

History and Status of Silicone Injection Technology

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Abstract: Over two decades have elapsed since the commercial introduction of the first solid dielectric enhancement technology. During those years, silane injection 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.

This paper traces the evolution of dielectric enhancement technology, compares the merits of the available technologies, and provides a comprehensive bibliography. The merit comparisons are made in the broad categories of safety, short-term and long-term post-injection reliability, and end-user value.

INTRODUCTION

From 1984 through 2006 approximately 75 million feet of medium voltage underground power cable were treated with available injection technologies as shown in Figure 1. As demonstrated by [5], injection is typically a fraction of the cost of replacement and the economics are almost always in favor of rejuvenation. Undoubtedly the favorable economics of rejuvenation fueled the rapid growth depicted in Figure 1.

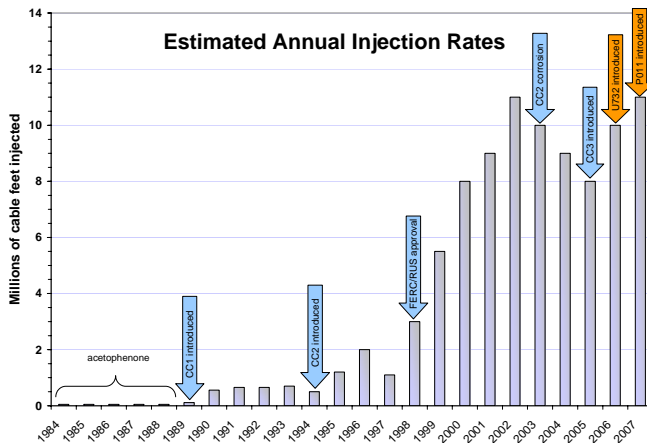


Figure 1. Cumulative injection compiled from dozens of industry sources including [1], [2], [3] and [4] demonstrate the growing importance of injection technology.

The first five years of commercial injections utilized acetophenone. While no cables treated with acetophenone ever failed in service, this technical success was not matched by commercial acceptance, largely because of the fugitive nature of acetophenone and the safety and economic penalties imposed by the need for an ongoing maintenance requirement to re-supply fluid to the cable. In 1989 a silicone fluid (phenylmethyldimethoxysilane) invented by Vincent and referred to as "CC1" [6] in Figure 1 was introduced. Because of its water reactivity, this new CC1 fluid largely eliminated

the need for a continual supply of fluid, at least for about 10 years at lower temperatures. About 5 years later in 1994, the authors of this paper Bertini and Vincent, et al, improved on the CC1 technology when they introduced an additive called trimethylmethoxysilane in [7]. The CC2 technology advancement solved a radial fluid distribution issue suffered by CC1 [7]. This reformulation together with the approval by the FERC and RUS of the capital treatment of fluid injection were the foundation for the rapid growth of injection at the turn of the century. This growth faltered after 2002 when it came to light in [3] and [24] that the CC2 technology could cause methanolic corrosion to aluminum strands. It was demonstrated in [7] that 30%_w of the trimethylmethoxysilane was preferred in the formulation together with 70%_w of the CC1 fluid to achieve optimum fluid distribution and dielectric performance. In 2005 CC3 was introduced when the concentration of the trimethylmethoxysilane was reduced by a factor of 6 to 5%_w, ostensibly to reduce the likelihood of corrosion of aluminum strands [23] experienced by the CC2 chemistry discussed in [3] and [24].

The balance of this paper examines four dimensions to compare commercially available rejuvenation technology. Those four dimensions are safety, short-term post-injection reliability, long-term post-injection reliability, and end-user value. Three technologies will be compared. All three of these technologies were conceived, reduced to practice and commercialized by the authors and their colleagues. The first technology referred to as CC (encompassing its three incarnations, CC1, CC2, and CC3) has been in widespread use since 1989 with the most recent formulation in use since 2005 and is defined by [6], [7], and [8]. The second technology introduced commercially in 2007 and described in [25] is referred to as P011 and utilizes the same base silane, namely phenylmethyldimethoxysilane, as CC, but it may be delivered with new sustained moderate pressure injection technology and an improved catalyst package. The third technology, referred to as U732 and described in [26], includes the field proven short and medium term technologies of P011 and CC, along with completely new materials designed for very long life extension. The U732 technology was available for the first time in 2006. A more complete history down to the chemical component level for all rejuvenation formulations is found in [30].

Sustained moderate pressure injection became possible in 2006 with injection adaptors described in [31] and [32] which can permanently seal fluid in the strands. Sustained moderate pressure injection has dramatically improved post-treatment performance as demonstrated in [18]. Injection pressures in excess of those utilized in the new process have been utilized routinely in the industry for over two decades. Even without

the benefit of sustained pressure, moderate pressure injection has demonstrated an improvement in post-injection reliability since at least 1987. For example in [33] injection pressures up to 1000 psig have beneficial effects on 1/0 cable per AEIC 582. In [34], [35], and [36] pressures of 350 to 500 psig are disclosed as routine.

SAFETY

Within the realm of safety there are two primary considerations in comparing rejuvenation technologies. The first is the exposure of injection contractors and circuit owner employees to high voltage. The second is the risk of fire and explosion.

When CC technology is applied to URD cables at least three visits (i.e. 1. injection; 2. vacuum tank removal, typically 24 hours after injection; 3. soak tank removal, 60 to 120 days after soak tank removal.) are required to manipulate energized or potentially energized high-voltage components. Potentially energized bottles are left connected to terminations for a 60 to 120 day soak period. During that soak period utility troubleworkers and line-workers may encounter unusual and potentially dangerous situations. Unfortunately each encounter with high voltage runs the risk of accidental electrical contact. Both the P011 and U732 technologies require a single visit and a single switching operation. There are no unusual pieces of potentially energized equipment left near terminations.

Consider	CC	P011	U732
Injection contractor HV electrical exposure	3+	1	1
Utility personnel exposure to unusual and potentially energized equipment	Yes	No	No
Potential flashover from open injection ports	Yes	No	No
Flammable	Yes	No	No
Known carcinogens	Yes	Yes	No
Known male reproductive toxins	Yes	Yes	No

Table 1. Safety Considerations

The CC technology utilizes injection elbows with ports described in [9], [10], and [11]. These ports are momentarily open to an energized conductor as permanent shielded caps are substituted for injection caps. These open ports have been known to flash over and create a hazard to employees including fire and explosion hazards as described by [12] and [13]. There are mitigating technologies described by [12] and [13] which remain unimplemented to date. With P011 and U732 technologies, injection is completed in minutes on de-energized cable and components. There is no open port injection into energized components.

Fire and explosion requires three components: fuel, oxygen, and a source of ignition. Unfortunately in a medium voltage distribution environment both oxygen and an ignition source

are ever-present. Not all fuels are equal when it comes to the ease of ignition. The ease of ignition is measured as a flash point and the higher the flash point the less likely the fluid will ignite. According to the current material safety data sheet (MSDS) of the CC fluid [14] its flash point is 0°C (32°F), well below the flash point of jet fuel A. Materials with these low flashpoints are rated by the U.S. Department of Transportation (DOT) as flammable. The P011 and U732 fluids have flash points in excess of 61°C (142°F) and are not rated as flammable by the DOT {49 CFR 173.115-120} or OSHA {29 CFR 1910.1200(c)}.

The CC fluid and P011 fluid include the carcinogen and male reproductive toxin benzene [14]. The U732 technology includes no known carcinogens or reproductive toxins.

SHORT-TERM RELIABILITY

Most post-treatment failures experienced with CC technology occur shortly after treatment. For example in [15], Florida Power and Light (FPL) reports a post-treatment failure rate of close to 5%. FPL primarily uses injection on segments which have recently failed. Another example, provided by [16], is Salt River Project (SRP), which reports a failure rate of about 1% during the first two years. The high short-term post-injection failure of CC technology is exasperated by at least two characteristics of the CC approach. First, there are no provisions in CC technology to address partial discharges (PD). Secondly, as demonstrated in [17], it takes about two years after treatment for CC technology to reach its maximum performance. Capital constrained cable owners often delay their treatment programs until the cables have demonstrated that they are nearing the end of their reliable life. In these circumstances rapid rejuvenation is desirable to avoid early post-treatment failures.

Consider	CC	P011	U732
Functionality included in technology to address partial discharges.	No	No	Yes
Dielectric performance of cable greater than 16 kV/mm (400 v/mil) within week of treatment	No	Yes	Yes
Fluid loss to molded components	Yes	No	No
Potential damage to molded or shrink-in-place components	Yes	No	No
Symmetrical penetration profile	No	Yes	Yes

Table 2. Short-term performance considerations.

In [18] it was demonstrated that the P011 and U732 technologies enjoyed an 87-fold faster performance increase compared to '841. Put another way, cables treated with P011 and U732 technologies perform with an AC breakdown strength comparable to new cables within a week of treatment. See Table 2.

Third and fourth short term considerations are fluid incompatibility with components including elbows,

terminations and splices. In [29] it was shown how the injection paradigm utilized with the CC approach where molded components are purposely exposed to silicone treatment fluids has two unintended consequences. First, a substantial amount of fluid is simply lost to the highly permeable EPDM splices and elbows typically employed to inject the cable. This lost fluid reduces the amount of fluid available to treat the cable. Second, fluid does sometime damage molded rubber components, particularly at higher temperatures.

As described in [30] the 2005 decrease of the fast-to-diffuse trimethylmethoxysilane component in the CC fluid (CC2 → CC3) has profound short-term performance consequences. In short and particularly acute with cables with 37 or more strands, the CC3 technology has a less than optimum penetration profile.

LONG-TERM RELIABILITY

In two-part paper [19] and [20] methods for the estimation of life for various conditions for each of the three technologies were provided and those estimations were validated against available accelerated-life data. The CC and P011 technologies utilize a single formulation for all conditions. As indicated by [19] and [20], while this one-size-fits-all strategy might simplify the operations of those performing the injection, inherent performance compromises are required as even modest temperature differences have a profound influence on long-term performance.

Figure 2 provides a validated simulation (see [19] and [20]) of post-injection performance for a 1/0 URD cable buried in mesic soils (e.g. above the Mason-Dixon Line) in 1980 with a moderate load. The reliability threshold of 16 kV/mm (400 v/mil) was established by Steennis [21] as a level where no failures are likely to occur in service.

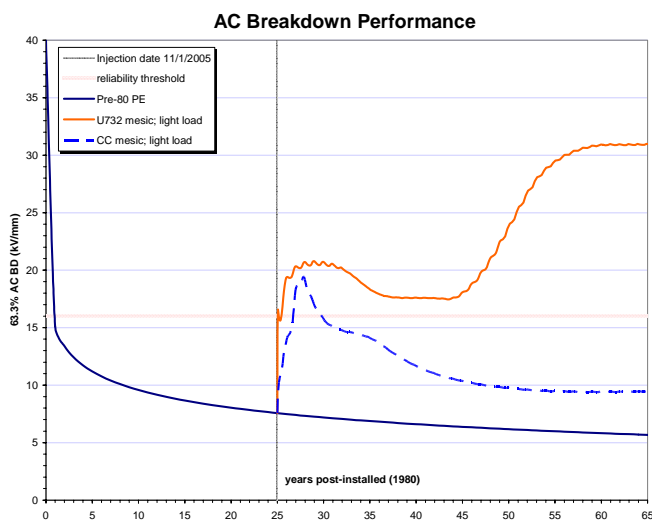


Figure 2. Post-treatment AC breakdown for lightly loaded cables in mesic (15°C) soils.

The CC approach suffers from a failure to stay in the insulation at a sufficiently high concentration for the long-term. CC drops below the reliability threshold of 16 kV/mm after about 5 years. P011 provide about a 30% boost in that performance because of the catalysis improvements described in [25]. In contrast, the U732 technology tailors the formulation for the anticipated thermal conditions the cable will face over its desired lifetime. With a temperature-adjusted formulation 732 can stretch life by 40 or more years for any cable with 19 or more strands, in any soil, with any anticipated load.

A theoretical framework and data to explain the substantial post-injection performance enjoyed by the U732 technology was provided in [26]. Table 3 provides a high level review of some of the key differences there described.

Consider	CC	P011	U732
AC BD performance > 16 kV/mm	<u>yrs</u>	<u>yrs</u>	<u>yrs</u>
• mesic soils; light load	5	10	>40
• thermic soils; moderate load	4	4	>40
• hyperthermic soils; heavy load	1	1	>40
Volume tailored to cable geometry	No	Yes	Yes
Chemistry tailored to cable conditions	No	No	Yes
Includes stress grading	No	No	Yes
Includes voltage stabilization	No	No	Yes
Includes UV stabilization	No	Yes	Yes
Includes PD suppression	No	No	Yes
Includes anti-oxidant	No	No	Yes

Table 3. Long-term performance considerations.

VALUE

In the end, circuit owners must weigh performance and economics in their decision-making process. There are a wide variety of conditions that affect cost. Individual circuit owner costs may vary from the typical case provided in Table 4.

Along with cost comes the confidence that the technology will perform as anticipated. The authors invented all three technologies compared in this paper and our collective representations have stood the test of time and peer review. All three technologies come with warranties that are far superior to the warranties offered by cable replacement contactors or cable manufacturers. Contrary to some public representations [22] however, there are no fully insured warranties.

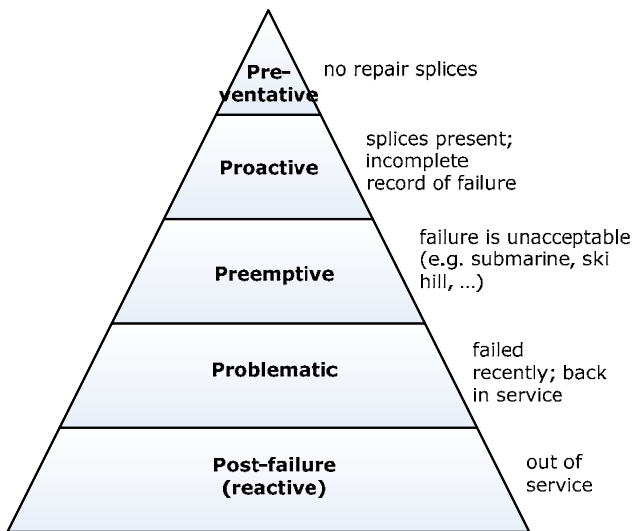
When it comes time to collect on a warranty decades after treatment, the circuit owner must judge the ability of the warrantor to pay in an uncertain future. In most cases, faith is better placed upon individuals than faceless institutions. For long-term warranties, however, some institutional trust is required. There are at least five elements to be considered to differentiate the commercially available warranties.

1. What conditions are established by the warranty provider to restrict a remedy?
2. What is the warranty length?
3. Is there a substantial portion of the warranty obligation that is insured?
4. Is there an actual fund of cash held by a third-party and accumulating interest to pay long-term obligations?
5. What is the history and future of the ownership and management teams for the suppliers?

The summary answers for each of these questions are found in Table 4.

Consider	CC	P011	U732
Typical fully absorbed cost as a percentage of replacement (single phase, direct buried, 1/0 15kV cable)	40%	35%	41%
Unconditional warranty	No	Yes	Yes
Warranty length in years	20	20 ¹	40 ²
Warranty fully insured	No	No	No
Warranty funding held in appreciating 3 rd -party trust	No	Yes	Yes
Management team with >2 decades of experience	No	Yes	Yes
Developed by technical team with >2 decades of experience	Yes	Yes	Yes
Introduced	1994	2007	2006

Table 4. Value Considerations. Notes: ¹Warranty is available only for lightly loaded cables in cool soils; ²40 year warranty is available only for cables with 19 or more strands – 7-strand cable has 20-year warranty.

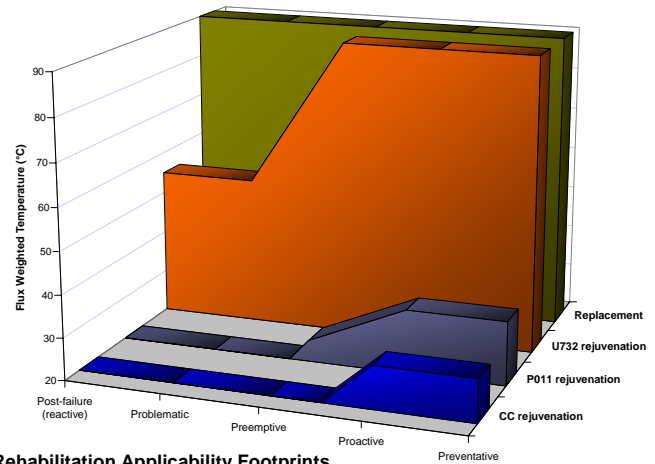


Distribution Hierarchy of Needs

Figure 3. The hierarchy sorts strategic cable rehabilitation funding priorities from the bottom up. The final comparison hinges upon the applicability of each technology to the strategic needs of the circuit owners.

In [27] a framework for strategic prioritization is provided which defines the distribution hierarchy of needs reproduced here as Figure 3. In short, CC and P011 technologies are only applicable to the highest portions of the Figure 3 pyramid, namely preventative and proactive. Those two technologies were simply not designed to address the bottom of the pyramid. Taken together with the thermal constraints on the three rejuvenation technologies, it is possible to build an applicability footprint as shown in Figure 4.

Of course, replacement can always be used for any strategic requirement up to the design temperature of the cable. Because the cost of replacement is typically several times that of rejuvenation, rejuvenation should be utilized whenever practical. CC rejuvenation is constrained on the top of its Figure 4 footprint by its one-size-fits-all chemistry and on the left by its lack of functionality for cables that have already failed. P011 improves slightly on both of these accounts. With 30% greater longevity, a slightly higher temperature can be tolerated. With an injection paradigm designed from the beginning to deal with the splices inherent on proactive work its footprint extends to the left of CC rejuvenation. U732 was designed from the outset to address the most problematic cables and hence covers all 5•Ps. There are certain high temperature cases where even the U732 technology is not applicable as of this writing, but an active R&D program is working to expand the U732 envelope to the entirety of the Figure 4 universe.



Rehabilitation Applicability Footprints

Figure 4. Thermal performance and strategic applicability define envelopes for each of the 4 rehabilitation tactics.

SUMMARY

Rejuvenation technology is almost always the most cost effective rehabilitation strategy. The circuit owner has three rejuvenation technology choices. The most recently developed technologies, P011 and U732, enjoy superior safety, short-term performance and value compared to the older CC technology. The U732 technology outperforms the CC and P011 technologies by over a factor of 3 in long-term reliability performance. For the cost conscious circuit owners,

the advantages of P011 can be enjoyed at a lower cost than the CC technology with a slightly improved medium-term performance. In light of recent discoveries, neither the CC nor the P011 technologies should be employed:

1. In the warmer soils below the Mason-Dixon line,
2. where cable loading exceeds 25% of rated ampacity if 20-year post-injection reliable life is desired, or
3. where the strategic circumstance of the cable is post-failure, problematic or preemptive.

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