Behind the Scenes of the Development of DC XLPE Power Cables
The Teachings of Prof. K. Yahagi: "Seek the Truth"

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The author received the Yahagi Memorial Award 2019 from the Technical Committee on Dielectrics and Electrical Insulation, the Institute of Electrical Engineering of Japan. In this paper, memories of the late Prof. Kichinosuke Yahagi and his teachings are described by a former student. The teachings of Prof. K. Yahagi can be summarized as "Seek the Truth." The author pursued a number of truths according to said teachings in his research and development endeavors. The development of cross-linked polyethylene insulated DC power cables rated for the world's highest voltage was brought about as one of the results of the teachings.

Keywords: Yahagi Memorial Award, XLPE cable, DC cable, space charge, treeing

1. Introduction

In 2019, the author received the Yahagi Memorial Award from the Technical Committee on Dielectrics and Electrical Insulation, the Institute of Electrical Engineers of Japan. The committee has three academic/technical memorial awards honoring the legacies of three professors—Prof. Yoshio Inuishi (Osaka University), Prof. Masayuki Ieda (Nagoya University), and Prof. Kichinosuke Yahagi (Waseda University), who each contributed to raising the quality of dielectric and insulating material research to a world-class level. The Yahagi Memorial Award is presented to persons who have made a significant contribution to industrial technology. The author belonged to the Yahagi Laboratory during his undergraduate and postgraduate student days and received tutelage from Prof. Yahagi. Consequently, he adopted Prof. Yahagi's research style. In this paper, some memories of Prof. Yahagi, his teachings, and research results achieved through his teachings, are described. This paper was revised based on the conference paper of the Yahagi Memorial Award commemorative lecture.(1)

2. The Teachings of Prof. Yahagi

Prof. Kichinosuke Yahagi was known as a professor who was inordinately strict about everything. In other words, he was a teacher with a "scary" image, but surprisingly, he taught me about Vermeer, a Dutch painter. When I was a postgraduate student, Prof. Yahagi called me, gave me a research paper, and asked, "Mr. Katakai, do you know of a painter named Vermeer?" Vermeer is particularly famous for "The Milkmaid," "Girl with a Pearl Earring," and others. However, at that time, I was totally unfamiliar with fine art. I was merely a student who came from the countryside to Tokyo. Moreover, I never dreamed that Prof. Yahagi would pose a question about a painter. Prof. Yahagi continued, "This is a research paper on the dielectric breakdown of glass(2) written by a person, who coincidentally had the same name as the painter. This paper describes the answer to the question posed to you by Mr. Hikita (then a doctoral student at Nagoya University, and later a professor at Kyushu Institute of Technology) at an academic conference. Read this paper carefully." Prof. Yahagi gave me the answer to the question, to which I had been at a loss for finding an answer. At the time, I was involved in research on the dielectric breakdown of polyethylene in a high-temperature range.(3) Prof. Yahagi intended to teach me that I should study the dielectric breakdown of glass, which is completely amorphous, because it has something in common with polyethylene in a molten state. However, "Vermeer, the painter" was more impressive to me than the theory on the dielectric breakdown of glass.

When Prof. Yahagi lectured on the dependence of the breakdown of polyethylene on applied voltage waveforms, he told us, "If you treat persons rigorously, they will also respond to you in a hostile manner. If you treat persons gently, they will also respond to you softly. Polyethylene behaves in the same manner as human beings. Polyethylene responds differently depending on the applied waveform such as steep wave fronts, slow wave fronts, direct current (DC), and alternating current (AC)." I was absolutely amazed at Prof. Yahagi's curious philosophical explanation.

Photo 1. The late Prof. Kichinosuke Yahagi (Center), Dr. Naohiro Hozumi (currently a professor of Toyohashi University of Technology) (left) and the author (right) (back in 1983)

After receiving such tutelage from Prof. Yahagi, I joined a cable manufacturer and have spent a career fascinated by polyethylene. What I will never forget is the advice Prof. Yahagi gave me when I left university after finishing my graduate studies: “Seek the truth. Then, you will be recognized by others.” Since then, I have devoted myself to research and development (R&D), with “Seeking the Truth” as my personal motto. Some examples of my R&D results are presented in the following sections.

3. Seek the Truth 1: Investigation into the Causes of Product Failures

—Discovery and reproduction of Cotton-like trees—

A manufacturer's research department is often required to respond to product failures when they occur. In particular, in the event of a failure involving an important or recorded product, the investigation of the true cause is a top priority. Investigating the true cause is not limited to its theoretical presumption, but it is necessary to carry out a reproduction test to verify that the presumption is correct. It is further necessary to limit the spread of failures to already-supplied products and to draw up failure-prevention measures. Although manufacturers are unwillingly to disclose product failures, some of them are presented at academic conferences when the elucidation of the failures led to discoveries or other technical achievements. An example is shown below.(4) When the dielectric breakdown part of a product is observed, a number of electrical trees of indeterminate directions were observed in the insulator, which resembles a “subarachnoid hemorrhage” as shown in Photo 2. No one had seen such a phenomenon previously. Everyone thought that it would be impossible to reproduce this phenomenon, even if the cause of the breakdown was determined. Since “subarachnoid hemorrhagic trees” was too inelegant a phrase to call this phenomenon, I wanted to find a name for it. Initially, I struggled to come up with a suitable name. In the end, I named this phenomenon “Cotton-like trees” after taking a cue from “cotton,” a term that appears in the once-popular song “Cyclamen no Kaori (The Scent of Cyclamen).” I then began solving the problem. The cause itself of the dielectric breakdown could be identified as the existence of “voids” in a relatively short time. However, when the breakdown tests for insulators containing an artificial void were conducted repeatedly, even though an electrical tree starting from the void was recognized, not even a glimpse of random electrical trees, as shown in Photo 2, appeared. Then, I tried to clarify the difference between the simulation test and the phenomenon in an actual product. A simulation test is carried out to reproduce a breakdown phenomenon in a very short time, while a phenomenon in an actual product occurs after the product is used for several years. Further, the breakdown electric field was not 10 to 100 kV/mm but was only a few kV/mm. For dielectric breakdowns (the generation of an electrical tree) attributed to void discharges, the life exponent n (V-t law ($V^n \times t$ = constant, where V: voltage, t: time)) is generally known to be 9.(5) This means that even if the discharges continue in the void, the erosion of the void wall surface does not rapidly progress, and it takes time until the void changes to (the generation of) an electrical tree.(6) Meanwhile, a breakdown test is usually carried out under the condition of a high electric field of several tens of kV/mm or more. Once an electrical tree is generated in the test, the test sample will be immediately broken down completely. I assumed that, since the electric field around the void is only a few kV/mm in an actual product, the electrical tree does not easily extend even if an electrical tree is generated from the void. The insulation will not breakdown completely until considerable time has elapsed. To check whether the above assumption was correct or not, the following test was carried out.(4)

A cross-linked polyethylene (XLPE) block made of the same material as that of the actual product was used as the test sample. As the first procedure of the test, a treeing needle with a tip radius curvature of 10 µm was inserted into the polyethylene block and AC 18 kV voltage was first applied for 30 minutes to generate an electrical tree (a so-called “Aegagropila-like tree”). Following the above procedure, the test voltage was reduced to 10 kV, and the voltage was applied continuously for a long time. Photo 3 shows the shape of the electrical trees of the sample after applying AC 18 kV for 30 minutes and AC 10 kV for 2 hours. This photo shows that an Aegagropila-like tree was observed at the tip of the needle, and a lot of dendritic trees were further generated in indeterminate directions around the Aegagropila-like tree. These dendritic trees extended

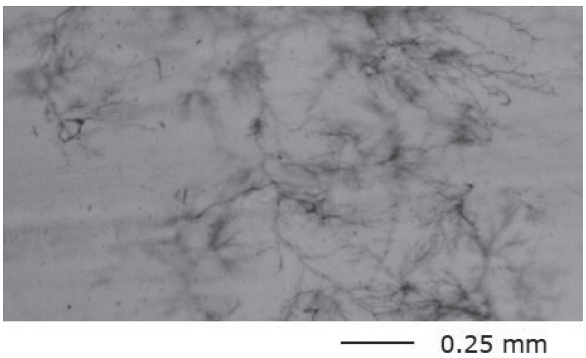

Photo 2. Electrical trees in random directions (named “Cotton-like trees”) observed near a breakdown path in XLPE base insulation of a product(1)

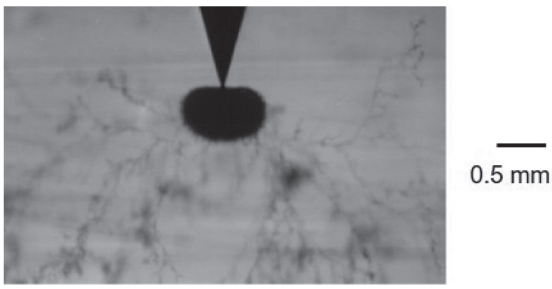

Photo 3. Feature of electrical trees (an Aegagropila-like tree & Cotton-like trees) after AC 18 kV × 30 min. & AC 10 kV × 2 h voltage application(4)

from the Aegagropila-like tree, when AC 10 kV voltage was applied. Though the shape of these intricate dendritic trees individually was the same as that of conventional electrical trees, when observed collectively, they extended in various directions in as complex a manner as the “Cotton-like trees” that were observed in the breakdown part of the actual product shown in Photo 2. An additional test was carried out using a new test sample manufactured by the same procedure, and the last AC 10 kV voltage was continuously applied until breakdown occurred. The breakdown occurred after 17 hours of AC 10 kV voltage application.

In this way, the “Cotton-like trees,” which had seemed to be unreproducible, could be reproduced. The next task was to explain why electrical trees of indeterminate directions are generated. These anomalous tree shapes reminded us of the Lichtenberg image[7] observed in an electron beam-irradiated polyethylene or a polymethyl methacrylate block, of which the phenomenon is caused by space charges. Then, I used the dust figure method[8] to check if the space charges are involved in the generation of electrical trees. Photo 4 shows the dust figure detected in the sliced cross-section of the sample shown in Photo 3. The adhesion of the toners was clearly observed in the cross-section, suggesting the accumulation of space charges. Positive and negative charges were mixed together, and the charges distributed in a complex manner. Specifically, it seemed that many positive charges gathered in the insulator near the tree trunk, while many negative charges gathered in the insulator near the tree tip. There was no report describing the fact that space charges are conspicuously accumulated in an XLPE insulator when it is exposed to AC voltage. However, the dust figure method clarified that space charges accumulate around these electric trees even when AC voltage is applied. In this test, an Aegagropila-like tree was generated at the first stage where AC 18 kV was applied. This Aegagropila-like tree can be regarded as a void in which electrical trees were generated. Therefore, it was considered that the electrical trees generated during subsequent AC 10 kV voltage application, extended with discharges. The possibilities that the accumulation of space charges was caused by the discharges in the electrical tree cavities was considered. The space charge accumulation was checked when the discharges occurred in a spherical void. As a result, no space charge was observed around a smooth void wall surface. However, the following assumption was drawn up. The discharges at the tip of the electrical tree cavities are considered to cause repetitive injection/extraction of charges since the tip of the tree is extremely sharp. Since the injection and extraction distances are unbalanced due to the polarity of the charges, this causes the accumulation of space charges. If the charges are intensively accumulated in the vicinity of the tip of the trees, partial destruction (extension of the tree) may be caused by a local high electric field that is generated when the polarity is reversed in each half cycle of the AC voltage. It is estimated that the generation of “Cotton-like trees” results from a repetition of the cycle of discharges, accumulation of charges, and extension of the trees. This tree generation mechanism is shown in Fig. 1 schematically.

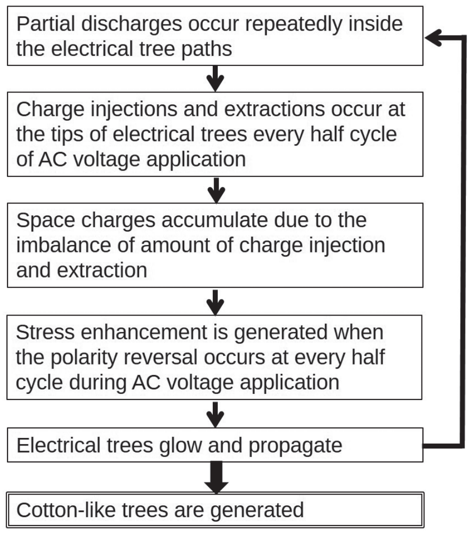

Fig. 1. Schematic representation of generation mechanism of Cotton-like trees[4]

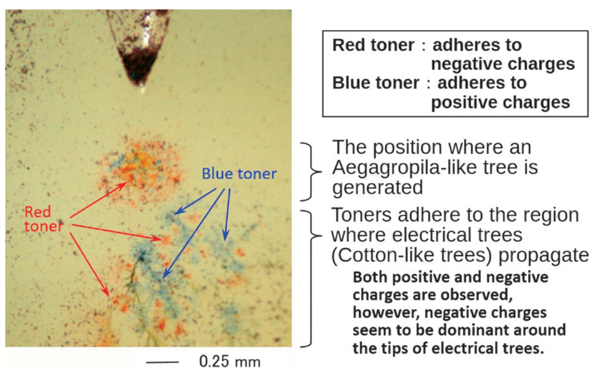

Photo 4. Dust figure pattern of treeing sample after AC 18 kV × 30 min. & AC 10 kV × 2 h voltage application[4]

Meanwhile, it may be difficult for manufacturers to avoid any product failures as long as they continuously make and sell products. However, manufacturers’ sincere efforts to solve the cause of product failures can improve not only their scientific analysis ability but also their design, manufacturing, and inspection abilities. In addition, if the causes are clarified and full countermeasures are taken, they can restore the trust of their customers. Manufacturers should be positive about dealing with product failures. Needless to say, it is more important to minimize product failures through preliminary examinations (such as Failure Mode and Effect Analysis and Design Review Based on Failure Mode).[9]

4. Seek the Truth 2: Development of DC XLPE Cables
—Overcoming setbacks—

I think that the development of a DC XLPE cable is one of the reasons that I received the Yahagi Memorial Award. In fact, I devised my own cable insulating material combination, which became an epoch-making technology that was actually used for the Hokkaido–Honshu interconnection and other transmission lines. Before inventing this technology, I experienced many setbacks. One of my typical setbacks is described below.

4-1 Examination into the problem related to the XLPE insulation under DC voltage

In 2000, AC XLPE cables were put to practical use for a 500 kV long-distance transmission line.(10) However, it was difficult to use the XLPE cables for DC applications due to the following problems(11): ① the DC breakdown strength is low; ② the DC breakdown strength is highly dependent on cable insulation thickness; ③ the DC breakdown strength is highly dependent on temperature; ④ the strength under superimposed reversed-polarity impulse application is low, and ⑤ the breakdown strength under polarity reversal voltage application is low.

First, I investigated the causes of these problems. Since the electric field of a DC cable depends on its volume resistivity ρ, I investigated how the ρ of an XLPE cable insulation is distributed in the radial direction of the insulator.(12) Figure 2 shows the investigation results. In this investigation, the insulator of the XLPE cable was thinly sliced in the radial direction to measure ρ and the amount of the residual peroxide byproducts W. When the wall of the insulator is divided into three layers (inner, intermediate, and outer layers), the ρ-values of the inner and outer layers are higher than that of the intermediate layer. When DC voltage is applied to an XLPE cable having such ρ-distribution, the voltage is mainly shared by the inner and outer layers, resulting in a reduction of the effective insulation thickness of the cable. The distribution of ρ is mainly attributed to the distribution of the amount of peroxide byproducts. The ρ-value of the XLPE cable depends on the concentration of the residue, and it decreases as the amount of residue increases. Since the residue in the cable insulator easily volatilizes toward the outside and the gap between the conductors, the radial residue amount distribution is larger in the intermediate layer than in the inner and outer layers, as shown in Fig. 2. As a result, the ρ-value in the inner and outer layers is higher than that in the intermediate layer.

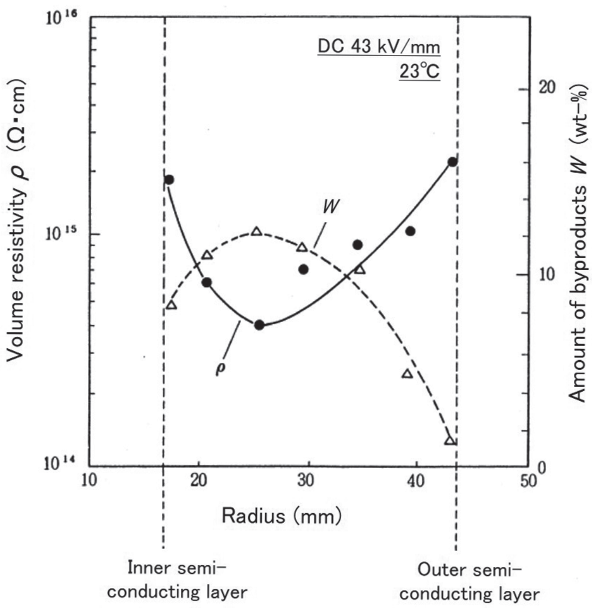

Fig. 2. Distribution of volume resistivity ρ and amount of peroxide byproducts W in 275 kV XLPE cable (27 mm-t, 600 mm^2) in the radial direction of the insulator(12)

The accumulation of space charges in the XLPE material was also investigated using the thermally stimulated current (TSC) measurements.(13) The investigation results are shown in Fig. 3. In addition to the data on XLPE and low-density polyethylene (LDPE), which is the base material of XLPE, this figure also shows the data on high-density polyethylene (HDPE) for comparison. The investigation results revealed that XLPE has an extremely high TSC peak value, which implies a large amount of charge accumulation. In contrast, the TSC peak value of LDPE, the base material of the XLPE cables, is not high. It seemed that the difference between the same types of base material would be attributed to additives. As a result of this detailed investigation, it was found that the increase was mainly caused by peroxide byproducts.(12)

As described above, it was found that the residual peroxide byproducts reduce ρ and increase the amount of space charge accumulation. Regarding ① to ⑤ mentioned as problems in XLPE cable insulation under DC voltage, ① to ③ can be explained by ρ distribution and its absolute value, while ④ and ⑤ can be explained by the accumulation of space charges. Problems ① and ② can also be explained by the local high electric field generated due to space charges. Since all of these problems are mainly attributed to the peroxide byproducts, the key to the development of a DC cable is how to minimize the adverse effect of peroxide byproducts.

4-2 Approach to the development of a DC cable using HDPE

Figure 3 shows the TSCs of XLPE, LDPE, and HDPE. Among these, the TSC of HDPE is the smallest, which means that the space charge accumulation is small. The accumulation of charges depends on the branch length of the polyethylene molecule. Because of its linear structure and short branch length, HDPE minimizes the accumulation of space charges.(12) Incidentally, the dielectric breakdown strength of polyethylene is correlated with its density. The higher the density, the higher the dielectric breakdown strength.(12),(13) That is, HDPE is a material that has a low accumulation of space charges and has a high dielectric breakdown strength. Moreover, when assuming that the continuous operating temperature is 90°C in DC cables, HDPE can be used without crosslinking because of its high melting point, approximately 130°C. It is therefore unnecessary to consider the influence of peroxide byproducts because no peroxide agent is used in HDPE. From this point of view, it was considered to be one way to use HDPE as a DC cable insulator. Therefore, a prototype eval-

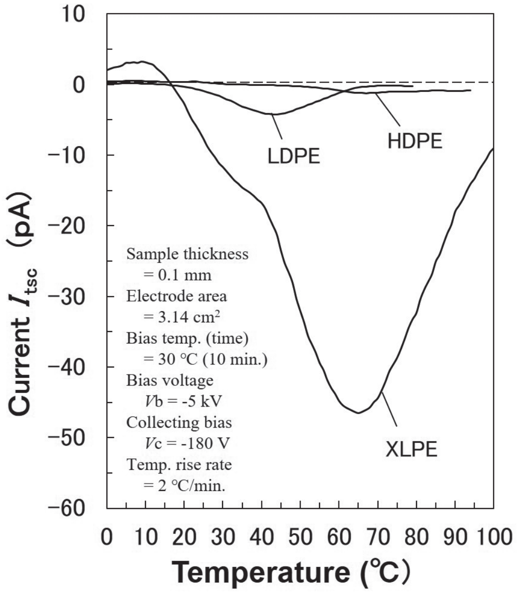

Fig. 3. TSC spectra of XLPE, LDPE and HDPE[13]

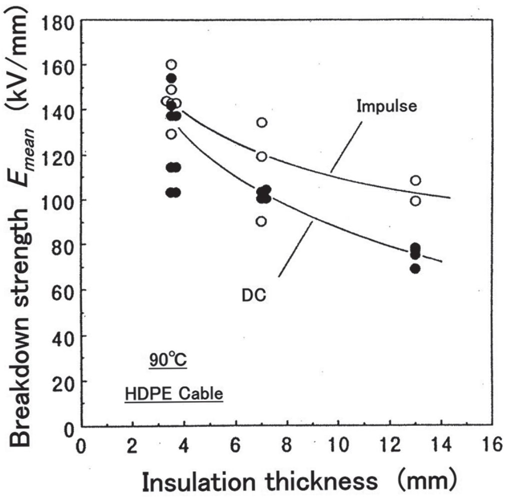

Fig. 4. Insulation thickness dependence of breakdown strengths of HDPE cables[13]

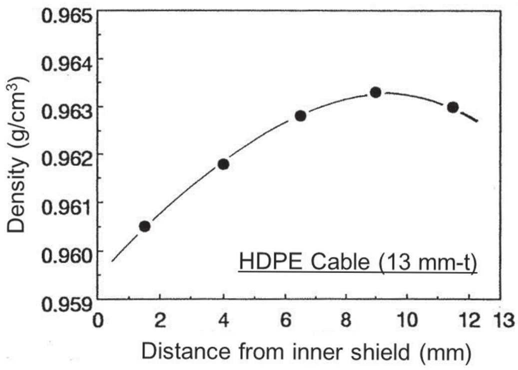

Fig. 5. Density distribution of HDPE cable insulation (13 mm-t)[13]

uation was made using the model cables with an insulation thickness of 3 to 13 mm. As expected, a cable with an insulation thickness of 3 mm demonstrated high impulse and DC breakdown strengths. However, as shown in Fig. 4, the DC breakdown strength dropped greatly as the insulation thickness increased. As a result of various inquiries into the cause, it was clarified that many voids are generated in the insulator as the insulation thickness increases. Figure 5 shows the density distribution of an HDPE cable insulator with 13 mm wall thickness. From this figure, it can be seen that the insulator density decreases towards the inner layer. However, in general, when the cables are manufactured, the inner layer of a cable insulator is gradually cooled as compared with the outer layer, so that the crystallinity and the density of the inner layer are high. Therefore, it was considered that the generation of voids might decrease the density of the inner insulating layer. Observation of the voids in the insulator was conducted, and it was confirmed that the quantity and size of the voids increase as the insulation thickness increases.[13] A feature of HDPE is that it rapidly and volumetrically shrinks during crystallization. As the cable insulation thickness increases, the temperature difference between the inner and outer layers of the insulator increases. Since the inner layer remains in a molten state even when the outer layer solidifies, a material that changes its volume significantly, such as HDPE, is subjected to large stress in the radial direction, and easily generates voids. That is, the generation of a void in HDPE is caused by its rapid volume change during crystallization. Due to such characteristics of HDPE during crystallization, HDPE was found to be unsuitable for thick-wall molding. It was impossible to obtain the expected performance from a thick-wall HDPE cable. As a result, the development of HDPE DC cables had to be abandoned. Although it was a setback in terms of product development, we learned from the setback that the insulator for an extra-high voltage DC cable must be of an excellent standard in thick-wall moldability as well as DC insulating performance.

4-3 Development of DC cables using filled XLPE

XLPE is excellent in terms of thick-wall moldability and it is actually used for AC cables with thick insulation. Based on the above achievements, we determined to focus on the development of a DC cable using XLPE as the base material. To this end, it was indispensable to limit the adverse effects of the residual peroxide byproducts, as discussed in Section 4-1. Fortunately, the study of a filled XLPE cable for DC applications had been conducted previously.[14] As far as DC performance is concerned, the filled XLPE cable had been found to have satisfactory characteristics. Then, we inquired into the effects of the fillers in more detail.

Figure 6 shows the distribution of ρ in a filled XLPE cable (insulation thickness: 13 mm) in the radial direction of the insulator.[15] For comparison, Fig. 6 also shows the distribution of ρ in a conventional (unfilled) XLPE cable. The value of ρ in the filled XLPE cable had a high absolute value and distributed almost uniformly in the radial direction. The amount of byproducts in the filled XLPE cable was larger in the inner layer than in the outer layer. This uniform distribution of ρ in the radial direction suggested that ρ in the filled XLPE would rarely be affected by the byproducts. Figure 7 shows the TSC measurement results for the filled XLPE.(15) This figure also shows the TSC of a conventional (unfilled) XLPE for comparison. The TSCs shown in the above figure were measured by alternating the polarity of collecting bias Vc. It can be seen from the figure that the unfilled XLPE changes the polarity of the peak TSC in response to a change in the polarity of Vc, while the filled XLPE does not change the polarity of the TSC even when the polarity of Vc is changed. It only exhibits a current whose polarity is opposite to that created when initial bias voltage Vb is applied. This means that the TSC of the unfilled XLPE reflects the current created by the internal real charges (accumulated charges), while the TSC of the filled XLPE mainly reflects the depolarization phenomenon and the fact that the accumulation of charges in the filled XLPE is rarely detected. It can be expected from the results shown in Figs. 6 and 7 that the addition of a filler will increase ρ, control the accumulation of space charges and eliminate the effect of peroxide byproducts.

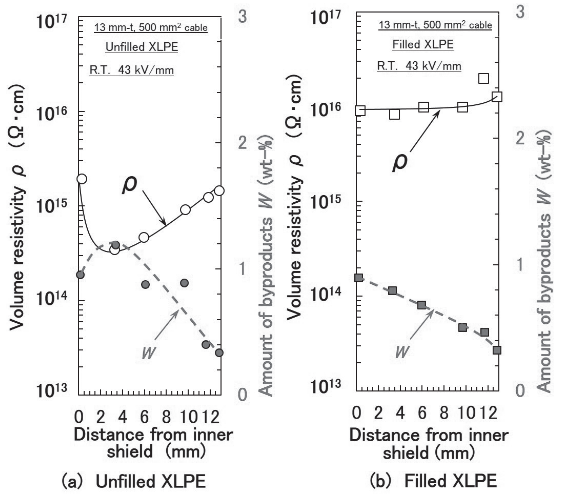

Fig. 6. Difference between filled and unfilled XLPE cables in volume resistivity ρ and amount of peroxide byproducts W in the radial direction of the insulator(15)

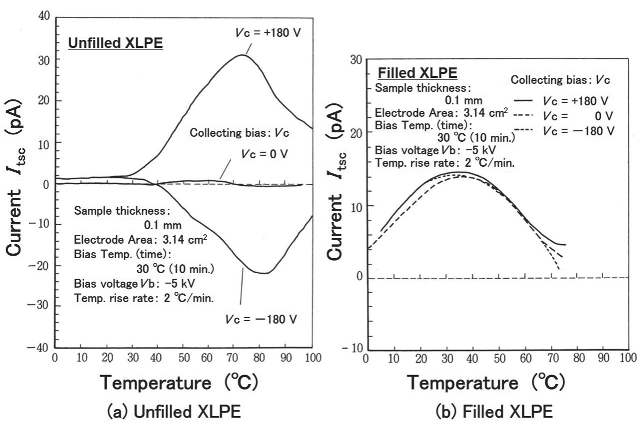

Fig. 7. TSC spectra of unfilled and filled XLPEs(15)

As discussed above, the filler has excellent effects on DC insulating properties. Consequently, the filler acts as a so-called contaminant in polyethylene, thus one drawback is a reduction of its impulse breakdown strength.(15) Therefore, for the development of an extra-high voltage DC XLPE cable, it was necessary to improve the impulse breakdown strength while ensuring the excellent DC characteristics of the filler. The filler used for the former study at that time was made of natural ores such as talc and clay. Since the filler contained various components, the component analysis of the filler was firstly performed to identify the components that improve the DC characteristics and those that do not adversely affect the impulse breakdown strength. For evaluation, samples made by kneading the reagent of each component with polyethylene were prepared, and the TSCs of each sample were measured, and their impulse breakdown strengths were evaluated. As a result, it was possible to determine the major components that improve the DC characteristics and the components that do not significantly affect the impulse breakdown strength. Subsequently, we conducted various investigations on fillers, and found that a highly pure and ultrafine filler (nanofiller) exists. After that, I evaluated the performance of XLPE containing the new filler (highly-purified nanofiller) and confirmed that the new XLPE dramatically improves the impulse breakdown performance and DC characteristics.(16) Figure 8 shows the ρ-characteristics at 90°C of XLPE containing the new filler.(17) For comparison, this figure also shows the ρ-characteristic of unfilled XLPE. XLPE containing the new filler has an extremely high ρ-value. In particular, the value is a hundred times higher than that of unfilled XLPE, even in a high temperature and high electric field. Figure 9 shows the space charge that was measured using the pulsed electro-acoustic method (PEA method).(18) Very few accumulations of space charges were observed in XLPE containing the new filler. Figure 10 shows the DC breakdown strength of a cable with an insulation thickness of 9 mm. The XLPE cable with the new filler had a DC breakdown strength of 140 kV/mm, which is more than two times that of unfilled XLPE.(17) Regarding the impulse breakdown voltage, a 500 kV class cable (insu-

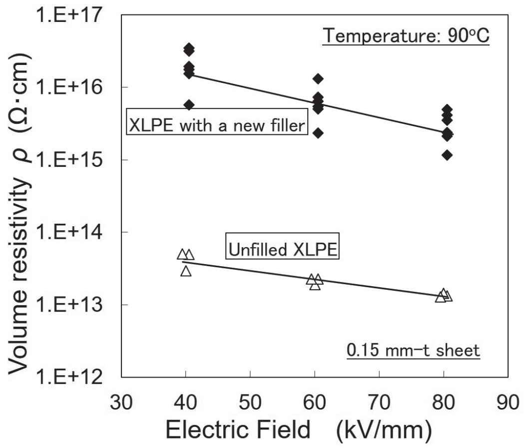

Fig. 8. Electric field dependence of volume resistivity of XLPE with a new filler (DC-XLPE) and unfilled XLPE (AC-XLPE)(17)

lation thickness: 23 mm, conductor size: 3,000 mm^2) proved to have a breakdown voltage as high as approximately 2,000 kV. This cable also had satisfactory superimposed impulse breakdown performance under reversed polarity. In particular, the Bahder coefficient K of the cable was 0.5.[16] The XLPE cable containing the new filler passed the ±250 kV class prequalification (PQ) tests and the type tests in compliance with CIGRE TB-219,[19] and has been operating as an actual ±250 kV DC cable for the HVDC link between Hokkaido and Honshu since December 2012.[18] In addition, XLPE cables containing the new filler started operation not only in Japan but also as a ±400 kV DC England–Belgium interconnection line in January 2019.[20] A ±525 kV class cable has already passed the type and PQ tests in compliance with the CIGRE TB-496.[21]

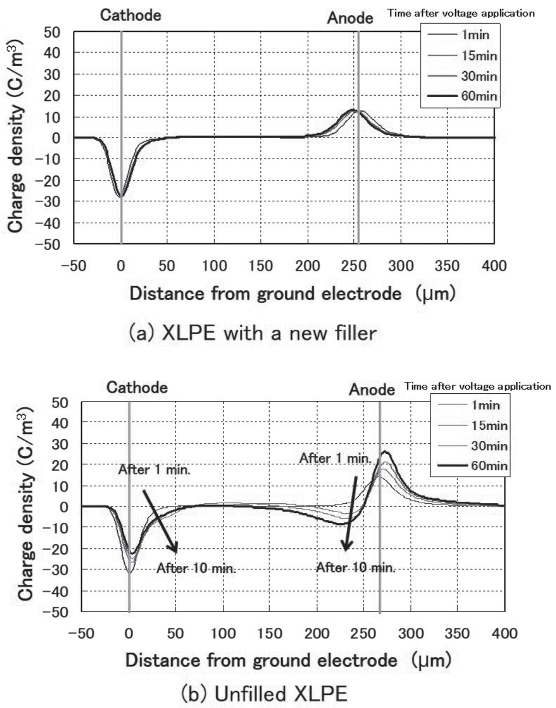

Fig. 9. Space charge distribution of XLPE with a new filler (DC-XLPE) and unfilled XLPE (AC-XLPE)[18]

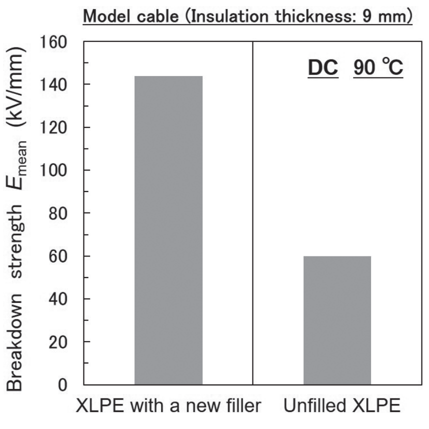

Fig. 10. DC breakdown strength of new XLPE cable with a new filler (DC-XLPE) and unfilled XLPE cable (AC-XLPE)[17]

5. Seek the Truth 3: Evaluation of Harmfulness of Bow-tie Trees (BTTs)

—Together with the investigation of an electrical tree generation mechanism—

Recently, I reevaluated a theme with which I had been especially concerned over the years. It was a semi-quantitative evaluation of the electrical tree generation mechanism from bow-tie trees (BTTs).[22] Furthermore, based on the reevaluation results, I thought that the influence of BTTs, which had not been considered in the current insulating design for AC extra-high voltage (EHV) XLPE cables, should be reconsidered.[23] Considering the fact that the AC 275 kV transmission lines were approaching the end of their 30-year design life, and the AC 500 kV transmission lines had been used for 20 years, a reexamination seemed necessary.

5-1 Study of an electrical tree generation mechanism from BTTs

If electric voltage is applied to an XLPE cable in a wet environment, water trees are generated and the cable's performance is degraded. When the water trees extend, the electrical trees are generated from the water trees, as shown in Photo 5, causing dielectric breakdown. In Photo 5, a BTT is illustrated as a kind of water tree, where BTTs grow from such defects as contaminants or voids in the cable insulator. The onset point of the electrical trees is often the tip of the BTT, when the BTT is small. When the BTT is extended, the electrical trees occasionally start from a position slightly inside the tip of the BTT, as shown in Photo 5. We focused on the phenomenon of electric tree generation from a BTT and conducted a semi-quantitative study on its generation mechanism.[22] Our study received the 2020 IEEJ Distinguished Paper Award for the intrinsic elucidation of a cable failure phenomenon. For details of its study, see reference.[22] In this section, the relationship between the length of the BTT and the breakdown strength of the cable, which is the harmful effect of the BTT on the cable performance, is discussed.

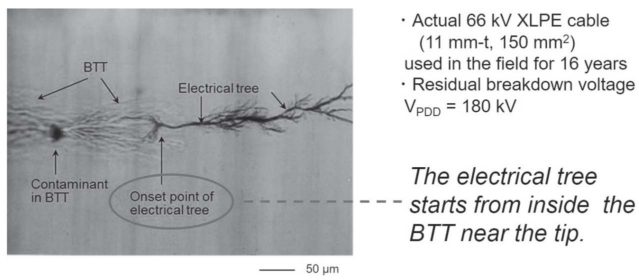

Photo 5. Example of electrical tree starting from a BTT in an actual 66 kV XLPE cable[22]

5-2 Evaluation of harmful effects of BTTs on XLPE cable performance

A water tree is said to be a group of small voids filled with water. Since the relative permittivity of polyethylene $\varepsilon_{r\,(PE)}$ is 2.3 and that of water $\varepsilon_{r\,(H2O)}$ is 80, the relative permittivity of BTT $\varepsilon_{r\,(BTT)}$ is estimated to be higher than that of the surrounding polyethylene. In other words, a BTT can be regarded as a heterogeneous dielectric in polyethylene. In this study, we viewed the relative permittivity inside a BTT as dielectrics having a uniform value, and assumed that an electrical tree would be generated or dielectric breakdown would occur when the electric field at the tip of the BTT reaches the electrical tree inception stress, a critical electrical tree generation value. The above assumption made it possible to derive the relationship between BTT length and cable breakdown strength by determining the value of $\varepsilon_{r\,(BTT)}$ and the value of electrical tree inception stress Ei.[22] The concept of this method is illustrated in Fig. 11.

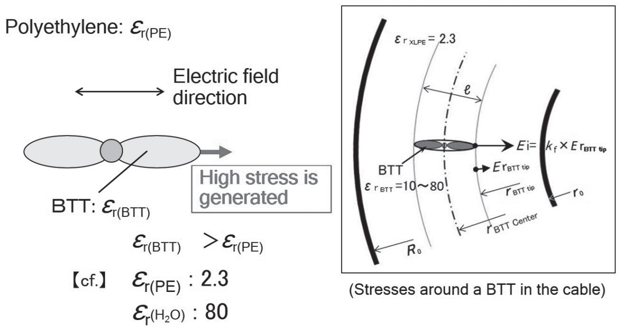

Fig. 11. Simple conceptual ε model (a BTT in polyethylene)[22]

Figure 12 shows the experimental results of the relationship of the BTT length and breakdown voltage obtained by an XLPE cable having an insulation thickness of 6 mm, and the calculation results obtained by using the above concept. It should be noted that, in the region where the BTT length is 500 µm or less (Region B in Fig. 12), the calculated values obtained by assuming that $\varepsilon_{r\,(BTT)}$ is 80 and the electric tree inception stress Ei is 220 to 300 kV/mm, are closer to the experimental values than the calculated values obtained by assuming that $\varepsilon_{r\,(BTT)}$ is 10. However, since ε_r = 80 represents the value of water itself, it is unlikely that $\varepsilon_{r\,(BTT)}$ reaches 80 in the region where BTTs are short or in the zone where degradation has not highly progressed. The result where the experimental plots fit the calculation assuming $\varepsilon_{r\,(BTT)}$ = 80 suggests that a phenomenon equivalent to $\varepsilon_{r\,(BTT)}$ = 80 must occur. In the region where the BTT length is less than 500 µm, the breakdown strength of the cables is as high as 30-50 kV/mm in an average field E_{mean}. Therefore, the possibility that nonlinear electrical conduction[24] of the BTT appears more likely to occur, where the resistivity of the BTT decreases sharply. When the resistivity is small, it is considered that the resistivity, rather than the permittivity, is dominant in determining the electrical field distribution. We evaluated

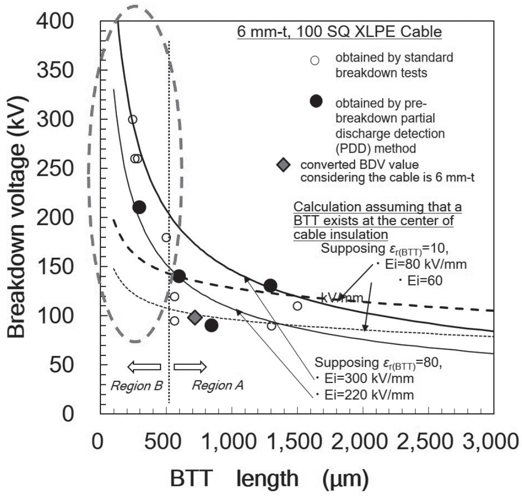

Fig. 12. Relationship between BTT length and residual breakdown voltage of the XLPE cable[22] (Comparison between experimental results and calculation based on assumption that BTTs are high dielectric constant heterogeneous dielectrics)

the value of ρ when the BTT tip electric field reaches 220 to 300 kV/mm. The calculation results are shown in Fig. 13. The value of ρ, which is equal to the electric field multiplication factor k_f when $\varepsilon_{r\,(BTT)}$ is 80, was obtained to be $\rho = 1.46 \times 10^9$ Ω•cm. This value of ρ is slightly less than $\rho = 10^{10}$ Ω•cm of which was that of BTTs described in the reference.[24] However, considering the phenomenon where the electric conduction of BTTs varies nonlinearly under a high electric field (30 to 50 kV/mm), the value of ρ being 1.46×10^9 Ω•cm is sufficiently realistic. In other words, in region B, where BTTs are short, it is considered that a phenomenon equivalent to ε_r = 80 will occur as a result of a decrease in the ρ of BTTs in a high electric field.

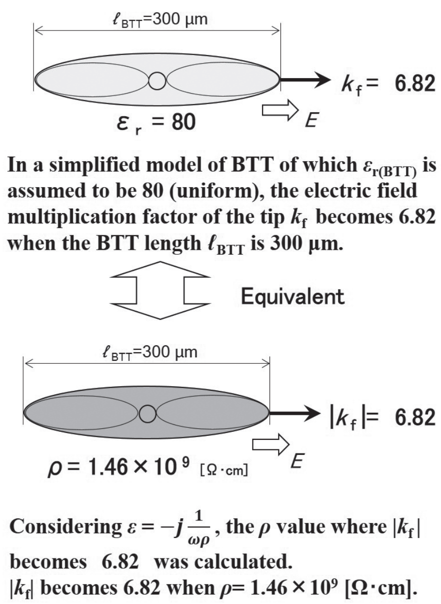

Fig. 13. Equivalent values of ε_r and ρ where the resulting $|k_f|$ values were the same[22]

5-3 Evaluation of harmful effects of BTTs on aged EHV XLPE cables

For EHV XLPE cables with a metal layer (waterproof layer), the effects of BTTs are not taken into account in the insulating design since the cable will rarely be affected by water immersion. Although the generation of large BTTs has not been observed, small BTTs are generated even in the presence of water that is contained in polyethylene itself. It is usually reported that the growth of BTTs saturates around 200 μm, in cables kept free from the penetration of external water.[25] Therefore, it is unnecessary to consider the effects of BTTs on such cables. However, as 30 years have passed, I examined the influence of BTTs on EHV XLPE cables again. Since the cable breakdown strength is high when BTTs are small, the value of the equivalent permittivity of BTTs $\varepsilon_{r\,(BTT)}$ can be regarded as 80, as shown in Fig. 12. In contrast, the electric tree inception stress E_i = 300 kV/mm in non-degraded XLPE is the value obtained by increasing the voltage application in 15 minute increments. Therefore, the value of electrical tree inception stress after 30 years of service, E_{i30y}, can be derived by the inverse power law ($E^n \times t$ = constant, where E: electrical stress, t: time, n: life exponent). Although the exponent n of EHV XLPE cables is 15, the exponent has been expected to be over 20 in practice.[10] According to this, E_{i30y} can be obtained as follows:

$$E_i^{\,n} \cdot t = E_{i30y}^{\,n} \cdot t_{30y} \quad \cdots\cdots (1)$$

Here, when E_i = 300 kV/mm, t = 15 minutes, t_{30y} = 30 years, and n = 20 are substituted into the formula (1), E_{i30y} = 150 kV/mm is obtained. Since the E_{i30y} obtained above is the value where a cable is assumed to have continuously been exposed to 150 kV/mm, the evaluation is considerably stringent. Using $\varepsilon_{r\,(BTT)}$ = 80 and E_i = 150 kV/mm, the relationship between BTT length and breakdown voltage was calculated for a 275 kV XLPE cable with a wall thickness of 23 mm and a conductor size of 1,000 mm^2. In the case of the 500 kV XLPE cable, a wall thickness of 27 mm and a conductor size of 2,500 mm^2 was considered. The results are shown in Fig. 14. The residual breakdown test result and observed maximum BTT length of a 275 kV XLPE cable that was removed from actual service after 19 years of use [26] was also plotted as mark ◇. According to Fig. 14, ◇ plot symbol seems to be relatively close to the calculation curve. The harmful BTT length ℓ in 275 kV XLPE cables is estimated to be ℓ = 1.57 mm, where the breakdown may occur under operating voltage V = 159 kV (= 275 / $\sqrt{3}$ kV) to ground. The harmful BTT length ℓ in 500 kV XLPE cables is estimated to be ℓ = 0.58 mm, where the breakdown may occur under operating voltage V = 318 kV (= 550 / $\sqrt{3}$ kV) to ground. The length of the BTT observed in the 275 kV XLPE cable that had been in service for 19 years was 200 μm.[26] Compared with the above length of 200 μm, the harmful BTT length in 275 kV cables has some performance margin. In contrast, the harmful BTT length of 500kV cables has a poor margin. Therefore, a sampling investigation (residual breakdown tests and BTT observation) of EHV cables (275 kV class and 500 kV class) is necessary to confirm such margins, as well as to better understand the actual deterioration of EHV XLPE cables.

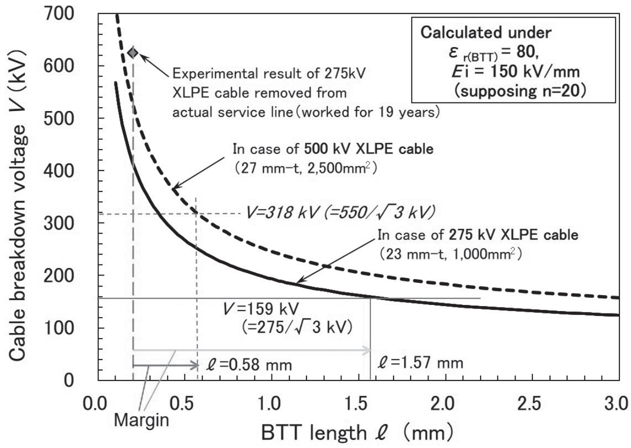

Fig. 14. Relationship between BTT length and breakdown voltage of 275 kV & 500 kV XLPE cables[23]

6. Conclusion

Receiving the Yahagi Memorial Award, some memories of Prof. Yahagi and the research results that have been achieved by his teachings—"Seek the Truth," are described. I hope that younger researchers will advance the R&D of the products of the next generation while keeping in mind the fact that Prof. Yahagi and other great professors have achieved world-class research results on dielectric and insulating materials.

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