

CABLE REJUVENATION – PAST, PRESENT AND FUTURE

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ABSTRACT

This paper discusses the basic theory behind the functionality of phenylmethyldimethoxysilane as a water tree retardant when injected into a power distribution cable with extruded dielectric insulation. Also discussed is a new class of fluids; dialkyldialkoxysilanes, that continue to show promise as next generation fluids.

KEYWORDS

Cable Injection Technology, phenylmethyldimethoxysilane dimethyldimethoxysilane water tree cable aging insulation.

CABLE REJUVENATION - THE PAST

Cable injection technology and cable rejuvenation are two terms commonly used to describe the introduction of engineered materials into an aged but still operational cable with the intent of counteracting the effects of cable insulation aging. The ultimate objective is to significantly extend the economically useful lifespan of an underground power distribution cable, deferring by decades the cost of cable replacement. Early attempts at cable rejuvenation included the introduction of a continuous stream of dry gas or alternatively a plasticizer such as acetophenone through the cable conductor's interstitial spaces [1], [2]. The introduction of dry gas was an attempt to alter the equilibrium water content of a cables insulation. Plasticizers were injected with the hope that they would diffuse into the cables insulation and swell the insulating material collapsing the voids and imperfections which seed water tree growth.

These approaches provided promising results [3] but they both shared the same weakness that would have to be overcome before cable rejuvenation was to become economically attractive. For these materials to have an affect on a cable's insulation they needed to diffuse into the material fairly quickly. The same property that allowed them to enter the insulation material quickly however, also allowed them to pass through and out of the cable in similar fashion.

They needed to be constantly replenished in order for their affects to be maintained. It did not take long for the maintenance and material costs to undermine their up front economics.

CABLE REJUVENATION - THE PRESENT

Dow Corning Corporation overcame the weakness noted in the earlier materials by employing materials which could diffuse quickly into a cable's insulation but which, once there, would undergo oligomerization rendering them much less mobile. The earliest material successfully employed using this strategy was Phenylmethyldimethoxysilane (PMDMS). This material is still in use today. Under some conditions it is still used as a standalone injection material. In most cases it has been blended with other materials for enhanced functionality. An understanding of its' effects on

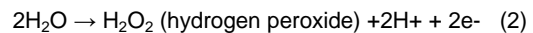
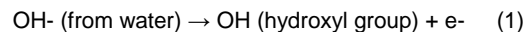
cable ageing provides a basis for understanding the formulations of this material that are currently being employed today, as well as the material advancements on the horizon.

Phenylmethyldimethoxysilane(PMDMS) functionality

To understand how this class of materials function one needs some background in the very broad topic of water tree growth, which is the primary aging mechanism of medium voltage cables employing extruded dielectric insulating materials.

Water Tree Growth

An understanding of the process by which water trees grow and degrade a cable's insulation was required before tree-resistant materials could be incorporated into newly manufactured cables. Certainly, this understanding was required before cable rejuvenation materials intended for use in existing field aged cables could be investigated. The subject of water tree growth has consequently been researched [4], [5] and reported on [6] in great depth. This paper discusses only those parts of the topic necessary for a cohesive treatment of the functionality of cable rejuvenation materials. It is known that water trees are imperfections in a cable insulation characterized by their polar hydrophilic nature. That is in contrast to perfectly crystalline polyethylene which is non-polar and hydrophobic. The polar nature of those imperfections attracts water and ionic impurities. Once there and under the influence of the cable's electrical field, water can be disassociated into damaging radicals. Equations (1) and (2) are examples.



The result is that the interfaces between the polar amorphous regions, and the non-polar crystalline regions of the insulating material are oxidized. The oxidation furthers the polarization propagating water tree growth. This explanation of water tree propagation requires the presence of: polar imperfections or voids in the dielectric structure; a sufficiently strong ac electrical field and of course, water.

Effects of Phenylmethyldimethoxysilane on Water Tree Growth

Phenylmethyldimethoxysilane (PMDMS), a moderately polar molecule is drawn to the areas of water tree growth by the same mechanisms which attract water. Once in contact with the water in water tree sights the PMDMS undergoes a series of reactions generalized as follows.

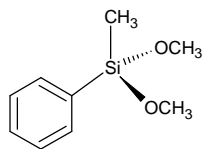


Figure One: Phenylmethyldimethoxysilane



Figure Two: Water reactivity of phenylmethyldimethoxysilane

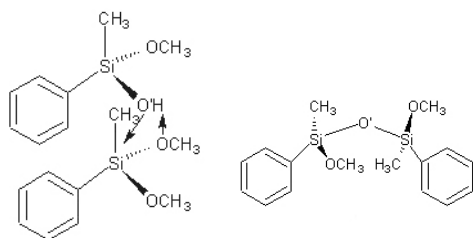


Figure Three: Dimer formation

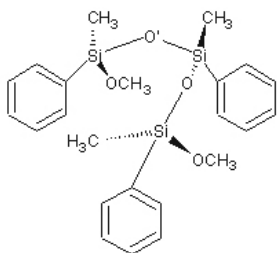


Figure Four: Higher order oligomer

Figures One, Two, Three and Four demonstrate the key features which account for the basic functionality of the phenylmethyldimethoxysilanol material. Figure One shows the basic structure of the molecule. The ring on the left hand side is symbolic of a phenyl group. Figure Two shows the water reactive nature of the PMDMS molecule. The

PMDMS molecule in contact with water forms a phenylmethyldimethoxysilane material. Figure Three demonstrates that the PMDMS molecule can combine with the newly formed phenylmethyldimethoxysilanol creating the dimer form which represents the initiation of oligomerization. There are several pathways to higher order oligomers such as the structure in Figure Four, however, in summary, the material combines with the existing water increasing in size and trapping itself inside the water tree structure. The material is at the same time eliminating the water and filling the insulation void. During hydrolysis steps in the reactions above a reaction by-product is the alcohol produced from the alkoxy moiety of the molecule. For simplification this portion of the reaction has been omitted from the illustrations.

PMDM mixtures

Phenylmethyldimethoxysilane has been in service since 1988. It has been researched and reported on in detail. There are many examples [7] [8], of peer reviewed research which demonstrates the efficacy of this fluid as a water tree retardant cable rejuvenating material. Perhaps a more important testament to its functionality is the fact that by the end of 2006 utilities had employed this technology on more than 60,000,000 feet of cable.

Clearly, however, nineteen years of real world application experience has led to some formulaic modifications. As cable rejuvenation technology was extended to larger diameter cables, for example, two observations were noted that required application adjustments. First, as cable diameter increases, the interstitial space available in the conductor core of the cable increases relative to the volume of the cable insulation surrounding it. Second, as cable size increases, cable shields get thicker and their effects on fluid diffusion increase. The first effect required that in larger cables, an inert, non water reactive silicone fluid be added to the phenylmethyldimethoxysilane material in order to dilute it and ensure that its concentration in a cables' insulation will never exceed roughly 6 percent. The second observation led to the addition of a second water reactive compound into the PMDMS solution. This second material; trimethylmethoxysilane, reacts more quickly with water and moves more quickly through the conductor shield material. This reduces the amount of PMDMS material; still considered to be the functional ingredient, that reacts with water in the conductor shield material allowing the material to more quickly and more evenly move into the cables insulation where it is functional in combating cable aging.

CABLE REJUVENATION - THE FUTURE

Phenylmethyldimethoxysilane, either alone or mixed as described above, has been the industry standard cable rejuvenation fluid for more than 19 years. Research over the past 10 years, however, has led to a new class of materials which is providing equal cable rejuvenation results while at the same time offering material properties which under some circumstances may be considered superior. These materials, known as dialkyldialkoxysilanes are similar in structure to phenylmethyldimethoxysilane, however, they replace the aromatic phenyl group of the traditional material

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with an alkyl group while maintaining the alkoxy water reactive functionality of the alkoxy silanes attached. A specific example of this class of materials would be dimethyldimethoxysilane (DMDM)

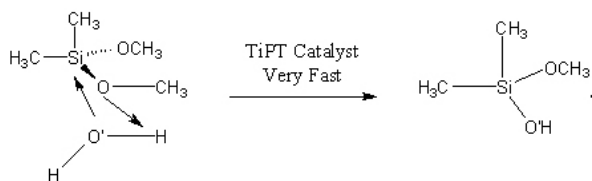


Figure Five: Hydrolysis of dimethyldimethoxysilane

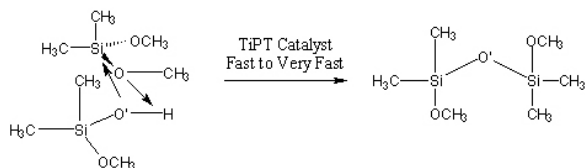


Figure Six: Dimerization of dimethyldimethoxysilane

Figures Five and Six demonstrate the similarity in form and function of the dialkyldialkoxysilane group by highlighting the features of a well researched member of this group the dimethyldimethoxysilane molecule. Looking first to the hydrolysis reaction highlighted in Figure Five, it should be apparent that the desiccating functionality of the molecule is identical to the functionality of the phenylmethyldimethoxysilane molecule. In fact the reaction is identical. Both molecules make use of a methoxy group for this conversion. It should be noted that a by-product of this reaction is the creation of methanol. The creation of methanol is not demonstrated in the outline steps above since it is not critical to functionality and adds complexity to the drawing. That accounts for the elemental imbalance in the figures above. What has changed slightly when looking particularly at the oligomerization initiation step described in Figure Six is that the aromatic phenyl portion (the ring) of the phenylmethyldimethoxysilane material has been replaced by an alkyl group in this case the dimethyl moieties. The reaction of course still results in a oligomeric chain analogous to the chain left behind by the phenylmethyldimethoxysilane reaction. That chain also serves the same stress grading and diffusion inhibiting functionalities that the chain created from the phenylmethyl performed.

Although the materials and reactions are very similar, there are some potential advantages that the dialkyldialkoxysilane class of materials have over the phenylmethyldialkoxysilane material. One is that by eliminating the phenyl ring (C_6H_5), one eliminates even the possibility that trace amounts of benzene (C_6H_6) might show up in side reactions during the manufacture of the material. Of course, since manufacturing processes exist to purge the phenyl based materials of benzene remnants the value is not great enough to accept any reduction in functionality.

Fortunately there is no decrease of functionality resulting

from the application of this particular dialkyldialkoxysilane material as a cable rejuvenation fluid. This has been demonstrated in numerous laboratory investigations and it has been a part of a nearly 14 year long field study which was discussed in brief during the 1995 Jicable technical conference [9] and again in the 1999 Jicable technical conference [10]. During the 1999 event it was described without specific compound disclosures that new materials had been injected into two of three phases of a very aged (20 years) 1000kcm, 260 mil (nominal) cable. Of course the third cable was left as an untreated control. The cables remained unloaded but energized underground. Periodically enough of the cable was excavated and removed to perform an evaluation of the condition of the cable and the remainder of the cable was re-energized.

The most recent testing of this cable was performed just in time to present some preliminary results in this paper. The most important results are represented by the following two charts.

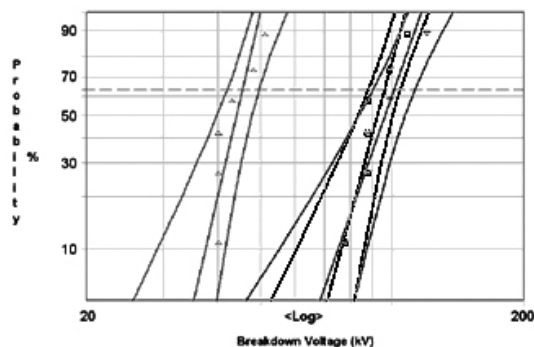


Figure Seven: Weibull distribution of breakdown voltages

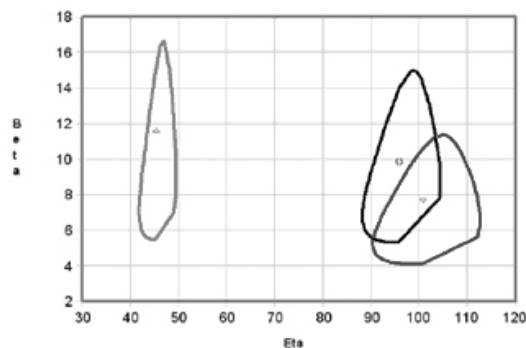


Figure Eight: Comparison of Weibull distribution parameters

Figure Seven demonstrates the effect of injection on this cable 14 years after the injection date and after 33 years of total cable aging on a nominal 25 kV system. The line on the left represents the values obtained from the untreated control cable and to the right are the two lines representing

the breakdown strengths of both treated cables. It is disclosed here that the two materials are in-fact dimethyl-dimethoxysilane and phenylmethyldimethoxysilane. There are two important observations to be gleaned from this figure. The first is that both of the treated cables maintain essentially double the breakdown strength of their untreated counterpart. The second point is that the effectiveness of the dimethyltimethoxysilane fluid is equal to the effectiveness of the phenylmethyldimethoxysilane based fluid. The lines representing the two materials are nearly indistinguishable in Figure Seven. The point is further emphasized by Figure 8 which compares the Weibull distribution parameters for all three injections. The two points representing the two different injection fluids (to the right of the chart) nearly sit on top of each other. Results are drawn from a complete battery of tests independently performed by Cable Testing Laboratories, Inc. based out of New Brunswick, NJ.

Having determined that the principles of functionality apply as surely to dimethyl-dimethoxysilane material as they do to phenylmethyldimethoxysilane, it becomes easy to extend the same logic parallels to other members of the same class of dialkyldialkoxysilane materials. One can modify the alkyl moiety of the dialkoxysilane portion of this class of materials and judge its effects by paying strict attention to its affect on the hydrolysis of the material. If the water reactivity is unaffected, i.e., comparable to that of phenylmethyldimethoxysilane, the long term efficacy determined by the identical dimethyl oligomerization reaction described above will be equivalent to phenylmethyldimethoxysilane, a material with 20 years of real world field success. It is therefore possible to alter the dialkoxysilane portion of the newer material for specific reaction by-products. For example, diethoxysilane base materials will create ethanol as a by-product while still maintaining the long term efficacy of the alkyl oligomer chain left behind in the insulating material.

CONCLUSION

The traditional phenylmethyldimethoxysilane-based injection materials have undergone nearly 20 years of concurrent laboratory investigation and field observation. Since the only goal of cable rejuvenation is to extend the life of aging power distribution cables, this long experience would seem to preclude other materials from consideration. However, there are some materials that have undergone extensive laboratory research and as this paper reports even 13 years of field observation. These materials may have utility as cable rejuvenation fluids especially in situations where their unique physical properties may offer an operational advantage.

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