Better Next Year

What Rejuvenation Teaches about PD Testing

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***Abstract*— For over three decades cable rejuvenation using dialkoxysilane fluids has been the most capital efficient method to prevent cable failure due to aging resulting from all manner of defects including but not limited to water treeing, electrical treeing, and manufacturing defects. Over the last decade rejuvenation has surpassed replacement as the most utilized method of rehabilitation. The work presented in this paper utilizes very large data sets to compare the post-installation reliability of rejuvenation and replacement. The results shed light upon off-line partial discharge diagnostic testing. Either or both of the following propositions are true: (1) Electrical trees are rare and/or (2) rejuvenation adequately addresses electrical trees. Data to support both propositions are presented.**

Keywords—cable rejuvenation; cable injection; cable replacement; cable rehabilitation, partial discharge testing, off-line PD testing, diagnostic testing

I. INTRODUCTION

This paper provides a robust analysis of decades of post-rejuvenation and post-installation reliability data. The analysis is likely to leave the reader wondering how such results are possible. [1] will begin to address the wonder.

II. INSTALLED AND REJUVENATED CABLES: A COMPARISON OF FAILURE RATES

A. Data

The authors have ready access to three decades of post-rejuvenation reliability data. These data are particularly robust, because circuit owners have a substantial economic incentive to report failures to the service supplier. Typically the circuit owners can recover 100% of the rejuvenation capital cost by simply reporting a failure. The rejuvenation data encompass over 100 circuit owners in more than 50 states and provinces of North America and include a wide variety of cable designs, conductor size, insulations, voltage classes, vintages and operating conditions. The data include high molecular weight polyethylene (HMWPE), cross-linked polyethylene (XLPE), tree retardant XLPE (TRXLPE), and ethylene-propylene rubber (EPR) insulations in approximate proportion to their incidence in the North American cable population. See [2] and [3] for cable installation population estimates. Figs. 1, 2 and 3 provide pie charts of some delimiting characteristics of the rejuvenated cable data set.

Unfortunately, and in contrast to the available data on rejuvenated cables, there is a dearth of data on new cable post-installation reliability. There is one publically available dataset in [4] from a North American circuit owner (hereafter NACO).

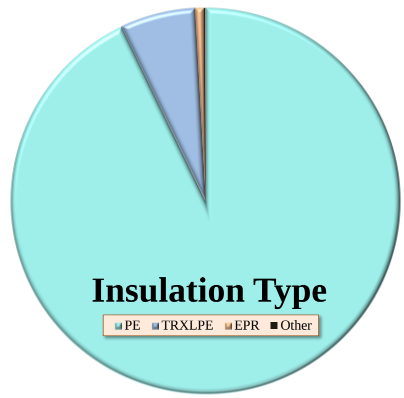

Fig. 1. Insulation type distribution in the population of rejuvented cables. PE includes HMWPE and XLPE cables.

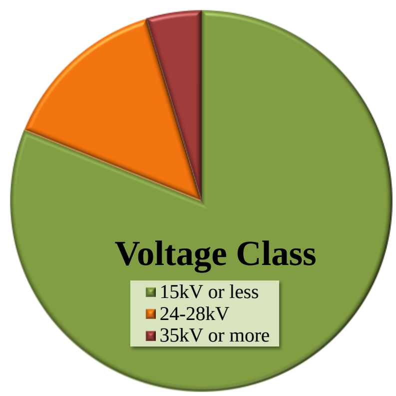

Fig. 2. Voltage class distribution in the population of rejvuenated cables.

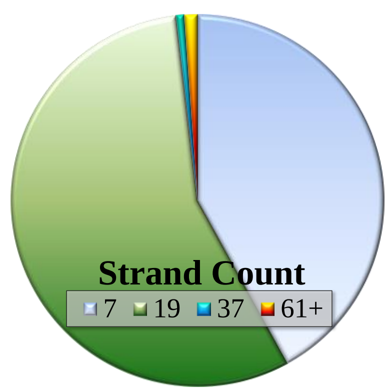

Fig. 3. Strand count distribution in the population of rejvuented cables.

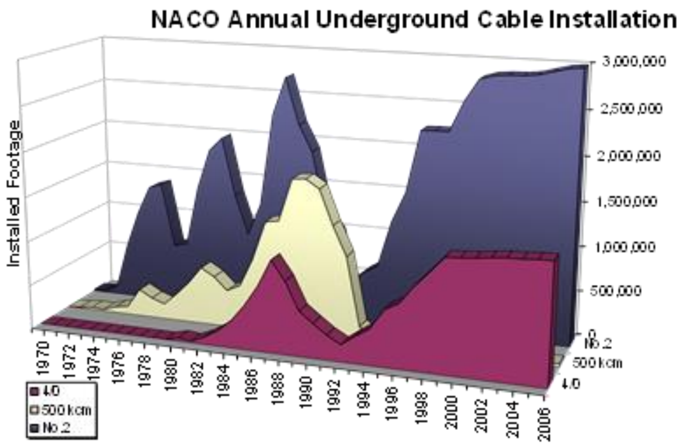

Fig. 4. Installation history for all cables at NACO from 1970 to 2006.

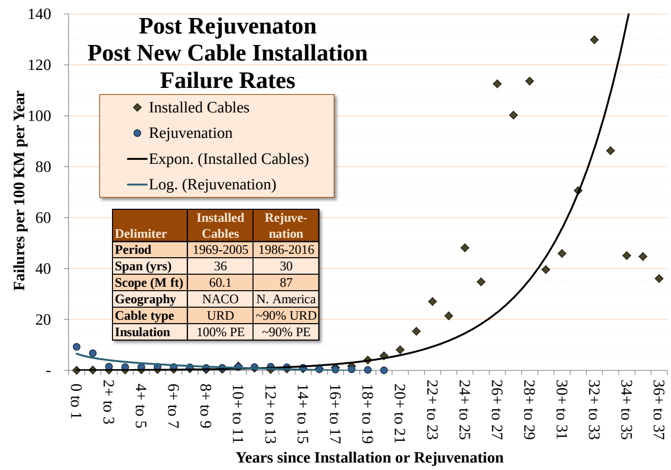

Fig. 5. Failure rates over time for installed and rejuvenated cables. Inset includes relevant population delimiters. While new cables age as expected, rejvuention enjoys at least two decades of ever improving reliability.

NACO has engaged in both replacement and rejuvenation for over two decades. NACO had gathered and shared over a decade of failure data on an installed base of over 29,000 km of XLPE (cross-linked polyethylene) cable. Fig. 4 shows the history of the cable installation. This paper will examine the largest of the three data sets representing 18,000 km of installed cable, namely the 7-strand, 33.6 mm^2 (AWG No. 2) cable. This direct buried cable was unjacketed prior to 1985 and typically had a nominal insulation thickness of 4.5 mm.

B. Analysis

Fig. 5 shows how failures progress over time for both installed and rejuvenated cables. Installed cables include new circuits and those which replace aged cables. The failure rate is represented in terms of number of failures per 100 kilometers of cable per year. While both rejuvenation and replacement enjoy low initial failure rates, the failure rate of replaced cable worsens with time, while rejuvenation failures decrease with time spanning a two-decade history. It is important to note that for most of the data spanning two decades or more, rejuvenated cables were covered by a twenty-year warranty. After the end of the warranty period circuit owners lose their incentive to report failures; the authors censor the data for all post-warranty periods. In contrast there is no financial incentive to report replaced cable failures and as a consequence there is a risk that these statistics underestimate actual failures for new cable installations.

Longer warranties of up to 40 years have been available commercially on advanced rejuvenation technologies for just under a decade so we will have to wait about a dozen years before we will have reliable field performance data beyond the two decade censored data limit. However, early auspicious comparisons between two generations of technology will appear in [1].

The post-installation failure history of new cable reliably follows the second law of thermodynamics: The older the cable, the poorer the reliability. That is not a surprise; it is precisely what we would expect. How is it that rejuvenation appears to reverse entropy and rejuvenated cable ages backward?

III. Better Next Year

The authors wish we could reverse the aging process in people. A Nobel prize would surely result, and untold riches would be showered upon us. Alas, we focused on distribution cables. That focus, however, is entirely good news. Had we tried to reverse aging in people, we would have surely failed. Human biology and chemistry are much too complicated; the chemistry and physics of cable aging is entirely understandable. Fig. 6 presents a diagram of that aging process along with a subset of the strategies rejuvenation employs to address those aging mechanisms. The “magic” to “reverse aging” is something we are all familiar with – time release. In biological systems time release is of relatively short duration. If we consume a pill it will reside in our alimentary canal for 24 to 48 hours. Whatever drug is in the pill must be absorbed through the walls of the alimentary canal within that time or the drug is wasted. As soon as the drug is in our blood our kidneys and liver begin to remove it. Most drugs are removed from our system in several hours or days. To create extended time-released drugs, medical researchers introduced external patches that deliver drugs transdermally or implanted polymer tubes. These two approaches share a common feature – the rate of drug delivery into the patient is controlled by the rate of diffusion of the drug through a polymer membrane. Implantable birth control drugs can last for 48 months. To reach decade-long delivery rates one would need thicker polymer tubes and larger reservoirs to hold the drug. This is precisely what a cable represents to rejuvenation scientists. The interstitial spaces between the strands and the ample carbon black in the strand shield represent a substantial reservoir and the cable insulation, several millimeters thick, is a timed release permeation barrier. These two features allow the multi-decade time release of ingredients into the cable insulation.

A thorough explanation of all the mechanisms illustrated in Fig. 6 by which rejuvenation interferes with cable aging and failure is beyond the scope of this paper, but is discussed in [1] and future work pending publication.

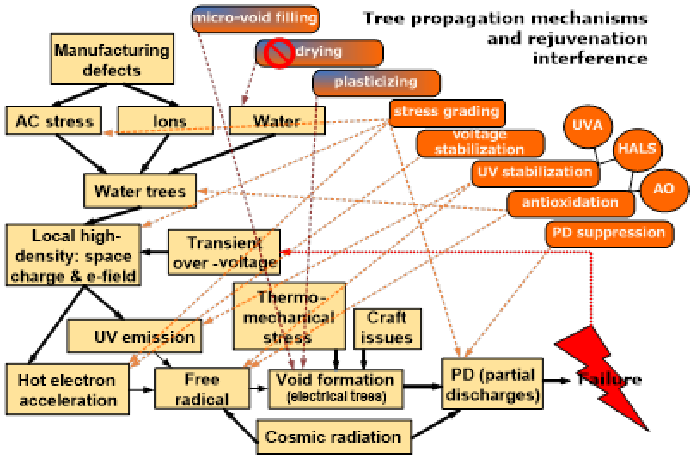

Fig. 6. Tree propagation mechanisms and rejuvenation interference with the same. Acronyms: UVA is ultra-violet absorber; HALS is hindered amine light stabalizer, a kind of anti-oxidant; AO is anti-oxidant.

IV. Pixie Dust and the Implications for PD Diagnostics

Arthur C. Clarke's 3rd Law from [5] provides that "Any sufficiently advanced technology is indistinguishable from magic." Perhaps this is why certain critics of rejuvenation technology describe rejuvenation fluid as "Pixie Dust." An internet search of the term yields the following definition: "A substance … with an apparently magical effect that brings great success …" While the critics brandishing the moniker undoubtedly harbor pejorative thoughts, the authors quite like the metaphor. We seek here to educate the readers so that they are fully informed and the critics so that they can distinguish data and science from magic and wishful thinking.

There are two propositions put forth by purveyors of off-line PD-based diagnostic testing that our work sheds some light upon. The first proposition: Electrical trees are common in field aged PE cables. If they were rare, there would be little justification to perform tests to identify them. The second proposition is that rejuvenation does not address electrical trees. If rejuvenation were to adequately address electrical trees, there would be little justification to perform tests to identify said trees prior to rejuvenation. To be clear the stakes of those who propound these propositions are very high. Their careers are at risk if either proposition lacks merit.

A. Confounded

The post rejuvenation results shed some light on these two propositions. There are only three possible conclusions one can draw from the two-decade post rejuvenation experience.

1) Rejuvenation is truly magical and laws of chemistry and physics are circumvented. The authors fancy this choice, but if we had such magic at our disposal we would deploy these skills on Wall Street or the Las Vegas Strip.

2) Electrical trees (bona fide or incipient) are rare (ephemeral) in operational field aged power cables.

3) Rejuvenation technology adequately addresses electrical trees in operational field aged power cables.

Unfortunately the authors do not have the power to circumvent the second law of thermodynamics, the Clausius-Clapeyron equation, or any other laws of physics and chemistry and hence we can safely rule out possibility 1. It is a little more confounding to discern if possibility 2 and/or possibility 3 best explains the results. The "and/or" in the previous sentence requires some consideration. For circuit owners the difference is of little consequence. Perhaps 2 is true and 3 is false, 3 is true and 2 is false, or 2 and 3 are both true. What is unambiguous is that at least one of 2 and 3 must be true. The proper conclusion of circuit owners is that there is no benefit in searching for electrical trees prior to rejuvenation of field aged PE medium voltage power cables. The confounding of these two independent questions illustrated in Fig. 7 demonstrates that off-line partial discharge testing is contraindicated.

However, it's not simply an academic issue if both 2 and 3 are true, because as purveyors of pixie dust the authors recognize that almost all cable failures experience electrical trees in the last moments of their operational life. We therefore seek to retard the formation of electrical trees and retard their growth. It turns out that conclusion 2 and 3 are both true.

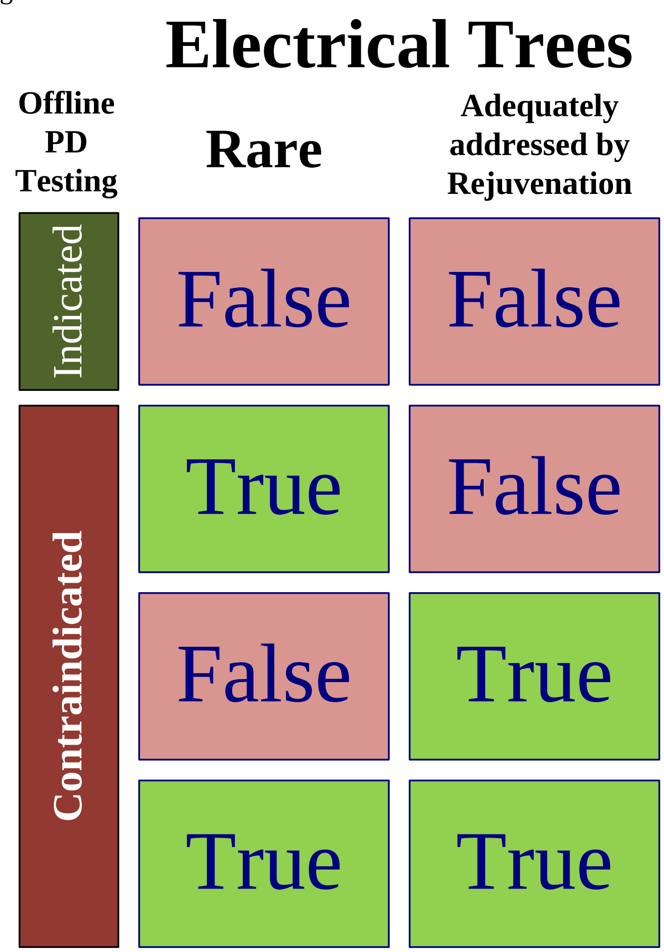

Fig. 7. Electrical tree truth matrix. There are four possibilities for two independent questions each of which are either true or false. For diagnostic testing to be indicated both statements must be false. Since at least one of the two statements must be true, and perhaps both are true, off-line PD testing is contraindicated.

B. Electrical Trees are ubiquitous, but ephemeral

As reported in [6] the authors' firm has a decade of experience measuring on-line partial discharge in millions of feet of power cables at operating voltage. In all of those millions of feet we have never found a single electrical tree. Those performing off-line testing at voltages above operating voltage that claim to find electrical trees are engaged in a self-fulfilling prophetic exercise of raising voltage until an electrical tree is initiated and then taking credit for finding a defect that previously did not exist. This is the equivalent of Apollo Creed taking prophetic credit for predicting Rocky Balboa's scripted black eye before the bout.

This rareness of electrical trees in the population of aging solid dielectric power cables is not a contradiction to their prevalence in almost all such cables moments before cable failure. The probability of detecting any phenomenon depends on the prevalence and duration of the phenomenon. To summon another medical metaphor, consider as shown in [7] that heart disease is the number one cause of death in the U.S. – about 600,000 each year. Even though heart disease is the number one cause of death, the mode of most of these deaths is a heart attack. See Fig. 8. A diagnostic for a heart attack would not be medically useful because in any given year only 0.2% of the U.S. population will suffer a heart attack. The mean duration of a fatal heart attack is less than one hour so the portion of the U.S. population suffering a heart attack in any given hour is vanishingly small. Water trees are to cable failure what heart disease is to mortality – the former are the root causes of the later. Electrical trees are to cable failure what heart attacks are to death – both are brief with dramatic endings, but neither are the root causes, and a diagnostic test for either ephemeral event would be unlikely to yield a true positive outcome. Off-line diagnostic testing above system voltage induces electrical trees. No one would consider doing such a thing to a human patient.

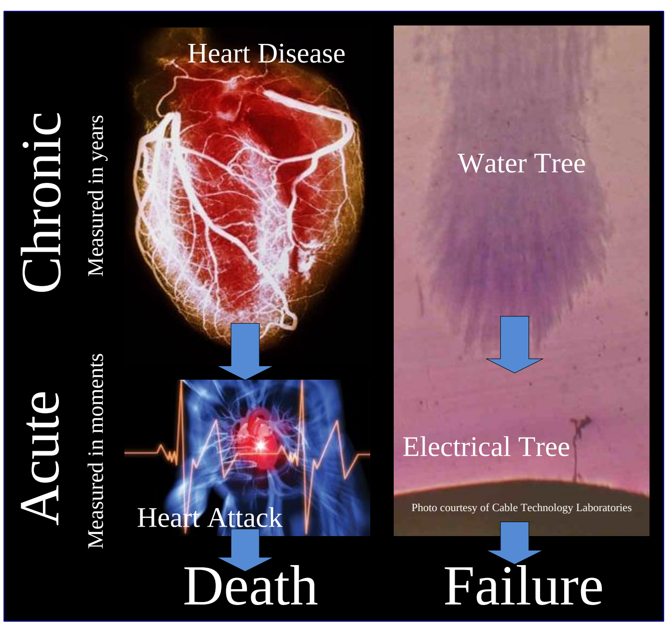

Fig. 8. Like heart attacks, electrical trees are ephemeral events and unlikley to be diagnosed short of intentional induction.

In a side-experiment undertaken by the authors, executed at the NEETRAC laboratory, underwritten by American Electric Power, Baltimore Gas & Electric, Borealis LLC, Con Edison, Oncor Electric Delivery, Florida Power & Light, Exelon, Southern Company, Southwire Company, and PEPCO, and described in [8] partial discharges were continuously measured (IPEC/HV OSM Longshot™ WR XI) for about 18 months as cable were run to failure under accelerated conditions. Partial discharges were detectable for only several seconds before any cable failure. Electrical trees in polyethylene are ephemeral.

C. Rejuvenation Increases Partial Discharge Inception Voltage

In [1] and in future work the authors will provide additional details on how rejuvenation technology directly addresses voids in solid dielectrics, including electrical trees created during normal operations and those created by destructive off-line PD testing. We will explain how rejuvenation addresses partial discharge in more detail than provided by Fig. 6 and this paper. Further, we will provide data with measurements of changes in PD inception voltage after rejuvenation occurs. Four primary mechanisms summarized in Fig. 9 will be described: (1) plasticization or the in situ creation of a solid-liquid dielectric where only a solid dielectric existed before, (2) void volume reduction, (3) electron sequestration, and (4) dielectric stress grading.

Paper-insulated lead cables (PILC) have extraordinarily long lives provided the outer lead sheath remains intact and retains the dielectric oil. Partial discharge (PD) can only occur in a gas and hence liquid dielectrics are immune from PD. Cable rejuvenation creates a solid-liquid dielectric. Many incorrectly assume that cable rejuvenation fluids gel with time. In fact, cable rejuvenation fluids begin their life as monomeric fluids and end their lives as oligomeric fluids.

The absorption of the silane fluid into the intermolecular spaces of the solid dielectric plasticizes the polymer and creates a gentle volume swell of about 1% to 3% that presses inwardly on any voids in the insulation. Thus the introduction of rejuvenation fluid decreases void volumes in two ways. The polymer swells pressing the void wall inward toward its center. Secondly, because of the very low surface energy of siloxanes, the rejuvenation fluid coats the inner walls of voids making the gas-filled volume still smaller. The smallest voids are entirely filled; larger voids are partially filled. The result of these two independent effects is to increase the partial discharge inception voltage which is tied directly to gas-filled void volume as demonstrated in [9]. Both the void volume and the mean path length for the acceleration of a free electron are reduced.

The third mechanism by which rejuvenation interferes with PD is the sequestration of free electrons. Modern rejuvenation fluids include anti-oxidants and other electron acceptors that have been proven in [10] and [11] to suppress the expression of PD and substantially increase the reliability of cables.

Finally, high dielectric constant components in the rejuvenation fluid reduce the local electrical stress dampening the local energy available to accelerate electrons to the level required to initiate an electron avalanche.

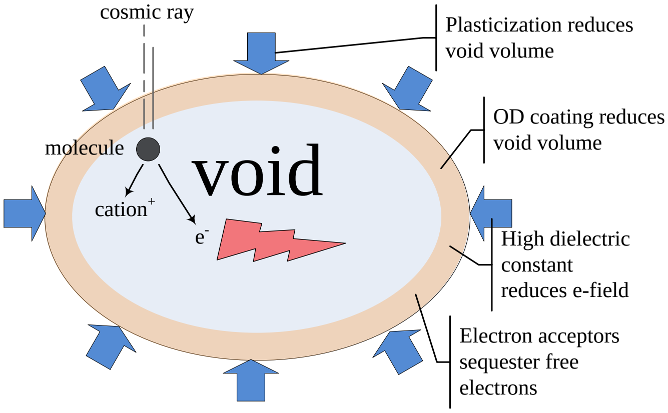

Fig. 9. Rejuvenation interferes with partial discharge inception with at least four meachanisms.

V. Summary

30 years of historical post-rejuvenation failure data alongside 36 years of historical post-installation new cable failure data were analyzed to illustrate the reliability of rejuvenation and replacement. That analysis demonstrates that rejuvenation reverses the failure trend of installed cables. There are several mechanisms that explain the apparent suspension of the second law of thermodynamics. The time released nature of the rejuvenation process allows long term delivery of functional materials to a cable over decades and the creation of a solid-liquid dielectric are two. Those mechanisms, and others that will be described in future work, demonstrate a reversal of the aging process for at least two decades and that the long term reliability of the latest generation of rejuvenation technology outperforms cable replacement. The authors are often asked why the cable manufactures do not include the technology we describe in their compounds and cables. There is a two-part answer to that question. First every technology described in this paper is protected by U.S. patents including but not limited to [12], [13], [14], [15] and [16], their foreign equivalents, and other pending patents. The second part of our answer is, “We have offered.”

These results taken together with a decade of online partial discharge testing shed light on destructive off-line partial discharge testing. The post-rejuvenation data by itself proves that either or both of the following propositions are true. (1) Electrical trees are rare in North American distribution cables, consistent with the research consensus. Once formed at operating voltage, electrical trees proceed rapidly to failure. (2) To the extent that there are any electrical trees, incipient electrical trees, or voids in operating service-aged cables, rejuvenation technology increases the PD inception voltage, adequately improves the reliability, and extends operational cable life. The available evidence supports both propositions, but as long as either proposition is true off-line PD testing is contraindicated.

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