Cable Injection Technology

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***Abstract*—This paper provides an overview of cable injection technology based on the phenylmethyldimethoxysilane (PMDMS) material in commercial use since 1987. It focuses specifically on process chemistry and how that chemistry interferes with the mechanisms of water tree growth. It summarizes some previously published laboratory results that demonstrate the effectiveness of cable injection technology at extending the life of aging solid dielectric power cables. Additionally, it documents previously unavailable real-world, long-term field data, which is now available due to the maturation of cable injection technology using PMDMS-based material. Knowledge of real-world performance correlates with a steep, industry-wide increase in annual injection footage, showing how real-world results have increased industry confidence in cable injection technology based on time-tested materials.**

***Index Terms*-- aged cable, cable rejuvenation, cable rehabilitation, rejuvenation, solid dielectric insulation, underground cable, water tree**

I. INTRODUCTION

PRIOR to the 1960s, power cables were placed underground only when metropolitan congestion or some other practical consideration required it. These cables were constructed of oil- soaked paper insulation and encased in lead. They offered an effective, albeit high-cost, method for meeting this infrequent demand. In the United States during the mid 1960s, the aesthetic value of buried power cables became more appreciated. This trend created a broader market for buried cables, which in turn placed pressure on price.

Solid dielectric cables were developed as a lower-cost alternative to paper in lead cables. When the first solid dielectric cables were installed, there was little understanding of how they might age. In the absence of a failure model, buried cables were expected to survive 50 or more years. Instead, cables began to fail in less than 10 years, making their average life significantly shorter than anticipated.

These early onset failures prompted research into the aging mechanism of solid dielectric insulating materials, particularly polyethylene. This early research led to the current understanding of the primary aging mechanism for polyethylene—water tree development and growth.

II. WATER TREE DEVELOPMENT AND GROWTH

Water trees were so named due to their branched structure and bush-like appearance. These tiny structures are almost unviewable without the use of dyes to enhance their contrast. Research showed that water trees increased in size over time, eventually leading to the dielectric failure of the cable's insulation. An understanding of that growth mechanism was required before tree-resistant cables could be manufactured. Ideally, polyethylene insulation is hydrophobic and homogeneous. In reality, though, a large percentage of a cable's insulation consists of amorphous, non-crystalline material with voids and interfaces that have a polar hydrophilic nature. Water and ionic impurities are attracted to these areas and readily diffuse into the insulation, concentrating in these polar areas. Once there, under the influence of the cable's electrical field, water can be disassociated into damaging radicals [1]. Equations (1) and (2) are examples.

$$\text{OH- (from water)} \rightarrow \text{OH (hydroxyl group)} + \text{e-} \qquad (1)$$

$$2H_2O \rightarrow H_2O_2 \text{ (hydrogen peroxide)} + 2H+ + 2e- \qquad (2)$$

These radicals are damaging to the polyethylene structure. They oxidize (degrade) the interfacing surfaces, further polarizing them—and thereby propagating water tree growth. This explanation of water tree propagation requires the presence of three factors: amorphous polar imperfections in the dielectric structure; a sufficiently strong alternating-current electrical field; and, of course, water.

A comment on the source and quantity of the water required for water tree development may be helpful. Water saturates polyethylene in quantities on the order of .01 to .001% by volume. Therefore, the source of the water that is responsible for water tree development is not typically bulk water sources, such as floods and high water tables. Simply the humidity of the air or the dampness of the soil is sufficient to initiate water treeing—even in what would typically be thought of as dry conditions. Fig. 1 shows one of the most severe water trees this author has seen. These trees were clearly visible to the naked eye from the outside of the cable without dye. Interestingly, the cable segment pictured was pulled from the Saudi Arabian desert.

With this understanding of water tree development and growth, new materials and manufacturing processes could be employed to create more resistive, tree-retardant cables. Unfortunately for the power distribution industry as a whole, billions of feet of cable had already been placed into service before the nature of the problem had been identified. The new water-tree retardant cables currently available do nothing to address previously buried infrastructure.

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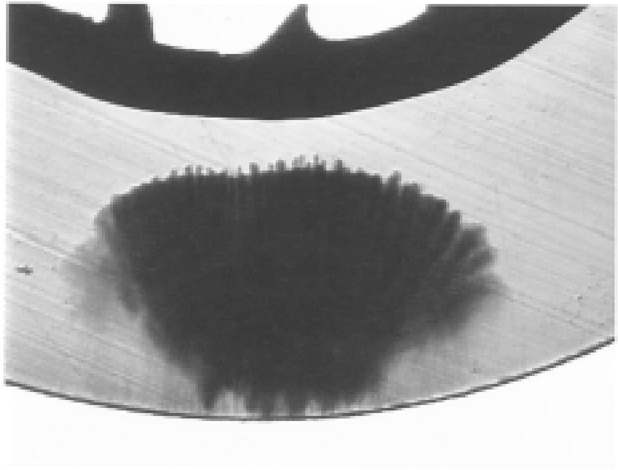

Fig. 1. Example of large water tree

III. CABLE RESTORATION PROCESS

In 1987 Dow Corning Corp. introduced a process for addressing these prematurely failing cables. This process involves injecting a specialized alkoxysilane fluid, phenylmethyldimethoxysilane (PMDMS), into the interstitial spaces between the conductor strands of a buried cable while it is still in the ground—and often while it is still energized. From the conductor strands, the fluid diffuses outward, into the cable's insulation. As the fluid molecules contact the water molecules diffusing through the cable's insulation or contained in the voids of the water tree structure, they react according to (3):

$$X - PhMeSi(OMe)_2 + (X+1) - H_2O \rightarrow HO(PhMeSiO)_xH + (2X) - MeOH \quad (3)$$

This reaction chemically replaces the water molecule—and, as the PMDMS oligomerizes, it fills the damaged void in the polymer. Thus, the process effectively eliminates two of the three requirements for water tree development: the presence of water and voids in the cable's insulation.

The electrochemical attraction of the PMDMS molecule to the polar region of the cable and to the mildly polar water molecule is the mechanism that ensures the fluid will reach the vulnerable areas of the cable. By eliminating the water, the fluid eliminates the source of the radicals, thereby also eliminating the source of continued polyethylene damage or water tree growth. By filling the void, the high-dielectric polymer protects the vulnerable interfaces of the water tree. This process is variously referred to as injection technology or cable rejuvenation technology.

IV. INDUSTRY-OBSERVED RESULTS

The original PMDMS formulation and injection process was disclosed in 1987. PMDMS therefore now has 18+ years of commercial history. Initially, the long-term positive effects of PMDMS were predicted through extensive laboratory research employing accelerated aging and diffusion studies. Those results have been well documented. For example, [2] reports some of the earliest data publicly available. It summarizes the results of a three-part battery of tests as follows: "Treatment with silicone fluid does increase the A.C. breakdown voltage. Moreover, the improvement in the dielectric strength of the cable has been maintained throughout the duration of additional accelerated aging."

The initial goal of the testing discussed by [2] was not only to document positive short-term results, but also to predict if those benefits would be retained for greater than 10 or 15 years. The authors of [2] determined and reported that the cable would in fact retain its benefits beyond this time frame. Of course, it is now known that 10 to 15 years was a modest goal. In fact, standard warranties on injection services are typically for 20 years—and cable longevity is expected to be much longer.

Positive results from accelerated aging tests in laboratory environments were repeatable. The positive data were published in a multitude of technical journals and reported on in numerous conferences. Further examples are presented in [3], which reports on data from a number of different experiments. In one of the experiments, the injection process achieved a 135% increase in ac breakdown level across five samples. In a second test summarized in the same paper—a test sponsored by Jersey Central Power and Light—a 69% increase in ac breakdown strength was observed after treatment. What was of particular interest in this case was that this increase was achieved in a brand-new cable.

In yet another published work [4], the PMDMS fluid was investigated to see if it could also rejuvenate cables constructed with ethylene propylene (EPR) insulation. The abstract of that work states, "The results indicate that [the PMDMS] liquid …(is) suitable to significantly increase the ac and impulse voltage breakdown levels of both black and pink EPR cables and thereby prolong their service life."

The continuous stream of positive information published about injection technology offered the power distribution industry proof that a cost-effective way existed to address the increasing problem of cable faults caused by aging. Still, there was— and is—concern that accelerated aging correlation data derived from conventional insulation materials may not be applicable to insulation permeated with injection fluid. This concern draws into question the value of laboratory-obtained accelerated data.

Fortunately, we now have over 18 years of real-world data to draw from when evaluating the effectiveness of injection technology. Of course, the results of this real-world evaluation are relevant only to injection processes employing the PMDMS-based fluids disclosed by the Dow Corning patent series, since these are the only fluids with such a long field history.

One of the best real-world indicators of the effectiveness of injection technology is the power distribution industry's response to this maintenance option. Fig. 2 demonstrates the yearly growth in the number of feet of cable rejuvenated with PMDMS technology.

More interesting than the aggregate footage is the steep growth curve. Clearly, the industry has reacted to positive real-world results by dedicating increasingly larger portions of their budgets to injection technology. It is worth noting that the budget involved here is usually not the maintenance budget, but rather the capital expenditures budget. The cable rejuvenation process is typically capitalized, since an injected cable is perceived as having equal value to a new (replaced) cable.

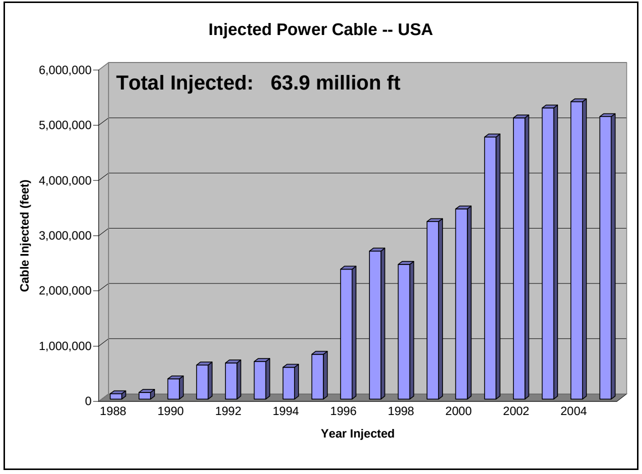

Fig 2. United States cable injection data, incomplete for 2005. This figure shows only fluid injections based on patented PMDMS chemistry.

Of most relevance are parameter studies of real-world cables many years after injection. It is not typically possible to obtain pre-injection data, such as ac breakdown voltage, on cable samples intended to remain in service. However, in some unusual situations, it has been possible to obtain meaningful pre- and post-injection data, allowing a comparison to be made between real-world results and the enthusiastic predictions made from accelerated lab data. One such case is discussed in [5], which describes a double, three-phase-circuit, 115kV transmission- class cable that included a spare cable, for a total of seven cable lengths. After one leg of one of the circuits developed a fault, the cable owners decided to replace the failed circuit and to inject the three phases of the remaining circuit. This approach allowed pre-injection data to be obtained from the failed circuit.

Ten years after the remaining circuit was injected, a termination failure led to a decision to replace the injected circuit. This replacement allowed the cable owners to make a post-injection evaluation of the injected cable. The real-world post-injection data they obtained compared very favorably with industry expectations. Though the report provides data on many cable parameters, this paper will highlight only the most relevant: the ac breakdown test values and the amount of fluid still present in the cable's insulation, 10 years after the cable had been injected.

The pre-injected cable reportedly had an average ac breakdown strength of 278kV across 3 samples. The ac breakdown strength of the post-injection cable 10 years after injection and 25 years after its initial installation exceeded the maximum voltage of 440kV that was available in the lab where this cable was tested.

Further laboratory analysis was performed to determine the quantity and penetration of the PMDMS-based fluid in the cable's insulation 10 years after injection. Fig. 3 indicates that there were still high levels of PMDMS-based fluid in the cable, and that the penetration was exceptional.

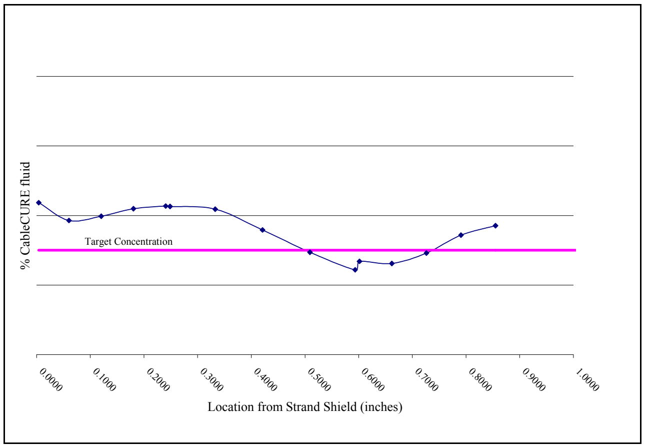

Fig 3. PMDMS-based fluid penetration data, showing good fluid penetration 10 years after injection. Target concentration line shows the ideal concentration for this particular cable.

V. CONCLUSIONS

Injection technology employing PMDMS-based materials and processes prolongs cable life by specifically acting on the known mechanisms of water tree growth. This technology has been scrutinized by engineers, scientists, and the marketplace for 18 years. Across that span of time, these fluids and materials have been demonstrated to be an effective—and cost-effective—alternative to both cable replacement and continuous fault repair. The positive acceptance of the technology in the marketplace is evidenced by the steep curve in cable footage injected per year. The dramatic increase in market confidence for this technology certainly is a reaction to the availability of real-world data. Distribution companies having 15+ years of experience with this technology can now rely on those experiences rather than accelerated laboratory data to help them prioritize the role of injection technology in their maintenance plan.

VI. REFERENCES

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VII. BIOGRAPHIES

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