

New Developments in Solid Dielectric Life Extension Technology

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Abstract: Twenty years have elapsed since the field introduction of the first solid dielectric enhancement technology. During those twenty years, this technology has proven itself as an important tool to enhance the reliability of aging infrastructure. Incremental improvements during those twenty years have aided in the widespread commercial acceptance of the technology on at least four continents. There are some concerns with the current technology, which has been utilized by over 150 utilities worldwide. These include: (1) A higher than desirable post-injection failure profile [11], due to the slow permeation of the fluid into the dielectric and the resulting slow increase in dielectric performance after injection of approximately 0.5% per day [13], (2) a limited cable life extension of 10-20 years as suggested by [13], (3) safety and operational issues related to the low flash point (-5.5°C), and (4) the corrosion of aluminum conductors that occasionally results in failure of treated cables caused by high concentrations of methanol by-product of the most widely-used treatment fluids [3], [9].

A novel approach, which includes new installation methods and new materials to extend the life of power cables, is described. Theory and experiments are discussed which demonstrate that the new approach addresses all of the current shortcomings associated with the first generation technology. In comparison to the technology employed over the last two decades, the new technology provides: (1) More rapid short-term reliability – the post-injection dielectric performance improvement slope is greater than an order of magnitude steeper, (2) longer rejuvenated cable life approaching the 40 year expected life for the highest performance modern cable designs, (3) an inherently safer installation, including lower flammability fluids, which have flash points in excess of 65°C, and an injection paradigm, which dramatically reduces the likelihood of electrical contact, and (4) compatibility with all aluminum alloy and copper alloy conductors.

INTRODUCTION

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.

Estimated Annual Injection Rates

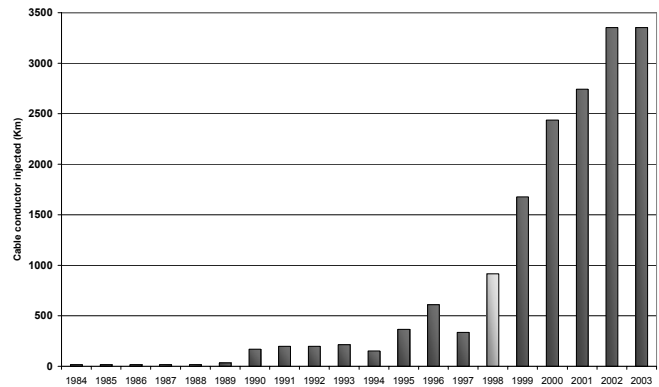


Figure 1. Estimated annual injection rates compiled from dozens of industry sources including [1], [2], [3] and [7] demonstrate the growing importance of injection technology.

There are two problems with acetophenone when it is used alone. First, its freezing point is 20°C which makes its injection at temperatures below that point problematic. Secondly, with a rapid diffusivity of $1.3 \times 10^{-7} \text{ cm}^2/\text{s}$ at 50°C, 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. The safety and maintenance issues associated with this life-time connection drove the development of an analogous silicone material phenylmethyldimethoxysilane or PMDMS. The properties and advantages of moderately diffusing ($D=5.73 \times 10^{-8} \text{ cm}^2/\text{sec}$ at 50°C) PMDMS are described in considerable detail in [4] and will be referred to as Fluid A. 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 to form siloxane oligomers generally to an equilibrium mixture with degrees of polymerization between 4 and 7.

The oligomerization of PMDMS was a major advancement because as described in Figure 8 of [5], it decreased the rate of exudation compared to the PMDMS monomer (or non-reactive acetophenone) by between one and two orders of magnitude. This slowing of the exudation rate largely

eliminated the requirement to provide a perpetual feed source of a fugitive material for some cable geometries.

In the early 1990's the short-term performance of PMDMS was enhanced with the addition of 30%_w trimethylmethoxysilane (TMMS) as a fast to diffuse ($D=2.4 \times 10^{-7}$ cm²/sec at 50°C) chemical drying agent fully described by [6]. This 70:30 mixture of PMDMS and TMMS will henceforth be referred to as Fluid B and represents the bulk of all injection performed over the last twenty years. There were three penalties imposed by the addition of TMMS.

First, TMMS is a very volatile material and it lowered the flash point from 65.5°C for the PMDMS to -5.5°C for Fluid B. Second, TMMS does not have any aromatic functionality which might absorb UV light or stabilize thermal electrons; hence its inclusion dilutes the active ingredient and reduces the long-term efficacy of Fluid B. Third, the TMMS is mono-water-functional and serves to end-block the PMDMS oligomer. This end-blocking has two negative effects, namely the reduction of the average oligomer chain length and the replacement of the highly polar hydroxy-end-block with the non-polar trimethyl-end-block. Each of these changes increases the permeation rate and hence decreases the time the fluid will remain in the polyethylene shortening the effective life of the treatment.

Cables treated with Fluid B and exposed to substantial thermal cycling developed a problem in that supersaturation of the insulation with the impregnant actually caused failures [7], [8]. The solution to circumvent the supersaturation problem was the addition of a non-active dilutant in larger, less compact conductor cables sizes [7], [8]. The combination of Fluid B with a polydimethyl-siloxane dilutant is referred to as Fluid C.

In 2002 and 2003 a new reliability problem came to light with the Fluids A, B and C. Methanol is formed as a by-product of the silane hydrolysis at up to 30.6%_w for Fluid B or up to 31.5%_w for Fluid A. Methanol at high concentrations can be quite corrosive to aluminum and the resulting failures have been well documented by [3] and [9]. The problems were particularly acute in Germany, but are likely to be much more widespread as will be demonstrated in this paper.

NEW DEVELOPMENTS

Research demonstrates that a new injection paradigm which is called Ultrinium™ and is referred to as Method U in this paper can enjoy:

- More rapid short-term reliability;
- Longer reliable cable life;
- An inherently safer installation, including lower flammability fluids, which have flash points in excess of 65°C, and an injection process, which

dramatically reduces the likelihood of electrical contact;

- Compatibility with all aluminum alloy and copper alloy conductors.

The old technology involves filling the interstitial spaces between the strands and in some cases providing a soak period where additional fluid is fed into the interstices to replace fluid that permeates into the insulation. There are two drawbacks to this approach. First, cables have widely varying geometry and fluid requirements. The volume available within the strand interstices is not conveniently equal to the fluid required to adequately treat the cable. In fact, they are generally at odds with each other.

Figure 2 shows the mismatch in the fluid requirements availability for Fluids B and C for 15 kV cables with various conductor sizes. The line labeled “Fluids B and C requirement” shows how much fluid is required to adequately treat the cable. The calculation of adequacy is detailed in [8], which also reviews the simple geometric principles required to calculate the interstitial volume for various cable sizes with various strand compressions.

The actual quantity of Fluids B and C supplied by methods currently employed for three different compressions (concentric, compressed and compacted) are also demonstrated by Figure 2. For concentric and compressed strands there is a single point where the “fluid required” line intersects the fluid supplied line. Those intersections are at 110 mm² and 175 mm² respectively. For compact conductors the lines do not intersect over the range shown.

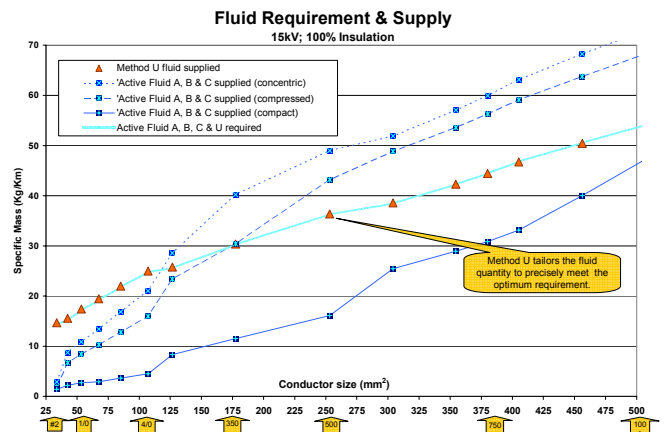


Figure 2. Requirements for the active portions of Fluids A, B & C vary considerably from the active fluid supplied in most cases.

Except for the two specific cases where the lines intersect, the present methods of injecting Fluids A, B and C either supply insufficient fluid or too much fluid. Neither condition is optimum.

Insufficient fluid means shorter life since there simply is a smaller reservoir of fluid – all of which is destined to exude

from the cable. Second, because there is an excess of water, the majority of cables treated with insufficient fluid will suffer from inadequate fluid penetration into the insulation during the early post-injection period. This is a result of the bulk of the fluid fully oligomerizing before it can diffuse to the outside of the insulation. Hence, dielectric defects near the outside of the insulation are poorly treated.

Too much fluid also shortens total life, because there is insufficient water to fully oligomerize the fluid and the resulting shorter chain oligomers permeate more quickly from the cable. The optimum amount of fluid is that which saturates the conductor shield and the insulation and fully oligomerizes with the water available for reaction.

The new injection technology, Method U begins with a calculation of the optimum fluid requirements. Besides the short-term (0-3 year) and medium-term (2-12 year) performance addressed by the old technology, the longer-term (10-40 year) is also considered in establishing the optimum treatment formulation and quantity of fluid to be injected. Both the temperature of the cable and the extent of the temperature cycling of the cable have a profound influence on the rate of permeation of treatment fluid into and out of the cable. The Method U takes these temperatures into account for the first time and tailors the formulation to the unique requirements of each individual cable.

While the specific fluids used to address each of these performance realms will be the subject of a future paper, Method U is utilized to tailor the ratios of various fluid components that address each of these time realms and the total amount of fluid supplied. The injection pressure is then varied to achieve a fill of precisely the optimum quantity of fluid mixture which this paper refers to as Fluid U. The triangles in Figure 2 which represent the quantity of fluid supplied by the Method U fall squarely on top of the fluid requirements line for all cable geometries.

Special terminators and splices are used to supply the pressure required. The tailored injection pressure varies depending on the circumstances of each individual cable, but generally medium pressures (up to 60 bar) are utilized for the smallest conductor sizes (30 mm²) and moderate pressures (near 6 bar) are utilized for the larger conductor sizes (500 mm²). In all cases the initial pressure is well below the point where the cable could be physically damaged.

Once the injection is complete, the injection ports at the terminations are sealed and the pressure begins to decay immediately as the fluid trapped in the interstitial area rapidly permeates into the shield and insulation. Depending on the geometry of the cable and the temperature at which it operates, the decay to zero can take from several days to several months.

To compare the performance of Method U and Fluid U to the traditional method and the most widely used Fluid B an experiment was performed at Cable Technology Laboratories (CTL) modeled after similar experiments reported in [11] and [13]. Two coils 67 metres long of 53.4 mm² (1/0) cable was laboratory aged for several years at 2.5 times rated voltage (2.5•U₀) until its AC breakdown strength was 14.6 kV/mm at the 63% probability level. The Weibull plot for this laboratory aged cable is the leftmost plot in Figure 3. The two cables were treated with a mixture of 25%_w acetophenone and 75%_w of a water reactive silane and injected at 32.7 bar. The cable voltage was maintained at 2.5•U₀ and the cables were aged in a water tank for 7 days at 25°C. At the end of seven days, one coil moved on to a longer term test described later and one coil was sacrificed to an ICEA S-97-682-2000 (Section 10.13) AC breakdown test.

Figure 3 provides results of that 7-day test where a several-fold increase in dielectric performance and reliability is demonstrated. The test conditions and timing were chosen to provide a direct comparison to the results published in [11]. That comparison is the “Energy” data point shown in Figure 4. The Method U and Fluid U approach surpassed the low pressure, Fluid B approach over 20-fold. Additional examples in the literature, including [10], [11], and [12] demonstrate non-sustained moderate to medium pressures had no adverse effects.

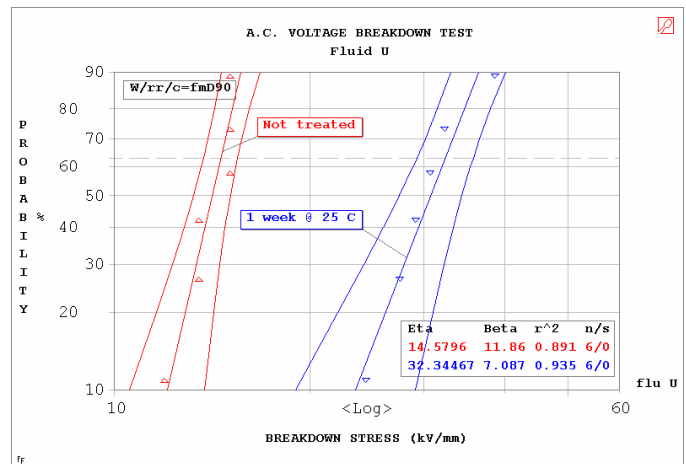


Figure 3. AC breakdown stress after 7 days when injection Method U was utilized at 32.7 bar and a tailored formulation composed of 25%_w fast to diffuse acetophenone and 75%_w of a moderately diffusing alkoxy silane.

The results of Figure 3 compared to the results of similar experiments with Fluid B technology reported in [2], [11], and [13] are presented in Figure 4. With Method U and Fluid U short-term penetration or permeation is enhanced by between 1 and 2 orders of magnitude yielding performance close to that of a new cable within seven days of injection versus approximately 732 days for the traditional technology and Fluid B. The slopes (in kV/mm per post-injection month) of

the two lines were fitted by linear regression. The slopes of 107.6 and 1.234 differ by a factor of 87.

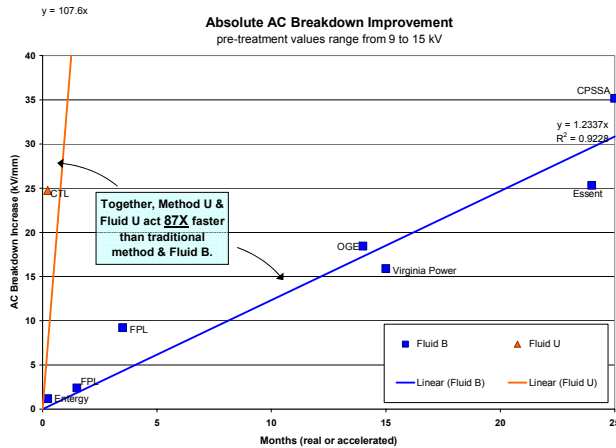


Figure 4. Method U and Fluid U improve dielectric performance 87-times faster than the traditional injection method with Fluid B. The data points labeled “CTL” and “Entergy” were both 7-day results.

Short-term performance is particularly important, because as has been reported in [11], most post-treatment failures occur within 120 days of injection, before the legacy method and Fluid B have made a significant impact on dielectric strength. Because cable owners generally wish to apply injection technology on their poorest performing cables, these short-term failures may be unacceptably high at an acknowledged 0.5% of all cables treated. Assuming an average segment length of 100 metres (which is typical for the population of North American URD cables, which makes up the bulk of the Fluids A, B and C experience) and a high failure rate of 17 failures per 100 km of cable per year one would expect a 2% failure rate over a 12 month period as described in [14] if there had been no injection. Accordingly a 0.5% failure rate over one-third of a year is only marginally better than if the cable had not been treated at all. Method U together with Fluid U all but eliminates this shortcoming of providing almost immediate high reliability service.

LONG-TERM PERFORMANCE

The key to providing long-term performance is providing just the right amount of fluid so that the fluid quantity and water reactivity is optimally balanced with the water content and anticipated temperature of the cable to be treated as described previously.

To compare the performance of Method U and Fluid U to the legacy method and Fluid B the second coil of the experiment described previously continued to be aged with parameters modeled after a similar experiment reported in [13]. After the 7 days test at 25°C, the temperature of the water bath was increased to 55°C for 1000 hours, so that the results would be directly comparable to those reported in [13]. At the end of the 1000-hour aging period the cable was subjected to an ICEA S-97-682-2000 (Section 10.13) AC breakdown test. The value of

29.7 kV/mm at the Weibull 63% confidence level was 71% higher than the 17.3 kV/mm published in [13] for the legacy method and Fluid B. Additional work is underway to further improve the long-term performance and the results of that effort will be reported in a future paper.

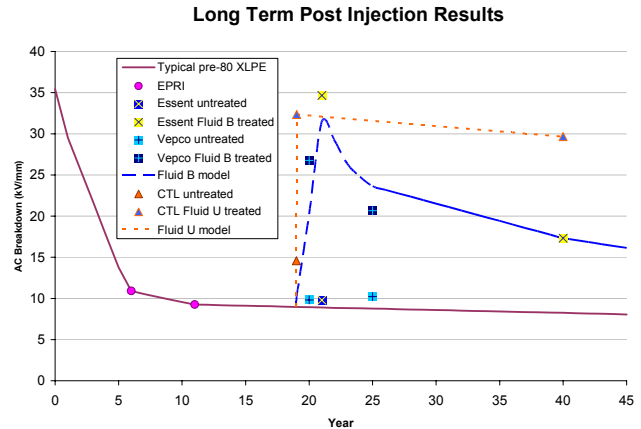


Figure 5. Method U and Fluid U provide 71% higher dielectric strength in a similar accelerated experiment designed to simulate permeation over a 20-year post injection period compared to the legacy method and Fluid B. The EPRI and Fluid B results are explained in detail in [13].

IMPROVEMENTS IN INJECTION SAFETY

Method U and Fluid U eliminate many of the costly and risk prone visits to energized cables inherent in the legacy injection method. Using a tailored pressure 100% of the fluid required to optimally treat each cable is provided in a single injection with the cable de-energized. A 100 metre cable can be filled properly in 30 minutes. Termination and splice preparations, not unlike those required by the legacy approach consume the majority of the time, but unlike the legacy technology there is never a need for a soak period or the repeated visits to a cable that the soak period entails.

Table 1. Comparison of relevant physical properties of trimethylmethoxysilane and acetophenone.

Material	Diffusivity (cm ² /sec)	Flash Point (°C)
TMMS	2.4x10 ⁻⁷	-5.5
Acetophenone	1.3x10 ⁻⁷	77

Second, the sustained Method U pressures provide enhanced permeation of restorative fluids, no matter what the molecular weight and polarity of the moieties. As demonstrated in Table 1 and Figure 4, acetophenone with a slightly lower diffusivity than that of TMMS, but a substantially higher flash point penetrates one or two orders of magnitude faster with Method U. This fact means that highly volatile and flammable materials like TMMS need not be used, largely eliminating the fire hazards such materials represent.

METHANOL-ALUMINUM INCOMPATIBILITY

The potentially damaging reaction between methanol (MeOH), a by-product of most treatment technologies, and aluminium (Al) has been recently described in [3] and [9]. For each formulation a maximum amount of methanol (or any hydrolysis) by-product can be calculated using the stoichiometry of the chemical reactions. For the Fluids B and C those maxima are 30.6%_w and 31.5%_w respectively. In contrast, Fluid U has an absolute maximum of 19%_w and can be tailored down to any value including 0%_w.

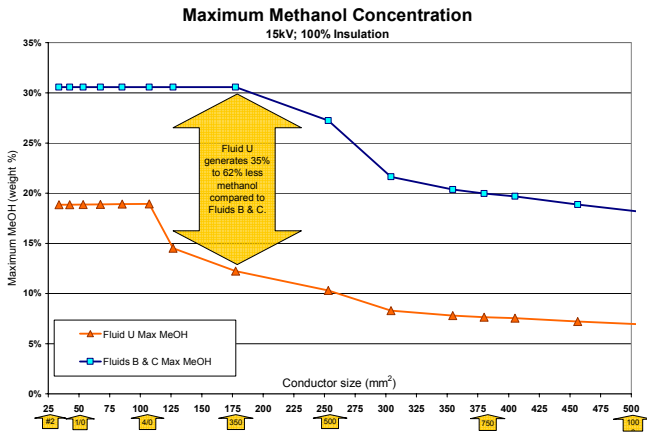


Figure 6. The maximum stoichiometric amount of methanol which can be generated for the Fluids B and C (top line) versus the maximum Fluid U values (bottom line).

It turns out that there is no need to covet maximum values below 19%_w as demonstrated by Figure 7. In an experiment modeled after that described by [3], aluminium strands from pre-1980 vintage U.S., Australian, and German cables and one sample of 2003 vintage German cable were immersed in solutions of the Fluid B and three different Fluid U formulations kept at 55°C.

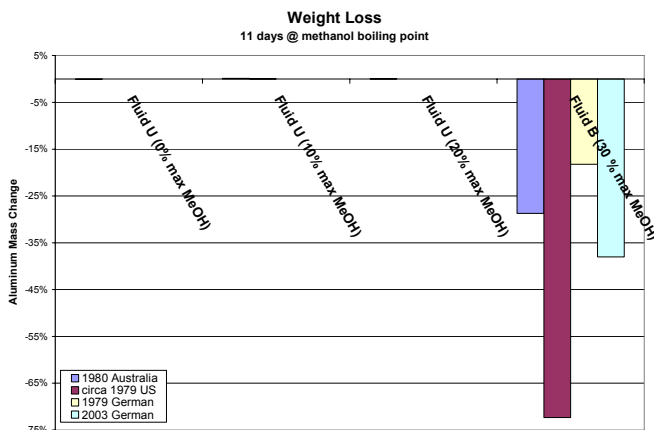


Figure 7. Weight loss for typical Australian, U.S., and German aluminum when exposed to the maximum stoichiometric concentration of methanol in anhydrous conditions. Note that no data for the German samples is available for Fluid U formulations.

In each case the maximum stoichiometric amounts of methanol which can be formed are added to the four formulations. The anhydrous samples were cooked with complete reflux for 11 days and while 18%_w to 72%_w of the aluminum was lost with Fluid B, there was less than 0.1%_w weight loss with the three Fluid U formulations.

SUMMARY

Tailored pressure and formulations with novel compounds and acetophenone enable a more rapid increase in post-injection performance and longer total reliable life. The tailored process allows the use of less volatile materials and less exposure to energized circuits improving the application safety. A decrease in the maximum possible methanol concentration all but eliminates the risk of aluminum corrosion.

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