Evaluation of Discharge Resistance of Solid Dielectric Power Cable Insulations

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The presence of electrical trees in service-aged cable suggests that partial discharges may be unavoidable; the inherent PD resistance of insulating materials may stabilize long-term performance.

Introduction

Ensuring the reliability of solid-dielectric power cable against failures caused by partial discharge (PD) activity is a challenging task for design engineers. It was suggested over 16 years ago that improved reliability could be achieved by 1) reducing the operating stress below PD inception levels, 2) using discharge-resistant insulating materials, and 3) using designs and manufacturing quality control measures to minimize partial discharge sites [1].

Over the past decades, most cable manufacturers have emphasized the development of new manufacturing technologies aimed at reducing the likelihood of voids and interfacial separations. Together with more stringent factory tests using advanced PD detectors, these new-generation cables were expected to provide longer life through reductions in manufacturing defects known to give rise to internal PD activity.

During the same time period, the development of materials inherently tolerant to PD degradation has been virtually inactive. Once a prerequisite in the selection of power cable insulation, the value of this concept has been lost to all but a few engineers.

This article traces the development of insulating materials with a focus on their performance in the presence of partial discharges. Methods of evaluating a material's resistance to partial discharge and the significance of these tests are discussed as they relate to the performance of modern cable construction.

Historical Use of Discharge Resistance Tests

One of the earliest records of laboratory tests using the effects of discharge on electrical insulation was Yale University Prof. Benjamin Silliman's recommendation in the 1860s to use some form of discharge test to find improved natural rubber compounds. His close friend, Samuel Morse, had found that rubber-covered telegraph wires rapidly lost their covering when exposed to the atmosphere. Ozone, a byproduct of electrical discharges, was recognized as the culprit that caused the exposed rubber to crack. By the turn of the century, some manufacturers were routinely using a mandrel test to produce ozone for both the development of a stable compound and as a quality control method for factory-mixed batches of compound.

With the introduction of higher voltage cables (3-12kV) around 1920, it was found that rubber-insulated cables suffered service failures from cracking originating either at the inner or outside surface. These failures were triggered at stranding defects or under outer coverings at points where mechanical stressing of the insulation surface occurred. This led to design innovations to minimize mechanical stresses as well as a realization that discharges *internal* to a cable were cause for concern. A good correlation was found between compounds having good mandrel test results and life tests on cable. The mandrel screening test was subsequently made more stringent and became a critical evaluation criterion. Later, the U-bend plate test was introduced for evaluating insulation materials used in larger power cables.

In the 1930s, non-shielded cables with rubber insulation and a neoprene jacket were manufactured for installation aerially in rings or underground in ducts. Failures occurred, first in over-voltage test installations and later in the field. The mode of failure was not just surface cracking due to partial discharges but also local erosion or carbonized tracking leading to burn-through. These effects were always observed in the vicinity of the contact points between phases or from phase to ground. Improvements in the jacket performance were achieved by

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changing the formulation. The development progress was expedited through the use of U-bend plate testing. The modes of degradation and failure with the U-bend plate test were found to correlate well with experience in both accelerated and normal field installations.

The supply cut-off of natural rubber during World War II forced much of the cable industry to shift to synthetic styrene-butadiene rubber (SBR). This shift and the extension of existing cable designs into higher voltage ratings were accomplished with a major use of both the mandrel and U-bend plate test methods. These tests gave high confidence in the service performance of new synthetic rubber insulation compounds at a time when long-term evaluations were not possible.

In the 1950s, butyl polymers were made available for cable insulation and jacket compounds. Heat ageing and vapor transmission properties seemed attractive, but inconsistencies in electrical breakdown and U-bend tests discouraged some from using the material in medium- and high-voltage applications.

Ethylene-propylene-rubber (EPR) compounds were introduced in the early 1960s. These compounds could be formulated to achieve an excellent balance of electrical and physical properties, and by the 1970s they displaced the use of both SBR and butyl rubber. Both mandrel and U-bend tests indicated that the discharge-resistant properties of these new EPR compounds were superior to those of their predecessors.

Commercially available after World War II, polyethylene (PE) became a predominant choice for solid dielectric, medium voltage (MV) and high voltage (HV) power cable because of its excellent short-term electrical properties and low cost. A crosslinked version (XLPE) was introduced later to achieve higher loading capacity through its higher-rated operating temperature. There was considerable optimism regarding the use of these low loss, low moisture-absorption insulations. However, polyethylene's performance in the presence of PD was poor. It appeared that polyethylene and partial discharge simply could not coexist.

Transition in Cable Design Approach

The susceptibility of PE and XLPE to partial discharge required that cables insulated with these materials be designed, manufactured, installed, and operated "discharge free." From a cable design and manufacturing perspective, this represented a major shift in design philosophy—from one employing discharge-resistant cable insulations to one requiring the production of "discharge-free" cables.

Cable design improvements aimed at reducing partial-discharge sites have been introduced over the past 40 years. Improvements to reduce partial discharge at the insulation interfaces include semiconductive shielding tapes (1950s), extruded shields (early 1960s), and triple-tandem extrusion (1970s). In addition, dry-curing methods to reduce the number and size of microvoids in XLPE were introduced.

Production partial discharge measurement techniques were introduced in the 1950s, and the acceptance criteria continue to become tighter.

These changes in designs and tests were also incorporated in cables employing EPR insulations. As cable constructions demonstrated less measurable partial discharge activity, the discharge resistance of the insulating materials was considered to be less important.

New Challenges to Modern Cable Design

Both field experience and laboratory research in the past decades have indicated that "treeing" is one of the major causes of premature cable failures [2]. Among the two major categories of "trees," electrical trees have long been associated with partial discharge [3]. A recent study using a novel technique of PD location has now provided evidence that long, vented water trees could initiate electrical trees and associated partial discharge signals when excited with an ac voltage of moderate magnitude (1.3 to 3.8 times rated voltage) [4]. Subsequent ac breakdown tests on these samples produced faults at the estimated PD locations, indicating that partial discharge activity may develop during the service life of cables regardless of their "discharge-free" design.

Considerable effort has been put into new insulation development for achieving a water tree-resistant property, while very little research has been done on electrical tree resistance. It is known that cables are not ensured to be truly "discharge free" due to limitations of the factory PD test [5]. With the growing evidence that PD activity can develop through service ageing, perhaps some re-focus on the inherent discharge resistant properties of insulating materials would be beneficial.

Test Methods for Discharge Resistance Evaluation

Internal Discharge Resistance Tests

This group of tests introduces partial-discharge activities into the cavities inside the insulation. Among the tests are *artificial voids*, which are usually produced between stacked insulation layers, and *electrical treeing* tests, which are typically introduced through a sharp needle at the tree initiation point [6]. Results on polyethylene are reviewed in the literature, but material comparisons are not available. Though they are more direct simulations of the internal void/tree channel situation, both electrical treeing and internal void tests suffer from sample fabrication problems, including mechanical stress at the needle tip and interfacial artifacts that occur between the stacked sheets. A controlled, reproducible test for materials development is relatively hard to achieve.

Surface Discharge Endurance Tests

Many methods have been employed to study the effects of discharge activities on the surface of insulating materials. Although this test group does not provide a complete picture of the internal discharge effects in voids and tree channels, it does utilize test instruments and set-ups that are easy to prepare. Three tests will be reviewed: the mandrel, the U-bend plate, and the ASTM/IEC cylindrical method.

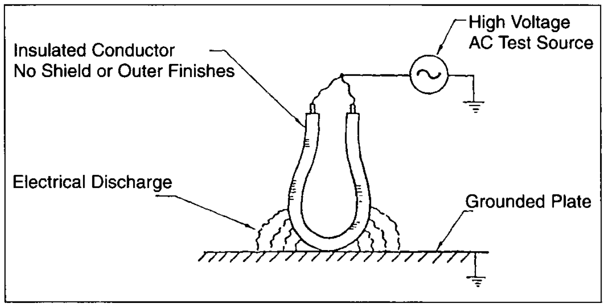

Fig. 1 — U-bend plate test set-up

Table I: U-bend plate test results [8]		
	Time to Failure (hours)	
Insulation	100 V/mil (4kV/mm)	250 V/mil (10kV/mm)
Oil Base	<2	-
PE	100 - 150	-
XLPE	100 -200	8
Butyl	>1000	10
EPR	>1000	125

MANDREL TEST

This is probably the earliest form of the partial discharge endurance test. Samples of insulated small wire, usually #14 AWG Cu wire with 40 to 80 mils (1 to 2 mm) of insulation, are wrapped around a grounded metallic mandrel. The conductor is energized to a voltage level that produces a partial discharge between the surfaces of the insulation and the grounded mandrel. The test voltage is sustained until the insulation breaks down or until a pre-established test duration is reached. Early natural and synthetic rubber insulations developed cuts perpendicular to the mechanical stress direction. This damage was attributed to ozone attack and was duplicated in a non-electrical test where ozone was created by methods other than discharges [7].

When polyethylene wires were tested, damage developed on the outside of the coils approximately at the point of greatest tension and was called electromechanical stress cracking under the influence of partial discharge [6].

The author is unaware of any direct comparison of various modern materials by this test method.

U-BEND PLATE TEST

This test is currently employed to qualify the discharge track resistance of non-shielded cable jackets. However, historically it has been used as a tool to evaluate the discharge resistance of cable insulation. Comparisons between insulating materials can be made provided the test conditions and samples (including surface conditions) are reasonably similar.

This test uses samples of full-sized cable, typically 15kV with #2 or #1/0 AWG conductor and 175-mil (4.4mm) insulation wall (without outer coverings). Test samples are bent around a mandrel to form a U-shape and are positioned vertically on a smooth metal plate (see Fig. 1). The sample conductors are energized at various voltage levels ranging from 17 to 42kV to produce discharge activity between the insulation surface and the grounded plate. The test continues until dielectric breakdown occurs or for a pre-selected test duration.

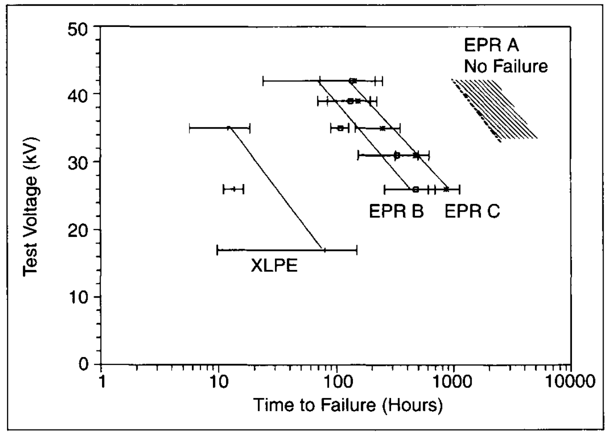

Fig. 2 — U-bend plate test results

Typical time-to-failure data for various materials subjected to U-bend plate tests are shown in Table I [8] and Fig. 2 (in-house data). Since the PD intensity varies with cable sizes and environ mental factors, especially humidity, there can be considerable variability in the results. However, performance differences between the generic insulation types and, in some cases, specific compound formulations, are easily discernible.

Some of the early tests on PE insulation showed unexplained failures within minutes after the voltage application. There were no erosion damages and only very shallow surface crazes (up to a few mils or several tens of microns) near the failure site. This failure mode is unique to the PE insulations and occurred more frequently at the higher test voltages.

EPR insulations show wide differences between various formulations. Most EPR formulations degrade and fail due to erosion cuts developed at the insulation surface, but as shown in Fig. 2, EPR compounds can be formulated to withstand PD activity without erosion for many hours after other compounds have failed.

CYLINDRICAL ELECTRODE METHOD

Since the early 1950s, many papers have been published on discharge endurance tests using cylindrical electrodes. Test data for polyethylene films, epoxy sheets, and laminates using IEC-type electrode systems are reviewed quite extensively in the references [1,6]. The applications of these insulating films, usually in combination with a dielectric liquid, are generators, motors, transformers, and capacitors. It is interesting to note that these apparatuses are also designed to be "discharge free." The selection of materials tolerant to the effects of PD for these applications apparently adds confidence in the reliability of these products in service.

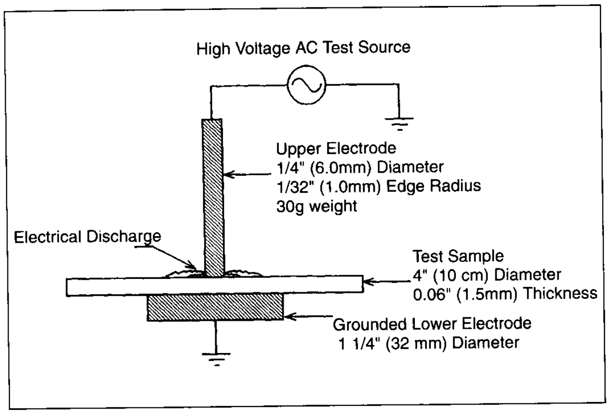

Fig. 3 — Cylindrical electrode test set-up (ASTM D2275-89/IEC 343-91)

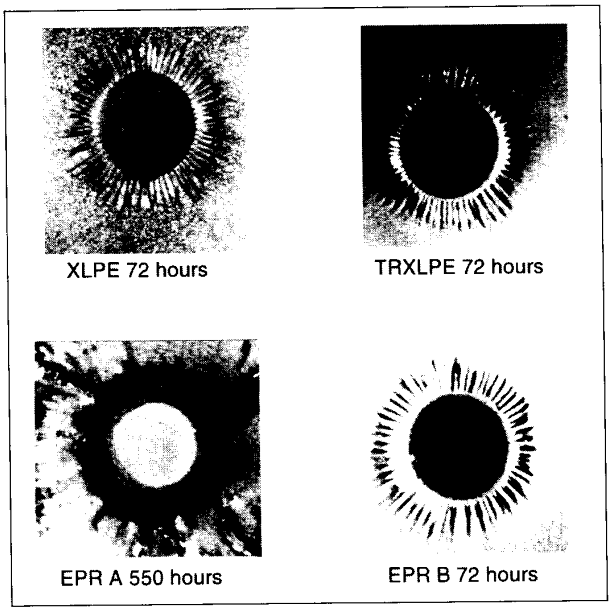

Fig. 4 — Discharge effects on insulating slabs 25°C, 20%RH, 21kV, 60Hz, thickness = 1.5mm

The cylindrical electrode test is ideally suited for material development. Test conditions (e.g., sample thickness, electrode edge radius, sample surface), as well as environmental conditions, affect the test results and can be controlled. Among them, environmental humidity seems to play the most important role [9].

An experimental arrangement following the general guidelines of ASTM and IEC standards [10,11] is shown in Fig. 3. The tests can be performed under a wide variety of controlled conditions but 25°C, 20%RH is relatively easy to achieve and control [11]. The test voltage is selected to produce stable discharge intensity at the specimen surface and degradation in a reasonable amount of time without causing surface flashover.

Typical material reactions are shown in Fig. 4 and time-to-failure data are listed in Table II. All samples were placed under

Table II: Time-to-failure data (60Hz Equivalent) 25°C, 20%RH, thickness = 1.5mm

Insulation	Time to Failure (hours) 21kV	10kV
XLPE	182 ± 19	1190 ± 93
TRXLPE	169 ± 33	1482 ± 54
EPR B	176 ± 23	3050 ± 105
EPR A	>500	NA

the probe without mechanical stress, and a minimum three-day waiting period was introduced to minimize the effect of internal mechanical stress introduced during sample fabrication. Erosion appears to be the mode of failure as channels developed for most insulating materials, and virtually all dielectric failures are located in these eroded channels. Premature failures rarely occur, and in each case can be traced to surface contamination introduced during sample preparation.

In addition to the time-to-failure data required by ASTM and IEC, the average depth of the erosion channels was also measured. Its progression, as indicated by the remaining wall thickness in the erosion channel, is plotted in Fig. 5 as a function of ageing time. Since dielectric breakdown is a very complicated phenomenon involving many factors, the erosion rate may provide a more direct measure of the insulation resistance to partial discharge.

From the above results, it is clear that significant performance differences exist, not only between EPR and PE families, but also within EPR compounds. As demonstrated in the past, excellent discharge resistance is practically achievable through compounding.

SIGNIFICANCE OF SURFACE DISCHARGE RESISTANCE TO SERVICE DEGRADATION

The partial discharge magnitude (value in picocoulomb or pC) is usually perceived as a quantitative measure of partial discharge "severity." As such, surface discharge tests are frequent ly considered over-accelerated due to their relatively high

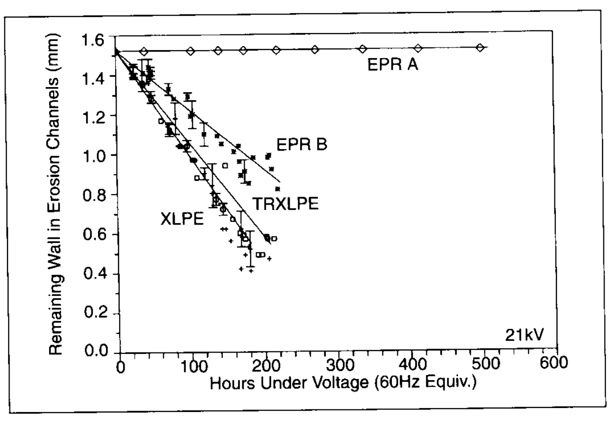

Fig. 5 — Erosion progress in cylindrical electrode test

partial discharge magnitude. Normally, a high discharge magnitude is associated with a large air gap. In the cylindrical test, erosion channels start at the edge of the probe where the air gap is very small and produce numerous PD pulses of low magnitude. The deepest penetration into the test sample is located near the edge. This observation supports the theory that the polymer degradation should be proportional to the energy density of the partial discharge [12], *not* the peak discharge magnitude.

The real issue regarding the significance of the partial discharge endurance test is the nature of the chemical reaction at the polymer surface, which depends on environmental conditions in the gap and the polymer surface. Comparative chemical analysis of degraded surfaces in various tests may yield clues to the relevance to service of this particular degradation mechanism.

Conclusions

For over a century, tests for evaluating the effect of PD on cable insulation have been a valuable tool. In recent decades, however, the emphasis has turned predominantly to the techniques and practices of measuring, as well as lowering, the magnitude and locating the sites of partial discharges in cable. The presence of electrical trees in service-aged cable suggests that partial discharges may be unavoidable. As such, the inherent PD resistance of insulating materials may add a stabilizing factor for cable long-term performance. Future research may be aimed at developing a better understanding of the reactions that take place at the polymer surface and a practical internal discharge-resistance evaluation method to study the relationship between the surface discharge resistance and the electrical tree resistance of insulating materials.

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