

ADVANCES IN CHEMICAL REJUVENATION : EXTENDING MEDIUM VOLTAGE CABLE LIFE 40 YEARS



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

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 mechanisms of cable failure, which are addressed by the newest injection technology, are briefly reviewed. The focus of the paper is on the chemistry of oligomerization, which determines how long a treatment persists in the cable. Three commercially available chemistry choices are compared.

KEYWORDS

Cable rejuvenation, cable life extension, silicone fluid treatment.

INTRODUCTION

Over twenty years have elapsed since the authors introduced the first commercially significant solid dielectric enhancement technology described in [1]. During those two decades, 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. Additionally, approximately 30M kg of aluminum, 7M kg of copper, and 11M kg of polyethylene have been effectively recycled – conserving scarce world resources. Incremental improvements during those two decades have aided in the widespread commercial acceptance of dielectric enhancement technology on at least four continents. There are some concerns with the first generation technology, which has been utilized by over 500 circuit owners worldwide. Concerns include: (1) a higher than desirable post-injection failure profile, due to the slow permeation of the fluid into the dielectric and the resulting slow increase in post-injection dielectric performance of approximately 0.5% per day, (2) a limited cable life extension of 10-20 years, (3) safety and operational issues related to the low flash point (0°C) of the fluid and required interaction with energized circuits for 7-strand and 19-strand conductors, (4) a one-size-fits-all delivery paradigm that ignores widely divergent operating considerations, namely ambient soil temperature, load induced temperature variations, and cable geometry, and (5) an inability to successfully restore the reliability of recently failed cables.

Novel approaches, which include new installation methods and new materials to extend the life of power cables, are described. 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 described in [3] and [4], (3) an inherently safer installation, including lower flammability fluids, which have flash points in excess of 94°C vis-à-vis the older technology, which has a flash point of 0°C as documented in [5], (4) a tailored formulation paradigm which adjusts the chemistry of the fluid to account for significant operational variables detailed in [3] and [4], and (5) process and formulation choices, which specifically address cables which may contain electrical trees described in [6].

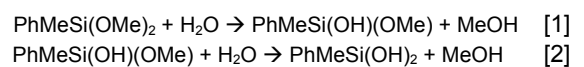
The most advanced second generation technology employs a fluid, which actively sequesters hot electrons, absorbs UV photons associated with the conversion of water trees to electrical trees, scavenges free radicals, increases the partial discharge inception and extinction voltages, and reduces the amount of damaging water in the insulation.

The balance of this paper focuses on the chemistry required to allow silanes to condense fully to allow their beneficial effects to persist for decades after treatment.

EXUDATION

The second law of thermodynamics demands that all mobile treatment materials injected into strand interstices must ultimately exude into the soil around the cable. Treatment materials must have some mobility in order to penetrate into solid dielectric materials. Lacking mobility would preclude them from having any influence over the dielectric. Absent a chemical bond to the insulation polymer backbone, the treatment fluid will migrate radially outward from the strands into the insulation, where it exhibits its rejuvenating characteristics and then these materials migrate radially outward into the surrounding environment at which point the materials cease to provide any reliability benefit.

Optimally modern treatment fluids should migrate into the insulation quickly, but then exude into the surrounding environment slowly. Beginning with the technology of Vincent described in [1], this was accomplished with the hydrolysis and subsequent condensation of dialkoxysilanes. The most common silane used was phenylmethyldimethoxysilane or PMDMS. PMDMS or $\text{PhMeSi}(\text{OMe})_2$ oligomerizes in two steps as follows ... first hydrolysis:



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



This second kind of reaction, the condensation of two

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monomers to a dimer in the presence of a catalyst, is but one example of dozens of the 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. 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 $\text{PhMeSi}(\text{OMe})_2$ in the presence of water after 2108 hours in a test tube at 25°C.

In [6], the authors provided a framework for an experimental protocol to assess the performance of monomer and catalyst combinations. [6] also revealed an oversight of the author's previous effort: The TIPT catalyst diffuses 5.8 times slower than the primary monomeric silane (PMDMS) of the '841 technology and 26 times slower than the fast-to-diffuse secondary monomeric silane, trimethylmethoxysilane (TMMS). Figure 1 demonstrates the effect of this mismatch with the PMDMS – less than 50% of the mass of fluid supplied remains in the cable shortly after treatment, because a substantial portion of the monomer is uncatalyzed and hence prematurely exudes into the environment.

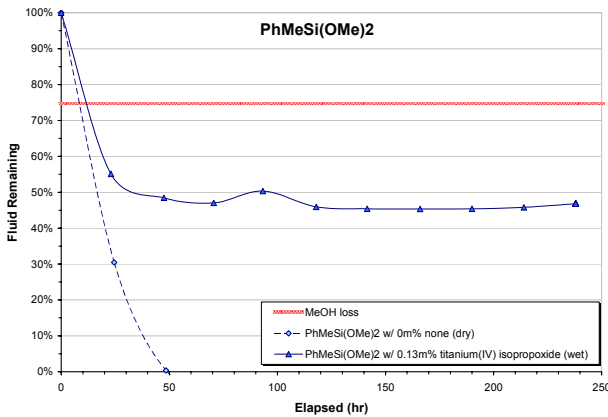


Figure 1. Exudation inefficiency of PMDMS catalyzed with TIPT at 55°C.

The dashed line in Figure 1 traces the rapid exudation of the monomer from a model cable which is 1/6th the scale of a 19-strand, 53.4 mm² (1/0 AWG) PE-insulated power cable in an anhydrous condition and hence no hydrolysis. Without a hydrolyzed intermediate there can be no condensation.

The solid line traces the exudation of TIPT catalyzed (0.2%_w) PMDMS when the model cable is immersed in 55°C water. This curve is characterized by an initial rapid decline as some uncatalyzed and under-catalyzed monomer exudes from the model cable (undesirable) and the methanol by-

product of the hydrolysis reaction exudes from the model cable (desirable). The part of the curve that is essentially horizontal is referred to as the “exudation plateau”. The exudation plateau represents the average value of fluid remaining in the model cable from 140 to 400 hours and is utilized to characterize the fluid/catalyst performance. The horizontal line at about 74.7% is the best theoretical performance possible, because stoichiometry dictates that about 25.3% of the mass of the PMDMS must be lost as the methoxy groups are converted to fugitive methanol which quickly diffuses out of the cable. Concurrently, silanol (SiOH) functionally is condensed to form Si-O-Si and water. The exudation inefficiency is the amount of uncondensed or under condensed silane mass lost, excluding the amount of methanol lost, divided by the starting mass less the amount of methanol lost. By this definition the PMDMS – TIPT (0.2%_w) system suffers a 39% exudation inefficiency. Since the introduction of the '841 technology in [7] the PMDMS has been diluted with between 5%_w and 30%_w trimethylmethoxysilane (TMMS). Because the TMMS diffuses 26 times faster than the catalyst and because at best it condenses to a very fast to permeate dimer, 100% of that component is fugitive. The exudation inefficiency of TIPT catalyzed TMMS is 100%. The combined '841 exudation inefficiency is the weighted average of the two components. For example with the current level of TMMS of 5%, the combined exudation inefficiency is about 42% (i.e. $0.95 \cdot 39\% + 0.05 \cdot 100\%$).

IMPROVED EXUDATION EFFICIENCY

In [6] significant improvements to exudation efficiency were demonstrated when a catalyst having good catalytic activity is paired with a silane monomer with a similar diffusion coefficient. Conventional metallic catalysts (most typically titanium and tin) demonstrated up to an 87% exudation efficiency when properly paired.

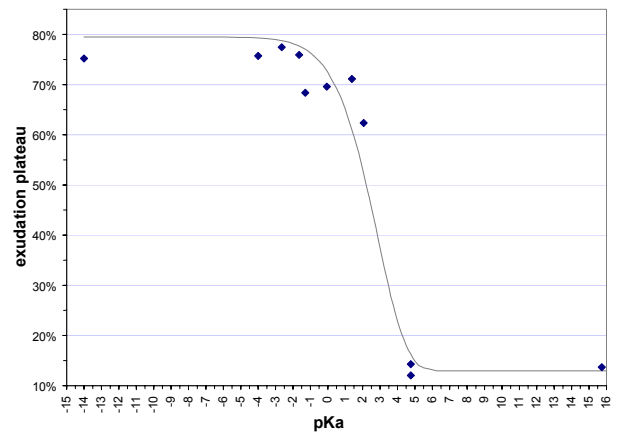


Figure 2. Exudation plateau for various acid catalysts as a function of the acidity. The strongest acids are on the left.

Figure 2 provides data for a better class of acid catalysts never before used for injection hydrolysis and condensation. This class of catalysts enjoy both higher condensation activity and potentially faster diffusion than conventional metallic catalysts. This class of catalysts provides exudation efficiencies very close to 100%. In Figure 2, the exudation plateaus of a proprietary dimethoxysilane with various acid

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catalysts are plotted as a function of their pK_a (negative log of the acid dissociation constant).

Very high exudation efficiencies can be obtained with acid catalysts with pK_a values less than about 2. There is little incremental benefit recognized as the acidity increases (decreasing the pK_a) below a pK_a of -2. Figure 3 shows how the exudation efficiency varies with a typical catalyst concentration. The majority of the benefit is realized at 0.1%_w and there is very little gain from increasing the concentration above 0.2%_w.

Together, the data of Figures 2 and 3 demonstrate that a very simple catalyst change can improve exudation efficiency to over 95%.

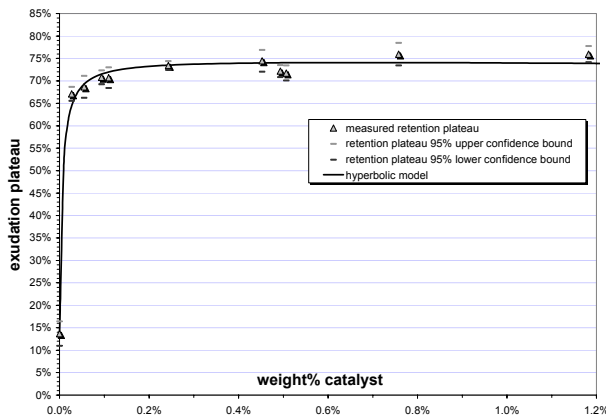


Figure 3. Effect of catalyst concentration on exudation efficiency.

Ingredients			Comment
'841	011	732	
Me ₃ Si OMe	aceto-phenone	aceto-phenone	short term
PhMe Si(OMe) ₂	PhMe Si(OMe) ₂	silane 1	medium term
TIPT	catalyst package	catalyst package	catalyst
		silane 2	long term; stress grading
		organic PC	short term; stress grading
		organic TH	UV stabilizer
		organic TU	UV stabilizer
		organic GA	voltage stabilizer; UV stabilizer
		organo-metallic F	PD suppression; UV stabilizer

Table 1. Ingredients of '841, 011 & 732 technologies. Materials not explicitly identified are proprietary.

Table 1 provides a summary of the three ingredients utilized by the older '841 approach alongside the analogous ingredients of the 011 and 732 technology. There are six ingredients in the 732 technology which have no analog in the '841 and 011 formulations – these absent functions are represented by grey.

THE 011 COMPROMISE

The overwhelming performance benefits of the 732 technology beg the question: Why perfect the catalyst package of the venerable PMDMS? While in the majority of the developed world the incremental manufacturing costs of the very special single purpose silane 1 material and silane 2 materials are small relative to the over 3-fold reliability improvements they provide, there are economic cases where the commodity pricing of PMDMS makes its application worth perfecting. PMDMS is manufactured in great quantity and used for literally hundreds of applications. Where the quantity of fluid required to rejuvenate is very high, such as in certain large diameter cables, or where the cost of more specialized components cannot be justified such as in developing economies, the optimization of the 011 technology has its place. The substitution of acetophenone for TMMS requires no compromises.

- **Safer** – the TMMS is the source of the low flash point of the '841 technology and the serious safety implications that entails.
- **Cheaper** – TMMS is considerably more expensive than acetophenone.
- **Better** – by all measures of performance, acetophenone excels in the short-term rejuvenation role.

Correcting the approximately 40% exudation inefficiency of the TIPT catalyzed PMDMS with an improved catalyst package breathes new life (about 40% more new life) into the old technology invented by one of the authors over two decades ago and improved by the authors over a decade ago.

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GLOSSARY

011: The perfection of the technology described by expired U.S. Patent 4,766,011 [1].

'841: The technology described by U.S. Patent 5,372,841
PMDMS: phenylmethyldimethoxysilane or PhMeSi(OMe)₂
TIPT: tetraisopropyltitanate or titanium(IV) isopropoxide
TMMS: trimethylmethoxysilane or Me₃SiOMe