Effect of Cable Restoration Fluid on Inhibiting Water Tree Initiation

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***Abstract*—Silicone fluid has been applied in cable rejuvenation for decades to "cure" existing water trees. However, whether it inhibits future water tree initiation is not known. An electrical aging test has been carried out at 5 kV/mm (127 V/mil) based on a sample which includes semicon electrodes on both sides of the insulation. Samples were tested untreated, treated prior to the test, and treated at the midpoint of the test (3500 h). The results suggest that treatment reduces water tree initiation by a factor of 25 for bow-tie and 100 for vented water trees for the samples treated prior to aging. In the case of samples treated at the mid-point of the test, both bow-tie and vented water tree density are reduced by an order of magnitude relative to the density present at the time of treatment.**

***Index Terms*—Cable rejuvenation, water tree.**

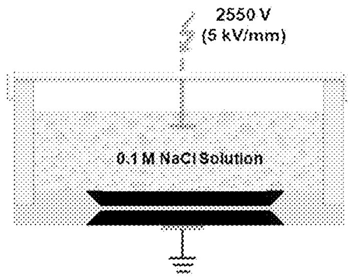

Fig. 1. Experimental setup for electrical aging test. The sandwiched semicon-PE-semicon sample is employed for simulation of stress exposure in cable. Standard conductor semicon and 0.1 M NaCl are used in aging as sources of ions.

I. Introduction

WATER TREEING or electrochemical degradation, first reported in 1969 [1]–[5], is an electro-chemo-mechanical phenomenon which has caused premature failure of XLPE and HMWPE cable. Water treeing takes place in dielectrics which can be electro-oxidized from a highly hydrophobic state to substantially more hydrophilic, which causes water to condense into the hydrophilic region, resulting in a self-propagating "water tree". Electrochemical degradation is accepted as the primary cause of unreliability of medium voltage XLPE cable [3]. As a result of the high failure rate of HMWPE and XLPE cable during the 1970s and 1980s, a great deal of effort was put into reducing the effects of water trees, including dry curing of cable, semicons with substantially reduced ionic content, and eventually, introduction of tree retardant compounds which reduce the propensity toward water treeing, usually by making the dielectric more hydrophilic. Cable rejuvenation technology was introduced around 1987 to "cure" existing water trees in HMWPE and XLPE cable, thereby extending substantially the life of the cable [6], [7].

Cable rejuvenation technology has been employed successfully in the field for over 20 years to cure existing water trees in URD cable [8]. To date, over 25 million meters of URD cable have been treated and remain in service [9]. As the silicone rejuvenation fluid diffuses into the cable insulation, it reacts with water in oxidized hydrophilic regions (water trees) to form a hydrophobic oligomer (short polymer) which fills the water treed region [8]. While the effect of silicone rejuvenation in "curing" existing water trees and extending the life of the cable is well established, the effect of silicone fluid on initiation of new water trees, especially for vented water trees, has not been reported. A well controlled laboratory test was carried out to study the degree to which formation of new water trees, including both bow-tie and vented trees, is inhibited by rejuvenation.

The only related research of which we are aware was carried out by Hydro Quebec [10], which removed aged cable from the field and carried out further aging in the laboratory. Their work showed that the rejuvenated cable had a much lower density of bow-tie water trees as well as a lower than usual water concentration in the cable insulation. Very few vented trees were present in either rejuvenated or non-rejuvenated cable samples.

II. Experimental Protocol

The effect of silicon fluid on inhibiting water tree initiation and growth was investigated using a sample configuration (Fig. 1) with semicons on both sides of the XLPE insulation which was developed at the University of Connecticut in the 1980s [11], [12]. The test protocol, based on the samples of Fig. 1, was as follows (Table I).

Group 1 (15 samples) was aged in an untreated state to 3500 h, at which time 5 samples were removed for water tree counting, 5 samples were aged to 7000 h in an untreated state after which they were subjected to water tree analysis, and 5 samples were removed to form Group 2.

Group 2 (5 samples) was taken from Group 1 after 3500 h of aging in an untreated state and subjected to silicone rejuvenation, after which they were aged for a further 3500 h.

Group 3 (10 samples) was subjected to silicone rejuvenation before aging, aged to 3500 h after which 5 samples were re-

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TABLE I
LONG TERM AGING TEST PLAN

Material	Aging Time	
	3500 hrs	7000 hrs
Untreated	remove for tree count	
	remove for treatment then continue aging	remove for tree count
		remove for tree count
Treated	remove for tree count	
		remove for tree count

moved for water tree analysis and the remaining 5 samples were aged to 7000 h after which they were subjected to water tree analysis.

The plaque samples of Fig. 1 were aged at room temperature and 5 kV/mm across the XLPE insulation. Silicone rejuvenation was applied by soaking the samples in rejuvenation fluid to saturation after which the samples were subjected to moist air until the fluid in them had oligomerized, as determined using gas chromatography/mass spectroscopy (GC/MS). The curing time in moist air was 4 days.

A. Sample Preparation

Cable grade polyethylene (Dow 4201) and conductor semicon are used in the test. The XLPE dielectric is moulded with two depressions for the semicon "buttons", which are prepared separately. The two semicon buttons are then cross linked to the XLPE in the final step. All components are inspected at every stage of manufacture to assure freedom from cavities, etc. The insulation thickness between the center of semicons is 0.51 mm. The completed test sample is glued to a polyethylene tube using a silicone RTV which does not evolve acetic acid during curing. The chamber is filled with 0.1 M NaCl which has a conductivity of $\sim$1 S/m. The semicon on the bottom side of the sample is grounded while the other side is exposed to the sodium chloride solution which is connected to the high voltage using a platinum wire. The test setup is shown in Fig. 1.

B. Sample Treatment

Silane treatment in this context involves both saturation of the test sample with fluid and curing of the fluid within the sample using humid air. "Curing" causes the fluid within the sample to oligomerize, which fixes it within the sample. If the fluid is not "cured" prior to aging, the fluid will elute into the sodium chloride solution. The rejuvenation fluid used in this research was provided by Utilx (2-2614) [13]. The sample plaques are first immersed into silane fluid at 50 °C until saturation. The fluid saturation level is 7.8 wt-% for XLPE and 64 wt-% in the semicon at 50 °C. As detailed in [8], rejuvenation fluid diffuses into aged insulation and reacts with water therein to form non-fugitive, hydrophobic oligomers which replace the water. Since oligomers are larger molecules relative to the monomer, they have much lower diffusivity through polyethylene. For example, the diffusivity of the tetramer (four units of the monomer reacted together) through PE is one tenth that of monomer at 50 °C and therefore the tetramer is retained in 15 kV XLPE cable

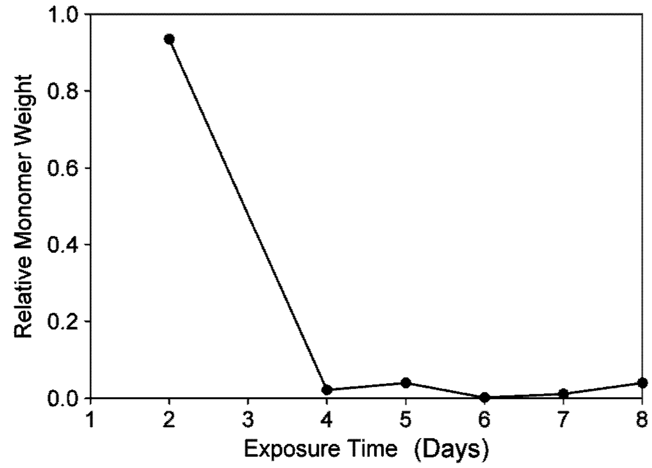

Fig. 2. Phenyl Methyl Dimethoxy Silane (PMDMS) content in the semicon-PE-semicon plaque as a function of exposure time in 100% relative humidity at 50 °C. Four days exposure of the fluid-saturated samples is sufficient for nearly complete curing.

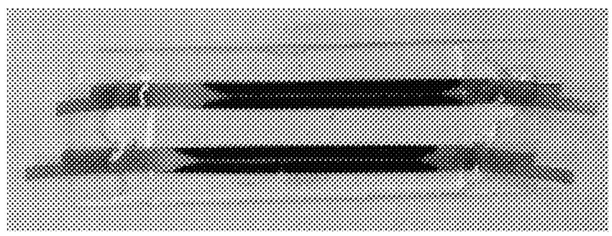

Fig. 3. Sample plaque is cut in half through the center, and 10 slices of 250 μm (10 mil) thickness are prepared from each plaque, stained, and mounted on glass slides using Canada balsam for water tree count and size measurement.

insulation for about 33 years [8]. In the present case, the rejuvenation fluid within the sample was oligomerized through exposure to 100% humidity air at 50 °C. GC/MS was used to monitor curing as a function of exposure time. The GC/MS analysis shows that 4 days exposure to 100% humid air after fluid saturation is sufficient for full curing, as shown in Fig. 2.

After removing samples from aging, the plaque samples are microtomed to 250 μm (10 mil) thickness, dyed with Methylene Blue (MB), and mounted on microscope slides (Fig. 3) for water tree count and size measurement. At least 10 slices are analyzed from each plaque.

III. RESULTS

Water tree analysis shows very large numbers of bow-tie trees in the untreated plaque samples, as a result of which the number of bow-tie trees has been recorded without size measurement. Vented water trees are far fewer, and the size of each vented water tree has been measured. Bow-tie water tree number density is presented as number of trees per unit volume of insulation, while vented water tree number density is presented as number per unit semicon-insulation surface area from which it can initiate.

Results from the untreated test set at 3500 h and 7000 h (based on 50 slices analyzed for each) are consistent. An average number density of 49 mm^{-3} bow-tie trees and 7 mm^{-2} vented water trees is observed after 3500 h aging, while 99 mm^{-3}

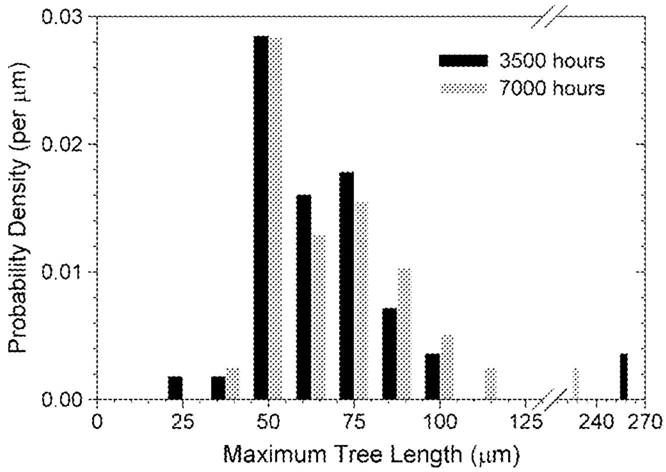

Fig. 4. Probability density for maximum vented water tree length in untreated sample plaques. The typical maximum vented water tree length per slice under examination is 50 to 75 μm at both 3500 h and 7000 h aging time.

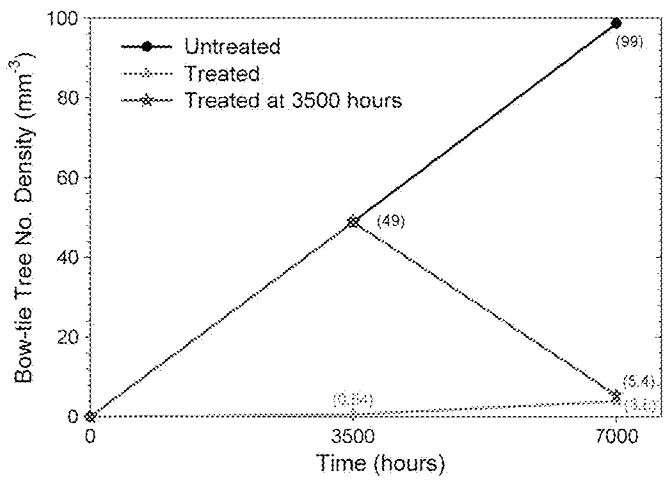

Fig. 5. Plot of bow-tie water tree number density as a function of aging time for the various sample classes. The numbers in parentheses provide the numerical value of the datum. Bow-tie water tree number density is presented as volume number density (mm^{-3}).

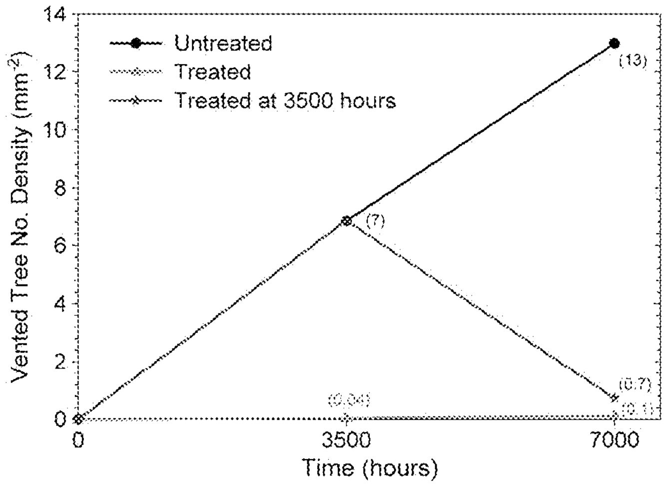

Fig. 6. Plot of vented water tree number density as a function of aging time for the various sample classes. The numbers in parentheses provide the numerical value of the datum. Vented water tree number density is presented as number of vented water tree per unit semicon-insulation interface area (mm^{-2}).

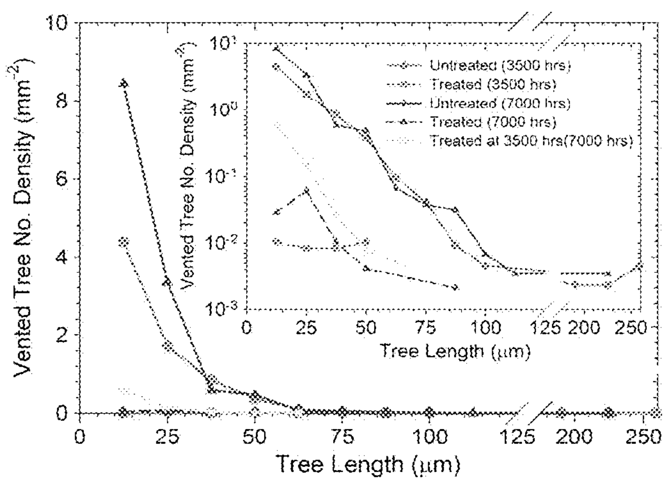

Fig. 7. Vented water tree length distribution for all five sets of sample plaques after 3500 and 7000 h aging at 5 kV/mm and exposure to 0.1 M NaCl solution. The main plot has a linear ordinate while the subplot presents the same data on a logarithmic ordinate. Treated samples, whether treated prior to aging or at the midpoint of aging, contain very few vented water trees.

bow-tie and 13 mm^{-2} vented is observed after 7000 h aging. The total number of vented water trees counted in the untreated samples, 66 at 3500 h and 125 at 7000 h over an effective surface area of 9.65 mm^2, suggests that the insulation has been aged to a sufficient degree that the effects of the rejuvenation fluid can be evaluated. The maximum vented tree length in each sample inspected at both 3500 and 7000 h is typically in the range of 50 to 75 μm or about 10% of the total insulation thickness of 508 μm, as shown in Fig. 4. The data suggest that the vented water tree initiation rate is approximately a linear function of time for both bow-tie and vented trees (Fig. 5). No electrical trees were found in any of the cable dielectric samples examined.

Figs. 5 and 6 plot the measured data for water tree density in untreated, treated, and samples treated after 3500 h of aging. Without treatment, the water tree density increases linearly with time, and large numbers of water trees occur. The treated samples have almost no bow-tie or vented water trees, with an average number density of 0.54 mm^{-3} bow-tie trees and 0.04 mm^{-2} vented water trees after 3500 h aging and 3.8 mm^{-3} bow-tie and 0.11 mm^{-2} vented at 7000 h of aging. The data indicate that treatment prior to aging reduces the initiation rate of vented water trees by a factor of >100 and decreases bow-tie tree initiation by >25 times compared to untreated samples. This result provides credible evidence that fluid treatment impedes water tree initiation significantly.

The maximum vented water tree length among the few such trees observed in treated or 3500 h treated samples is in the range of 50 to 87.5 μm, while over 200 μm long vented water trees are observed in untreated samples, relative to a total insulation thickness of 508 μm (Fig. 7). By reducing the diffusion rate of water into the insulation, water tree growth is apparently retarded.

The samples treated after 3500 h of aging contained, on average, 49 mm^{-3} bow-tie and 7 mm^{-2} vented water trees. After silicone rejuvenation and aging for an additional 3500 h, the samples contained only 5.4 mm^{-3} bow-tie and 0.7 mm^{-2}

vented trees, as shown in Figs. 5 and 6. Thus, the rejuvenation not only "cured" the existing water trees, it retarded the growth of additional water trees so that the water tree density after treatment and an additional 3500 h of aging was reduced by an order of magnitude relative to the density present at the time of treatment. At 7000 h, the density of water trees differs little between the samples treated prior to aging and those treated after 3500 h of aging.

IV. Discussion

The effect of rejuvenation in inhibiting water tree initiation and growth is expected for the following reasons:

1) Silane-based rejuvenation fluid reacts with water as it diffuses rapidly into the cable insulation. As a result, it "consumes" water in the insulation and within degraded, hydrophilic regions created by water trees and fills the free volume within the insulation with hydrophobic oligomers which remain in the insulation, deny water access to electro-oxidized regions, and reduce the moisture diffusion rate through the insulation. Reference [10] reported that only 2 ppm (by weight) water content was detected in field-aged silicone treated cable insulation. This suggests that the silicone fluid cures pre-existing water trees and impedes water tree initiation and growth by filling the free volume within the insulation to reduce the moisture diffusion rate.
2) The silane-based fluid fills micro-voids from which bow-tie water trees grow. Although dry curing has replaced steam curing, which decreases the density of micro-voids in XLPE by two orders of magnitude [14], the formation of micro-voids during cable manufacture is still inevitable as a result of byproducts of cross linking, creation of gas during cross linking, migration of antioxidants, etc. [2]. The long term growth of bow-tie water trees is diffusion limited, as once the local supply of moisture is consumed, the only source of further moisture is by diffusion. Thus, filling of micro-voids with a hydrophobic oligomer impedes bow-tie water tree initiation, while reduction of the moisture diffusion rate reduces the growth rate of any existing bow-tie trees.
3) The moisture diffusion rate in the cable insulation may be reduced to a degree that water tree formation and growth is not possible. In part, this could be the result of reducing the moisture diffusion rate through the semicons, as they are also treated. If the moisture diffusion rate of a semicon is reduced to that typical of a highly polar polymer, vented water trees will not grow. Unfortunately measuring the water diffusivity through a treated material is complicated by reactions between the fluid products and moisture. Future work will continue attempts to measure water permeability in treated cable materials.

V. Conclusion

The effectiveness of silicone rejuvenation for life extension of HMWPE and XLPE cables is well established. The present contribution has improved understanding of the mechanisms by which life extension is achieved and established that fluid treatment not only cures existing water trees but impedes future formation of water trees.

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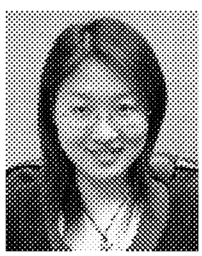

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