

IEEE Guide for Accelerated Aging Tests for Medium-Voltage Extruded Electric Power Cables Using Water-Filled Tanks

Sponsor

**Insulated Conductors Committee
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IEEE Power Engineering Society**

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Abstract: Accelerated aging tests on extruded medium-voltage cables using water-filled tanks are addressed. Information on the equipment, cable samples, test conditions, and measurements to perform the aging tests is provided. Techniques on how to analyze the test data are also included. The implementation of this guide will allow a better description of the test data obtained by different laboratories.

Keywords: accelerated cable life test (ACLT), accelerated aging test, cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), medium-voltage cable, tank structure, temperature measurement and profile, test conditions, water-filled tanks

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Introduction

(This introduction is not part of IEEE Std 1407-1998, IEEE Guide for Accelerated Aging Tests for Medium-Voltage Extruded Electric Power Cables Using Water-Filled Tanks.)

This guide addresses accelerated aging tests of extruded medium-voltage cables using water-filled tanks. Information is provided on the equipment, cable samples test conditions, and measurements to perform the accelerated aging tests. The guide identifies the critical test parameters and describes techniques for their measurement and control. The implementation of the techniques will allow test data obtained by different laboratories at different times to be better compared. Specific test values (e.g., maximum temperature and voltage) have not been included in this version of the guide, but may be recommended in future revisions.

The work of preparing this guide was carried out by Task Force 12-35 of the Tests and Measurements Subcommittee 12 of the Insulated Conductors Committee of the IEEE Power Engineering Society. At the time this guide was approved, the task force had the following membership:

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IEEE Guide for Accelerated Aging Tests for Medium-Voltage Extruded Electric Power Cables Using Water-Filled Tanks

1. Overview

The insulations commonly used in extruded power cables are cross-linked polyethylene (XLPE), tree-retardant XLPE (TRXLPE), and ethylene propylene rubber (EPR). These materials are known to gradually deteriorate with time due to the synergistic action of moisture and electrical stress. This degradation causes a reduction in the breakdown voltage and an increase in the dielectric loss. The degradation can be so severe that failures can occur in service at operating stresses. The mechanisms of moisture-induced degradation have been studied extensively and it is believed that several mechanisms are occurring. A thorough knowledge of the degradation mechanisms allows optimum choices of test parameters to be made; this results in an accelerated aging test that evaluates the long-term performance of a cable in the absence of scattered defects. Although there is not a complete understanding of the mechanisms of moisture-induced degradation, the urgency to develop an aging test has resulted in the proposal of several accelerated aging tests for materials and cables (Banks, et al., [B4],¹ Bartnikas, Densley, and Eichhorn [B5], Bartnikas, et al., [B6], Mashikian, et al., [B21], Schroth, et al., [B24], Steenish and Faremo [B26]). A problem inherent in all accelerated aging tests is the choice of test parameters in the test itself. These should contain the deterioration factors causing service aging and not introduce aging mechanisms that do not occur in service. The diagnostic test must measure a property representative of service aging. Research has shown that the most important parameters in tests to evaluate moisture-induced degradation are electrical stress, temperature, water characteristics, and time.

One accelerated aging test that has evolved in North America into a qualification test is the accelerated water treeing test in which lengths of cables are aged in water-filled pipes for 4, 6, and 12 months and then subjected to a step ac breakdown test, the diagnostic test (AEIC CS5-94, AEIC S6-96). An alternative test has emerged where cables are aged either for a fixed time or to failure in water-filled tanks, i.e., an accelerated cable life test (ACLT) (Lyle [B19], Walton, et al., [B29]). The time-to-failure test has the advantage of involving the whole aging process, initiation, growth, and final failure. The main disadvantage is that the test duration is unknown and there can be considerable time between the first and the last failure. Several laboratories have performed and are now performing tank-type tests using different aging conditions of voltage, temperature, water characteristics, etc. This makes a direct comparison of the data between laboratories very difficult. The situation is further complicated because the methods of measuring some of the critical param-

¹The numbers in brackets correspond to those of the bibliography in Annex B.

ters differ significantly. As a result, apparently similar test conditions can, in fact, be entirely different in two separate test arrangements. An example of this ambiguity is the temperature measurement. Although a nominal temperature of 90 °C is sometimes used as the maximum temperature during temperature cycling, the precise location where this temperature is measured may vary. It can be measured in the length of the cable outside the water or in the length of cable immersed in the water. If the water temperature is not controlled, however, the temperature of the immersed cable will depend upon the following:

- Tank size
- Shape and material
- Volume of water
- Number of cables in the tank
- Whether the tank is thermally insulated, etc.

This guide directly addresses tank-type accelerated aging tests. Accelerated aging test parameters are presented which, if reported, will allow test data obtained by different laboratories at different times to be better compared.

This guide will:

- Identify the critical test parameters and techniques for their measurement and control.
- Review the levels of the test parameters, such as voltage (V), temperature (T), etc. It is not the intention of this guide to recommend specific test values.
- Identify the test parameters to be included in reports, etc.

The following will be discussed:

- Test specimens
- Prior tests and preconditioning of specimens
- Test structure
- Temperature
- Water
- Voltage
- Failures
- Abnormalities
- Diagnostics
- Data analysis
- Final report

It must be pointed out that some parameters are interrelated so that a change in one will have an effect on others (e.g., as already mentioned, the size of the tank could influence the temperature of the cable immersed in the water).

1.1 Scope

This guide provides information on the equipment, cable samples, test conditions, and measurements to perform accelerated aging tests on medium-voltage cables using water-filled tanks. The guide identifies the critical test parameters and describes techniques for their measurement and control. The implementation of the techniques will facilitate a comparison of data obtained by different laboratories.

2. References

This guide shall be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the revision shall apply.

AEIC CS5-94, Specifications for Cross-Linked Polyethylene Insulated Shielded Power Cables Rated 5 through 46 kV.²

AEIC CS6-96, Specifications for Ethylene Propylene Rubber Insulated Shielded Power Cables Rated 5 through 69 kV.

3. Definitions, abbreviations, and acronyms

3.1 Definitions

3.1.1 abnormality: Any deviation from the pre-established test conditions, including the tolerance limits, that may affect the outcome of the test.

3.1.2 air failure: A failure in the cable above the waterline but below the termination.

3.1.3 termination failure: A failure in the portion of the cable, which does not have a metallic shield covering.

3.1.4 water failure: A failure in the active, shielded cable length that is below the waterline and which did not occur as a result of mechanical damage.

3.1.5 waterline failure: A failure at the interface between air and the tank water to include the distance of the total water line variation.

3.2 Abbreviations and acronyms

ACLT	accelerated cable life test
DSC	differential scanning calorimetry
EPR	ethylene propylene rubber
GMTF	geometric mean time to failure
I	conductor current
mle	maximum likelihood estimators
PL	polymer or polymer-lined
R	conductor resistance
SS	stainless steel
Tan δ	loss tangent of insulation
THD	total harmonic distortion
TRXLPE	tree retardant cross-linked polyethylene
V_o	line to ground voltage
ω	$2\pi f$ where f is the frequency in Hz of applied voltage
XLPE	cross-linked polyethylene

²AEIC publications are available from the Association of Edison Illuminating Companies, 600 N. 18th Street, P. O. Box 2641, Birmingham, AL 35291-0992, USA (<http://www.aeic.org/>). AEIC publications are also available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112-5704, USA (global.ihs.com/).

4. Test specimens

Table 1 lists a format for documenting the cable under test and provides example information. The values listed in Table 1 are compatible with tanks shown in Figure 1, Figure 2, and Figure 3.

Table 1—Example of cable documentation

Voltage class	15 kV, * 4.4 mm (175 mil) insulation thickness [†]
Conductor	53.5 mm ² (1/0 AWG) 1350 H-19 stranded compressed aluminum*
Conductor shield	0.38 mm (0.015 in) state grade and manufacturer, blend number, and date of manufacture
Insulation	4.4 mm (0.175 in) state grade and manufacturer, blend number, and date of manufacture
Insulation shield	0.76 mm (0.030 in) state grade and manufacturer, blend number, and date of manufacture
Metallic shield	≥6 #14 bare copper wires*
Jacket	None or identify material, thickness*
Cable extrusion	True triple
Cable extrusion date	To be included*
Cure process	Dry cure
Extrusion run identification	Job number, reel number
Cable manufacturer	To be included*
Cable quality control tests	To latest relevant AEIC spec*
Number of specimens in population	≥10*
Specimen total length	≥5 m (16 ft)
Specimen length under water	≥3.7 m (12 ft)
Number of cable coils	≥1
Inner diameter cable coil	610 mm (24 in)*
Date water added to tank	To be included
Date initial water added to conductor	To be included
Start voltage/heat cycles date	To be included
Replacement sample	Same type and construction of cable as test specimen if cable heating is necessary to maintain consistent water temperature*

*Values or tests in common use according to a survey conducted by the task force.

[†]Insulation thickness at point of failure is recommended for reporting in Clause 11, Clause 12, and Clause 13.

5. Prior tests and preconditioning of specimens

Partial discharge tests should be performed on every test cable to ensure that the cable and terminations are discharge-free prior to the aging test. The partial discharge test should be carried out according to AEIC CS5-94 and AEIC CS6-96.

It is well known that the most commonly used chemical cross-linking agent, dicumyl peroxide, produces a number of cross-linking agent by-products which include acetophenone, cumyl alcohol, α -methyl styrene and smaller quantities of other by-products. Their formation cannot be avoided, but they are migratory and can theoretically volatilize from the cable. Methods for by-product analysis and data for new and aged cables have been reported (Damon, et al., [B7], EPRI Report EL-7076 [B12]).

Silane-cured XLPE does not use dicumyl peroxide as the curing agent and thus contains different cross-linking by-products. No data are available at this time on the effects of the by-products for silane-cured insulation and the procedures in this clause may not be applicable to silane-cured XLPE. Also no data are available in the published literature on the effect of cross-linking by-products on EPR-insulated cables.

Residual cross-linking agent by-products may influence the electrical properties of polymeric insulating materials such as XLPE, tree retardant cross-linked polyethylene (TRXLPE), and EPR. The residuals will depend on the specific chemical reactions, which occur during manufacture and the rate at which the by-products subsequently diffuse through the extruded layers. Although the same cross-linking by-products occur in TRXLPE and EPR, the rate of diffusion will differ from that for XLPE and may vary for different TRXLPE and EPR formulations. In carefully controlled experiments on XLPE molded slabs and ribbons, removed from cables, the short-term 60 Hz breakdown strength increased but the impulse breakdown strength decreased with increased concentration of by-products (Damon, et al., [B7], Eichhorn [B9], EPRI Report TR-103908 [B13], Wartusch and Wagner [B30]). The ac breakdown strength of XLPE increased between 10% and 15% when the by-products were present up to 2% but decreased when the by-product concentrations exceeded 2% (EPRI Report TR-103908 [B13]). This study also showed that mixtures of the volatile by-products gave synergistic results. The electrical and water treeing resistance was improved by the presence of by-products (Ashcraft [B3], Wartusch and Wagner [B30]). Although this discussion is not intended to be a comprehensive literature review, the results show that the influence of the by-products on breakdown strength is quite complex.

There are limited data available on the effects of by-products on the long-term behavior of either molded slabs or cables. Controlled tests to examine the long-term effects are difficult to carry out due to the already-mentioned migratory nature of the by-products. An examination of new and service-aged steam-cured XLPE cables showed that the acetophenone level decreased from approximately 3000 ppm to 40 ppm during the first two years of installation and that very little (<15 ppm) remained after 8–10 years (Martin and Hartlein [B20]). The loss of by-products also occurred when a cable was stored on the reel. It was concluded that the loss of acetophenone would be expected to increase the water tree growth rate. In another study of steam-cured XLPE cables that had failed after 6–13 years in service at six utilities (EPRI Report EL-5387 [B10]) organic volatiles and halos were present in many of the cables. The total organic levels in the aged cables were <100 ppm. Although the levels of acetophenone were <10 ppm the levels of the cross-linking agent, dicumyl peroxide, were found to be variable, typically <20 ppm but up to 70 ppm in one cable after 11 years in service. The halo contained several thousand ppm of water. The ac breakdown strength was lower in the cables with halos.

The effects of three types of thermal preconditioning on dry-cured 15 kV XLPE cables aged in tanks have been studied (EPRI Report TR-108405-V2 [B14]). The preconditioning procedures were:

- a) Cyclically heat the conductor to 90 °C for 8 h on and 16 h off for 120 h.
- b) Heat the conductor to 60 °C continuously for 120 h.
- c) Heat the conductor continuously until the temperature of the insulation shield reaches 110 °C and immediately switch off the conductor heating current.

The results are shown in Table 2.

Table 2—Results of preconditioning tests on 15 kV XLPE cables aged in tanks

Type of preconditioning treatment	Age of cable after extrusion (months)	Geometric mean time to failure (GMTF) in days (–90, +90% Confidence Limits)	
		Aged at 4 V ₀ and 90 °C* (4/90)	Aged at 3 V ₀ and 75 °C* (3/75)
None (i.e., fresh cable)	2	64 (56, 74)	386 (366, 406)
90 °C on conductor cycled 8 h on 16 h off for 120 h	60	45 (40, 50)	264 (214, 325)
60 °C on conductor continuous for 120 h	60	46 (37, 57)	321 (309, 333)
Insulation shield to 110 °C then immediate cool down	54	103 (85, 124)	325 (284, 371)

*Maximum temperature during load cycling

Preconditioning treatment A subjected the cables to a total 40 h at 90 °C, 120 h at 60 °C for the cables in Treatment B, while the conductor temperature in Treatment C was not measured but was probably significantly greater than 110 °C for a short time (on the order of minutes). Neither the amounts of cross-linking by-products nor the morphology were measured before or after the preconditioning. Treatments A and B would be expected to yield different insulation morphologies. Melting and recrystallization will occur through part of the cable insulation wall thickness. Treatment C probably resulted in a temperature at the conductor in excess of 130 °C for a short time; this could lead to diffusion of species into or out of the shields into the insulation in addition to morphological changes, the rearrangement of crystalline imperfections, and relaxation of the insulation. Complete melting of the entire wall was probable as the temperature reached 110 °C; hence remelting and recrystallization of the entire wall occurred, in contrast to procedures A and B.

Preconditioning treatments A and B yielded similar values of GMTF for the 4/90 conditions. Although there was a 20% difference under 3/75 conditions there was considerable scatter in the data, particularly for treatment A. Without knowledge of the amounts of the cross-linking by-products or the morphologies it is difficult to interpret the results with respect to the effects of the cross-linking by-products or morphology. The results demonstrate that there is a wide variation in GMTF as the preconditioning procedure is changed for XLPE and therefore great care is required in applying a preconditioning procedure. Good temperature measurement and control are essential. The effect of such temperature variations on TRXLPE and EPR is not currently known.

Although their effects on the performance of extruded cable insulation are not precisely known, there is sufficient published data, at least for steam-cured XLPE, to show that an increased concentration of by-products improves the resistance of the insulation system to water treeing and that the concentration of by-products in XLPE gradually decreases with time. Based on the data in EPRI Report EL-5387 [B10] and Martin and Hartlein [B20], the concentration of cross-linking by-products in 15 kV XLPE cable may be less than 100 ppm after 10 years in service and, as a result, may not contribute to the tree retardancy. However, in accelerated aging tests lasting a year or even longer, if the accelerated temperature does not drive off the cross-linking by-products, an apparent improved resistance of the insulation to water treeing could result. Thus the long-term behavior, determined by the insulation with a low concentration of by-products, may not be as good as that predicted by the results of the accelerated aging test. To reduce this possibility the cables are preconditioned in order to reduce the amount of by-products in the insulation before being subjected to the aging test. The most common form of preconditioning is to subject the cables to elevated temperatures to increase the rate of diffusion of the by-products from the insulation (AIEC CS5-94, AIEC CS6-96).