

Extending Power Cable Life an Additional 40 Years

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Abstract: For more than 20 years, cable rejuvenation has been used at electric utilities to extend power cable life. Most cable rejuvenation has been carried out in residential subdivisions. However, with the latest improvements in injection fluids, industrial customers are beginning to adopt cable rejuvenation for chemical, industrial, and power plants as an insurance policy against power cable failures. For about one-half the cost of replacement, power cable life can be extended up to 40 years.

INTRODUCTION

If only we could do for humans what can now be done for medium voltage power cables. Imagine that as you approached the end of your life, you could drink a magic elixir and within a week you could perform at your peak in every way for another 40 years. That is precisely what rejuvenation fluid does for power cables – but is not magic it is chemistry and physics. You have another option: you can replace the aging plant power cables with new cable. The new cable will perform reliably, but installing it will disrupt the plant, take a lot longer, squander scarce world resources, and cost 2 to 5-times more, which must ultimately be reflected in your production costs. Rejuvenation is a safer, faster and better alternative.

From 1984 through 2008, over 80 million feet of medium voltage power cables were rejuvenated as shown in Figure 1. As demonstrated by [5], injection is typically less than one-half the cost of replacement, and cable rehabilitation economics almost always favor rejuvenation over replacement. Undoubtedly, the favorable economics of rejuvenation fueled the rapid growth in rejuvenation depicted in Figure 1.

How successful has rejuvenation been for circuit owners that have injected cables? According to [6], of the over 80 million feet of cable rejuvenated, less than 1% of the cable has failed. In a soon to be published paper, recent improvements in fluid formulations have dropped the failure rate to less than 0.5% for the most advanced fluid and injection techniques. In addition to having an attractive cost profile, cable rejuvenation also saves time. At an industrial plant, it takes less than one day to inject even long lengths of medium voltage cables, and typically only a couple of hours for most cables.

What is the cost of a failure in your plant?

Many industrial plants were constructed between 1965 and 1985. From the time of construction until now, the medium

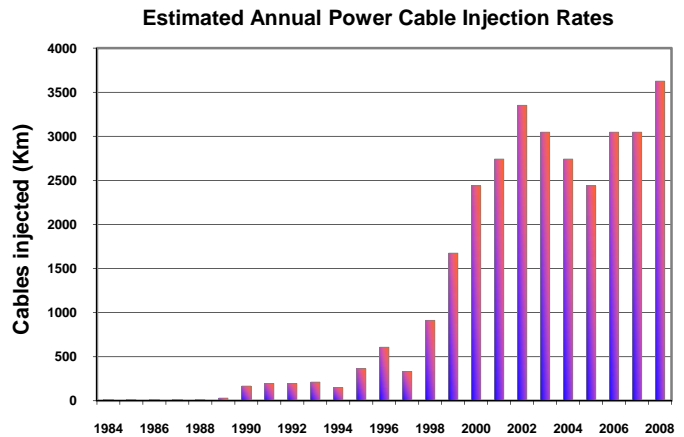


Figure 1. Cumulative injection compiled from dozens of industry sources including [1], [2], [3] and [4] demonstrate the growing importance of injection technology.

medium voltage power cables have worked without failure. However, many industrial plants of this vintage are facing failures that could shut down the plant for an extended period, or at least shut down a line for a day or two.

Failure costs vary widely in industrial facilities. On the low end, there may be a cable that runs 20 meters from switchgear to a motor through a lightly loaded, easily accessible cable tray, where the cables are not interlaced with other cables. This cable should be easy and inexpensive to remove and then install a replacement cable. Its failure should not cause the failure of adjacent cables.

However, this is not typical in industrial plant settings. Power cable runs of up to 750 meters are common. The cable paths are not straight. Cable might be in conduit, or interlaced with other cables in one or more cable trays on different levels. The cable trays might not be accessible. The conduit may have collapsed, preventing the cable from being easily pulled out. Where cable is buried, additional problems can occur. Many times new buildings are constructed over the original path of the cable.

The impact of a failure can be a significant economic event. In one aluminum smelter, the cost of a one hour power outage to the line was about \$250,000. If it extended over an hour, the cost rose to over \$100,000,000, because the aluminum solidified and the plant had to be rebuilt from the ground up.

Think about what a power cable failure in your plant might cause in downtime, repair cost, lost production value, and environmental damage.

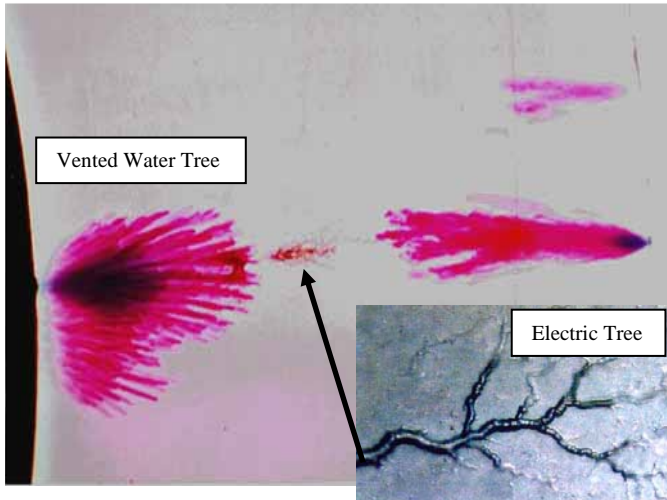


Figure 2. Water trees initiate from defects (dirt) in the insulation. When water trees grow large enough, an electric tree is formed (see inset). After an electrical tree is formed, cable failure usually follows.

What Causes Medium Voltage Power Cable Failures?

Medium voltage cables fail due to a phenomenon called water trees. Water trees can grow from the inside of the cable out, from the outside of the cable in, or from defects within the insulation. As they grow, they look like trees or bushes. Figure 2 shows how water trees grow until they can no longer hold the voltage stress and an electric tree is formed. Once an electrical tree is formed, the cable usually fails within two weeks.

Figure 3 provides an overview of cable aging and failure mechanisms (rectangles) and the mechanisms by which cable rejuvenation (rounded rectangles) interfere with aging and failure. It is not the purpose of this paper to recite the work of countless others to explain the mechanisms of water treeing and how those water trees ultimately lead to failure. Instead, we briefly review the process described by Figure 3.

Manufacturing Defects – while not absolutely required for water tree growth, they certainly accelerate the growth and propagation of water trees and hence the longest water trees in any section of cable are quite likely to involve some imperfection.

AC stress, Ions, and Water – are the three requirements for the growth of water trees (see Figure 2). In general, reductions in any of these three elements retard water tree growth.

Local high-density space charge and electrical fields – are the inevitable consequence of large water trees and are exacerbated by transient over-voltage events such as switching, failure, lightning, and off-line cable testing.

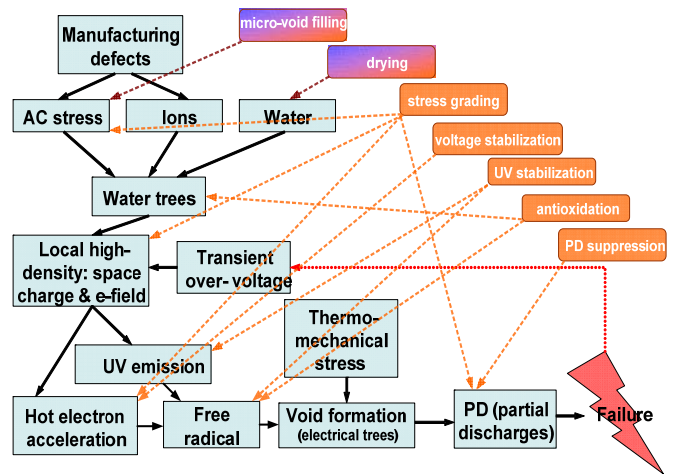


Figure 3. Cable aging, failure and rejuvenation mechanisms.

UV emission – is a consequence of space charges returning to their ground state. Ultraviolet photons are emitted, which have sufficient energy to destroy polyethylene bonds and spawn damaging free radicals.

Hot electron acceleration – is a consequence of very high local fields created around some dielectric imperfections including space charges. Hot electrons can break polyethylene bonds and create free radicals.

Thermo-mechanical stress – causes the halo visible in most aged cables, which are exposed to water and a 24-hour temperature cycle and is described in [7]. As the cable warms, the solubility of water in polyethylene increases substantially and more water rapidly diffuses into the cable from the surrounding soil. As the temperature of the cable falls, the solubility of water decreases and water cannot permeate out of the cable quickly enough to avoid supersaturation. Driven by thermodynamic forces, the supersaturated water seeks its liquid state and condenses to the micro-voids of the halo.

Void formation – is caused by UV photons and hot electrons created primarily through the water tree process and by the thermo-mechanical stress.

PD (partial discharges) – manifest in voids, which are large enough for the gas within the voids to be ionized by the electrical field. The PD inception voltage is greater than the extinction voltage, because once the gas within the void becomes ionized; the PD is more easily sustained.

Failure – results as partial discharges erode the wall of the void in which they occur. The erosion of each discharge in a PE void increases the size of the void and hence decreases the partial discharge inception and extinction voltages for that void. This self-acceleration means that any PD occurring at operating voltages in polyethylene is likely to lead to rapid failure.

What is Cable Rejuvenation?

- Cable rejuvenation introduces silicone fluid into medium voltage power cable strands.
- The fluid migrates into the conductor shield and the insulation.
- Injection fluids modify the chemistry of the insulation and the physics of the cable to extend the reliable life of the cable circuit.

What Problems does Cable Rejuvenation Solve?

Problems You Face	Rejuvenation Outcomes Achieved
Declining cable reliability	Same reliability as new cable in a fraction of the time
Spending more than \$10/ft to solve power cable reliability problems	50% cost reduction
Insufficient maintenance budget for cable failures	Shift cost of cable failures from O&M \$ to CAPX \$

Table 1. Problems and outcomes.

What applications for fluid injection in power cables have proven to be successful?

- HMWPE, XLPE, TR-XLPE, EPR, butyl-rubber insulation
- Single phase cables (conductors generally 4/0 or smaller)
- Feeder cables (3 conductors generally larger than 4/0)
- Network cables
- Transmission cables
- Submarine cables

It is not possible to inject:

- Solid conductor cable
- Strand blocked cable
- Paper-lead cables

How Does Rejuvenation solve the cable failure model?

Figure 3 shows seven rejuvenation mechanisms (as rounded rectangles) along with arrows, which indicate the steps of the aging and failure process, which are interfered with by each rejuvenation mechanism. The seven rejuvenation mechanisms are described below.

Ingredient	Purpose
Isolauryl alcohol	Short term
Tolyethylmethyldimethoxy-silane	Medium term silane
Dodecylbenzenesulfonic acid	Condensation catalyst
Cyanobutylmethyl-dimethoxysilane	Long term silane; Stress grading
Tinuvin® 123	HALS UV stabilizer
Tinuvin® 1130	UVA stabilizer
Geranylacetone	Voltage stabilizer
Ferrocene	PD suppression; UVA stabilizer
Irgastab® Cable KV10	Antioxidant

Table 2. A summary of the ingredients utilized by the cable rejuvenation process. (Tinuvin and Irgastab are registered trademarks of Ciba Specialty Chemicals.)

MICRO-VOID FILLING—Not to be confused with voids, which can be imaged with an optical microscope, micro-voids are on a much smaller scale. These micro-voids are usually chemical imperfections in the polyethylene and are characterized by the presence of bonded oxygen, often carboxyl-groups, which have an affinity for water relative to non-treed PE. The silanes react with and displace (see DRYING) water at oxidized PE sites within the water trees. The replacement of conducting ionic water with a silicone dielectric increases the dielectric strength of the insulation.

DRYING—There are two drying effects. The first, the chemical reaction of silanes with water, is the most widely reported in past literature, but is the less important of the two drying effects. Much more important than the transient chemical drying is the ability of the treatment to reduce the reentry of water. To this end, materials, which have an improved affinity for polyethylene, provide superior water repellent capability.

STRESS GRADING—The inclusion of high dielectric constant layers to grade the electric field within cables and cable components is widely practiced and well understood. Cable rejuvenation provides stress grading on a micro-scale inside the voids.

VOLTAGE STABILIZATION—The voltage stabilizing effects of ketones are due to keto-enol-tautomerism and were first demonstrated by [8] and later in [9]. Tautomers provide a stable receptor for hot electrons. The enol form of the tautomer absorbs much of the energy of hot electrons and converts to the transition forms and a free proton. These resonant transition forms delocalize the excess negative charge. The theory is that a hot electron is first captured, then thermalized, and finally released.

UV STABILIZATION—Rejuvenation technology includes components, which absorb photons in the 275 to 400 nm range. These are called ultra violet absorbers or UVA for short. Specifically Tinuvin 1130 and ferrocene provide the appropriate absorption. Tinuvin 1130 and ferrocene are each quite soluble in PE, but diffuse slowly. Their beneficial UVA effects persist for over 4 decades in most applications. In addition to the UVA component, a hindered amine light stabilizer, or HALS component, is included. HALS are free radical scavengers that trap radicals before subsequent reaction leads to polymer degradation. As demonstrated in [10], HALS are self regenerative. After quenching a free radical, the HALS regenerate and can then quench another free radical. UVA and HALS enjoy a chemical synergy. Since UVA materials attenuate UV emissions, there will always be some UV photons, which damage the polymer, and this is the case where the HALS comes to the rescue. However, by itself, a HALS would be overwhelmed, if 100% of the UV photons damaged polymer bonds. Together, UVA and HALS provide greater UV stability than either one alone.

ANTIOXIDATION—Antioxidants are included in virtually all modern cable compound formulations. While originally deployed to prevent oxidation during the extrusion process, it has been shown in [11] that antioxidants also slow the growth of water trees. It has also been demonstrated in [12] that the presence of antioxidants increases the electrical tree inception voltage. KV10, a sulfur containing phenolic antioxidant, has been demonstrated to slow the growth of water trees by a factor of four. This class of sulfur containing phenolic antioxidants has been shown to increase electrical tree initiation voltage by up to 75% at just 0.2%_w. KV10 enjoys a very high solubility in polyethylene, and because of its high molecular weight of 424.7, a very low diffusion rate. The combination of high solubility and low diffusivity yields a very low sweat out or exudation as was shown in [11].

PD SUPPRESSION—There are several mechanism involved in the suppression of partial discharges or PDs. First as described previously, local stress reduction though stress grading increases the partial discharge inception and extinction voltages. As described in [13], a free electron, sometimes from cosmic rays, is a necessary precursor to the initiation of a PD. Therefore, a second suppression mechanism is provided by the electron affinity of the previously described voltage stabilizer (geranylacetone) described in [8] and [9], and the electron accepting ferrocene as shown in [14].

Third and fourth mechanisms are also provided by the ferrocene. The presence of ferrocene is designed to prevent the inception of partial discharges. This is accomplished by rendering the walls of large voids partially conductive when voltages exceed a threshold well below typical inception voltages in a manner analogous to the electronic activation of a transistor. Once the walls are partially conductive, the e-

field all but disappears. In the event that a PD does occur, a small portion of the ferrocene is consumed and simultaneously raises the pressure in the void and releases an oxygen scavenger, namely atomic iron. These effects act to quickly snuff out incipient partial discharges and mitigate the damage normally incurred when a discharge occurs.

How are cables injected in the field?

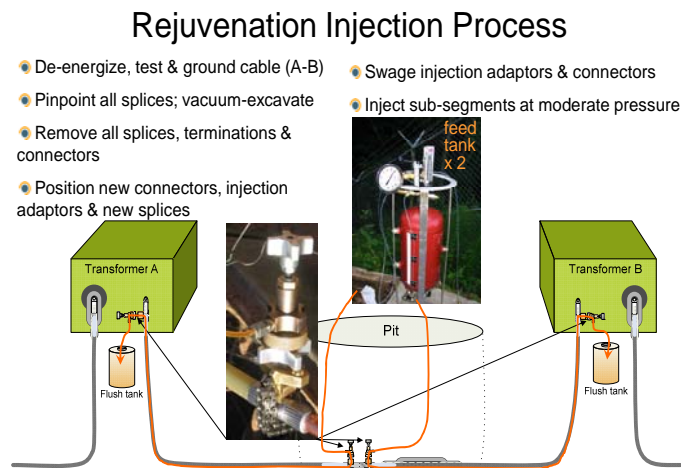


Figure 4. Overview of injection process.

What is the Business Case for Injection?

Engineering experts now believe the nation is entering a period that could be marked by a dramatic increase in power cable failures unless considerably more is spent on addressing old and deteriorated cables in industrial plants.

Cable rejuvenation is at a minimum one-half the cost of replacement. More typically it is 1/3 to 1/5 the cost of replacement. Factors that increase the cost advantages of injection are:

- Copper conductors vs. aluminum conductors
- Direct buried cables or collapsed conduits
- Longer cable runs
- Unknown cable routes
- Cable routes with many turns
- Interlaced cables in cable trays
- Cable tray inaccessibility

The time to inject a cable is significantly less than the time to replace a cable. Typically once the cable ends are replaced, injection takes from 1-12 hours depending on the cable length and the strand compaction. Runs of 100 meters can be injected in less than one hour. Cables of 600 meters could take 12 hours. Cable replacement for runs of 100 meters could take up to a day and runs of 600 meters could take up to 3 days or more, depending on accessibility.

The space, accessibility, and equipment required for cable rejuvenation is considerably less than for cable replacement. No lifting or heavy pulling equipment is required, only small tanks of fluid on either end of the cable are utilized.

Because rejuvenation is typically less than one-half the cost of replacement, you can extend the life of at least twice as much cable with the same budget. New cables and rejuvenated cables today both have an expected life of 40 more years.

Once an older vintage cable is over 20 years old, there is a definite risk of cable failure. Cable rejuvenation can be like “buying an insurance policy”, once this point in time is reached in a cable’s life. With rejuvenation, cable life can be extended another 40 failure-free years.

Where has cable rejuvenation been used for industrial plants cables?

Terra Industries, Oklahoma — This anhydrous ammonia plant in Woodward, OK was built in 1975 and the cables are now 34 years old. The plant has eight 3-phase, 5 kV, 1000 kcm, EPR insulated cables feeding the plant. In 2007, there was a cable failure on one phase of one cable. Terra was concerned that an additional failure could shut down the plant. Consequently, the plant wanted to insure that the cables did not fail.

Each cable was about 200 meters long and ran from the incoming power line pole, then underground across the parking lot, and into the switchgear from underneath. Three of eight cables were injected during plant operations in January 2008. The last cable in the first half was not injected, because excavating the cable fault could have caused damage to other live cables encased in the same concrete slurry. The injection of these three cables took 3 days out of 7 days onsite. Three phases of each cable were injected at one time. In addition to replacing the terminations, the rejuvenation crew carried out proactive preventative maintenance by installing new arrestors for the plant.

Mark Jensen, Engineering Manager, said,

“We were very impressed with the rejuvenation process. The people were knowledgeable and worked efficiently. They found problems with our terminations and solved them.

We liked the fact that the injection did not leave any smell in our plant. All chemical preparation was done outside. When they came inside everything was sealed.

We were disappointed that we could not repair the faulted cable, but the risk was too great to the other live cables. Based on the success of this project, we plan to inject the remaining four 3-phase cables next year after the weather cools down and the plant electric load is lower.”

In January 2009, during a plant shutdown, the remaining four 3-phase cables were injected. Because of the success of these cable injection projects, the plant is considering injecting additional cables. When complete, all medium voltage cables will last another 40 years.

Power Plant, Texas—In September 2008, Hurricane Ike struck the Texas coast and the storm surge that followed resulted in flooding at a power plant near the coast and most of the plant was underwater.

Two weeks after the storm, when disconnecting a motor, plant personnel found water running out of one of the cables. After many years in operation, the cable ends were no longer sealed. It was important to remove this salt water from the cable strands before restarting the plant.

Cable rejuvenation was selected for this work, because the work could be completed in days vs. the weeks that it would have taken to replace the cables. The schedule advantage was the key decision factor in selecting injection in order to maintain the plant restart date.

Rejuvenation injection adaptors were also an important decision factor, because the injection adaptors permanently seal the ends of the cable. If a future storm surge ever flooded this plant, no salt water will get into the treated and sealed cable strands.

First, a survey was carried out. Cables to be treated were identified and the required parts and equipment were ordered. Two days later the equipment, fluid, and personnel were onsite and had begun work to restore the cables. Over the next 14 days, over 25,000 feet of cable were rejuvenated.

The cost of the rejuvenation was about 1/3 the cost of buying and pulling in new cables, and much less plant labor was required to complete the work. Rejuvenation also provided a significant schedule advantage over pulling in new cables.

Because the plant knew very little about cable rejuvenation before this project, there were many skeptics at the plant about this process. After treatment and before plant startup, the cables were tested. The results were exceptionally good—better than new cable, and 100 times better than the last test on the cables before the storm. After this project, the plant said that cable rejuvenation would be part of their regular decision process in the future.

How can cable rejuvenation help industrial plants reduce their carbon footprint?

For every meter of cable injected

- 16 grams of silicon fluid are used
- 195 grams of aluminum are saved

- 484 grams of copper are saved
- 963 grams of plastic are saved

Diesel fuel-1.09 gal/meter is eliminated for:

- Transporting the cable, factory to site
- Taking bigger construction equipment to the site
- Drilling, trenching, or using a backhoe

What impact can rejuvenation have on your plant?

Was your plant built before 1985? If so, have any of the medium voltage power cables failed? If not yet, what would be the impact of a cable failure on your plant?

SUMMARY

As medium voltage cables age past 20 years, they will begin to fail and cause plant outages. These outages can cause a major disruption to plant operations, depending on the cable location. One solution is cable replacement before failure.

Another solution is cable rejuvenation. Cable rejuvenation is almost always the most cost effective rehabilitation strategy. In addition, the time and disruption required to implement this solution are much lower. With the 40-year cable life extension provided by rejuvenation, more and more industrial plants are choosing to rejuvenate.

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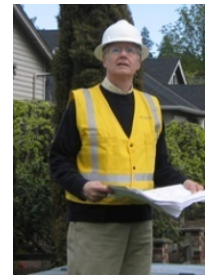
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AUTHORS

Richard K. Brinton is the Vice President of Business Development of Novinium. He has been responsible for introducing cable rejuvenation to utilities around the world. Brinton has over 30 years experience in business development in the Americas, Europe, Asia, and Australia. He has focused his career on the worldwide introduction of new technologies and has gained worldwide experience in industrial processes, machine tools, robotics, and construction. Mr. Brinton holds a B.S. in Industrial Engineering and a B.A. Liberal Arts from the Pennsylvania State University, is a Senior Member of the IEEE, and is a licensed professional engineer.



Glen J. Bertini is the President, CEO and Chairman of Novinium, Inc. He has spent the last two decades working with cable rejuvenation technology beginning with its development at Dow Corning in 1985 and continuing through its commercialization and growth to over 80 million feet of cable rejuvenated so far. Mr. Bertini was employed by Dow Corning, a silicon chemical manufacturer, as a development engineer, where he was part of a small team that developed and commercialized the first cable rejuvenation products. Mr. Bertini has over 40 articles published on the subject of cable rejuvenation technology, holds 23 patents, and has 7 more pending. Mr. Bertini holds a B.S. in Chemical Engineering from Michigan Technological University, is an IEEE Fellow, a voting member of the ICC, and a licensed professional engineer.

