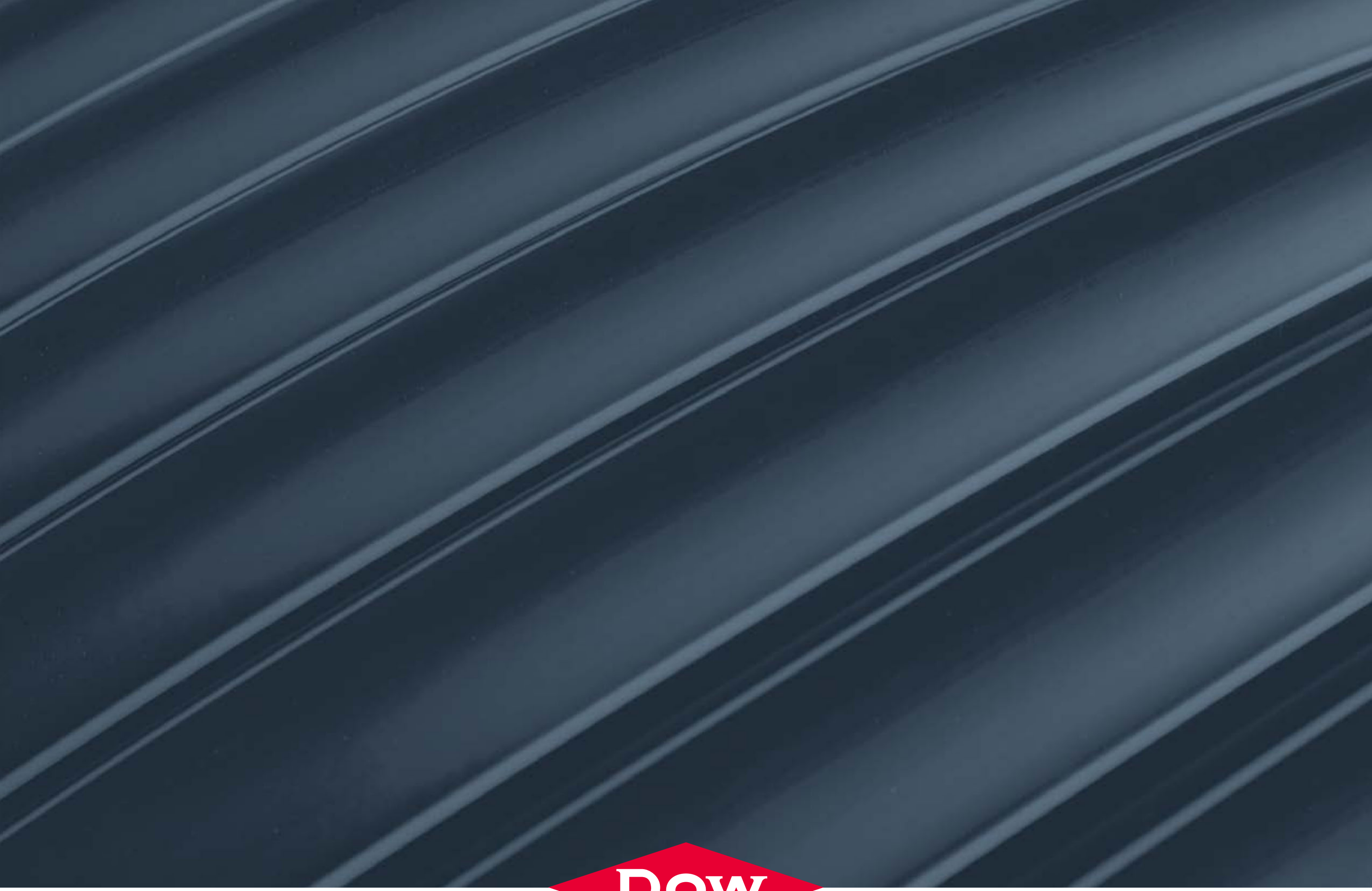


ENDURANCE™ 4202 Tree-Retardant Insulation

A continuing advancement in proven
tree-retardant performance

Table of contents

Introduction

During the past 60 years, the service life of extruded medium voltage underground distribution (UD) power cables has continuously improved due to advances in materials, cable manufacture and design technologies. As a result, current UD cables insulated with Dow's tree-retardant crosslinked polyethylene (TR-XLPE) – ENDURANCE™ HFDC-4202 Insulation Compound – not only differ significantly from early vintage extruded dielectric cables, but also offer far superior performance.

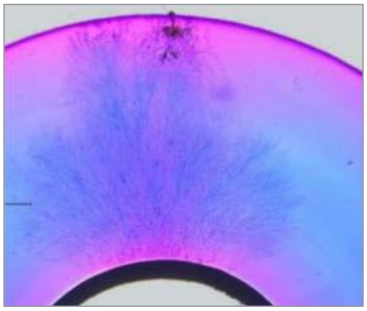
The EPRI Distribution Cable Research Digest is a useful reference for utilities seeking more reliable and cost-effective systems. Among the key findings of the EPRI Distribution Cable Research Digest 2000 is the longevity of TR-XLPE insulated cables. According to the Digest, "Based on research results and field data, it appears the service life of both of these insulations (i.e., TR-XLPE and EPR) will be greater than 40 years when incorporated into a cable when all the suggestions in this Digest are followed."[1]

In the 1970s, underground cables insulated with crosslinked polyethylene began failing prematurely in a wet environment due to the phenomena we now understand as water treeing.[2,3] Water trees in insulation are generally considered to be degraded, chemically oxidized structures which are observed as a dendrite pattern of water-filled micro and sub-micro cavities (see Figure 1). As water trees grow, the electrical stress on the insulation can increase to the point where an electrical tree initiates at the tip. Once initiated, electrical trees grow rapidly and lead to catastrophic failure of the cable.

To avoid or minimize this water treeing phenomenon, different approaches were taken. One option is to modify the design of the cable to eliminate the possibility of water or moisture ingression. This is done using a metal sheath resulting in a so-called "dry design" cable. Although successful, this is a relatively expensive solution. It can also impact cable bending and the cable installation process. The alternative is to use a more cost-effective "wet design," whereby the moisture-impervious metal sheath is eliminated and replaced by diffusion-resistant polyethylene jackets that can also incorporate water absorbing tapes and conductor strand filling compound. However, in this case, the cable insulation needs to be more robust relative to the growth of water trees. As a result, the wet design cable preferably employs a water tree-retardant insulation material.[4]

One of the most significant material advancements in the 60-year history of using XLPE for power cables occurred in 1983 with the introduction of HFDA-4202 NT EC Insulation Compound by Union Carbide (now The Dow Chemical Company). This was the first commercial TR-XLPE specifically designed to retard the growth of water trees while maintaining XLPE's excellent electrical and physical properties as well as its extra-clean (EC) purity designation.[5] The proprietary tree-retardant technology used in ENDURANCE™ 4202 Compounds has proven to be extremely robust. After more than 38 years of excellent performance, ENDURANCE™ 4202 TR-XLPE is the acknowledged industry standard and has replaced XLPE for North American medium voltage utility power cable applications. More North American utilities include 4202 TR-XLPE in their specifications than any other insulation compound due to its long life and low total life cycle cost. The performance of ENDURANCE™ 4202 TR-XLPE is also recognized internationally based on approvals and growing usage in Mexico, Latin America, Europe, the Middle East and Asia.

Figure 1: Water trees growing from semiconductive screens
(courtesy of NEETRAC)



Since its introduction in 1983, our TR-XLPE technology has undergone evolutionary and revolutionary advancements. In 1998, an evolutionary improvement occurred with the introduction of ENDURANCE™ HFDB-4202 NT EC Insulation Compound (B4202).[6] B4202 represented a technology advancement designed to improve on cable manufacturing characteristics while maintaining the excellent water tree-retardant and cable performance characteristics obtained with HFDA-4202 NT EC compound. These advancements in ENDURANCE™ 4202 TR-XLPE Compound stabilization and cure additive technologies resulted in a material that was easier for the cable manufacturer to process in the extruder. B4202 minimized amber and gel formation during extrusion thus minimizing defects and providing higher quality insulation.

Though cables insulated with ENDURANCE™ 4202 TR-XLPE have shown excellent field performance within current cable operating practices, there is continual interest from utilities to further optimize asset performance by serving more load without increasing cable dimensions and explore ways to reduce cable costs without impacting cable life performance. A dramatic advancement of ENDURANCE™ 4202 TR-XLPE performance was to incorporate enhanced resistance to the initiation and growth of both water and electrical trees. Though water trees are associated with cable failures, it is accepted that the failure of cables is due to electrical treeing. The electrical treeing occurs when the water tree grows large enough that the electrical stress across the remaining insulation is high enough to cause failure of the insulation.[7]

In 2010, we introduced an evolutionary improvement in ENDURANCE™ 4202 TR-XLPE Technology with the introduction of ENDURANCE™ HFDC-4202 NT EC (C4202).[8,9] C4202 builds upon the proven field performance of ENDURANCE™ 4202 Technology while incorporating resistance to the initiation and growth of electrical trees. The enhanced (water and electrical) tree retardancy of C4202 TR-XLPE is providing utilities the opportunity to further improve cable system reliability.

ENDURANCE™ 4202 Insulation Compound performance

Laboratory electrical testing

The tree-retardant, longer life characteristic of ENDURANCE™ 4202 TR-XLPE was obtained without compromising the desirable features of XLPE such as excellent physical and electrical properties, extra-clean purity, good cable manufacturing characteristics and low cost. The low power factor of ENDURANCE™ 4202 Compounds over the range of normal cable operating temperatures ensures low dielectric losses to the power utility during the entire service life of the cable.[10] The electrical and water tree-retardant technologies in ENDURANCE™ HFDC-4202 TR-XLPE were specifically selected to be permanent and non-migratory while using the same water tree-retardant technology used in earlier generations.

It is generally agreed that most non-mechanical cable failures for unfilled crosslinked polyethylene cables result from a loss of dielectric strength of the insulation due to water treeing. Figure 2 shows the comparison of the length of water trees grown in XLPE, ENDURANCE™ HFDB-4202 and ENDURANCE™ HFDC-4202 Insulation Compound samples aged for 30 days per ASTM D6097-97.[11] The ASTM D6097 water tree growth test involves compression molding a defined defect geometry into a plaque of the material. The sample is aged in a 0.01 molar NaCl solution at 23ºC, 1 kHz and 1.6 kV/mm. Water trees are grown originating from the defect point and are measured from the point defect with the data presented in terms of the "Water Tree Length." As seen in Figure 2, there is a significant drop in water tree length for ENDURANCE™ B4202 and C4202 Compounds when compared to XLPE. This demonstration of water tree-retardance has translated to improved performance in accelerated wet cable aging tests. Additionally, the C4202 compound maintains a constrained water tree shape, as expected for an ENDURANCE™ 4202 TR-XLPE (see Figure 3).

Definitions of dissipation factor and power factor are beyond the intent and scope of this report, but the terms can be used interchangeably for low loss materials such as ENDURANCE™ 4202 TR-XLPE and 4201 XLPE because the values are basically the same.[10] The power factor of ENDURANCE™ 4202 TR-XLPE is slightly higher than conventional XLPE due primarily to the water tree-retardant technology (Figure 4). However, it is well below the 0.5% maximum requirement for a TR-XLPE insulation.

The dissipation factor of ENDURANCE™ 4202 TR-XLPE and three commercially available ethylene propylene rubber (EPR) insulation compounds is shown in Figure 5. As illustrated in Figure 5, the dissipation factor of ENDURANCE™ 4202 Compound is substantially lower than for filled EPR insulation, and this translates across a cable's entire operating range. Dissipation factor is a measure of electrical losses in insulation materials. The significance of the differences in dissipation factor values between ENDURANCE™ 4202 TR-XLPE and EPR is relevant when comparing the cost of losses from the electrical system.[12]

Figure 2: Water tree length of ENDURANCE™ 4202 TR-XLPEs compared to XLPE*

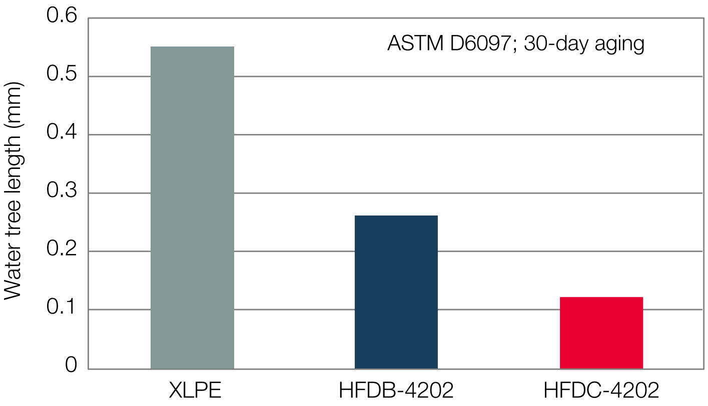


Figure 3: Water tree shape of ENDURANCE™ 4202 TR-XLPEs compared to XLPE at 80X magnification*

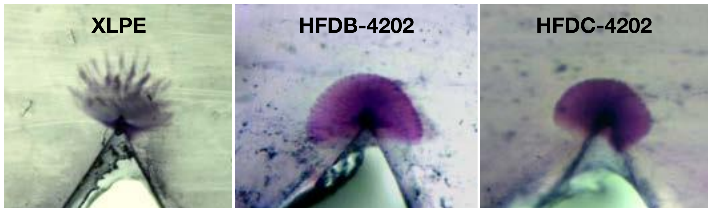


Figure 4: Dissipation factor of ENDURANCE™ 4202 TR-XLPE and XLPE at 3 kV/mm*

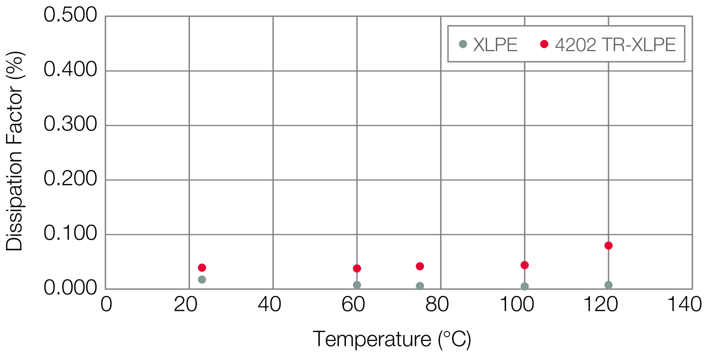
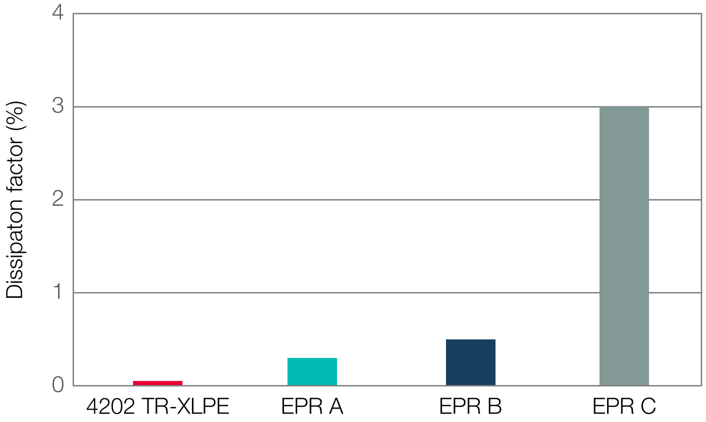


Figure 5: Dissipation factor of ENDURANCE™ 4202 TR-XLPE and three commercial EPRs at 40ºC*



*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

MV 105°C testing

Cables made with ENDURANCE™ 4202 TR-XLPE have been successful in meeting the MV 105°C temperature rating for a class III insulation, whereby a 15 kV cable is continuously loaded to achieve a 140°C conductor temperature at Vg for a minimum of 3 weeks.[13] As Figure 6 shows, cables insulated with ENDURANCE™ C4202 TR-XLPE aging under the MV 105ºC test conditions meet industry requirements and maintain a low dissipation factor; well below the maximum allowable of 0.5% at all three test temperatures. While cables insulated with ENDURANCE™ C4202 Compound are capable of meeting industry requirements for high temperature operation, we encourage cable system owners to consider the risks associated with this method of operation to make sure this is in their best interest and recommend comprehensively assessing system components for operation at the elevated temperature.[14] For example, accessory connector temperatures have been shown to exceed the conductor temperature when the conductor is operated at 90ºC by as much as 50ºC. Elevated temperature induced degradation of the polymeric joint housings and cables in the localized overheated regions need to be considered when operating systems at high temperatures.[14]

Industry qualification testing

ICEA accelerated water treeing test

In North America, the accelerated water treeing test (AWTT) is an ANSI/ICEA cable core qualification requirement and widely specified by utilities.[13,16,17] The objective of the AWTT is to provide a standardized qualification test to yield minimum performance requirements, within a reasonable period for extruded medium voltage cables operating in a wet environment. The AWTT test protocol is well established and conducted by a variety of laboratories. The AWTT is a useful indicator of poor insulation and/or shield materials or poor cable manufacturing practices.[18]

The AWTT is conducted on extruded 1/0 AWG (53.5 mm^2), compressed, unblocked, stranded 15 kV distribution cable cores with 175 mil (4.4 mm) insulation thickness, concentric wire neutrals and no jacket. Before aging is initiated, the cables are load cycled for 14 days at a conductor temperature of 130°C to drive off peroxide decomposition by-product volatiles. To accelerate the growth of water trees, the cables are aged continuously at 3 Vg (150 V/mil or 6 kV/mm average stress), at 60 Hz, in water filled conduits with local tap water introduced into the strands, which are not water blocked. The cables are load cycled for five consecutive days to achieve an in-water insulation shield temperature of 45+/-3°C by the end of the current-on period followed by two consecutive non-load cycle periods. Three cable samples are removed from aging after 120, 180 and 360 days for high voltage time tests (HVTT). The ICEA requirement for a TR-XLPE is the retention of a minimum AC breakdown strength after each aging time.

Figure 7 summarizes the AWTT performance of cables insulated with ENDURANCE™ HFDC-4202 and HFDB-4202 Compounds versus the ICEA requirements for a cable insulated with TR-XLPE. As can be seen in the figure, whether with a conventional semiconductive shield or a supersmooth semiconductive shield, ENDURANCE™ 4202 TR-XLPE Technology far exceeds the industry requirements.

Figure 6: ENDURANCE™ HFDC-4202 TR-XLPE performance in the ICEA dry electrical test for class III insulation*

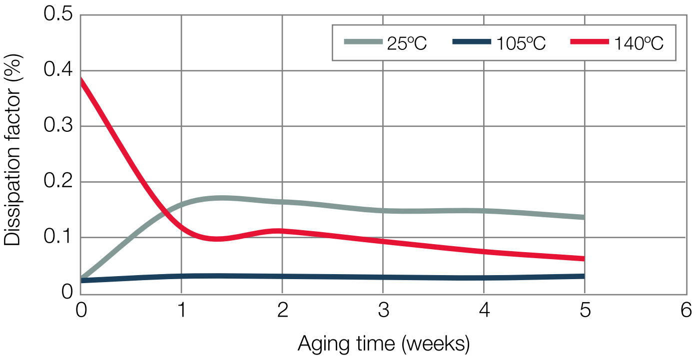
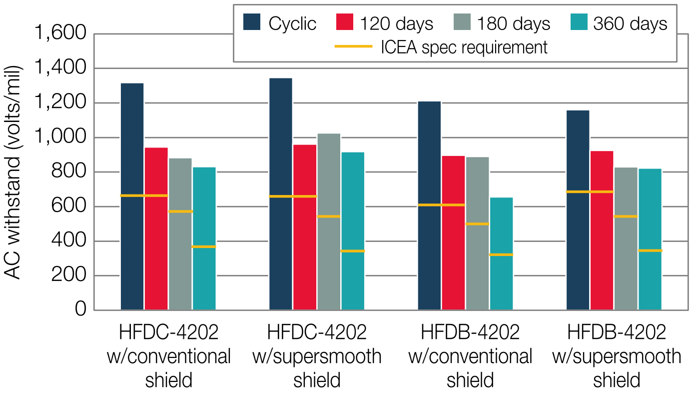


Figure 7: Performance of ENDURANCE™ 4202 TR-XLPEs in the AWTT qualification test*



---

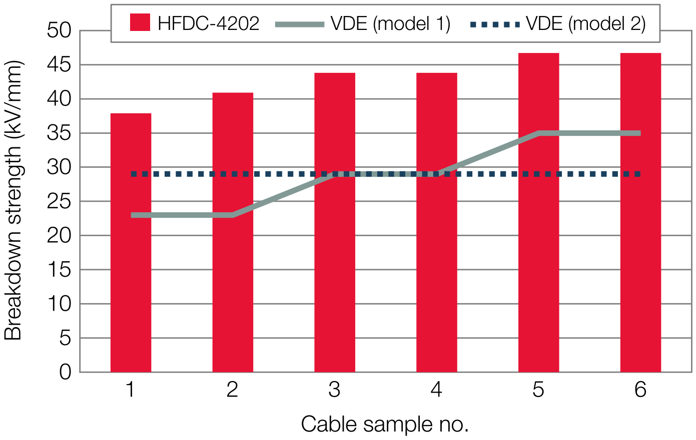
*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

CENELEC

European countries generally favor less severe cable tests conducted for longer time periods. This is based on the theory that acceleration parameters that more closely approximate actual service conditions offer a more reliable indicator of cable performance. As a result, European cable aging is typically run at lower temperatures ranging from ambient to 50°C for two years.[19] The CENELEC HD 605 S1/VDE 0276-620/A3 test requires a specific retention of dielectric breakdown strength after two years of wet aging at $3U_0$ in 40°C water.

ENDURANCE™ HFDC-4202 TR-XLPE is designed to exceed these requirements, and long-term qualification testing on 12/20kV cables was completed at several European cable manufacturers. As Figure 8 illustrates, cables made with the C4202 compound exhibit excellent retention of breakdown performance and have values well above both the minimum CENELEC requirements and the enhanced requirements of the German region (that utilize Verband der Elektrotechnik [VDE] requirements).

Figure 8: ENDURANCE™ HFDC-4202 TR-XLPE performance in the CENELEC HD 605 and comparison to VDE requirements



Accelerated cable lifetime testing (ACLT)

In 1980, an accelerated cable life test (ACLT) described by Lyle and Kirkland utilized full-sized cables with accelerating factors such as temperature, water, electrical and mechanical stress.[20] The ACLT test protocols are outlined in IEEE 1407, and as the name implies, the test measures the times to failure which is consistent with most utility operation.[21] Normally 8 to 12 cable samples are placed under test and the data is analyzed using Weibull or logarithmic normal distributions to calculate the characteristic life (63.2 %) or geometric mean time to failure (GMTF). The original ACLT utilized 15 kV power cables with 175 mil (4.4 mm) wall insulations employing a 2 AWG (33.6 mm^2) x 7 strand aluminum conductor stressed at four-times rated voltage to ground (34.6 kV), giving a maximum stress at the conductor of 284 volts/mil or 11.1 kV/mm. The original work established the influence of voltage, temperature, and water in the strand as accelerating factors for cables insulated with XLPE.

The ACLT test for cables with XLPE was initially conducted under “4,4” conditions, which is four-times x voltage to ground (Vg) stress, at a conductor temperature in air cycled to 90°C (~ 75°C conductor temperature in water) for 8 hours each day. Cables are aged in water-filled tanks and water is supplied to the conductor strands. Prior to ACLT aging, the cable samples are preconditioned for 72 hours at 90°C conductor temperature in free air to reduce the peroxide decomposition byproduct level. Data from the early 1980s comparing 4202 TR-XLPE and 4201 XLPE using conventional conductor shields and the first-generation strippable insulation shield had a GMTF of 4202 TR-XLPE being approximately four times that of 4201 XLPE.[22] At a time when 10% of the sample population is estimated to fail, 4202 TR-XLPE shows an eight-fold improvement compared to 4201 XLPE. This is perhaps more meaningful as utilities will typically replace cables after one or two failures.

Since the early 1980s, performance improvements in cable made with 4202 TR-XLPE and 4201 XLPE were demonstrated using the ACLT.[10] The testing is still conducted on a 15 kV cable, though a 1/0 (53mm^2) aluminum stranded conductor is used. This results in an approximately 11 kV/mm maximum stress in the cable when conducted at “4,4” conditions (four-times rated voltage to ground, 90ºC conductor temperature under the stress cone). The performance of cable made with three generations of 4202 TR-XLPE under “4,4” conditions is highlighted in Figure 9 (page 7). The Weibull plot in Figure 9 shows that the cable insulated with ENDURANCE™ HFDC-4202 Compound exhibits a dramatic improvement in cable life in a wet environment. Compositional improvements targeting the retardation of water tree growth and their conversion to electrical trees have delivered longer characteristic time to failure. The Weibull curves in Figure 9 include the 90% confidence limits that demonstrate the performance of ENDURANCE™ HFDC-4202 TR-XLPE is statistically significant and a significant improvement in time to failure under the ACLT test conditions.

There are two approaches to achieve water tree retardance in XLPE, with one being to utilize a polar polyethylene copolymer and the other to utilize a tree-retardant technology.[23] A comparison of the ACLT performance of ENDURANCE™ 4202 Water Tree-Retardant Technology, a competitor’s water tree-retardant technology, and a competitor’s polar polyethylene copolymer technology is highlighted in Figure 10 (page 7).[24] As demonstrated in the figure, ENDURANCE™ HFDC-4202 TR-XLPE offers outstanding performance over these competitive materials in long life performance. As utilities will typically be concerned after the first cable failure, the time to first failure ENDURANCE™ C4202 TR-XLPE was 3.8 times longer than the competitive technology. This is expected to lead to improved cable life performance in the field. In addition to its long life performance, the C4202 technology enables utilizing a strippable semiconductive shield on the cable, which facilitates accessory installation that is not achievable with the copolymer technology.

Modern cable designs in accelerated cable testing

The accelerated cable testing discussed (AWTT, ACLT, CENELEC) are conducted on shielded, unjacketed cable cores with a high exposure to water. The ACLT and AWTT are conducted with water introduced to fill the conductor strand interstices. Though these are excellent tests for screening material and cable designs for improving cable life performance or meeting industry standards, these tests are not representative of modern utility power cable designs, which typically include solid or strand-filled conductors and over 90% of current cables have an overall protective polyethylene jacket.[25,26]

National Electric Energy Testing, Research & Applications Center (NEETRAC), a Center of the Georgia Institute of Technology, which is a consortium of utilities and cable manufacturers carried out an extensive test program on 21 modern cable designs. The test program's objective was to evaluate full cable design as installed by utilities such as solid or strand filled conductor and jacketed cable with commercial materials available at the time of the study. The conductor was 1/0 (53 mm²) aluminum solid or strand filled. The insulations included ENDURANCE™ 4202 TR-XLPE, competitive TR-XLPEs, 4201 XLPE and two different EPR insulations (semi-crystalline and amorphous EP polymers). The cables were 25 kV class having a 260 mil (6.6 mm) wall insulation and 35 kV class having a 345 mil (8.8 mm) wall insulation. The cables were all jacketed with either 50 or 80 mils (1.3 or 2 mm) LLDPE. Six cables had a moisture impervious layer. The aging was conducted in water filled tanks, patterned after the ACLT, with aging periods of five years for the 15 kV cables and four years for the 35 kV cables. The cables were aged at either a 45ºC or 90ºC conductor temperature and at two stresses (either 280 volts/mil or 347 volts/mil). The results of this test were previously summarized in which the time to failure was the primary performance indicator as well as that the TR-XLPE insulated cables performed well while the EPR insulated cables experienced the majority of the failures during the testing.[10,27,28] However, further diagnostics on these accelerated, wet aged cables were conducted such as dielectric loss measurements, water tree counts, residual AC breakdown and impulse strength.[29] The goal was to determine if the diagnostic testing could be correlated to field aging. Key findings from this diagnostics program were that aging TR-XLPE insulated cables with a 45ºC conductor temperature was more severe than aging at 90ºC conductor temperature and that not all TR-XLPEs performed the same (see Figure 11). Overall, ENDURANCE™ 4202 TR-XLPE performed better in the diagnostic breakdown tests than the other TR-XLPE and EPR materials under the NEETRAC modern cable design test conditions. As cables in the field are typically operated with conductor temperatures peaking in the range of 40 to 60ºC, this finding is particularly relevant for cable operations.

Figure 9: Performance of 4202 compounds in 4,4 ACLT

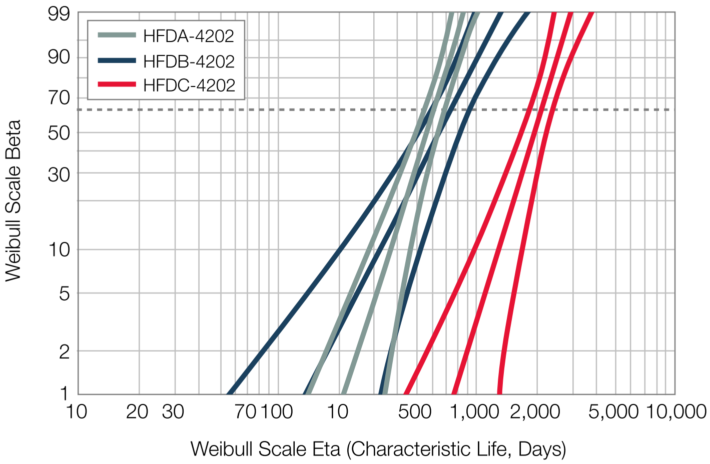


Figure 10: ENDURANCE™ C4202, Competitor TRXLPE and Copolymer XLPE Performance in "4,4" ACLT

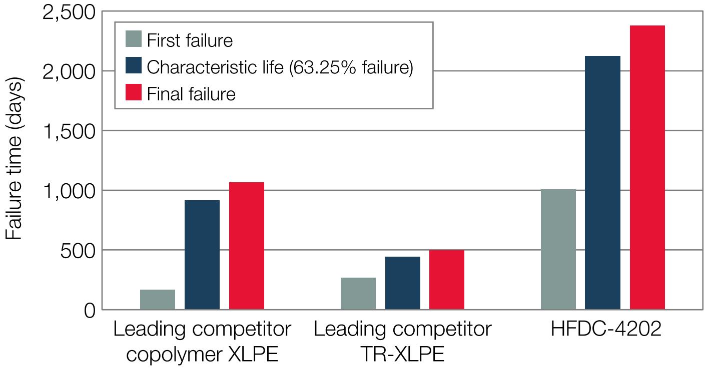
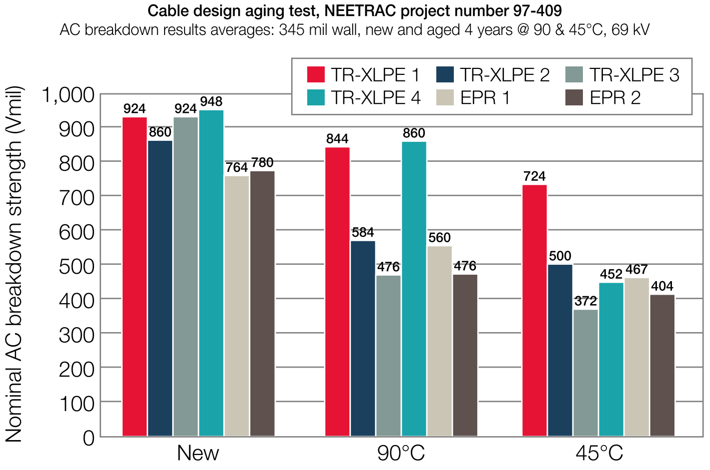


Figure 11: AC Breakdown strength of full cable designs after 4 years wet aging



Note: The insulation shield used on EPR1 was found to be incompatible with the insulation at the elevated conductor temperature of 90°C
This graph is a compilation of data from various figures included in NEETRAC Baseline Project Report 97-409. It was prepared and provided under Clause 6 of the terms and conditions outlined in the *NEETRAC Publication Policy on the use of Baseline Project Results/Data*. In keeping with that policy, the graph was approved by NEETRAC and only Dow Chemical products can be identified outside the NEETRAC Membership.
It is also important to note that AC breakdown was one of several tests used to evaluate the performance of complete cable designs in this accelerated aging test program. While comparing average ac breakdown strength values provides some insight into cable performance differences (or similarities), a statistical analysis/review of all measured performance values and characteristics is required to provide a complete indication of performance.

Importance of compound quality for long life performance

Studies have been conducted to highlight the importance of using quality compounds for achieving long life cable performance. In the early 2000s, a study was conducted in China at the Wuhan High Voltage Research Institute to compare our insulation compounds (B4202 EC TR-XLPE and B4201 EC XLPE) to a locally manufactured XLPE compound used in medium voltage cables.[30]

The cables used in the test program conformed to the quality standards as outlined in IEC 60502 which is followed in many regions outside of North America. Key findings from the study were that the locally manufactured XLPE compound did not perform as well as our compounds with the local XLPE compounds all failing in the AWTT test within 160 days (see Figure 12). Additionally, the local XLPE compound had many bow-tie trees indicating a poorer cleanliness level (see Figure 13). This test program demonstrated that just meeting initial quality expectations as defined in various industry specifications (such as IEC 60502) does not necessarily ensure a long life cable performance.

In discussing cable performance, the role of the semicon can be as important as the insulation. A study was conducted comparing competitive semiconductive compounds to our semiconductive materials with 4201 XLPE insulation compound.[31] The competitive semiconductive materials are used for medium voltage cables and the materials comply with the requirements of IEC 60502.

Figure 12: Performance of Dow compounds versus local compounds in ICEA AWTT

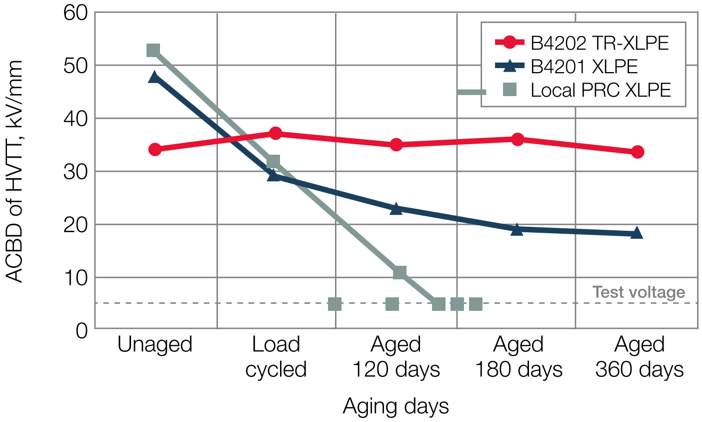


Figure 13: Bow-tie water tree performance of Dow compounds versus local compounds[1]

	B4201 XLPE									B4202 XLPE									Local PRC XLPE								
	1-13	1-14	1-15	1-16	1-17	1-18	1-19	1-20	1-21	2-13	2-14	2-15	2-16	2-17	2-18	2-19	2-20	2-21	3-13	3-14	3-15	3-16	3-17	3-18	3-19	3-20	3-21
0.28-0.51mm	1	3	1	0	14	2	0	8	0	0	0	0	0	0	0	0	0	0	48	8	15	193	191	100	94	75	83
0.52-0.77mm	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	1	0	1	0
0.78-1.02mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[1] Local PRC XLPE cables intended for 180 and 360 days failed before 160 days

This study showed there was a variation in the semiconductive compound's smoothness and cleanliness; see Figures 14 and 15 where shield 1 was a conventional Dow semicon. These variables contributed to a difference in cable life performance expectations as highlighted in "4,4" ACLT testing shown in Figure 16 where Cable A used the Dow conventional semiconductive semicon. Table 1 summarizes the semiconductive compounds key quality parameters of smoothness and cleanliness with the resulting cable performance. As demonstrated in Table 1, a cleaner, smoother semiconductive compound leads to significantly improved cable performance.

The smoothness characterizations in this program focused on the protrusion height. Though other semiconductive compound smoothness programs include an assessment of the protrusion width, the geometric stress enhancement of a protrusion is dominated by the aspect ratio of the protrusion. For semiconductive compound quality testing, the detection and characterization of smoothness using the protrusion height is a more conservative means of assessing the material.

The role of the semiconductive conductor shield material in the electrical performance of insulated cables was highlighted in our program to demonstrate the suitability of ENDURANCE™ 4202 TR-XLPE for a 105ºC cable rating. This program showed that long-term continuous aging at elevated conductor temperatures results in increased cable dissipation factor. It was observed that cables with one type of conductor shield exhibited higher dissipation factor than other types of conductor shields while using the same insulation. The increase in dissipation factor was mainly due to a corresponding increase in conductor shield volume resistivity, though this increase in conductor shield volume resistivity showed no adverse effect on long-term cable performance.[32] The role of the outer semiconductive shield has also been addressed in which a study showed that cable dissipation factor increases were observed with changes in the outer semiconductive shield volume resistivity.[33] Though the cable capacitance was stable, the cable's dissipation factor increased which increases the electrical loss from the cable.

Table 1: Semiconductive compound quality parameters and cable performance in accelerated testing

Attribute	Cable A	Cable B	Cable C	Cable D
Protrusions (> 50 µm)	2	185	138	160
Total chemical impurities	532	7217	4318	13359
"ACLT" performance				
First failure (days)	148	13	9	15
Characteristic life (days)	358	31	24	27
Retained breakdown strength > 7.8kV/mm after 120 days wet cable aging	Yes	No	No	No

*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

Figure 14: Surface mircoprotrusion height for semiconductive shield compounds *(note the inset plot focuses on counts > 50 mm)*

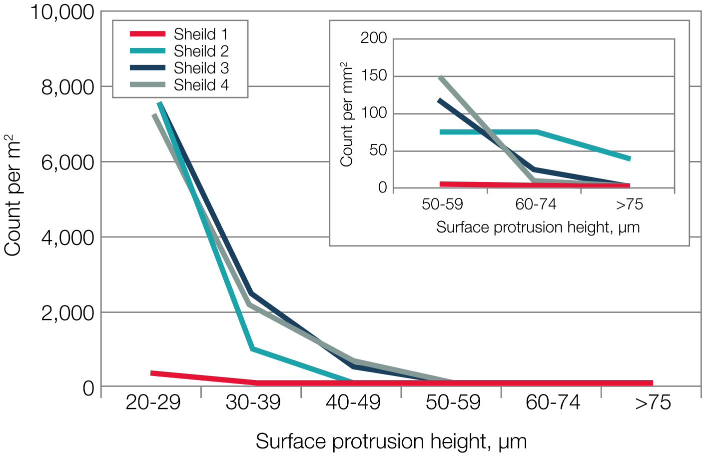


Figure 15: Total inorganic element, sulfur and ash content impurity levels of semiconductive shields compounds

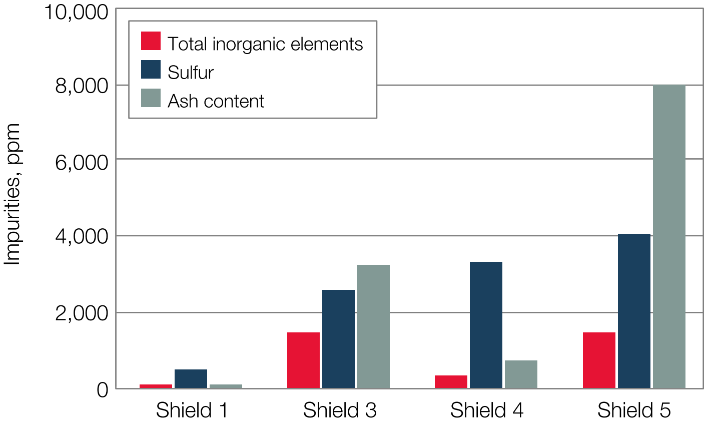
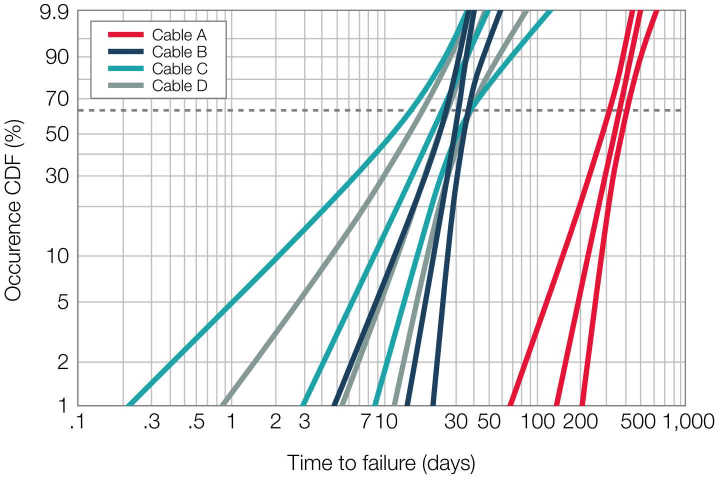


Figure 16: "4,4" ACLT performance of XLPE cables with different semiconductive compounds



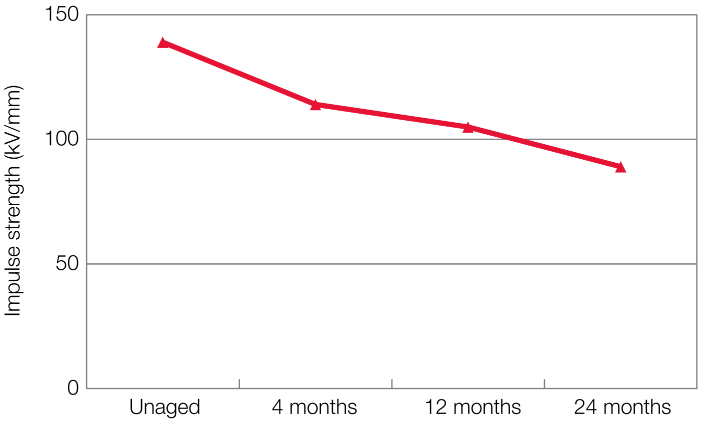
A key message is that the semiconductive material matters in the cable's electrical performance and that cable testing is not solely an insulation test; it is an evaluation of the cable material system. Using materials that are engineered to be used in a system of cable materials insures the most successful cable design.

Impulse strength retention

The retention of impulse strength for cables insulated with ENDURANCE™ 4202 TR-XLPE after wet aging and its ability to maintain a high impulse strength with aging has not been widely discussed. While many studies reported the retention of AC breakdown strength for aged TR-XLPE cables, less has been published on the impulse strength characteristics of aged TR-XLPE cables. Several field aged cable studies as well as accelerated aging tests have been conducted that included assessing the impulse strength of 4202 TR-XLPE.[34] The data collected for this summary is from field aged cables (Alabama Power, Houston Light & Power, Orange & Rockland/CTL) and accelerated aging tests (CTL/Houston L&P/EPRI, CTL/EPRI, Union Carbide 105°C Wet Aging Tests, NEETRAC Cable Design Aging Test, Dow Hot Impulse after Dry Aging). The results of a CTL/HL&P/EPRI study in which 15 kV cables were accelerated aged at 20 kV in water-filled tanks are representative of the performance of ENDURANCE™ 4202 TR-XLPE impulse performance with wet aging (see Figure 17).[35]

A summary of the impulse performance of ENDURANCE™ 4202 TR-XLPE Insulation Compound shows that the impulse strength has an initial reduction of 30-40% after wet aging. After the initial drop, impulse strength remains relatively flat with further aging. This performance is like that of EPR cables aged under the same conditions. The residual impulse strength of cables insulated with ENDURANCE™ 4202 TR-XLPEs after extended field or accelerated aging is typically more than 50-100% higher than that of EPR cables aged at the same conditions.

Figure 17: Impulse strength of wet, accelerated aged cables insulated with ENDURANCE™ 4202 TR-XLPE[35]



Impact of contamination

Florida Power & Light (FP&L) conducted a project to quantify via pellet sortation the level of contamination in the (B4202 EC) TR-XLPE insulation being used to manufacture their cables. FP&L asked their cable suppliers, General Cable and Pirelli (both now Prysmian Group), as well as Dow, the supplier of the insulation (B4202 EC TR-XLPE) used by the cable manufacturers for FP&L at the time of the study, to perform a pilot evaluation of the cleanliness of their insulation material used for cable production. The study was conducted using pellet sorters to inspect the insulation compound in the cable manufacturing plant. Dow was already using pellet sorters for inspecting 2% of their insulation material production at packaging consistent with ICEA requirements. A key concern for FP&L was to understand the effect of the "contaminants" found in a pilot study have on the aging cables in service and the reliability of their cable system. Discussions were held and agreement was reached to set up a cable aging test program to address this question. General Cable, Pirelli and Dow agreed to participate in such a program with FP&L.[36]

A plan was developed to select some typical "contaminants" based on the findings of a pellet sorter pilot study and to make cables with artificial contaminant particles representative of those found in the pilot study. An accelerated cable aging protocol for testing the effect of these particles was utilized.[36]

The cables produced for this program were:[37]

- **Cable Type 1**: Control ENDURANCE™ HFDB-4202 TR-XLPE (B4202)
- **Cable Type 2**: Control B4202 TR-XLPE with ground B4202 TR-XLPE carrier
- **Cable Type 3**: B4202 TR-XLPE with ground carrier and **degraded TR-PE**
- **Cable Type 4**: B4202 TR-XLPE with ground carrier and **degraded TR-XLPE**
- **Cable Type 5**: B4202 TR-XLPE with ground carrier and **rubber gasket**
- **Cable Type 6**: B4202 TR-XLPE with ground carrier and **aluminum**

The "contaminants" added in cables 3 through 6 were approximately 25 mils in diameter and were introduced to the cables of at a rate of about 1 per foot of cable.[37] The cables for this test program were manufactured on a state of the art, true triple cable production line and manufactured without a screenpack in the insulation extruder. The materials used in the study consisted of ENDURANCE™ HFDA-0802 BK for the conductor shield, B4202 EC for the TR-XLPE insulation compound and ENDURANCE™ HFDA-0693 BK for the insulation shield. These "contaminated" cables had at least an order of magnitude higher "contamination" level than allowed by industry specifications and would not have met the AEIC and ICEA contamination requirements.

The accelerated, wet cable aging protocols utilized in the program were:[38, 39, 40]

- **AWTT**
  - The testing was conducted per the ICEA protocols.
  - Figure 18 is a statistical analysis of the AC breakdown test results on the cable specimens after 360 days of AWTT aging.[38] The 360 day AC breakdown strength of the cables were in the range of 630 to 810 volts/mil. This testing did not show a statistical difference in the results between the control cable and cables with the contaminants.
  - To better understand the influence of the water ionic content and the effect of preconditioning on the AWTT results, another series of 360-day aged AWTT tests were conducted on the control cable, the cable with degraded TR-XLPE and aluminum metal contaminants.[40] The cables used in this second phase study had been stored outside on cable reels for 30 months. Water quality and two different cable preconditioning protocols were evaluated and seen to not be an explanation for the first phase study results. An analysis of the results within a sample for this second phase of testing showed the results to be statistically equivalent between the different aging conditions studied. In Figure 21, we've combined the 360-day AWTT data for the different aging conditions studied in phase 2. As seen in Figure 19, the AWTT performance of the cable with the degraded TR-XLPE contaminants was statistically equivalent to the performance of the cable with the aluminum metal contaminants and the control cable. These results indicate there is not a clear effect of the contaminants on these TR-XLPE insulated cables compared to their non-contaminated TR-XLPE control cable.
- **ACLT**
  - This testing involved preconditioning for 500 hrs at 90ºC conductor temperature then aged at 34.6 kV with a conductor temperature of 75ºC in water, load cycled 8 hrs on/16 hrs off for 7 days a week with a 50ºC water temperature. These samples were aged to failure.[39,40]
  - A statistical analysis on the results from the first phase ACLT testing is in Figure 20.[39] As highlighted in Figure 20, this testing did not show a statistical difference in the ACLT results between the control cable and cables with the contaminants.
  - To determine if testing more specimens in the ACLT would provide differentiation in the results, further testing was conducted on the control cable, the cable with degraded TR-XLPE and the cable with aluminum metal contaminants.[40] Statistical analysis of these second phase results with the first phase results showed the cable with degraded TR-XLPE from each phase was statistically equivalent and the cable with aluminum metal contaminants was statistically equivalent, however, the control cable from Phase 1 and Phase 2 was not statistically equivalent. Figure 21 summarizes a statistical analysis of the three cables tested from only Phase 2. The results show that the cable contaminated with aluminum particles is statistically equivalent to the control cable and the cable with degraded TR-XLPE contaminants while the control cable and the cable with degraded TR-XLPE contaminants are not statistically equivalent to each other. These results indicate there is not a clear effect of the contaminants on these TR-XLPE insulated cables compared to their non-contaminated TR-XLPE control cable.
- **HVTT on samples after 490 days ACLT tank aging**
  - This testing involved preconditioning for 500 hrs at 90ºC conductor temperature then aged at 34.6 kV with a conductor temperature of 75ºC in water, load cycled 8 hrs on/16 hrs off for 7 days a week with a 50ºC water tank temperature. These samples were removed after 490 days for dielectric strength assessment.[39]
  - Figure 22 is a statistical analysis of the dielectric strength assessments for the samples. As shown in Figure 22, the samples are statistically equivalent. These results indicate there is not a clear effect of the contaminants on these TR-XLPE insulated cables compared to their non-contaminated TR-XLPE control cable.

An unexpected finding from this study was that even though two wet-aging protocols with three diagnostic cable tests were used, no statistically significant effect of the added contaminants was observed.[41] Though the results did not suggest the added contaminants impacted the cable's wet electrical performance, the group recommended that vigilance to maintain and improve cleanliness of compounds and cables should not be relaxed.

Selected cables were tested in a second phase of the study, where testing was designed to answer questions raised in the first phase testing. These questions were:

- A development of unusual, large vented water tree clusters due to the test water
- Small AWTT and ACLT population sizes
- In the presence of contaminants, there were possible differences in the effects of contaminants depending on the preconditioning protocol (ACLT or AWTT)

The second phase of accelerated cable testing confirmed the results of the first phase testing as well as answered the questions; the test water quality did not impact the results, the unusual vented water tree clusters were due to the water quality, and a statistically larger test sample size did not show a different result that the first phase testing. This second phase testing proved these three variables were not the cause of the observed result in Phase one.

In the following figures, when a contour confidence curve intersects another curve then the sample populations are considered statistically equivalent; the analysis used 90% confidence limits. Figures 18 through 22 contain the key data generated in this extensive study.

Figure 18: First phase 360 day aged AWTT test results on contaminated TR-XLPE cables statistical analysis[39]

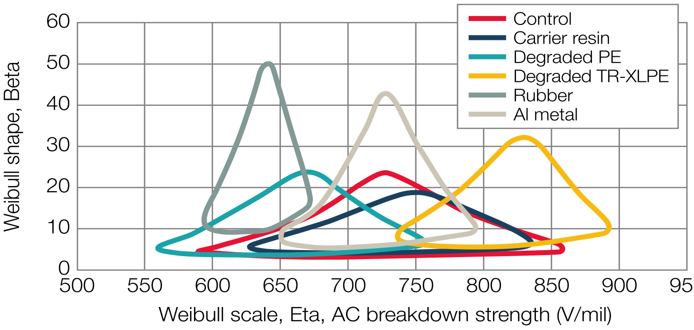


Figure 19: Second phase 360-day-aged AWTT type aging on contaminated TR-XLPE cables statistical analysis[40]

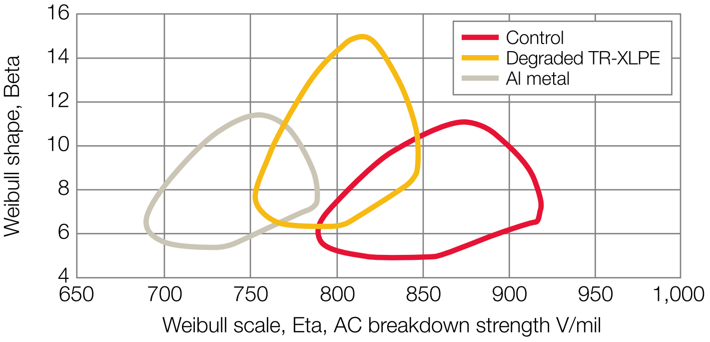


Figure 20: First phase ACLT performance of contaminated TR-XLPE cables statistical analysis[39]

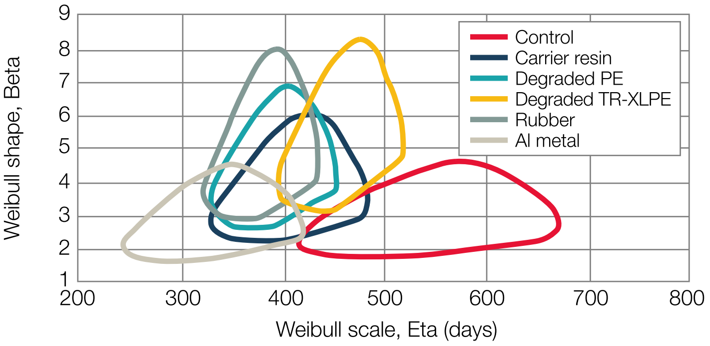


Figure 21: Second phase ACLT performance of contaminated TR-XLPE cables statistical analysis[40]

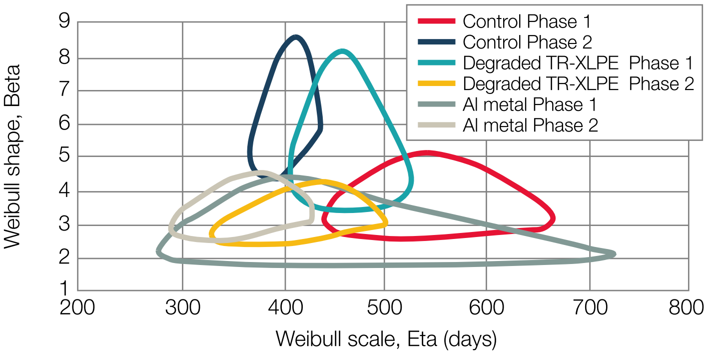
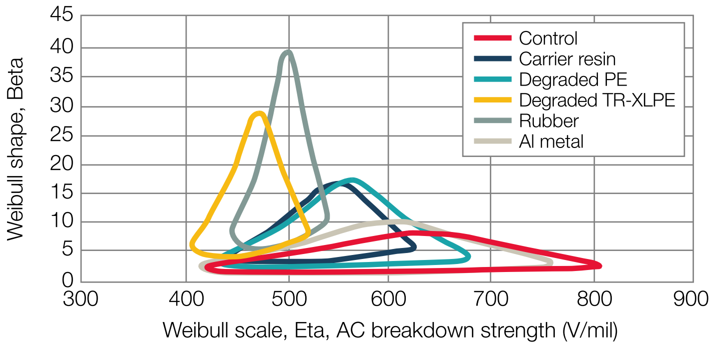


Figure 22: HVTT results on contaminated TR-XLPE cables after 490 days ACLT aging



The major conclusions and observations from the project are:[41]

- A comprehensive review of all the aging test data on cables insulated with ENDURANCE™ HFDB-4202 (B4202) TR-XLPE indicates there is no statistical difference in the accelerated, wet electrical performance of the cables with the various artificial contaminants when compared to the control cables in all the aging tests conducted, with the sample sizes prescribed in the various aging protocols. This leads to the conclusion that the tree-retardant technology in B4202 is highly effective at resisting aging degradation in the presence of contaminants. It is possible however that with a larger sample size, if a separation exists, it may be easier detected.
- The preconditioning method, used to remove crosslinking decomposition products from the cables before performing HVTT and aging tests, has a significant effect on initial HVTT test results and may also affect the aged ACBD results. Preconditioning at 90ºC for 500 hours results in lower initial ACBD, than the standard AWTT preconditioning method of 14 cycles of conductor heating to 130ºC.
- The tap water quality for the AWTT tube test, as reflected in the ionic content of the water, can induce significant vented tree development during the AWTT wet aging to 360 days and result in lower ACBD values.

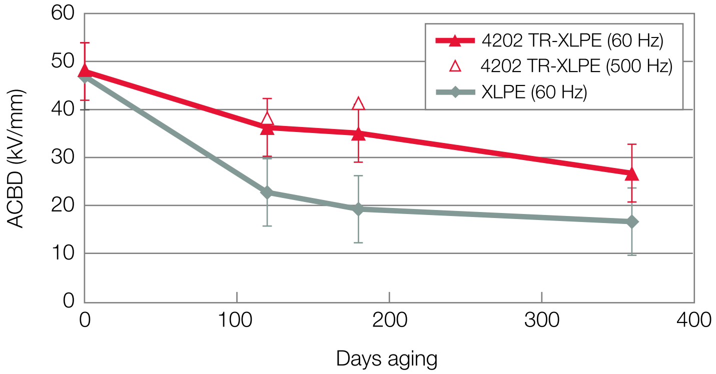
Dow's opinion on findings from the study of contaminants:

- We introduced ENDURANCE™ 4202 TR-XLPE Technology to minimize the impact of defects such as contaminants on cable wet electrical performance.
- The results of this study support the performance projections of 4202 performance and the adoption of ENDURANCE™ 4202 TR-XLPE for cables in wet environments.
- This contaminated TR-XLPE Cable Project demonstrates the robust performance of ENDURANCE™ 4202 TR-XLPE Technology; other TR-XLPE technologies have not been tested or evaluated in this type of study and performance with contaminants is unknown without testing.

Effect of high-frequency aging

In Europe, a typical CENELEC wet aging test is conducted at 50 Hz for two years, though based on their experience with XLPE, aging at a higher frequency is allowed to shorten the aging time (CENELEC HD605). The shortened test program involves aging at 500 Hz for 4 months. Limited cable aging studies with TR-XLPE under high frequency conditions have been reported. In one study, an objective was to assess if the ICEA AWTT aging conditions could be modified by testing at a higher frequency to shorten the test time from 1 year to 6 months.[42] In this study, 15 kV cables with a 1/0 conductor using a 230 mil insulation thickness (133% insulation level) were aged at 500 Hz under "AWTT" aging conditions. Cable samples were tested after 3 months and 6 months of aging. The key result was that ENDURANCE™ 4202 TR-XLPE aging, under AWTT conditions, was not accelerated by high frequency (see Figure 23).

Figure 23: AC breakdown strength of ENDURANCE™ 4202 TR-XLPE at 500 Hz and 60 Hz



In another study, high frequency aging was conducted per the CENELEC HD 605 procedures on commercially available TR-XLPE insulated cables.[43] This study found that 125 days of CENELEC HD605 500 Hz aging is equivalent to, or more stringent than, 360 days of ICEA S-94-649 60Hz AWTT aging for the TR-XLPE insulated medium voltage cables studied. This study's conclusions on the CENELEC HD 605 long duration test at 500Hz when compared to the ICEA AWTT test at 60Hz for commercially available XLPE or TR-XLPE insulated cable were:

- Reduces dielectric ACBD approximately 3 times faster
- Grows more trees
- Grows the same type of tree

The study identified that the two protocols' method of water heating and the per unit time at temperature are different. The authors hypothesized that the AWTT method of inductive heating or lack of preconditioning nullified the frequency effect when all other factors were held constant. This study agreed with the previous study in that it concluded that increasing only the frequency used for the ICEA AWTT medium voltage cable qualification will not reduce the time of the test.

Cable longevity predictions

The Wire & Cable industry has long sought to correlate accelerated wet aging in a laboratory with actual field experience. The industry also would like to answer the question, what is the difference in cable life predictions between using materials that just meet the industry specifications and those that outperform the industry specifications?

The following is an analysis on the differences in cable life performance between two materials: one that meets the industry minimum requirements and one that exceeds the industry requirements.

Cable longevity based on ICEA accelerated water treeing test performance

In North America, the industry requirements for a TR-XLPE insulated cable are outlined in ANSI/ICEA S-94-649 clause 10.1.6 which is the accelerated water treeing test (AWTT). This testing outlines the minimum AC withstand requirements for a cable after different aging protocols, as shown in Table 2. The requirements are different for XLPE, TR-XLPE and EPR insulated cables. With its excellent long life performance in wet environments, TR-XLPE is the insulation of choice for most NA utilities and will be the focus of this discussion.

Focusing on the ICEA requirements for a TR-XLPE insulated cable, Table 3 tabulates the ICEA requirements and the performance of C4202 in the AWTT test. As highlighted in Table 3, C4202 exceeds the industry requirements for a TR-XLPE insulated cable by as much as twofold. Could we anticipate a difference in the service life of a cable insulated with a material that performs just above the specification requirements, compared to a material that far exceeds the specification requirements? We will address this question in this analysis.

Table 2: ICEA S-94-649 minimum AC withstand values after AWTT aging

Insulation type	Minimum AC withstand values (volts/mil [kV/mm])				
	Prior to cyclic aging	After cyclic aging	After 120 days of AWTT aging	After 180 days of AWTT aging	After 360 days of AWTT aging
Crosslinked Polyethylene	620 (24.4)	620 (24.4)	300 (11.8)	Not required	Not required
Tree-Retardant Crosslinked Polyethylene	629 (24.8)	660 (26.0)	660 (26.0)	580 (22.8)	380 (15.0)
Ethylene Propylene Rubber	500 (19.7)	500 (19.7)	420 (16.5)	340 (13.4)	340 (13.4)

Table 3: ENDURANCE™ HFDC-4202 performance in ICEA AWTT with conventional semiconducting shields

Days aging	ICEA requirements (volts/mil)	HFDC-4202 (volts/mil)
0	660	1320
120	660	940
180	580	830
360	380	830

*Typical values, not to be construed as specifications. Users should confirm results by their own tests.

The ICEA AWTT test is conducted under very highly accelerated, wet aging conditions at a voltage stress of 3 Vg which translates to a maximum electrical stress of 209 volts/mil (8.2 kV/mm). Additionally, the cables undergo cyclic thermal aging at elevated operating temperatures. Cables, of the same design used in the ICEA AWTT, are operated or aged in the field under much lower stresses and typically at much lower operating temperatures. In the field, these cables are operated at Vg which translates to a maximum electrical stress of 70 volts/mil (2.7 kV/mm).

Electrical insulation degradation can be modeled following an inverse power law relationship (IPL) between lifetime and electrical stress:[44]

$E^n * t = \text{constant}$

Where:

E = electrical aging stress

n = aging parameter, typically ~ 3 for XLPE and TR-XLPE[45]

t = lifetime

The industry accepts the AWTT as a proxy for field aging as well as the assumption that cables fail during AWTT aging similar to field aging. We also know that field aging has many unknowns (environment, installation, water content, temperature, operating conditions). Accepting these unknowns as well as assuming the IPL applies not only for aging but also throughout a subsequent ramp to breakdown test, what would be the predicted difference in cable lifetime between a cable with a TR-XLPE insulation that "just" meets the ICEA AWTT minimum requirements and a cable insulated with HFDC-4202 that exceeds the ICEA AWTT requirements? The following theoretical analysis addresses this question.

At end-of-life, based on the inverse power law,

$E^n * t_{life} = K,$

Where K is proportional to lifetime at a given stress, for example operating stress.

Translating an increment of aging as:

$E^n * dt = dK$

Where dK/K = fraction of life consumed.

In an electrical breakdown test to failure:

$E(t) = R*t$, or $t\text{-fail} = E_b/R$

$$\text{then } \int_0^{t-fail} [E(t)]^n dt = K$$

$$\text{or}\ldots\ \frac{R^n}{n+1}\left[t_{fail}{}^{(n+1)}\right] = K = \frac{1}{(n+1)R} E_b^{(n+1)}$$

Assuming material II has breakdown strength that is increased (higher) by a factor X relative to material I.

$$K_I = \frac{1}{(n+1)R} E_b^{(n+1)}$$

$$K_{II} = \frac{1}{(n+1)R} [XE_b]^{(n+1)}$$

$$\frac{K_{II}}{K_I} = X^{(n+1)}$$

Where KII/KI is the relative increase in cable lifetime at operating stress.

The data in Table 3 shows that ENDURANCE™ C4202 breakdown performance in the ICEA AWTT averages 68% higher than the ICEA specification requirement which translates to X = 1.68. With an aging parameter (n) of 3, then a theoretical lifetime increase of ~800% is predicted.

While it is recognized that in field applications an 800% increase in cable lifetime is extreme, it is reasonable to expect a dramatically better lifetime performance from an insulated cable that significantly exceeds the ICEA AWTT requirements, such as ENDURANCE™ C4202, than one that "just" meets the minimum requirements.

It is also recognized that the ICEA AWTT is conducted on short 5 m (15 ft) lengths and the requirements in Table 2 are for the 5 m cable length tested. In the field, cable lengths of 100 m (330 ft) or more are used, one could ask "what is the influence of cable length on the projection of cable lifetime?"

Adjusting the cable breakdowns in Table 3 to account for the influence of a longer cable length can be done by the following equation:[45]

$\alpha_L = \alpha_1 (l/L)^{1/\beta}$

Where,

Eta = Weibull alpha = 209

Beta = Weibull beta = 3.82

A translation of the 5 m test lengths in Table 3 to a service length of 100 m is tabulated in Table 4, such that a translation to a service length of 100 m will yield 55% of the 5 m AC withstand stress.

The data in Table 4 shows that the 100 m length of cable insulated with ENDURANCE™ C4202 maintains a 68% higher breakdown than the specification requirement such that a theoretical lifetime increase of ~800% is predicted. Thus, it is still reasonable to expect a dramatically better lifetime performance from an insulated cable using ENDURANCE™ C4202 that significantly exceeds the ICEA AWTT requirements as compared to one that simply meets the minimum requirements.

Table 4: ICEA requirements and ENDURANCE™ C4202 AWTT breakdowns adjusted for 100 m of cable

Days aging	ICEA requirements (volts/mil)	HFDC-4202 (volts/mil)
0	300	600
120	300	430
180	265	380
360	170	380

Cable longevity based on accelerated cable life test performance

In addition to the ICEA AWTT test, the Accelerated Cable Life Test (ACLT) is another highly accelerated wet aging cable test protocol widely used in the industry to compare lifetime performances of cable insulations.[20] The ACLT is conducted under a different set of aging conditions than the ICEA AWTT with multiple aging mechanisms in effect during the test. Though there is no industry specification for ACLT performance, one can compare the performance of cables with different materials under this same protocol. Figure 24 compares the ACLT performance of ENDURANCE™ HFDC-4202 to a competitive TR-XLPE that meets the ICEA AWTT requirements. As seen in Figure 24, ENDURANCE™ C4202 exceeds the competitive TR-XLPE in ACLT lifetime performance with a characteristic lifetime improvement of nearly fivefold. It is reasonable to expect a significantly better lifetime in a field application with a C4202 insulated cable as well.

The accelerated cable life test (ACLT) utilizes cable test lengths of approximately 5 m and applies a 4x rated voltage-to-ground for accelerated wet electrical aging. The "handbook" states a range of IPL exponent values of n = 3.3 to 3.6 for wet electrical aging.[43] If we consider a service length of cable to be 100 m, then we will need to adjust failure expectations determined in the ACLT for length effects as well as for the enhanced stress. A Weibull beta value of 4 has been assumed based upon experience in failure distributions under accelerated aging conditions.

Using the appropriate length correction for 5 m to 100 m, [(5/100)^(1/4) = 0.47], a 100 m length under ACLT test conditions should have only 47% of the life of a 5 m test length.

The IPL provides a means to compare the lifetimes of a given cable length under different stress conditions. Namely, the power law exponent, n = ln (Service life/ ACLT life)/ln(Eaclt/Eservice).

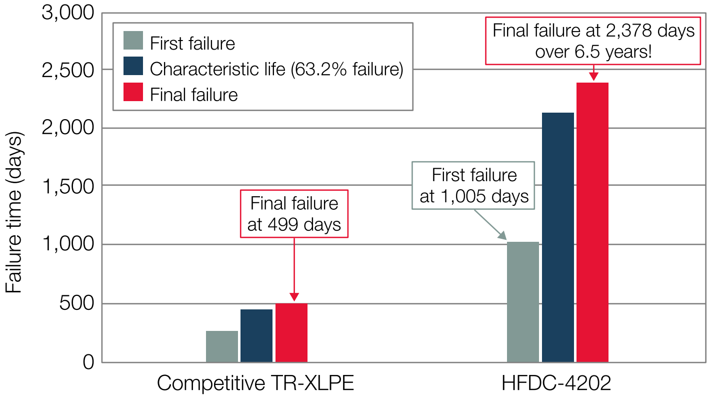
Thus, under these assumptions of length correction and suitability of the inverse power law with a given value of n, we can utilize a result for aging of a 5 m length under ACLT aging conditions to estimate the expected service life of a 100 m length under normal service conditions. [No corrections are applied for differences in other aspects of the aging conditions, such as temperature or water content or the presence of a protective jacket.] An analysis is shown below based upon an assumed ratio of Service life to ACLT life, which then defines the value of the exponent n; reference Table 5. Then for an assumed 5 m ACLT life of 100 days, a length correction and the life ratio provide an estimate of the expected life of the 100 m length under service conditions. Over the range of n = 3.3-3.6, we find that 100 days of 5 m ACLT aging translates to 12.9 to 19.3 years of 100 m service life. It should be noted that this analysis applies for any defined B-value within a failure distribution and leads to a proportionality of lifetimes. Thus, a 5x extension of 5 m ACLT lifetime at a B10 level will translate to a 5x extension in the expected 100 m service lifetime at the same B10 level.

Table 5: Modeling the impact of a 5 m cable ACLT performance on a 100 m cable

5 m ACLT life (days)	Eaclt/E	100 m service life/ 100 m ACLT life	n	Expected 100 m service life (days)	Expected 100 m service life (years)
	4	80	3.16		
	4	90	3.25		
100	4	100	3.32	4,700	12.9
	4	110	3.39		
	4	120	3.45		
	4	130	3.51		
	4	140	3.56		
100	4	150	3.61	7,050	19.3

Typical values, not to be construed as specifications. Users should confirm results by their own tests.

Figure 24: ACLT performance of HFDC-4202 and a leading competitor[24]



Overall, if a material extends the test life by a factor of X, then this analysis would suggest a proportional extension of the cable's service life.

In conclusion, we have shown that cables made with ENDURANCE™ HFDC-4202 exceed the industry minimum AWTT requirements and significantly exceeds the ACLT performance of other competitive materials. Based on the material presented in this paper, we have shown that one could expect significantly longer cable service life with ENDURANCE™ materials.

High stress performance for high voltage applications

Currently, cables operated above 46 kV generally use a dry cable design which involves a metallic moisture barrier as well as water absorbing layers to keep the cable core dry. A dry cable typically uses XLPE as the insulation at these higher voltages to achieve maximum transmission efficiency (i.e. by reducing dielectric losses). Manufacturing a dry cable design complicates the overall cable manufacturing process and complicates the installation of cable accessories. With its excellent field performance in wet medium voltage cable applications and in several dry high voltage cable applications, studies were initiated to access the performance of ENDURANCE™ 4202 TR-XLPE for wet high voltage cable designs, i.e., eliminate the metallic moisture barrier and water absorbing components.[46]

Typically, medium voltage cables operate with maximum stresses up to 4 kV/mm at the conductor shield-insulation interface while high voltage cables operate with maximum stresses up to 16 kV/mm. Historically, A4202 TR-XLPE insulation had not been used at stresses above 4 kV/mm. With the growth of extruded dielectrics being used for high voltage cables, a laboratory study was initiated to assess the suitability of ENDURANCE™ B4202 and C4202 for high stress cable applications. The study demonstrated that the ENDURANCE™ 4202 TR-XLPE dissipation factor is well below the high voltage cable specification maximum allowed dissipation factor of 0.1% at temperatures up to 60 to 80ºC and electrical stresses of 10 kV/mm (see Figures 25 and 26).[47] At higher electrical stresses and temperatures, model cable testing (using a 24 mm^2 conductor with 3 mm insulation) indicated the ENDURANCE™ 4202 TR-XLPE would be challenged to meet a 0.1% dissipation factor, though it could meet a 0.5% dissipation factor requirement as currently allowed for TR-XLPE insulated medium voltage cables (see Figure 27).

ENDURANCE™ C4202 TR-XLPE Technology was tested in an accelerated, wet, high stress cable design to assess its performance under wet, high voltage aging conditions.[46] Two 53 mm^2 conductor cables with an insulation thickness of 4.4 mm and 2.7 mm respectively were aged in a water tank at 26 kV and 90ºC conductor temperature. The test voltage of 26 kV corresponds to 3 Vg for a typical 15 kV class cable. For the cable with the 4.4 mm insulation thickness, this corresponds to a maximum electrical stress at the conductor shield of 8 kV/mm and for the cable with the 2.7 mm insulation thickness, this corresponds to a maximum electrical stress at the conductor shield of 12 kV/mm. These electrical stresses are typical of today's high voltage cable designs. Prior to the wet aging, the dielectric strength of the 4.4 mm insulation thickness cable and the 2.7 mm insulation thickness cable were comparable. After an aging period of 120 days under these accelerated wet conditions, the dielectric strength of the cable was measured and is summarized in Table 6. These wet, high electrical stress aging conditions did not show a difference in dielectric strength retention between the two cable designs; both cables had approximately 65% retention of the initial breakdown strength.

Hydro-Quebec, a major Canadian utility, conducted a study with the ENDURANCE™ C4202 TR-XLPE to assess its performance under electrical stresses typical of high voltage cables by reducing the insulation wall thickness on a 53 mm^2 conductor 15 kV cable. The objective of the study was to enable the utility to change the underground cable design to improve the economics of the underground distribution cables while maintaining the system's ampacity and high reliability performance.[48,49,50,51] The cable designs studied were a standard insulation wall thickness of 175 mil (4.4 mm). Experimental Cable Design 1 utilized a 125 mil (3.2 mm) insulation wall thickness, and Experimental Cable Design 2 utilized a 110 mil (2.8 mm) insulation wall thickness. The cables in this test program were assessed in the ICEA AWTT test with the same voltage applied to the three cable designs. This translated into the conductor shield maximum stress during the wet aging of 8.2 kV/mm, 10.6 kV/mm and 11.8 kV/mm respectively for the three cable designs studied.

Figure 25: Dissipation factor of ENDURANCE™ 4202 TR-XLPE at room temperature

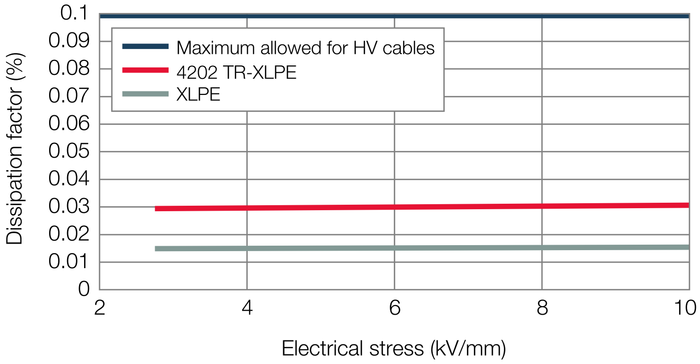


Figure 26: Dissipation factor of ENDURANCE™ 4202 TR-XLPE at 60ºC

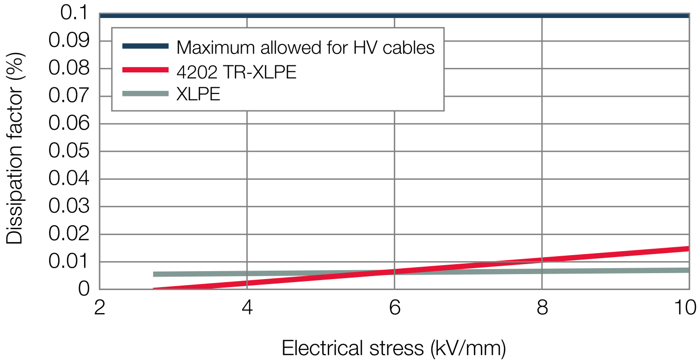


Figure 27: Model cable dissipation factor of ENDURANCE™ 4202 TR-XLPE and XLPE at 100ºC

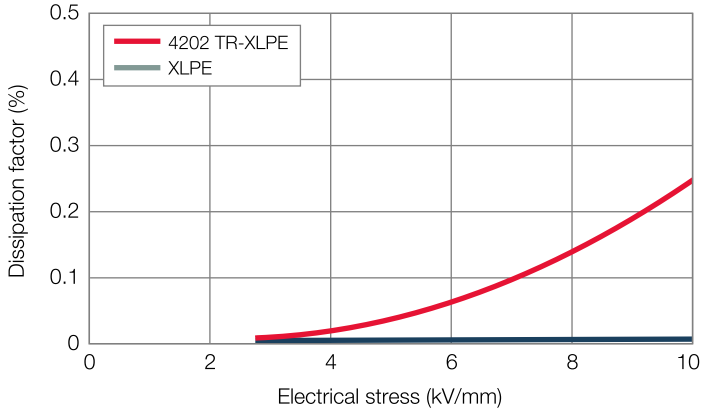


Table 6: AC breakdown strength of cables made with ENDURANCE™ C4202 after high stress wet aging

Insulation thickness (mm)	Maximum electrical stress during aging (kv/mm)	AC breakdown stress after 120 days wet aging (kv/mm)
4.4	8	35
2.7	12	35

The Hydro-Quebec requirement for a standard 1/0 15 kV class cable with 175 mil of insulation after 120, 180 and 360 days of wet electrical aging per the AWTT test is for the cable to have over 26.3, 21.9 and 20.5 kV/mm retained AC dielectric strength, respectively. All three cable designs met this rigorous retained AC dielectric strength requirement that are higher than the industry requirements.

In actual field operation, the cable is expected to withstand an operating voltage while in operation. To determine if the experimental cable designs could meet the voltage withstand requirements for the field application, a voltage withstand requirement was included in the test program. For a 1/0 conductor cable with the standard insulation wall thickness of 175 mils (4.4 mm), the retained dielectric stress requirement was converted to an AC voltage withstand requirement. Thus, after 120, 180 and 360 days of aging, to meet Hydro-Quebec's requirements the cables needed to meet an AC voltage withstand requirement of 117, 97 and 91 kV, respectively after aging. Experimental Cable Design 1 which was subjected to wet electrical aging at 10.6 kV/mm stress, exceeded this requirement, while Experimental Cable Design 2 which was wet electrically aged at 11.8 kV/mm stress, had marginal performance in meeting this requirement. Experimental Cable Design 1 even met the Hydro Quebec voltage requirements after 777 days of wet aging. The cable breakdown voltages obtained in this study are in Table 7. This demonstrates that ENDURANCE™ C4202 has excellent performance under high stress wet aging conditions at 10 kV/mm.

Additionally, "4,4" ACLT testing was conducted on the two experimental cable designs as well as a standard thickness cable design in which the cables were aged to failure. The voltage was maintained at 34.6 kV for all three cable designs with a conductor temperature of 90ºC under the stress cone in air/75ºC in water tanks. The performance is statistically equivalent for all three designs (see Figure 28). The cables were aged at maximum stresses of 11.1 kV/mm for the 175 mil (4.4 mm) wall cable, 14.3 kV/mm for the 125 mil (3.2 mm) wall cable and 15.8 kV/mm for the 110 mil (2.8 mm) wall cable. These studies demonstrate the excellent potential of ENDURANCE™ 4202 TR-XLPE for wet and dry high voltage cable applications.

Figure 28: "4,4" ACLT testing of designs with ENDURANCE™ C4202 TR-XLPE under high stress

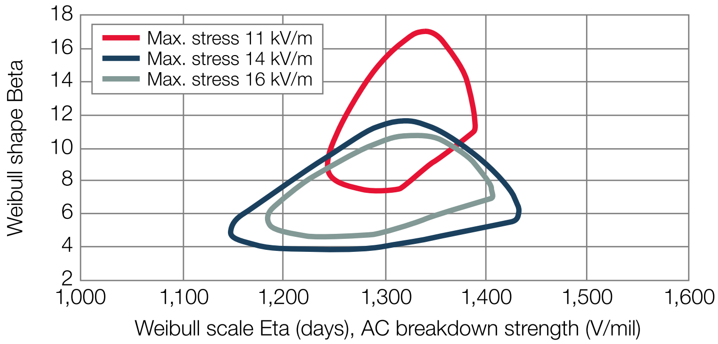


Table 7: AC breakdown voltages of cable designs after high stress wet aging

Aging time (days)	HydroQuebec withstand requirement (kV)	Standard cable (kV) aged at 8.2 kV/mm max. stress	Test cable 1 (kV) aged at 10.6 kV/mm max. stress	Test cable 2 (kV) aged at 11.8 kV/mm max. stress
0	–	227.5 269.5 276.5	108.5 143.5 150.5	129.5 157.5 171.5
120	117	157.5 192.5 206.5	129.5 150.5 171.5	108.5 129.5 136.5
180	97	143.5 164.5 192.5	115.5 122.5 136.5	94.5 115.5 122.5
360	91	115.5 136.5 150.5	101.5 108.5 108.5	80.5 80.5 101.5
777	–	–	87.5 101.5 108.5	94.5 94.5

What's next for ENDURANCE™ 4202 TR-XLPE?

In their 2017 Annual Market Report, the Global Wind Energy Council reported that 52.5 GW of wind power was installed globally in 2017, bringing the total the total installed capacity up to 539 GW.[52,53] Additionally, substantial growth in offshore wind was projected in the coming years. Reports of offshore wind installations in the USA were as follows:

- New York committed to developing 2.4 GW of offshore wind by 2030
- Massachusetts issued its first solicitation for 400 to 800 MW of offshore wind
- Maryland awarded offshore renewable energy credits for the first time to two offshore projects
- At the end of 2017, there were 14 proposed offshore wind projects representing over 12,500 MW of potential capacity

To reduce the cost of off shore wind energy, operators are increasing the array cable voltages from 35 kV to 66 kV, as a 66 kV cable can support 60-65 MW of power generation versus 35 MW for a 35 kV cable, as well as to reduce the cable cost. There is growing interest in using TR-XLPE insulated cables for submarine cable applications, and in April 2018, a CIGRE technical brochure was issued that included "wet" cable designs for submarine cable applications up to 60 kV (with a maximum voltage of 72.5 kV).[54] As referenced earlier in this paper, a "wet" cable design does not have a metallic moisture barrier such as a lead or welded aluminum sheath and is a lower cost solution. As these "wet" design, high voltage submarine cables will be installed in a saltwater environment, the CIGRE technical brochure recommends testing a "wet" cable design in a saline solution with an ionic content between 3 to 6 weight percent. The effect of ionic concentration on the water treeing characteristics of ENDURANCE™ 4202 TR-XLPE was studied following ASTM D6097.[11] Figure 29 demonstrates the effect of ionic content over the range outlined in the CIGRE technical brochure which had minimal impact on ENDURANCE™ 4202 TR-XLPE Insulation Compound water tree growth characteristics, while the ionic content had a major impact on the water tree growth of 4201 XLPE.

These results suggest even in a wet, saltwater environment, ENDURANCE™ 4202 TR-XLPE would maintain excellent water tree-retardant performance similar to that obtained in land environments. This is a component of the recommendation for using ENDURANCE™ C4202 for wet design, offshore wind farm array cables. Figure 30 shows that even with immersion in a 5% saltwater solution, the C4202 TR-XLPE maintains a low dissipation factor. The C4202 was immersed in the 5% saltwater solution at room temperature for 24 days.

Based on the excellent wet electrical performance of ENDURANCE™ C4202 under high electrical stresses, its water tree resistance performance in salt solutions, and its low dissipation factor when wet, the C4202 is actively being tested and qualified for wet high voltage submarine cable applications up to 150 kV and beyond.

Figure 29: Effect of ionic content on ENDURANCE™ 4202 TR-XLPE water tree growth

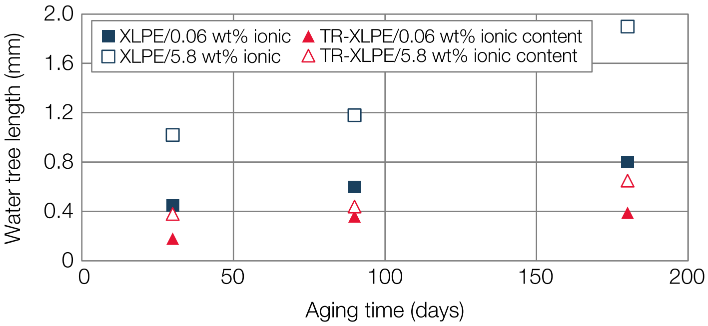
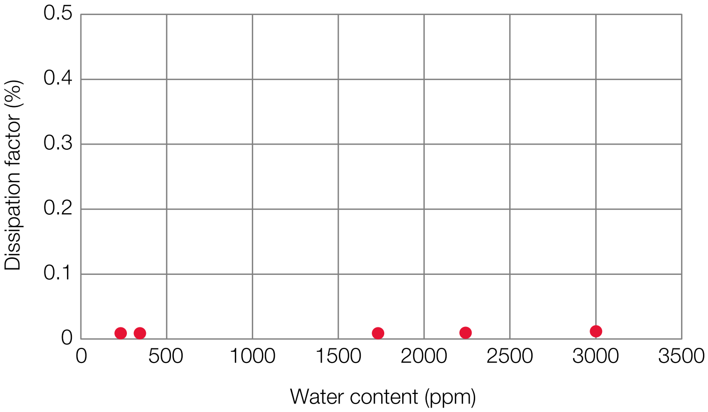


Figure 30: Dissipation factor of C4202 at 60ºC after immersion in 5% salt solution



Summary

Since its introduction in 1983, 4202 TR-XLPE insulation technology has brought significant value to end-users world-wide by significantly extending the life of underground distribution cables. The early success of 4202 TR-XLPE generated competitive insulation products claiming to be TR-XLPEs. In the 1990s, the North American power cable industry initiated defining the performance requirements for a TR-XLPE insulated cable as numerous materials were claiming to be TR-XLPE insulations.[55] The IEEE Insulated Conductors Committee initiated working group 5-31 to develop recommendations and the ICEA cable standards group initiated efforts into defining the performance of a TR-XLPE insulated cable. Both groups utilized the AWTT protocol as a key test to develop a performance requirement.[56] These groups considered the AWTT performance of several competitively claimed TR-XLPEs as well as 4202 TR-XLPE in developing a recommendation which contributed to today's ICEA specifications. With its pioneering ENDURANCE™ 4202 TR-XLPE Insulation Technology, we proposed a TR-XLPE definition that is higher than the ICEA industry requirements. Our recommendations were a minimum AC withstand breakdown of 670 volts/mil (26.4 kV/mm) after 120 days, 550 volts/mil (21.7 kV/mm) after 180 days, and 530 volts/mil (20.9 kV/mm) after 360 days.[57] With its commitments to the power cable industry, Dow has continued to use its higher standard for developing future generations of ENDURANCE™ 4202 TR-XLPE.

In the current economic environment, electric utilities are being forced to cut operating costs and specify the most cost-effective power cable construction. Dow Wire & Cable recommends comprehensive economic analysis based on the present worth of revenue requirements be considered when selecting underground distribution power cable materials. Such analysis will clearly demonstrate that ENDURANCE™ 4202 TR-XLPE Insulation Compound has the lowest total revenue requirements (total owning cost) and lowest annual cost.[58] Specifying ENDURANCE™ 4202 TR-XLPE as the cable insulation compound therefore offers the electric utility a high performance material – proven in the laboratory and in the field – that gives a lower initial cable cost, lower operating cost than other insulation systems during the life of the cable, and a longer service life, which delays costly cable replacement; i.e. a low total cable life cost insulation.

We recommend a total materials system approach to long life cable design. In addition to tree-retardant XLPE insulation compound (C4202 EC), supersmooth, extra-clean conductor shield (A0800 BK or A0802 BK) virtually eliminates water trees from the conductor shield. The A0693 BK strippable insulation shield provides consistent adhesion levels and no pickoff over a range of temperatures and assures a smooth insulation-insulation shield interface. An overall polyethylene jacket will retard the ingress of water and ionic contaminants from the soil, protect the neutrals from corrosion, and protect the cable from mechanical damage during handling and installation.

ENDURANCE™ 4202 TR-XLPE is well established – after 38 years of excellent proven field performance – it is the leading, industry standard, commercial, tree-retardant, long life, lowest total cable life cycle cost utility distribution cable insulation compound.

References

1. Thue, W., Bernstein, B.S., EPRI Distribution Cable Research Digest -2000, BR-110693
2. J. Lawson, and W. Vahlstrom Jr., 1973, “Investigation of Insulation Deterioration in 15 kV Polyethylene Cables removed from Service, Part II.” IEEE Trans. PAS Vol. 92, March/April, p. 824-831
3. G. Bahder, C. Katz, J. Lawson, W. Vahlstrom Jr., 1974, “Electrical and Electromechanical Treeing Effects in Polyethylene and Crosslinked Polyethylene Cables.” IEEE Trans. PAS Vol. 93, p. 977-986
4. Potential Use of New Water Tree-Retardant Insulation in Offshore Wind Farm Array Cables, by S. Cree, et.al., paper B1.3, Jicable 9th International Conference on Insulated Power Cables, June 2015
5. Turbett, R.J., Kabelitems 158, “New Long Life Insulation Compounds,” Union Carbide Corp., 1984
6. Caronia, P.J., Furno, J.S., Pang, K.P., Szaniszlo, S.R., “Advances in TR-XLPE Insulation,” IEEE/PES Transmission and Distribution Conference, April 11-16, 1999, pp.56-61
7. Eichorn, R.M. “Engineering Dielectrics,” Vol. II A, pp. 355-444, 1983
8. A New Generation of Tree-Retardant Crosslinked Polyethylene (TR-XLPE) Insulation by S. Sengupa, T. Person, P. Caronia, 2010 ISEI paper
9. ENDURANCE™ HFDC-4202 EC Enhanced TR-XLPE medium voltage insulation system by P. Caronia, S. Sengupta, T. Person, M. Burtch 2010 2010 IEEE Power Engineering Society, Transmission and Distribution Conference and Exposition
10. HFDA-4202 NT EC/HFDB-4202 NT Tree-Retardant Insulation: Reviewing 20 Years of Proven Performance, S. Szaniszlo, Dow Technical Report, August 2003
11. ASTM D6097 Standard Test Method for Relative Resistance to Vented Water-Tree Growth in Solid Dielectric Insulating Materials
12. A Comparative Economic Analysis for Underground Distribution Cables Insulated with TR-XLPE and EPR by S. Ramachandran, et. al., IEEE Transmission and Distribution Conference, April 1999
13. ANSI/ICEA S-94-649-2013 Standard for Concentric Neutral Cables Rated 5 through 46 kV
14. October 2018 NEETRAC Paper on “High Temperature Operation of Extruded Distribution Cable Systems”
15. Operating Extruded Distribution Cable Systems at Elevating Temperatures by R. Hartlein, et.al., 10th International Conference on Insulated Power Cables, Paper C1-4, June 2019
16. ANSI/ICEA S-94-682-2013 Standard for Utility Shielded Power Cables Rated 5 through 46 kV
17. AEIC CS8 Specification for Extruded Dielectric Shielded Power Cables Rated 5 through 46 kV
18. Hartlein, R.A., “The Accelerated Water Treeing Test (AWTT), Background, Summary, Examples Data, Pros & Cons,” Presented at the Spring ICC Educational Session, Minutes of ICC, IEEE-PES 111th Meeting, April 28-May1, 2002, pp 799-820
19. Banks, V., “Harmonization of Long Duration Test in Europe,” Minutes of ICC, IEEE-PES 111th Meeting, April 28-May1, 2002, pp. 875-890
20. Lyle, R., and Kirkland, J.W., “An Accelerated Life Test For Evaluating Power Cable Insulation,” IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 8, pp. 3764-3771, 1981
21. IEEE Guide 1407 for Accelerated Aging Tests for Medium-Voltage (5 kV-35 kV) Extruded Electric Power Cables Using Water-Filled Tanks
22. Kabelitems No. 164: HFDA 4202 NT EC Tree-Retardant Insulation: Eleven Years of Performance
23. Long-life XLPE-insulated Power Cables by H. Orton, R. Hartlein, pages 40-41, 2006
24. Borlink™ LE4212 provides enhanced performance for medium voltage cables, 2014
25. Dudas, J.H., Cochran, W.H., “Technical Advancements In The Underground Medium Voltage Cable Specifications Of The Largest Investor-Owned Utilities,” Minutes of ICC, IEEE-PES 106th Meeting, Oct. 31-Nov. 3,1999, pp.114-123
26. E. Shu, N. Hampton, “Evolution of MV Extruded Cable Designs Used in the US from 1996 to 2014” JiCable 10th International Conference on Insulated Power Cables, Paper E7-15, June 2019
27. Hartlein, R.A., Cable Design Aging Test, Final Report on project 96-073 available within NEETRAC membership, December 1997
28. Hartlein, R.A., “The ACLT as a Cable Design Aging Test,” Minutes of ICC, IEEE-PES 111th Meeting, April 28- May 1, 2002, Educational Program, pp. 929-941
29. Hartlein, R. A., New Cable Design Aging Test final report on project 97-409, available within NEETRAC membership, April 2009
30. Mendelsohn, A., “The Importance of Quality Compounds for Long Life Cables” Fall 2004 ICC meeting
31. Impact of Semiconductive Shield Quality on Accelerated Aging Cable Performance by P. Brigandi, et.al., 2014 PES Transmission and Distribution Conference
32. Szaniszlo, S.R., Caronia, P.J., “105°C/140°C Rated TR-XLPE Medium Voltage Power Cables”, ICC/T&D Meeting Paper Session Fall 2001

33. The Influence of the Semicon on Cable Dielectric Losses by T. Person, P. Caronia, S. Han, IEEE ICC Spring 2006 Meeting
34. Impulse Strength Retention for Aged TR-XLPE Cables by A. Mendelsohn, T. Person, ICC Subcommittee A, May 19, 2009
35. Katz, C. et al "Comparative Evaluation by Laboratory Aging of 15 kV TR-XLPE and EP Cables", JiCable 6th International Conference on Insulated Power Cables, Paper B.9.4, June 2003
36. The Effect of Contaminants on Aging of TR-XLPE Insulated Cables: An Evaluation of Commercially Produced 15 kV Cables by G. Valdes, et.al. 2011 Spring ICC Meeting, May 24, 2011
37. The Effect of Contaminants on Aging of TR-XLPE Insulated Cables: An Evaluation on Commercially Produced 15 kV Cables, Part 2: The Technology to Produce Commercial Cables with Uniformly Distributed Contaminants by G. Valdes, et.al., 2011 Fall ICC meeting, October 25, 2011
38. The Effect of Contaminants on Aging of TR-XLPE Insulated Cables: An Evaluation on Commercially Produced 15 kV Cables, Part 3: Effect of Preconditioning Protocol on Initial AC Breakdown Strength of Cables with Uniformly Distributed Contaminants by G. Valdes, et.al. 2012 Spring ICC meeting, March 28, 2012
39. The Effect of Contaminants on Aging TR-XLPE Insulated Cables: An Evaluation on Commercially-Produced 15 kV Cables, Part 4: Cable Aging Results and Key Findings from First Phase of Testing Completed in 2010 by G. Valdes, et.al., 2012 Fall ICC meeting, November 12, 2012
40. The Effect of Contaminants on Aging TR-XLPE Insulated Cables: An Evaluation on Commercially-Produced 15 kV Cables, Part 5: Cable Aging Results and Key Findings from Second Phase of Testing Completed in 2012 by G. Valdes, et.al., 2013 Spring ICC meeting, April 29, 2013
41. The Effect of Contaminants on Aging TR-XLPE Insulated Cables: An Evaluation on Commercially-Produced 15 kV Cables, Part 6: Overall Conclusions and Recommendations by. G. Valdes, et.al., 2014 Spring ICC meeting, May 6, 2014
42. Laboratory Aging of TR-XLPE Cables at 500 Hz by T. Person, A. Mendelsohn, 2004 IEEE International Symposium on Electrical Insulation, September 2004
43. 500Hz Accelerated Aging of MV Power Cables by M. Lauxman, GCC, Spring 2014 ICC – A06D
44. Long-life XLPE-insulated Power Cables, Chapter 4.6.2 by H. Orton, R. Hartlein, 2006
45. Bridging the gap between Lab Tests and estimates of Service Performance by N. Hampton, J. Perkel, T. Parker, Spring 2017 ICC A6D Meeting
46. Exploring TR-XLPE Insulation for High Voltage Cables by T. Person, et.al., ICC Subcommittee A, Fall 2008
47. Advancements in TR-XLPE Insulation Technology to Enable Use in High Voltage Cable Application, P. Caronia, et. al., Jicable 2019, B5.1
48. Hydro-Quebec's Test Program on Reduced Wall High Stress MV TRXLPE Cables, Part 1: Objectives and Design by J. Cote, et.al., IEEE ICC Meeting Subcommittee A, Spring 2017 meeting, May 10, 2017
49. Hydro-Quebec's Test Program on Reduced Wall High Stress MV TRXLPE Cables, Part 2: Experimental Testing by C. Dang, et.al., IEEE ICC Meeting Subcommittee A, Spring 2017 meeting, May 10, 2017
50. Hydro-Quebec's Test Program on Reduced Wall High Stress MV TRXLPE Cables, Part 3: Cable Life Expectancy by C. Dang, et.al., IEEE ICC Meeting Subcommittee A, Spring 2018 meeting, May 8, 2018
51. Accelerated Aging Test and Life Expectancy of Reduced Wall High Stress MV TRXLPE Cables by C. Dang, et.al., IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 25, Issue 3, pages 1039 to 1046, June 2018
52. Global Wind Report, Annual Market Update 2017 by the Global Wind Energy Council
53. TR-XLPE Insulated Cables For Wet High Voltage Cable Applications by P. Caronia, et.al., IEEE ICC Fall 2018 Meeting, subcommittee A
54. CIGRE Technical Brochure 722 Recommendations for Additional Testing for Submarine Cables from 6 kV up to 60 kV
55. Ad Hoc Group 5-31-Definition of Tree-Retardant Crosslinked Polyethylene, IEEE ICC Spring 1997 Meeting, April 21, 1997
56. A Review of Possible Methods for Defining Tree-Retardant Crosslinked Polyethylene, by S. Pelissou, et.al., IEEE Electrical Insulation Magazine, 2008)
57. TRXLPE Definition Based on New XLPE AWTT Data Base by J. Hansen, et.al., IEEE ICC Fall 2000 meeting, Working Group A4W, November 1, 2000
58. A Life Cycle Analysis Study of Competing MV Cable Materials by S. Sutton, CIRED 21st International Conference on Electricity Distribution, Paper 0203, June 2011

Back to contents

For more information about Dow, visit www.dow.com/about. To contact a Dow representative, visit, www.dow.com/contact.

NOTICE: No freedom from infringement of any patent owned by Dow or others is to be inferred. Because use conditions and applicable laws may differ from one location to another and may change with time, Customer is responsible for determining whether products and the information in this document are appropriate for Customer's use and for ensuring that Customer's workplace and disposal practices are in compliance with applicable laws and other government enactments. The product shown in this literature may not be available for sale and/or available in all geographies where Dow is represented. The claims made may not have been approved for use in all countries. Dow assumes no obligation or liability for the information in this document. References to "Dow" or the "Company" mean the Dow legal entity selling the products to Customer unless otherwise expressly noted. NO WARRANTIES ARE GIVEN; ALL IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE ARE EXPRESSLY EXCLUDED.

THIS INFORMATION IS OFFERED IN GOOD FAITH FOR YOUR CONSIDERATION, BUT WITHOUT GUARANTEE OR WARRANTY (EXPRESS OR IMPLIED), AS ANALYTICAL CONDITIONS AND METHODS OF USE OF THE INFORMATION AND MATERIALS DESCRIBED HEREIN MAY VARY AND ARE OUT OF DOW'S CONTROL. ALTHOUGH THIS INFORMATION IS BASED ON DATA DOW BELIEVES TO BE RELIABLE AND ACCURATE, WE DO NOT INTEND FOR YOU TO USE, AND YOU THEREFORE SHOULD NOT CONSTRUE, THE CONTENTS OF THIS DOCUMENT AS BUSINESS, TECHNICAL OR ANY OTHER FORM OF ADVICE. WE RECOMMEND YOU DETERMINE THE SUITABILITY OF THE INFORMATION AND MATERIALS DESCRIBED HEREIN BEFORE ADOPTING OR USING THEM ON A COMMERCIAL SCALE. DOW ASSUMES NO LIABILITY IN CONNECTION WITH THE USE OF THIS INFORMATION.

This document is intended for use in North America.
© 2021 The Dow Chemical Company

®™Trademark of The Dow Chemical Company ("Dow") or an affiliated company of Dow

Form No. 250-174-01-1121 SMG
SMG 14079