

# Considerations for Injecting Cables with High Conductor Temperature

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**Abstract:** The first generation of injection technology was intended for lightly loaded cables in cooler soils. Attempts to utilize this first generation approach for more heavily loaded cables in warmer climates, particularly feeder cables, have not always been successful. Formerly identified issues including, supersaturation, over saturation, asymmetrical penetration profiles, and aluminum corrosion are reviewed. A previously unidentified failure cause is described. A new generation of injection technologies that addresses all of the identified post-injection performance issues is introduced.

## INTRODUCTION

The first large scale use of injection technology on feeder cables was at Arizona Public Service (APS) in 1991. This initial incarnation of the first generation of technology was essentially pure phenylmethyldimethoxysilane (PMDMS) with 0.2%<sub>w</sub> tetraisopropyltitanate (TIPT) catalyst [1]. The technology was entirely abandoned by APS, because of the very high failure rate as in [2]. As reported in [3], the failure rate was ten times higher than experienced with URD cables. In [4], over 30 failures were documented in cables, splices, and terminations. The majority of these failures occurred in the late summer when the ambient soil temperature and the loads were the greatest.

During the course of the investigation into the APS failures, it was discovered that there were non-uniform or asymmetrical penetration profiles of the silicone PMDMS into the polyethylene (PE) at the sites of many of the cable insulation failures. Bertini et al, modified the formulation utilized by adding a new fast-to-diffuse component, trimethylmethoxysilane (TMMS) at 30%<sub>w</sub> of the total as in [5]. This new formulation referred to as '841 was introduced in about 1994 and remained unchanged until 2005 when the concentration of TMMS was reduced from 30%<sub>w</sub> to between 5%<sub>w</sub> and 10%<sub>w</sub> as indicated in [6]. As suggested by [5], this reduction of TMMS in 2005 is likely to lead that technology "back to the future" where asymmetric penetration will decrease short term reliability. In addition to the formulation change, two procedural changes were also implemented as a result of the APS failures.

First, rejuvenation fluid was no longer intentionally allowed to directly contact splices. A large number of splice failures occurred as described [2], [3], and [4], because of over saturation of the EPDM splice bodies, and because of leaks across splice interfaces with insufficient hoop strength. The phenomenon of over saturation of EPDM rubber has been described in [7].

Second, it was recognized that the soak period routinely employed with small diameter URD cables was counterproductive for large conductor cables. Specifically the round conductors of the 750 kcmil APS cable held more than enough fluid without a soak period. Especially at higher temperatures the soak contributed to a detrimental over saturation of the insulation.

In February 1998 when the new formulation was applied in Midland, Texas in a 1000 kcm feeder cable belonging to Texas Utilities (TU), the cable failed six months later in July as described in [8]. Again, the failure occurred in the late summer as the temperature of the soil and the cable load ramped toward annual maximums. One possible cause of this class of failure was identified in [8] as supersaturation. While there is new evidence to suggest that supersaturation is an unlikely cause of cable failure, that discussion is beyond the scope of this paper. The subject of supersaturation will be addressed in a future publication. Whatever the cause of the TU failure, the response taught in [8] was to dilute the active ingredients of the fluid for those cables with larger conductors with an inactive ingredient that was essentially insoluble in PE. This dilution was an extension to the earlier elimination of the soak phase for large conductor cables and further recognition that at high temperatures too much '841 fluid could be supplied to the detriment of the cable.

Even after the adoption of the changes outlined above, the first generation of technology has failed to provide an adequate level of post-injection reliability for larger conductors. In [9], Dudas indicates that at least two large investor owned utilities reported disappointing results:

"Lots of failures in treated 750MCM"  
"Tried it on 750MCM - Not happy"

Dozens of failures in Europe for feeder cables utilizing the first generation technology were identified in [10], [11], and [12]. A contributing cause of these failures was identified as corrosion of the aluminum strands when the conductor temperature was high. As with supersaturation there remains a spirited debate regarding the precise mechanism by which these cables failed, but high temperature is implicated in all proposed mechanisms.

## VAPOR PRESSURE

Whether or not supersaturation, over saturation, asymmetrical penetration profiles, or aluminum corrosion contributed to the feeder failures of the first generation technology, it is clear that there must be at least one other previously unidentified failure cause. Even after all the formulation and procedural

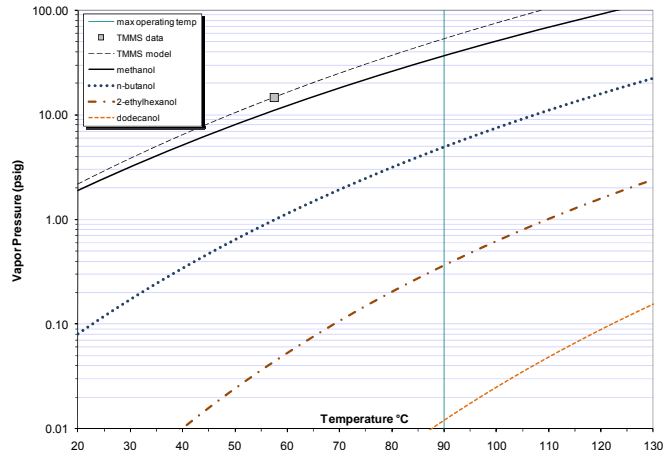
changes of the first generation of treatment chemicals, post-treatment reliability of feeder cables remained enigmatically poor compared to lightly loaded URD cables in cooler soils. The common link between most of the reported failures is a high temperature conductor.

Figure 1 compares the vapor pressure over the range of cable operating temperature of several of the more volatile components and by-products in commercially available rejuvenation fluids. The most volatile component is TMMS, a component of ‘841 technology. The pure component vapor pressure of TMMS is greater than 50 psig at 90°C and rises to over 100 psig at emergency overload conductor temperatures. In contrast, the most volatile component of the second generation of technology, 732, is dodecanol, which has a vapor pressure over three orders of magnitude lower. Both the ‘841 and 732 technologies employ methoxysilanes, which are designed to react with water and form the by-product methanol as a consequence of that reaction. Methanol is present in the fluid within the strands of a cable treated with ‘841 or 732 technology and also contributes to the vapor pressure of the fluid. After TMMS, methanol is the second most volatile material.

As a cable heats up to near its design ampacity with ‘841 fluids in the strands, the pressure in the interstices of the cable includes any head pressure from hills or risers, plus vapor pressure, which may be as high as 50 psig at 90°C. When the same field conditions occur with 732 fluids, the vapor pressure is much lower for two reasons. First, there is no TMMS or other highly volatile component in the formulation. Second, there is 35% to 62% less methanol because there is less methoxy functionality as shown in [13]. The previously unidentified cause of failure in cables treated with the ‘841 fluids is likely the excessive pressure produced by volatile components in the treatment fluid. It is suggested in [10] that these high vapor pressures cause corrosion of the aluminum strands. We believe that the mechanism of corrosion proffered by [10] is erroneous, but agree that high vapor pressure does indeed have profound implications for post-injection reliability. Not only must the termination and splice seals be able to withstand the pressure, as described in [14], but even more ominously, the cable itself must be able to withstand that pressure at cable operating temperature.

## A PERFECT STORM

As in the “Perfect Storm” of October 31, 1991 made famous by the novel and movie of the same name, a confluence of independent events can create synergistically destructive catastrophes. Unlike the Perfect Storm, however where the probability of each meteorological event occurring simultaneously is quite rare, feeder cables often do run near, at, or even above their maximum operating design temperature.



**Figure 1. Comparison of vapor pressure of pure components in commercial rejuvenation technologies.**

The previous section and Figure 1 demonstrated how the internal pressure of the cable containing a volatile component like TMMS increases exponentially with temperature.

While the pressure is increasing dramatically, the mechanical strength of the polyethylene is decreasing precipitously as demonstrated by Figure 2 reproduced from [15]. In fact, as the temperature changes from 15°C to 90°C, the pressure increases about 33-fold and the strength decreases about 36-fold. Referring to equation 1, these two factors together represent over three orders of magnitude change in radial deflection at any given pressure.

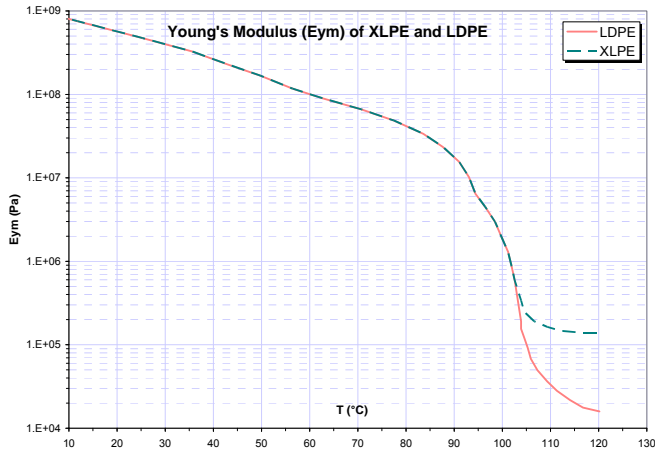
The radial deflection at any radius with internal pressure can be calculated as demonstrated in [16] and here with equations 1, 2, and 3.

$$(1) \quad u(r) = \frac{-p_i a^2 r}{2 \cdot (\lambda + G) \cdot (b^2 - a^2)} - \frac{p_i a^2 \cdot b^2}{2 \cdot G \cdot (b^2 - a^2) \cdot r}$$

$$(2) \quad G = \frac{E}{2 \cdot (1 + \nu)}$$

$$(3) \quad \lambda = \frac{E \cdot \nu}{(1 + \nu) \cdot (1 - 2\nu)}$$

Where  $E$  is the elastic modulus,  $\nu$  is Poisson’s ratio for the cable insulation,  $u(r)$  is the radial deflection at a given radius  $r$ ,  $a$  is the inner radius of the polymer,  $b$  is the outer radius of the polymer,  $G$  is the shear modulus,  $\lambda$  is Lamé’s parameter, and  $p_i$  is the pressure in the interstices.



**Figure 2. The strength of polyethylene decreases exponentially as temperature increases.**

The third element of the perfect storm is the effect the geometry of larger conductor size has upon the hoop stress with a given internal pressure. As the conductor size increases from URD laterals with conductor areas typically about 50 mm<sup>2</sup> to feeder cables with 500 mm<sup>2</sup> of conductor, the hoop stress increases. The radial deflection for constant internal pressure, insulation thickness, and PE modulus yields a roughly 3-fold increase in radial deflection going from a 50 mm<sup>2</sup> to a 500 mm<sup>2</sup> conductor.

Taken together, the last two of these effects combine to create over a 100-fold difference between the pressure holding ability of a 1/0 cable at 15°C (between 500 and 2000 psig) and a 1000 kcm cable uniformly at 90°C (between 5 and 20 psig). Fortunately, because of the temperature drop across routinely operating cable insulation, the outside of the cable seldom approaches 90°C even as the conductor approaches 90°C. Temperature graded PE can generally support the 15 to 30 psig required to reliably contain the gravity head of cables flooded with water or with low volatility injection technology, assuming there is no significant reaction of alcohol with the aluminum strands, which will be discussed in the next section.

Cable components must also accommodate the pressures without leaking. To that end, 732/733 technologies employs a new genre of injection adaptors described in [7], [17], and [18], which are leak-proof and permeation-proof even in the most demanding thermal and hydraulic circumstances. The 732/733 generation of injection technology has been successfully deployed in cables with conductors as large as 630 mm<sup>2</sup> in tropical thermal environments.

## ALUMINUM REACTION WITH ALCOHOL

The previous discussion would be enough were the conductor copper. For aluminum conductors there is an additional complication, because of the possible reaction of the alcohol by-products created when alkoxysilanes react with water described in [11], [12], and [19]. The 732 and '841 fluids are

both formulated with methoxysilanes, which yield methanol when they react with water. [11] and [20] demonstrate that of all the alcohols methanol is the smallest, strongest Lewis acid (i.e. most reactive with aluminum), and has the highest vapor pressure. The latter two properties create a potential problem at higher circuit operating temperatures. Under the right conditions of high alcohol concentration and high temperature described by [11], alcohol will react with aluminum to create hydrogen gas. Luzzi demonstrated in [21] that hydrogen gas pressures can reach 26 to 46 psig from the reaction of aluminum with water, a slightly weaker Lewis acid than methanol. The 732 fluid includes a hindered amine light stabilizer (also known as a HALS), which retards the rate of the reaction of alcohol with aluminum. This chemical mitigation together with the lower concentration of methanol allows the 732 technology to reliably be applied at temperatures higher than previous methoxy-based technology. The maximum recommended conductor temperature for 732 technology is 60°C for the six months after a cable has been rejuvenated. After the first six months, the methanol concentration will be so low that the conditions for the reaction are unlikely to occur.

As shown in [11], methanol (1 carbon atom) is more reactive with aluminum than water, which in turn is more reactive than ethanol (2 carbons), which is more reactive than propanol (3 carbons), which is more reactive than butanol (4 carbons). The decrease in reactivity as more carbon atoms are added to the alcohol continues up the homologous chain of alcohols. For practical purposes, we will examine the range of 6 to 12 carbon atoms, because the compatibility of these alcohols are well established in [22]. Fatty alcohols, such as dodecanol (or lauryl alcohol) in particular, are a common by-product of the cross-linking process used to make many insulations and shields. Such fatty alcohols have proven compatibility in billions of installed cable feet worldwide. Besides being compatible with the aluminum cable strands, it was demonstrated in [22] and [23] that fatty alcohols with 6 to 12 carbon atoms make very effective electrical tree retardants and very effective water tree retardants.

## TEMPERATURES GREATER THAN 60°C

Two examples of a new class of materials were introduced in 2008 with larger alkoxy ligands – either 4 or 8 carbon atoms. The 4 carbon atom variety (n-butanol by-product) described in [19] is dimethyldibutoxysilane or DMDB. The fatty alcohol or 8 carbon atom variety (2-ethyl-hexanol co-product) is coded 733. The 733 fluid mixture includes three silanes. The three silanes are the 8-carbon fatty alcohol (2-ethyl-hexanol) analogs to the proven silanes of the aforementioned 732 fluid.

In all cases, the reactivity of these larger alcohol by-products is so low that there is no measureable reaction with aluminum as demonstrated by [24] and [25]. With the rare and undesirable evolution of hydrogen gas all but eliminated, the remaining technical considerations are:

1. The vapor pressure of the fluid
2. The flash point of the fluid, which has an effect on the safe use of the technology.
3. The short-term and long-term post-injection reliability of the treatment.

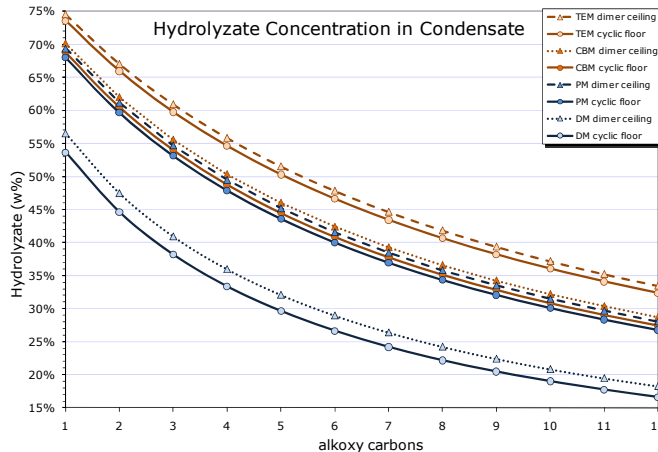
The pure component vapor pressures of the by-product alcohols are shown in Figure 1. At 90°C, n-butanol (DMDB by-product) has a vapor pressure of about 5 psig and is unlikely to create any problems. At 130°C the vapor pressure can be above atmospheric (14.7 psig). The 733 fluid vapor pressure cannot exceed 3 psig, even at 130°C.

The higher vapor pressure of the DMDB and its by-product alcohol make it more flammable than the 733 fluid mixture. From [26], the flash point of DMDB is 79°C or below the maximum intended operating temperature of the cables in which it is injected. From [27], the flash point of the 733 fluid mixture is greater than 120°C, well above the maximum operating temperature of a treated cable.

While 732 fluid and 733 fluid include organic functional additives, which are actively involved in the life extension process, 732, 733, '841, and DMDB are predominately alkoxy silanes. Until the introduction of 733 fluid, the long-term life extension performed by these alkoxy silanes was provided by the backbone of the alkoxy silane, without any direct benefit from the alkoxy functionality. After the alkoxy was hydrolyzed and diffused away as an alcohol, the condensed siloxane fluid remained behind. The resulting alcohol by-product is a diluent and a nuisance, which in the worst case might corrode aluminum strands, but in most cases, just diffuses harmlessly away.

The introduction of 733 fluid means that for the first time there are no by-products – instead there is a co-product. As demonstrated in [22] and [23], the fatty alcohol that results from the hydrolysis reaction of 733 fluid retards water trees and electrical trees. Fatty alcohols with 6 or more carbon atoms have been shown in [22] and [23] to reach a stable equilibrium in the polyethylene for an extended time period. The authors call this property persistence. The 4-carbon n-butanol by-product of DMDB diffuses faster and is less soluble in the insulation and was not included in [22] as an effective tree retardant.

Figure 3 provides additional insight on the question of insulation longevity. Both 732 and 733 fluids use tolylethylmethyl (TEM) dialkoxy silane and cyanobutylmethyl (CBM) dialkoxy silane. The alkoxy portion of 732 and 733 fluids are methoxy (1 carbon) and 2-ethylhexoxy (8 carbons) respectively. The alkoxy portion of the phenylmethyl (PM) '841 fluid is methoxy (1 carbon). The alkoxy portion of DMDB is n-butoxy (4 carbons). Figure 3 compiles the stoichiometric efficiency, or the portion of the silane molecule left behind expressed as a hydrolyzate weight percent.



**Figure 3. Stoichiometric efficiency of various alkoxy-silanes as a function of the number of alkoxy carbons. Below 6 carbons a low molecular weight alcohol by-product is produced. Alcohols with 6 or more carbons have been shown to be effective water and electrical tree retardants in [22].**

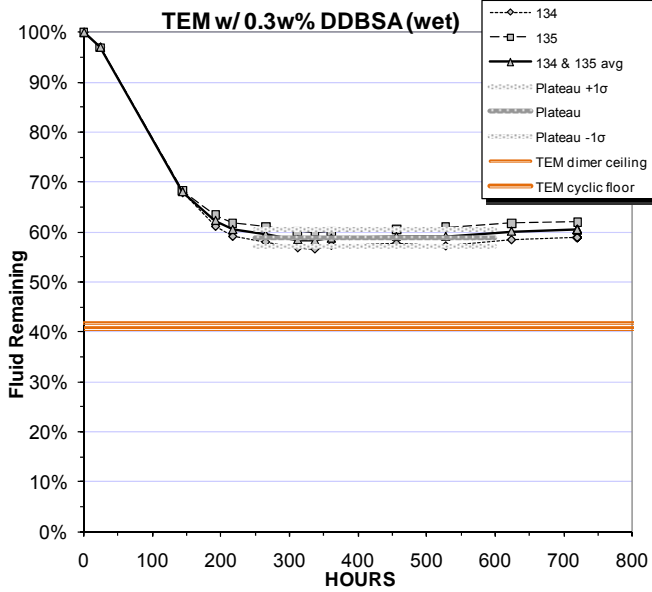
The stoichiometric efficiency values from Figure 3 for the commercially utilized silanes are summarized in Figure 4. The stoichiometric efficiencies reported in Figure 4 are the best that may be achieved with perfect catalysis. In [28], it was demonstrated that the '841 fluid catalyst suffers a 39% catalytic inefficiency. The condensation reactions for the DMDB monomer are catalyzed as described in [19] with tetraisopropyltitanate (TIPT). The condensation reaction for the 733 monomers is catalyzed with dodecylbenzenesulfonic acid (DDBSA).

Figures 5, 6, and 7 show the exudation profiles of the two 733 silane monomers and the DMDB monomers from a 1/6<sup>th</sup> scale model-cable analogous to the geometry of a 15kV, 1/0 AWG cable. The model cable is completely submerged in water at 55°C for the duration of the experiment. Catalytic efficiencies for these three silane monomers with their respective catalysts are calculated as the portion of hydrolyzate and other tree retardants remaining at the exudation plateau compared to the amount of hydrolyzate predicted by stoichiometry. Because the stoichiometric amount of hydrolyzate lies between a dimer ceiling and cyclic floor, the average of those two numbers is used to represent 100%.

**Figure 4. Approximate stoichiometric and catalytic efficiencies for various alkoxy silanes. The catalytic efficiency of 733 fluid is the apparent average. Higher overall efficiency correlates to longer life extension.**

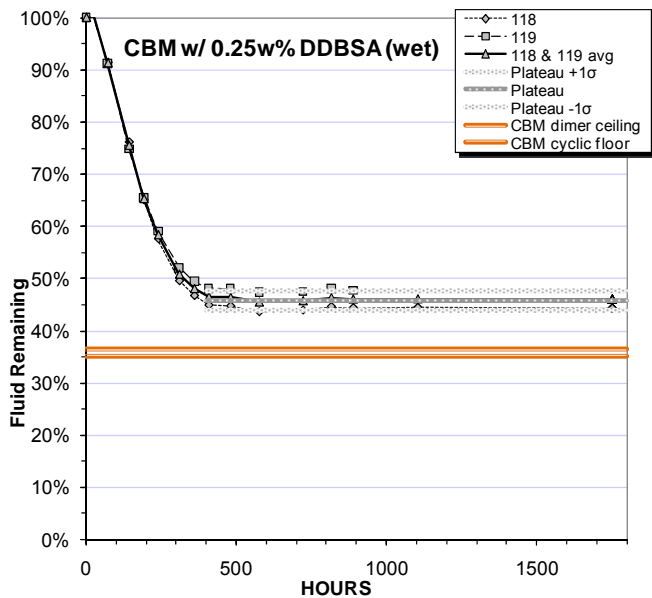
| Treatment Fluid     | Stoichiometric efficiency | Catalytic efficiency | Overall efficiency |
|---------------------|---------------------------|----------------------|--------------------|
| 732 fluid (TEM+CBM) | 72%                       | 98%                  | 71%                |
| '841 fluid (PM)     | 68%                       | 61%                  | 41%                |
| 733 fluid (TEM+CBM) | 38%                       | 133%                 | 50%                |
| DMDB                | 35%                       | 40%                  | 14%                |



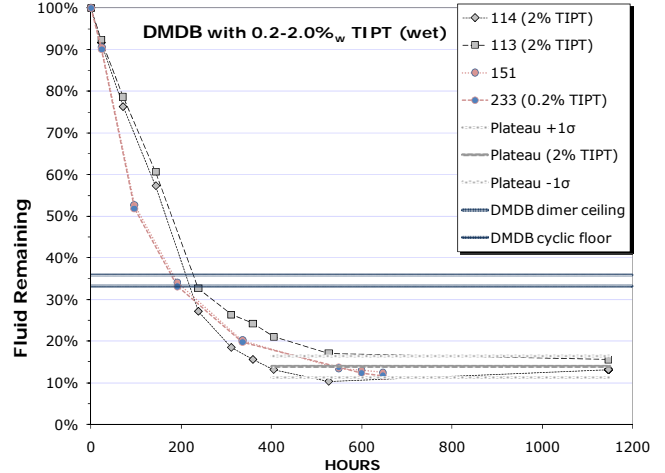


**Figure 5. Exudation profile and plateau for TEM (8 carbon alkoxy) with DDBSA catalyst. Apparent catalytic efficiency is 143%. Duplicate data samples 134 and 135.**

Actual catalytic efficiency of 732 fluids is over 98%, because of the co-diffusing properties of the dodecylbenzenesulfonic acid (DDBSA) catalyst described in [28] and [29]. The apparent catalytic efficiency of 733 is unexpectedly 133%. This better-than-perfect performance is likely due to the aforementioned longevity of the fatty alcohol. The actual catalytic efficiency is likely about the same 98% of the analogous 732 monomers. The unexpected and additional 35% efficiency likely results from the persistence of the tree-retardant fatty alcohol hydrolysis co-product.



**Figure 6. Exudation profile and plateau for CBM (8 carbon alkoxy) with DDBSA catalyst. Apparent catalytic efficiency is 128%. Duplicate data samples 118 and 119.**



**Figure 7. Exudation profile and plateau for DMDB (4 carbon alkoxy) with TIPT catalyst. Catalytic efficiency is 40%. Samples 113, 114, 151, and 233.**

The experimental results summarized in Figures 5 and 6 are not able to resolve the individual values for catalytic efficiency and fatty alcohol persistence as the two effects are confounded. The apparent catalytic efficiency (i.e. the combination of catalytic efficiency and fatty alcohol persistence) is summarized in Figure 4 for the 733 fluid. The overall efficiencies in Figure 4 are the product of the stoichiometric and catalytic efficiencies. Like 732 fluid, 733 fluid also includes slow-to-diffuse organic additives described in [30] and [31] including voltage stabilizers, ultraviolet stabilizers, partial discharge suppressors, and anti-oxidants, which have been proven to extend cable life via mechanisms not addressed with silanes. These organic additives are not reflected in Figures 5 and 6.

Because of the lower stoichiometric efficiencies of DMDB and 733 fluids, their use is limited to larger diameter cables. This is not such a restrictive constraint, because generally smaller diameter conductors are not run at or near their maximum operating temperatures. In a process described in [32], 733 fluids are tailored to specific geometries and operating temperatures to accommodate those differences. The low catalytic efficiency of the DMDB/TIPT system reduces the potential life extension relative to more efficient silane-catalyst combinations.

In [19], the authors suggest that the DMDB fluid life will be substantial. The argument propounded is that a similar fluid DMDM (dimethyldimethoxysilane) was injected in 1994 in 1000 kcmil (round conductor), 35kV<sup>1</sup> cable and demonstrated excellent AC breakdown performance after 12 years when it was excavated in 2006. Regrettably, the authors did not disclose that the test circuit was a dead end and had no load. The location of the cable in Virginia's thermic soils means its

<sup>1</sup> The authors of [19] incorrectly identify the cable as 25kV in their presentation. The Virginia Power cable is 35kV rated.

average temperature is between 15 and 22°C as shown in [33]. Each 10°C increment in operating temperature has a roughly 3X impact on the rate of fluid exudation. For example, if the flux weighted average temperature of a cable was 40°C instead of 20°C, the 12 years would be reduced by a factor of about 9. Additionally, the thicker insulation and round strands make this sample representative of a best-case-scenario. Evident from Figure 4, the overall stoichiometric and catalytic efficiency of DMDM is about 41%, compared to the 14% for DMDB. That difference represents another factor of about 2.9. As described previously, the condensation products of 732 and 733 fluids are the same, except that 733 fluids enjoy the additional benefit of the fatty alcohol co-product. Long term accelerated experiments have been carried out on the 732/733 siloxanes, which result after the hydrolysis. Those experiments and models reported in [34] demonstrate life in excess of 40 years when applying that technology. In addition to the laboratory results and modeling, these siloxanes have been proven in field use for over 3 years with an overall failure rate of less than 0.5% as reported in [35].

## SUMMARY

Supersaturation, over saturation, asymmetrical penetration profiles, and aluminum corrosion undoubtedly contributed to the feeder failures of the first generation rejuvenation technology. A previously unrecognized issue is the confluence at higher temperatures of high vapor pressure, softening polyethylene, and the weak hoop strength of large conductor cables. A 15kV cable with a conductor larger than 250 mm<sup>2</sup> (500 kcm) treated with the '841 technology and including TMMS may balloon and fail at 90°C. Second generation fluids such as 732 and 733 avoid the consequences of high vapor pressure and extend the maximum operating temperature. DMDB and 733 represent a new genre of treatment fluids that eliminate the aluminum corrosion issue entirely, and more importantly the generation of hydrogen gas, which accompanies that corrosion. The hydrogen gas creates pressure, which the hot insulation may not be able to contain.

The 733 fluid has a flash point greater than the maximum operating temperature of the cable. The 733 fluid has the highest stoichiometric and catalytic efficiencies of the new genre of fluids resulting in longer anticipated life. The 733 fluid also includes functionality to address stress grading, voltage stabilization, UV degradation, oxidative degradation, and partial discharges. The 733 fluid is also applied with a process, which tailors the chemistry to the unique circumstances of each cable.

Finally, 733 fluid's fatty alcohol hydrolysis co-product alters the alkoxy paradigm. Earlier generations of rejuvenation fluid produce non-useful, or in some cases, undesirable by-products upon hydrolysis. The 733 fluid creates a useful and persistent co-product. The 733 fluid is more concentrated and can provide longer life even at temperatures up to 90°C.

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## AUTHORS

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**Norm Keitges** is the Manager of Engineering at Novinium. He has spent the last three years on the research, design and manufacture of new cable rejuvenation hardware. He has 28 years experience in mechanical, fluid mechanics, hydraulics & power generation applications. Mr. Keitges is a Senior Member of the IEEE and has a B.S. in Mechanical Engineering from Washington State University.



**Gary Vincent** is the Chief Research Scientist of Novinium, Inc. Mr. Vincent holds 34 patents including the very first patent on a commercially viable cable rejuvenation fluid and has another patent pending. Mr. Vincent holds a B.S. in Chemistry from the University of Michigan, an M.S. in Organic Chemistry from Michigan State, and an M.B.A. in Finance from Central Michigan University. Gary is a Senior Member and Life Member of the IEEE and a thirty year member of the Dielectric and Electrical Insulation Society (DEIS). Mr. Vincent has been awarded two R&D 100 awards for Silicone Transformer fluid and Cable Rejuvenation in 1973 and 1992 respectively.

