is invariably utilized. The maximum pressure allowable is largely a function of the cable design. The most important variables are the outside diameter of the strand bundle and the thickness and composition of the insulation. At the maximum pressure, the flow rate for any given cable is determined by the fluid viscosity. The dashed line in Figure 2, shows the result of the integration of equation 4 for a 19-strand 107 mm^2 (4/0 AWG), round copper-stranded, EPR-insulated cable where the maximum sustainable pressure delta (ΔP) is 4.2 bar injected with uncatalyzed PMDMS.

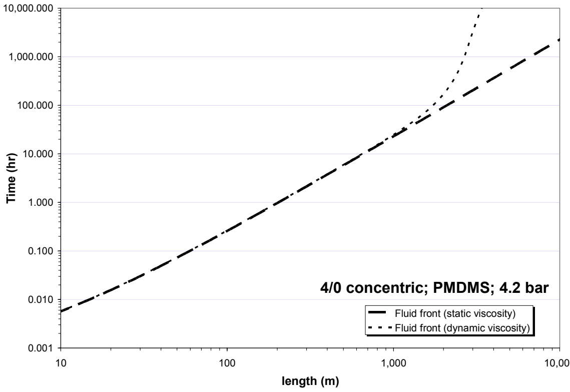

Figure 2. Time required to advance fluid front for a 107 mm^2 (4/0 AWG) round conductor at 4.3 bar.

If there were no condensation reaction, any length of cable could be injected with sufficient patience. When catalyst is added to PMDMS, however, the viscosity is not static and at around 1 km the dotted line diverges from the dashed line and the viscosity escalates quickly, making the injection of this cable design in lengths greater than 2 km impractical or impossible.

To validate the Poiseuille flow model, the actual injection times for hundreds of cables of different geometries injected at different pressures were compared to the model predictions. A representative subset of those cables (107 mm^2 round conductor) are plotted in Figure 3. The actual results typically fall just above the predicted value because of non-uniform end effects. That is, the fluid enters the intesticies through an injection adaptor, which is installed by different craft workers. A craft worker may introduce a positive resistance deviation – it is not possible to introduce a negative deviation.

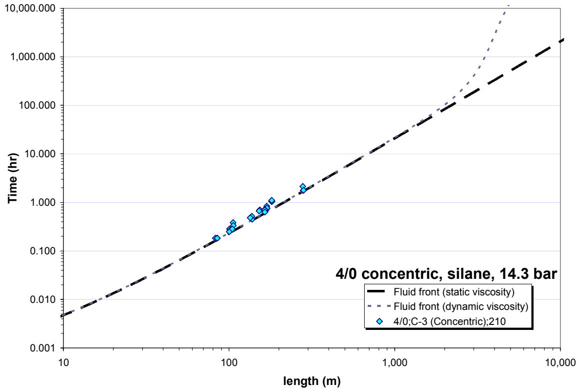

Figure 3. Representative sample of actual injection time versus Poiseueille law predicted.

STRAND DESICATION

Desiccating cable strands before injection as taught by Bahder in [9] has been practiced for over 25 years. Strand desiccation may temporarily remove water from the strands, but as demonstrated in [10], water quickly diffuses back into the insulation, strand shield, and the strand core. The second law of thermodynamics together with the high diffusion coefficient of water assures that water makes it back into the strands quickly. There is a fugacity gradient of water from the exterior of the cable, which as shown in [10] is essentially always saturated, toward the cable interior if the water has been removed or partially removed. As a practical matter, strand desiccation has no significant impact on the amount of water present and hence on the rate of silane condensation during injection on long cables such as a 3.75 km, 19-strand, 107 mm^2 cable which serves as an example in this paper.

THREE FLUID DYNAMIC PHASES

A novel process that involves three fluid dynamic phases overcomes the limitations of the older approach. The first fluid dynamic phase is the injection of a non-reactive radial exclusion fluid into an empty cable. The “empty” cable has air in its interstices, but the viscosity of air is about two orders of magnitude lower than treatment fluids and hence it is effectively empty from a Poiseuille’s law perspective. The second phase is the sustained flow of the radial exclusion fluid through the cable. This second phase is terminated when it is determined by mass balance that sufficient radial exclusion fluid has been supplied to the polymeric portions of the cable. The third and last fluid dynamic phase is the introduction of water-reactive condensable treatment fluids behind the radial exclusion fluid. In this last phase all of the radial exclusion fluid is flushed from the strand interstices.

RADIAL EXCLUSION

To circumvent the injector’s conundrum, what is required is to essentially remove and exclude all of the water, not only from the strand interstices, but also from the conductor shield and adjacent insulation. Further, the water must be kept out for the duration of the injection period. Put another way, there must be a water fugacity gradient from the inside of the cable outward, so that water does not penetrate radially inward. Figure 4 illustrates the concept.

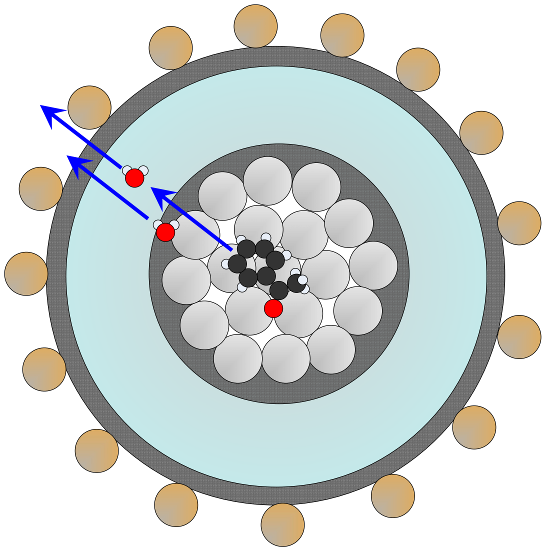

Figure 4. Radial exclusion of water by the more soluble acetophenone.

Acetophenone (the large molecule in the strand interstices of Figure 4) is over 300-times more soluble in polyethylene than is water, as shown in Figure 5. Acetophenone preferentially wets those polymers at the expense of the more polar water molecules. A fugacity gradient is established against the concentration gradient driving water from the cable and largely precluding its re-entry until the bulk of the acetophenone has exuded out of the cable.

The radial exclusion fluid, acetophenone, is mixed with other components including propylene carbonate. Among its several purposes, propylene carbonate lowers the acetophenone crystallization point allowing injection at almost any practical temperature. The mixture of acetophenone and propylene carbonate is an example of a radial exclusion fluid.

Figure 6 shows the Poiseuille’s law predictions for three cases along with a field observed value. The dashed line shows the predicted time required to inject the example cable design for any length between 10 meters and 10 km. The observed time for a 3.75 km field injection is shown as a diamond.

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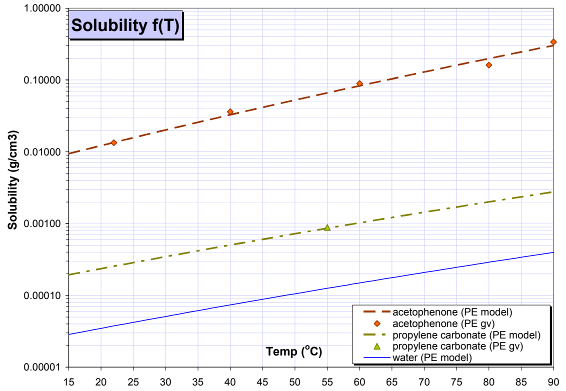

Figure 5. The relative solubilty of acetophenone, propylene carbonate, and water. The values for water are taken from [11].

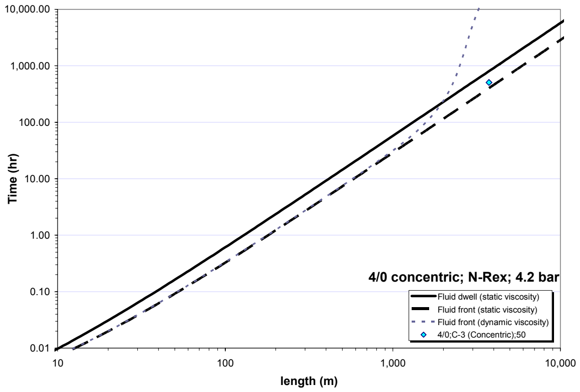

Figure 6. Radial exclusion model and actual injection time as a function of cable length for a 107 mm^2 (4/0 AWG) concentric stranded conductor injected with 4.2 bar ΔP with a mixture of 50%$_w$ acetophenone and 50%$_w$ propylene carbonate coded as N-Rex.

Once the radial exclusion fluid has traversed the entire length of the cable a new time parameter, the dwell time (represented by the solid line), becomes interesting. The dwell time, is the time it takes a fluid element to traverse the length of the cable when the cable is entirely filled with fluid. This is in contrast to the first phase of the injection process where the fluid front is demarcated with a gas of inconsequently low viscosity.

In the second fluid dynamic phase radial exclusion fluid is fed continuously into the cable until sufficient exclusion fluid has been absorbed by the cable to effectively exclude water for the subsequent injection period. Finally, the dotted line in Figure 6 shows what would have happened to the injection time had the injection fluid been a water reactive component like PMDMS. The fluid would likely have never come through as the time to traverse the entire length of the cable would be in excess of 10,000 hours (416 days).

Figure 7 shows the progress of a submarine injection using the radial exclusion process. Flow rates are calculated based upon changes in fluid levels in feed and receiving tanks and hence there are considerable variations in the data. The vertical line at 65 days in Figure 7 delineates the end of Phase II and the beginning of Phase III of the injection process. Phase II involves continuous flow of non-condensing fluid until water has been effectively excluded from the entire cable length and the inner portion of the insulation radius.

The results are constrained by two mass balance considerations. First at infinite time, the exudation rate (radial flux of fluid out of the conductor) must be equal to the feed rate less the outlet flow rate. Second, the cumulative exudation mass must be equal to the cumulative feed mass minus the cumulative outlet mass. Application of these two conservation of mass constrains to the available flow and mass accumulation data yield the three curves of Figure 6. The solid line is the volumetric feed rate, the dashed line is the volumetric outlet rate, and the dotted line is the volumetric exudation rate.

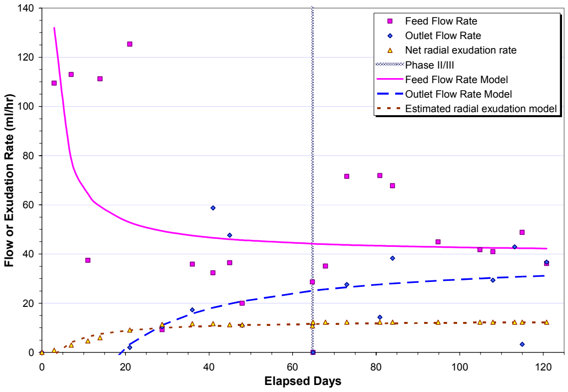

Figure 7. Field application of radial exclusion.

CONUNDRUM RESOLVED

Perhaps the only thing worse than not being able to extend the life of a submarine cable with fluid injection technology, is to incur the expense of an unsuccessful attempt. In such a scenario, at least a portion of the cable is left untreated. The untreated cable is the weakest link and it makes little practical difference that a portion of the cable enjoys improved reliability as a failure anywhere along the cable length involves wither costly water repairs or replacement.

In the actual field application of the radial exclusion process illustrated in Figure 7, there was no significant increase in the viscosity of the treatment fluid in the final phase of the injection process. Careful tailoring of the chemistry and the duration of the phase II exclusion period allows any cable length and geometry to be accommodated.

In what would have been a paradox with the historical injection paradigm, even more effective condensation catalyst systems can be utilized such as those described in [8]. Improved condensation catalyst systems provides an over three-fold improvement in longevity over the legacy technology. The radial exclusion process permits the application of formulation improvements without sacrificing the maximum possible injectable length. Finally, even better short-term post-injection reliability can be realized, because of the highly effective and fast-to-diffuse performance of acetophenone during the radial exclusion step.

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GLOSSARY

PMDMS: Phenylmethyldimethoxysilane
TIPT: Tetraisopropyltitanate or titanium(IV) isopropoxide