Total System Reliability - Extending the Life of Electrical Cable Systems

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Cable Installation History

Medium Voltage Underground Utility Cable Installation History

2.3 Billion feet installed before 1985
~20% has been treated or replaced so far

Underground Distribution Systems
Failures are Imminent

- While the failure rate for cables installed after 1985 is about 1 failure per 100 miles per year, the failure rate for pre-1985 vintage cable is typically 20 failures per 100 miles per year.

- 75,000 distribution cable failures per year on PE and EPR cable installed before 1985 - affects 8.6 million Americans each year.
Degradation Profile

“The [AC breakdown] values obtained were at best 1/3 of the level generally regarded as normal for … new cable (800 V/mil).”

Source: Characterization of Failed Solid-Dielectric Cables: Phase 2, EPRI EL-5387, project 1782-1, Final report September 1987.

Cables with less than 400 v/mil are “poor”

After the first decade, the degradation slope makes it difficult to distinguish “poor” from “bad”
Why Cables Fail

- After some years, electrical breakdowns caused by “Water Trees” occur. Over time, the increasing presence of water trees seriously degrades the dielectric performance of the solid dielectric cable.

- The first generations of medium-high voltage polyethylene cables were particularly vulnerable to this aging mechanism. Design and production technique have considerably improved, so modern cables are likely to perform much longer. The pre-1985 vintage cables however, are at or near the end of their useful lives.
Water Intrusion

- Manufacturing process
- Storage
- Installation
- **Diffusion**
- Dig-in or failure
- Flooding
- Termination leaks
Water Trees

Vented Water Tree

(Shown here with Electrical Tree)

Vented water trees are generally initiated at protrusions on the interfaces between the dielectrics and conducting materials.

The visible tubules in the water trees are tracks which have been oxidized to form water-filled channels.

Bow Tie Water Tree

Bow Tie water trees usually initiate inside the bulk of the dielectrics at voids or contaminations.

Halo Water Tree

Halos are caused by water buildup from load and thermal cycling.

Underground Distribution Systems
Water Tree in EPR Cable

- Reliant Energy and EPRI performed work and reported at IEEE/PES winter meeting in Singapore (January 2000).
- AC breakdown strength and impulse breakdown strength increases to values better than for new EPR cables treated with Silicone fluid.

General Cable Photo

Underground Distribution Systems
Untreated, water trees become electrical trees, which cause failure in days or weeks.

Electrical Tree
How Silicone Fluid Technology Works

- The Siloxane dielectric enhancement fluid is injected into the conductor strands.

- The fluid rapidly diffuses from the conductor strands into the solid dielectric material.

- Once inside the insulation, the fluid repairs the damage caused by existing water trees and other dielectric defects.

- The Siloxane fluid also retards the growth of future water trees and extends the life of even badly-aged cable by more than 20 years.
The Injection Process

- De-energize, test and ground cable.
- Inspect manholes, enclosures devices and cable.
- Apply TDR (Time Domain Reflectometer).
  - Confirm actual cable length.
  - Confirm condition of neutrals.
  - Verify number of splices and locations.
Flow & Pressure Tests are Performed

- Nitrogen is injected into one end of cable.
- Outflow is measured at other end and pneumatic resistance is calculated.
- Cable is pressurized from both ends and flow is monitored to ensure there are no leaks.
Inject Strand Desiccant Fluid

- A Strand Desiccant is used as a purging and drying agent.
- A small feed tank injects desiccant fluid into the cable.
  (Typically at 15-20psi)
Inject Silicone Fluid

- The Silicone fluid is injected completely through the cable within hours.
- Bladder Tanks are secured in an external enclosure (if required to be left overnight).
- Vacuum Tanks are placed on the receiving end of the cable to hasten the fluid through and ensure a thorough fill.
Diffusion

- The Silicone fluid rapidly diffuses from the strands into the insulation.

- Inside the insulation, our siloxane fluid reacts with the water in the tiny micro-voids and fills them with a dielectric oligomer, repairing the damage.

- Since the molecules of the resulting oligomer are 47 times larger than water molecules, they lock into place and retard the growth of future water trees.
Chemistry

- The next few slides highlight the chemistry.
- Note that we are only doing two things:
  - Water reaction (Called condensation reactions)
  - Polymerization (Making larger silicone molecules)
Chemistry of Rejuvenation Fluids

Reaction 1

This reaction is the very fast first step of water reacting with Phenylmethyldimethoxy silane (PMDMS). This reaction is also reversible and can generate water and PMDMS but the reverse reaction is not as kinetically feasible and hence the bulk of the PMDMS will be converted to the silanol. Note also that the oxygen of the silanol came from the water and not the methoxy moiety.
Silane Dimerization

Reaction 3

\[
\begin{align*}
\text{SiCH}_3\text{OCH}_3\text{O'H} & \quad \rightarrow & \quad \text{SiCH}_3\text{OCH}_3\text{OCH}_3\text{CH}_3
\end{align*}
\]

Slower than hydrolysis due to Steric Hindrance

This is the first step toward oligomerization. Here the dimer is formed along with another mole of methanol. Therefore, in the cleanest route to dimer (Reactions 1 then 3) we create 2 moles of methanol for each mole of dimer. Also the dimer still has two reactive methoxy functional sites as well as the reactive dimer bridge oxygen. Hence, this reaction is also reversible in the presence of water, methanol or some other Lewis acid source.
Reaction 7

This reaction forms the trimer and as one can see the molecules are getting much larger. Also note that one still has two reactive methoxy moieties present in the trimer. Not shown is the formation of another mole of methanol which is made in any step involving a methoxy group.
Hydrolysis Reactions

- PMDMS plus Water (1 to 1.9 on a molar ratio)
- Ambient Temperatures

<table>
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<th>Time</th>
<th>Monomer</th>
<th>Dimer</th>
<th>Tetramer</th>
<th>Hexamer</th>
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<tr>
<td>22 hrs</td>
<td>5%</td>
<td>7%</td>
<td>27%</td>
<td>10%</td>
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<td>2%</td>
<td>6%</td>
<td>27%</td>
<td>12%</td>
</tr>
<tr>
<td>166 hrs</td>
<td>1%</td>
<td>7%</td>
<td>20%</td>
<td>16%</td>
</tr>
</tbody>
</table>
Diffusion Rates

- At 50°C in Polyethylene
  - Monomer  \(6.7 \times 10^{-8} \text{ cm}^2/\text{sec}\)
  - Dimer  \(1.08 \times 10^{-8} \text{ cm}^2/\text{sec}\)
  - Tetramer  \(5.97 \times 10^{-9} \text{ cm}^2/\text{sec}\)
- The larger oligomers are slowing down and staying put inside the water tree.
MicroIR Analysis of the Diffusion

FTIR Spectra
Treatment Penetration Profile

% PhMeSi(OMe)2 to Polyethylene vs. Position from I.D. to O.D.

Percent

Location (in)
Oligomer Diffusion

- Monomer (1) 16.8 to 45 Days (based on Thickness)
- Dimer (2) 5.01 Years
- Tetramer (4) 32.99 Years
- By GC/MS one can see oligomers up to octomers(8) so we know that the oligomers will be around for a very long time.
- This is what gives us the confidence that the cable is effectively treated for a very long time.
Chemistry Highlights

- The Silicone reacts with the water in the polar regions (trees) and oligomerizes.
- These oligomers “fill” the void of the tree and prevent further water ingresses.
- Presence of oligomers by GC or IR prove that water has been removed from the areas containing treatment fluid.
- Too much chemistry rots the brain and can cause water tree growth by oxidizing PE.
Accelerated Treatment with DMDB:

“The obtained [AC breakdown] values are comparable to voltage breakdown values of new cables manufactured in the late Seventies.”

-CTL
Silicone Injection

- So how long will a treated cable last?
  - It Varies!
  - **Well treated** cables are expected to last a very long time
  - Much longer than the stated “Warranty” time
  - After 25 years >99% of all cables we have injected are still in service!
  - We will let you know when they start failing…
Silicone Injection is Proven Technology

- For more than 25 years, over 125 million feet of cable have been treated with Silicone fluid, saving customers more than two billion dollars in replacement costs.

- This technology is customer friendly.
  - it is easily administered
  - it requires no lay down area

- Because of it’s high capital efficiency, Silicone injection technology should be a first choice for dealing with aged cables.
Why Siloxane treatment?

- The service is typically 3 to 6 times more productive than cable replacement. (Not including the added benefit of lower carbon tax costs)
- The service is substantially less cost than cable replacement.
- The process is clean, quiet, and not intrusive to electric customers.
- Engineering, inspection, materials handling, and other overheads are all minimized.
- Enables you to cost-effectively preempt interruptions due to cable faults.
- Improves reliability and increases value, while reducing unit costs as much as 50%.
- Treated cables are backed by a 20-year 100% satisfaction warranty.
Questions?

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