Accelerated Life Testing of EPR-Insulated Underground Cable

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It is known that insulations based on ethylene-propylene rubber vary widely in short- and long-term physical and electrical properties, due to variations in their base polymers and in the types and levels of compounding ingredients employed. Accelerated life testing of full size cable, using a method which earlier indicated the superiority of tree-retardant XLPE over standard XLPE, has shown an even greater superiority of a commercially available semi-crystalline EPR compound. Testing is still continuing, and the program is being used to define performance levels in EPR insulation and to relate these levels to variables in the base polymer, the compounding ingredients and the overall quality of the insulation compounding process.

Overall cable performance is a function of the entire construction, including the conductor, the associated shields, the dielectric, the neutral wires, perhaps even the jacket ... and the multiple effects of voltage, moisture, and temperature.

Introduction

Numerous investigations of dielectric failures have used small-scale samples due to their low cost and ease of manipulation, and much of the screening work has employed small slabs or molded parts with a controlled defect in the part. Although these methods frequently provided an acceptable "primary screen" for insulations, test results have not always correlated well with actual cable performance.

Frequent use has also been made of "model" cables based on small conductors. Although temperatures and voltage stresses can be accurately controlled in such specimens, the sizes of the water and electrical trees produced in testing are a constant with electrical stress regardless of insulation thickness and thus can't be accurately modeled. They also cannot reproduce the mechanical and thermal stresses experienced in large

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TABLE I.
CONDITIONS FOR THE ACCELERATED CABLE LIFE TEST

Parameter	Test Condition
Cable Construction	#2x7 strand aluminum, 0.175" wall, concentric neutral, unjacketed
Sample Length	5m (16.4 ft)
Voltage Stress	$4 \times V_g$ (34.6 kV) at 60 Hz
Voltage Stress, Avg.	200 V/mil ≈ 8 kV/mm
Preconditioning	72 hrs, 90 °C
Conductor Test Temperature	90 °C for 8 hrs each day
Ambient Temperature	35 ° ± 2 ° C (95 ° ± 4 °F)
Water	Deionized in Strands and Tank
Water Containment	Stainless Steel Tanks, Wood Lagged, 4 ft x 5 ft x 3-1/2 ft
Load Cycle	8 hrs on, 16 hrs off, 7 days per week to failure

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cables. Finally, it is well recognized that overall cable performance is a function of the entire construction, including the conductor, the associated shields, the dielectric, the neutral wires and perhaps even the jacket.

An accelerated cable life test has been developed by Lyle and Kirkland [1] which, as originally envisioned, was to explore the multiple effects of frequency, mechanical stress, voltage, moisture, and temperature. In later work [2] Lyle concluded that frequency and mechanical stress were relatively less important in their effect on cable life than the other three variables.

The test is performed on a cable size and construction commonly used in underground distribution. It is a test performed to failure on a sufficiently large sample population so that reliable, reproducible statistics are obtained. It is important to note that this reproducibility arises from the control exercised on certain variables which other investigators have often left uncontrolled. These include the ambient temperature in the test room, the use of deionized water and the use of insulated tanks instead of PVC pipes to contain the test samples. The large volume of water in the insulated tank provides a considerable degree of thermal inertia during load cycling of the cable. Equilibrium water temperatures were found by Lyle and Kirkland to remain within ± 5 °C during the entire time span of the tests [1].

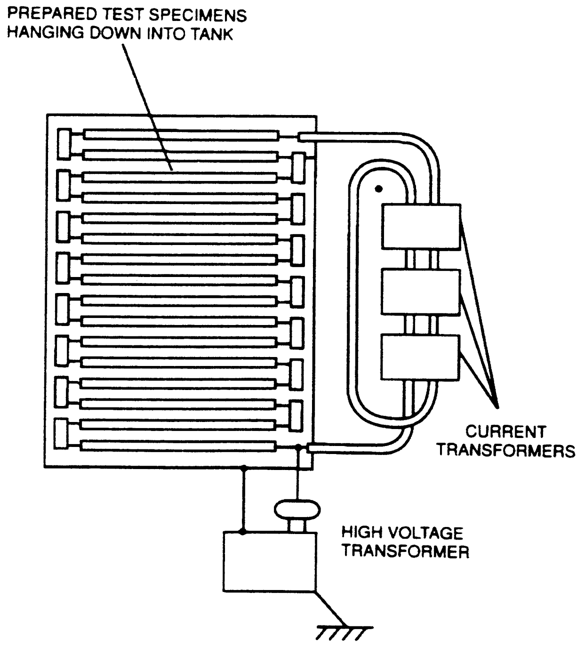


Fig. 1. Schematic of Test Specimen Interconnections (Top view [1]).

Table I summarizes the test conditions used on the cables in this work, while Fig. 1 is a schematic diagram from [1] of the configuration of the samples in the test tank. All cables were preconditioned in air by application of enough current to maintain conductor temperatures at 90 °C for 72 hours. Cables were subjected to a continuous electrical stress of four times voltage-to-ground at 60 Hz while being load cycled with current to a conductor temperature of 90 °C for 8 hours each day until failure.

This test has been used to compare the performance of crosslinked PE insulation with so-called tree-retardant crosslinked PE [3,4]. The latter insulation shows an approximate 3-4X increase in lifetime over XLPE in this test. Lifetime is the geometric mean time to failure of the cables in each sample set. Although the correlation of actual service life with the data derived from this test has not yet been quantified, it is generally agreed that the improved test performance of tree-retardant XLPE will also carry over into its field performance and result in a more reliable cable. EPRI has begun an extensive, long-term program (EPRI RP-2713-02) to correlate results from this accelerated cable life test to in ground cable performance.

This test method is being used to study medium voltage EPR insulation for underground distribution. EPR insulation has long enjoyed an excellent reputation in industrial power cable and has been used successfully in underground utility distribution cable, as well. However, there exists no quantitative measure of EPR performance in this application. Furthermore, the question is clouded by the fact that some cable suppliers use proprietary EPR compositions which vary in both mechanical and electrical characteristics. This paper presents Du Pont's test program involving EPR in the accelerated cable test previously described, discusses the current status of the testing and also indicates the long-term thrust of the program. In this program EPR insulation compounds used will be fully disclosed as to their compositions so that test results can be unequivocally related to a single composition. Because of the on-going nature of this program, some of the test sequences reported are incomplete at this stage. For these sequences, this publication should be regarded as a status report with further updates planned.

Cable Constructions

In addition to the EPR constructions, our program began with the testing of cable insulated with crosslinked PE and with tree- retardant crosslinked PE. The shield systems for these cables were those in wide commercial use today. Although data have been published [1, 2] regarding the performance of these insulations in the accelerated cable test, they were included in this test program in order to:

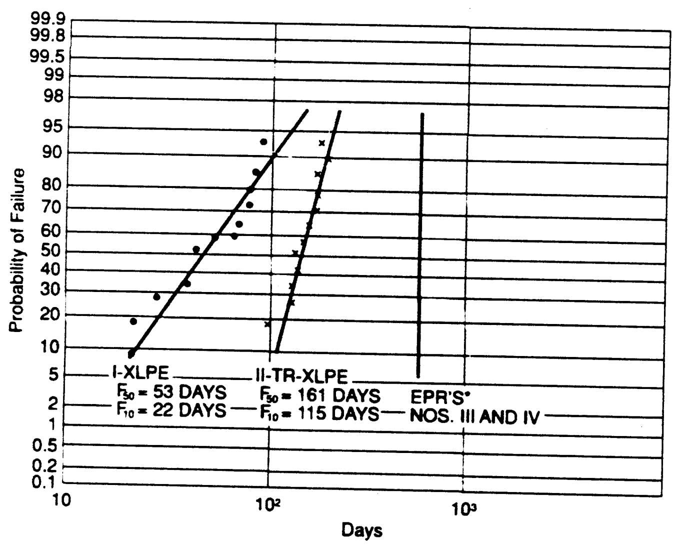
TABLE II.
EPR INSULATIONS FOR 5-69 KV

	Parts By Weight	
	Semi-Crystalline	Amorphous (WCZ-5550)
NORDEL® 2722	100	-
NORDEL® 2522	-	100
Low Density PE, MI = 2	5	-
Surface-Treated Calcined Clay	60	60
Zinc Oxide	5	5
Red Lead, 90% Dispersion in EPR	5	5
Paraffin Wax	5	5
Vinyl-tris(Methoxy ethoxy)-Silane	1	1
Poly-Dihydroquinoline Antioxidant	1.5	1.5
Dicumyl Peroxide	2.6	2.6

- Provide internal controls for comparison with EPR constructions and
- Determine if advances in both polymer quality and extrusion technology have resulted in improved test performance since publication of the earlier data.

Both the XLPE and the tree-retardant XLPE cables were triple-extruded, dry cured and water quenched on the same extrusion line. Both used the same commercially-available controlled adhesion ethylene copolymer shield system. These control samples were provided by Conductor Products Inc. (now Reynolds/CPI), and met the requirements of AEIC CS-5-87.

Two EPR-insulated cables were also tested. Both used an insulation derived from the same semi-crystalline base polymer. One construction used a U.S.-mixed insulation compound with the same insulation shield system as used in the XLPE and TR-XLPE constructions. The other construction used an insulation compound mixed in Europe (compounding ingredients from European sources but the same EPR-base polymer) combined with a European-source controlled adhesion shield system. Both EPR constructions were triple-tandem extruded (1+2), steam-cured and water-quenched on the same extrusion line by Cablec Utility Company. The complete formulation for these semi-crystalline insulations is shown in the attached Table II and the complete constructions of the XLPE- and EPR insulated cables used in this first testing phase are summarized in Table III.



*Test concluded with none of cable samples failing.

Fig. 2. ACLT data for XLPE; TR-XLPE, and semi-crystalline EPRs.

Results and Discussion

Figure 2 is a log normal distribution plot which summarizes the failure data obtained with XLPE and tree-retardant XLPE. The geometric mean failure times (F_{50}) were 53 and 161 days, respectively. They are significantly superior to the values reported in [1] and [2], namely 33 and 98 days respectively. In more recent publications [3], the manufacturer of the XLPE and TR-XLPE compounds used here claims F_{50} times of 46 and 186 days, respectively, which are very good checks on the results in our work. It is considered that these increases in lifetimes represent improvements in the quality of the insulations and shields, as well as improvements in the extrusion process developed in the intervening time period since the earlier work. It is important to note, though, that in both cases TR-XLPE has a lifetime approximately 3-4X that of XLPE.

Based on the experience of personnel at Conductor Products Testing Laboratories (Now Reynolds/CPI Test Center, Scottsville, TX), water flow in the stranded conductors of the EPR constructions III and IV was tested monthly, beginning after approximately 200 days of testing. The purpose of these tests was to detect strand pluggage, presumably due to deposition of salts from the water (even though deionized water was used). Such pluggage would have caused the strands to dry and would have made questionable any failure statistics thus obtained.

After 597 days of accelerated aging, no failures in either EPR test population were observed, but strand pluggage was detected in the majority of the two test populations. Even so, the conductors were still filled with water. AC breakdown tests by a slightly modified AEIC five-minute step-rise method indicated that these EPR-insulated cables still retained approximately 40-50% of their original AC strengths and were still comfortably above the nominal applied stress level of 200 V/mil (≈ 8 kV/mm) used in the accelerated test regimen, Fig. 3. An initial stress of 100 V/mil was increased in increments of 40 V/mil to failure with 5-minute hold times. Four-foot sections stripped from both ends of the sixteen-foot cable sample were used as water terminations. The remaining eight-foot center section under shield served as the active length.

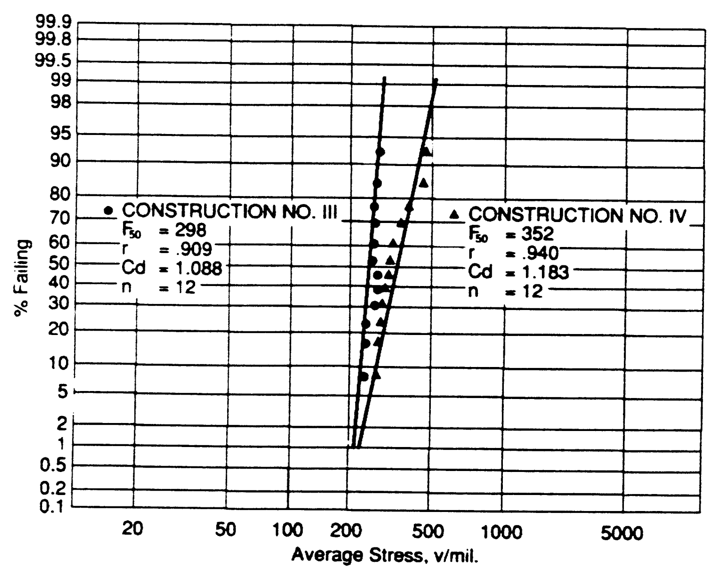


Fig. 3. AC breakdown strength after ACLT 597 days (per AEIC-CS-6-87, Para L.1.6.6.6.).

Dissection of the EPR cables after AC testing revealed extensive corrosion of the aluminum conductor, accompanied by deposition of copious quantities of white aluminum salt(s). Gravimetric analyses of the solids removed from the conductor gave aluminum contents of 30-33% (dry basis).

It is apparent that, given such long-lived insulations, the corrosion resistance of the aluminum conductor serves as a limiting factor in the length of the test program. Furthermore, it can also be stated that even though deionized water was used to fill the strands of the conductor, the corrosion of the aluminum gradually increases the ionic strength of the water (at least up to the solubility limit of the aluminum salts formed by the reaction of aluminum with water) beginning on the first day that the cable is energized. Thus, ions are present very early on in the deionized water used to fill the conductor strands whether the cables are insulated with XLPE, TR-XLPE, or EPR.

Effect of Filler Level

EPR insulations contain a reinforcing mineral filler. Generally this filler is a highly refined surface-treated calcined kaolin clay which imparts some very desirable properties to the rubber, including physical toughness and the ability to be extruded at high rates with a smooth surface. Of the many possible fillers which are used in compounding of elastomerics, this special clay is chosen because of its low moisture absorption and its low electrical loss properties.

It has also been reported that the kaolin contributes significantly to the resistance of the basic EP rubber to both tree-initiation and growth [5]. These conclusions have been supported by other investigators [6] who additionally found evidence there was an optimum level of kaolin required for the highest resistance to tree initiation and/or growth. However there are other properties of EP rubber which require optimum levels of kaolin which are likely to be quite different from the levels needed for tree resistance. Generally speaking, increasing clay levels result in increased hardness, density, tensile properties and increased dielectric losses, but also result in reduced cost and AC breakdown strength. Furthermore, the level of kaolin required to optimize each of these properties is likely to be different for each EP base polymer.

The effect of varying kaolin levels on the accelerated life test is now being studied and preliminary data are now available. This test series was made possible through insulation compounds supplied in Europe by Dolder A.G. which employ varying levels of kaolin in the same base

TABLE III.
CABLE CONSTRUCTIONS USED IN ACCELERATED CABLE TESTS

	INSULATION		CONDUCTOR SHIELD		INSULATION SHIELD	
Construction	Designation	Mfrd. by	Designation	Mfrd. by	Designation	Mfrd. by
I	HFDE-4201EC	1	HFDA-0580	1	HFDA-0691	1
II	HFDA-4202EC	1	HFDA-0580	1	HFDA-0691	1
III	Superohm 3728	2	HFDA-0585	1	HFDA-0691	1
IV	IS-02	3	MLP-43A	3	HLS-45	3
V	IS-14	3	MLP-43A	3	HLS-45	3
VI	IS-15	3	MLP-43A	3	HLS-45	3
VII	WCZ-5550	4	HFDA-0585	1	HFDA-0691	1

Manufacturers:

1. Union Carbide Co., Danbury, CT
2. A. Schulman, Inc. Akron, OH
3. Dolder AG., Basel, Switzerland
4. Not commercially available

polymer. In Table III the lowest level of kaolin is exemplified by cable No. VI (30 parts per hundred of rubber), an intermediate level by cable No. IV (see Table II for the insulation formulation) and the highest level by cable No. V (90 parts).

Construction No. V had two failures at 315 and 477 days out of a population of twelve when testing was stopped after 497 days because of conductor strand pluggage. Construction No. VI with the lower clay level has developed six failures (146, 286, 286, 509, 631 and 631 days) out of twelve with testing still proceeding at 676 days. *It will be recalled from the earlier discussion that construction No. IV showed no failures in 600 days,* at which time testing was halted due to conductor corrosion and strand pluggage. These results suggest that there is an optimum kaolin filler level for resistance of the insulation to the combined stresses of the accelerated cable life test. Construction No. VI may yet develop strand plugs and require removal from the test program. We hope that this problem is delayed such that more failures occur so that reliable statistics can be obtained.

Effect of Crystallinity

Semi-crystalline EP polymers have been developed for use as bases for the preparation of high performance insulation compounds, as disclosed in Table II. Compared with amorphous grades of EP, these semi-crystalline types can be manufactured as a pelletized material and the resulting insulation compound may also be produced in a pellet form. Pellets may be handled by automated pneumatic transfer techniques in controlled dust-free environments, making it possible to produce a contaminant-free insulation.

Amorphous grades of EP polymers may only be manufactured in the form of a bale because the polymer is too soft and sticky to survive in the form of pellets. The insulation manufactured from these amorphous polymer grades is also too soft and sticky to be pelletized. Therefore, the insulation compound must be manually handled and transferred, prior to extrusion on the cable, as an extruded slab or belt. It is therefore much more prone to adventitious contamination which can adversely effect cable life.

Semi-crystalline EP has a distinct quality advantage over amorphous types because it allows manufacture of insulation in a pellet form which can be handled in a completely enclosed environment without exposure to dust and other foreign contaminants.

It has been claimed [7] that crystallinity in an EP compound, whether it arises from the base EP polymer or from a small quantity of low-density PE added to facilitate pelletization (see Table II), contributes to reduced cable life through a decreased resistance to the initiation and/or growth of water trees. Amorphous EP insulations are claimed to be superior for this reason, but no supporting data have been published.

In order to explore this point, a cable was prepared for our accelerated test program which was insulated with a completely amorphous EP (Table II). Polymer crystallinity was eliminated from the compound by omission of the low-density PE ingredient and by the use of an amorphous EP base polymer. This insulation was designated WCZ-5550 (see Table II) and was converted into construction No. VII (Table III) using the same extrusion line that was used for construction Nos. III-VI.

In the accelerated cable life test at $4 \times V_g$ (200 V/mil) and with a 90 °C conductor temperature, four failures at 509, 522, 597, and 627 days out of a population of twelve samples have been observed. The remainder of the population is still under test at 675 days without any detection of conductor pluggage. These results do not support the contention that low levels of crystallinity contribute to reduced cable life.

The unaged AC breakdown strength of construction No. VII was ≈ 630 ± 50 V/mil vs. 750 ± 50 V/mil for the semi-crystalline version in No. III. It is known that increased crystallinity in the case of polyethylene as well as EPR results in higher breakdown strengths, but it is possible that the differences observed between Nos. III and VII, both in their original properties as well as the earlier aging failures, may be due instead to differences in insulation cleanliness for the reasons discussed above.

Summary

The data presented here reflect the current status of our accelerated cable life test program as applied to EPR-insulated MV power cable. This program has shown that:

- A high-quality ethylene-propylene rubber insulation can be prepared which will resist the combined stresses of moisture, heat and voltage better than commercially available cables insulated with XLPE or tree-retardant XLPE. These EP-insulated cables outperform TR-XLPE in this test by *at least* a factor of 4 and XLPE by *at least* a factor of 12 at an average stress of $4 \times V_g$ and at a conductor temperature of 90 °C.
- The contention that an amorphous EP insulation will have superior resistance to tree initiation and growth is not supported by the data. In fact, test failures have been obtained with the amorphous types in shorter time periods than with the semi-crystalline types.
- There is some indication that there is a level of kaolin filler which is optimum for the resistance of the insulation to the combined stresses of the accelerated cable life test.
- The limiting factor in the performance of a high-quality ethylene-propylene rubber insulation in the accelerated cable life test is the corrosion resistance of the conductor, particularly at $4 \times V_g$ and 90 °C. It is recommended copper conductors be utilized for long-term testing to failure if water is introduced into the strands of the conductor.

Future Work

Additional programs which are planned or already in progress include:

- the use of copper conductors in the accelerated life test so that the test life is not limited by aluminum conductor corrosion. Such constructions are already in the test tanks at $4 \times V_g$ and at 90 °C conductor temperature and have in excess of 600 days aging with no cable failures
- testing at reduced levels of voltage stress and conductor temperatures to determine the relative importance of these variables.

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