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FEATURED TOPIC

A New Testing Method for Evaluating the Long-term Water Tree-Retardance and Highly Reliable Tree-Retardant Insulation

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In recent years, efforts to reduce greenhouse gas emissions have intensified globally, leading to the increased adoption of offshore wind power generation. To address the manufacturability, cost, and workability challenges of submarine cables that transmit electricity from wind turbines, our company has been developing submarine cables without water barriers. When moisture infiltrates cable insulation, water tree deterioration occurs. Therefore, the use of water tree-retardant (TR) insulation is essential in the absence of a water barrier; however, there was no appropriate evaluation method for this. We previously proposed a water aging test focusing on the supersaturated moisture generated in the insulation due to heat cycles. This time, we compared the results of this test with those of various other tests and confirmed that water tree degradation occurs within a practical timeframe and that a long-term TR performance evaluation, equivalent to 30 years, is feasible. Additionally, we applied this test to evaluate the 30-year TR performance in TR insulation development, discovering materials with high TR performance and low dielectric loss suitable for future high-voltage applications. We continue to advance cable development that will contribute to the expansion of offshore wind energy.

Keywords: power transmission cable, water-tree retardance, long-term reliability, oversaturated moisture, water aging test method

1. Introduction

In recent years, efforts to reduce greenhouse gas emissions have intensified globally. Japan and the European Union have declared carbon neutrality by 2050, aiming to reduce their net greenhouse gas emissions to zero by 2050. The Green Growth Strategy of Japan, drawn up in response to this declaration, sets out a policy focusing on the introduction of the maximum amount of renewable energy sources. Among them, offshore wind power generation is characterized as the most promising candidate for developing renewable energy sources as a main power source.(1)

As a solution to the manufacturability, cost, and workability challenges associated with submarine cables for offshore wind power generation, Sumitomo Electric Industries, Ltd. has worked on developing a cable that lacks a water barrier structure (no water barrier) but has highly water-tree-retardant insulation(2) and on establishing a water aging test method for evaluating the long-term service life of no-water-barrier cables.(3)

Recently, we have verified that this test method is appropriate for evaluating the service life of no-water-barrier cables in 30-year applications on actual lines; moreover, the materials we have discovered are compatible with future high-voltage applications, with their high water-tree retardance (TR) and low dielectric loss factor.

2. Water Tree Growth in No-Water-Barrier Cables

Degradation due to water treeing progresses in no-water-barrier cables as moisture infiltrates the insulation under voltage application (Fig. 1). A water tree is an aggregate of micro-voids in insulation and is generated and grows from very small foreign matter, a void, a projection, and the like present in the cable core (inner semiconducting layer [ISL], insulation, and outer semiconducting layer [OSL]). As degradation progresses due to water treeing, the electrical breakdown strength may decrease and breakdown may occur. For this reason, the generation and the degree of growth of water trees have a significant impact on the cable's service life.

Sumitomo Electric has looked for TR insulation that is highly resistant to water treeing and studied long-term water tree testing methodology used to evaluate the TR performance of cables, considering actual long-term use of cables for 30 years.

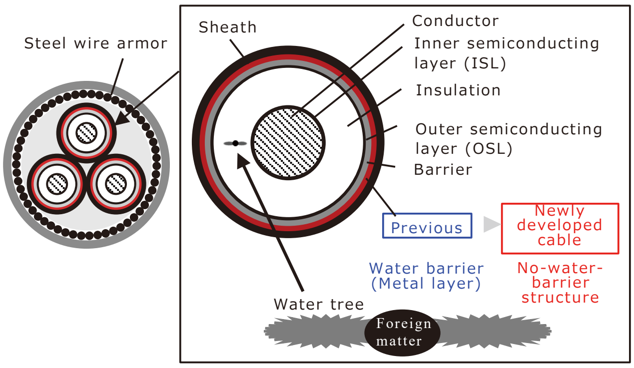


Fig. 1. No-water-barrier submarine cable and water tree

3. A New Water Aging Test Method for Evaluating Long-term TR Performance (A New Accelerated, Water Tree Aging Test Method)

3-1 Test condition consideration

When studying the long-term water treeing test method, Sumitomo Electric conducted various water aging tests on prototype cables and found that the growth of water treeing tends to become noticeable under certain heat cycle (HC) conditions (under which oversaturated moisture is generated).(2) In addition, as described in previous reports,(3)-(5) we ascertained through computer-aided engineering (CAE) analysis that oversaturated moisture is generated in actually installed no-water-barrier submarine cables; hence, we focused on oversaturated moisture and looked for long-term water tree testing methodology that enables evaluation to be conducted within a practical test period in an equivalent manner to long-term use for 30 years. The test conditions are listed under the heading of "New accelerated, water tree aging test method" in Table 1. For comparison purposes, Table 1 also gives conditions used for other submerged cable voltage endurance tests. Note that the severe test is a water aging test, which uses Sumitomo Electric's original condition settings, with the OSL and the conductor being submerged in water and HCs created using an external heat source. Additionally, regarding the conditions of the conductor-energized, long-term water aging test,(6) the test simulates actual long-term submerged voltage application, with the exterior being submerged in water, HCs created by means of conductor energization and water temperature control, and voltage application stress multiplied by a factor of approximately 3 being applied.

Table 1. Conditions of new accelerated, water tree aging test method and other water aging cable tests

Parameter		CIGRE TB722		Severe test	Conductor-energized, long-term water aging test(6)	New accelerated, water tree aging test method
		Regime A	Regime B			
Electric field		6.4 kV/mm		4.0 kV/mm	10–15 kV/mm	4.2 kV/mm
Conductor size		50 mm² or more		150–325 mm²	100 mm²	150–200 mm²
Insulation thickness		5 mm or more		3 mm	6 mm	1–10 mm
Frequency		50 / 60 Hz	500 Hz	50 / 60 Hz	50 / 60 Hz	50 / 60 Hz
Water submersion		OSL		Conductor / OSL	Exterior (OSL or sheath)	Conductor / OSL
Water quality		Seawater		Tap water	Tap water	Seawater (e.g. artificial seawater)
Heating method		Exterior		Exterior	Conductor / Exterior	Exterior
Temperature condition	HC	None		Used	Used	Used
	Test temperature	Pretreatment at 55°C for 500 h, then 40°C constant		60°C for 8 h ⇔ Room temperature for 16 h	Conductor at 90°C and exterior at 60°C for 8 h ⇔ Room temperature for 16 h	60°C–70°C for 3 days ⇔ Room temperature for 2 days
Generation of oversaturated moisture per cycle (Inner insulation layer)		None		1 ppm or less	Approx. 1 ppm	Approx. 50 ppm

It is highly probable that HCs and water submersion are suitable for configuring test conditions focusing on oversaturated moisture. Accordingly, we conducted an analysis using a diffusion equation, as described in our previous report. Diffusion factors were determined according to Fig. 2. Seawater contains various ions; therefore, their measurement results are also presented in Fig. 2. The same sources of ions are found in the common instance of conduit installation and pools of water in manholes. Diffusion factors for Na$^+$, Ca^{2+}, and K$^+$ are relatively close to that for moisture, as illustrated in Fig. 2.

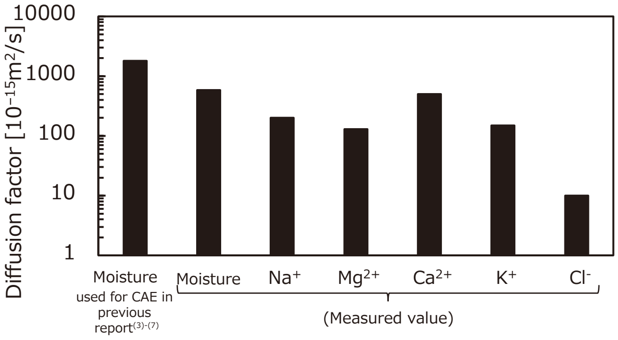


Fig. 2. Diffusion factors of moisture and different ions in seawater at 90°C in crosslinked polyethylene (XLPE)

Water tree growth is maximum at a temperature between 60°C and 70°C in XLPE.(8) Accordingly, the high-temperature process of HC was set to between 60°C and 70°C. The low-temperature process was set to room temperature. The length of low-temperature period per cycle was set to two days in light of the period required for the water bath with a simultaneous testing capacity of several tens of cables to cool down. Additionally, the conditions included submerging the conductor in addition to the OSL to supply moisture to the inner layer side, where the strongest electric field is present in the insulation.

An analysis-based trial calculation of the oversaturated moisture content on the inner layer side of the insulation is illustrated in Table 2, with the test periods being 50 and 100 days while varying the high-temperature process retention time per HC between one and five days. Table 2 reveals that when conducting long-term testing, the highest moisture content level is reached when the high-temperature period is three days. Consequently, it is highly probable that the HC conditions shown in Table 1 are appropriate.

Table 2. Oversaturated moisture contents for different HC conditions

HC condition	High-temp period	1 day	2 days	3 days	4 days	5 days
	Low-temp period	2 days				
Oversaturated moisture content (Inner layer side of insulation) [ppm]	50 days later	270	380	420	450	440
	100 days later	600	850	940	920	830

The cable insulation thickness was determined based on Fig. 3. Figure 3 shows analysis results for the time required for the water vapor level to reach several tens of ppm or more, exceeding the saturated water vapor level at room temperature due to moisture permeation when varying the insulation thickness between 1 mm and 20 mm and, as an example, immersing the cable at a constant water temperature of 65°C. An oversaturated moisture content of 50 ppm (see Table 1) or more is reached within three days of a high-temperature process when the insulation thickness is between 1 mm and 10 mm; hence, we considered that this range of insulation thickness would be appropriate.

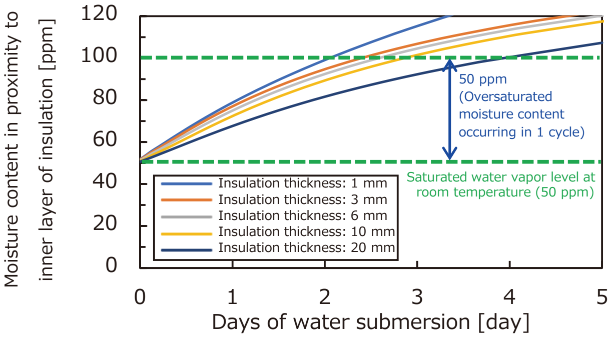


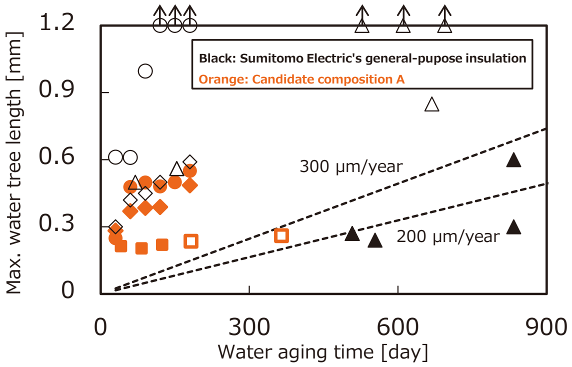
Fig. 3. Changes in moisture content with time in proximity to inner layer of insulation

Water quality also has an effect on water tree generation and growth. Potassium carbonate (K_2CO_3) solution, calcium chloride ($CaCl_2$) solution, and sodium chloride (NaCl) solution tend to have higher electrical conductivity and facilitate water treeing rather than tap water.(9) Moreover, the concentration of sodium chloride at which water trees grow efficiently is 0.5 mol/L,(10) substantiating the appropriateness of seawater. Thus, with the notion that the effects of water quality should be taken into account when evaluating the long-term service life of no-water-barrier cables, we used seawater to submerge both the OSL and conductor for the new accelerated, water tree aging test method.

3-2 Test results

Sumitomo Electric's general-purpose insulation and candidate composition A, currently under consideration for use in no-water-barrier cables for offshore power generation, were tested by the new accelerated, water tree aging test method. The test used a cable with a 150 mm^2 aluminum conductor and 3 mm thick insulation and checked for water treeing every 30 days for a period of 180 days. A water tree investigation revealed relatively long water tree growth on the inner side of the insulation. In addition, vented treeing from ISL was also observed, and the effect of conductor submersion in seawater was also verified. Figure 4 shows the relationship between the water submersion/voltage endurance time and water tree growth length observed in this instance. The results of the other tests listed in Table 1 are also presented in Fig. 4. Furthermore, the water tree growth rate of actually installed general-purpose XLPE cables is known at approximately 200 to 300 μm/year, which is also depicted in Fig. 4.

Figure 4 reveals that water trees grow long in the shortest period of time by the new accelerated, water tree aging test method, followed by the conductor-energized, long-term water aging test (with the OSL submerged) and the severe test. These results suggest that the occurrence of oversaturated moisture, its amount, and its amount of accumulation significantly contribute to water tree growth. Note that the conductor-energized, long-term water aging test (with the sheath or OSL submerged), which approximates actual installation conditions, produced a result lying between the 200 and 300 μm/year lines at about 900 days. Meanwhile, candidate composition A exhibited TR performance in both the new accelerated, water tree aging test method and severe test.



Legend for test methods.
○: new accelerated, water tree aging test method,
◇: severe test,
△: conductor-energized, long-term water aging test (submerged polyvinyl chloride [PVC] sheath or OSL represented with black filled icons),
□: TB722, International Council on Large Electric Systems (CIGRE) (Regime A represented with outlined icons and Regime B with orange filled icons)

Fig. 4. Results of different water aging tests

3-3 Validity study on the new accelerated, water tree aging test method

To verify whether or not the results of testing using the new accelerated, water tree aging test method can be used to evaluate long-term TR performance, the test results obtained with Sumitomo Electric's general-purpose insulation, given in Fig. 4, are represented in Fig. 5, plotting the number of water submersion and voltage endurance days along a logarithmic x-axis spanning 30 years. Figure 5 additionally provides a line to estimate long-term water tree growth (an approximate line of the test results; coefficient of determination: $R^2 = 0.72$) based on the test results. Additionally, Figure 5 presents HCs possibly causing oversaturated moisture—although the magnitude is unclear—and the maximum water tree lengths revealed through investigation of 66 and 77 kV cables, including those for civilian uses, in use for 14 to 41 years in a moist installation environment, as well as secular water tree lengths indi-

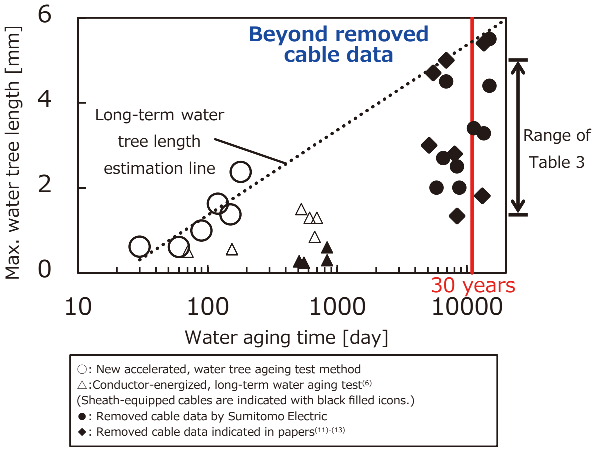


Fig. 5. Results of different water aging tests using Sumitomo Electric's general-purpose insulation

cated in removed cable data reported in papers and other literature.(11)-(13) The maximum water tree length found in the removed cable data resides within the range of the results of 180-day testing on Sumitomo Electric's general-purpose insulation using the new accelerated, water tree aging test method, thereby indicating the possibility of TR performance evaluation of actual 30-year installation within a practical test period.

Next, this section discusses the maximum water tree length reached after the passage of 30 years. For this purpose, we used a report that evaluates the harmful effect of water treeing from the perspective of reduced breakdown field, considers the permittivity of water trees in terms of complex permittivity, and uses a model, in which conductivity is taken into account, to explain breakdown field and water tree lengths—observed in breakdown testing and the like—with a relatively favorable correlation.(6)

The electric field E_i at the water tree tip, approximated by a spheroid, is expressed by the following equation.

$$E_i = E_{r\,BTT\,tip} \cdot k_f \quad \cdots\cdots (1)$$

where $E_{r\,BTT\,tip}$ is the electric field present at the position of the water tree tip in the absence of any water tree.

$$E_{r\,BTT\,tip} = V/\{r_{BTT\,tip} \cdot \ln(R_0/r_0)\} \quad \cdots\cdots (2)$$

V : Applied voltage (kV)
$r_{BTT\,tip}$: Distance between cable center and water tree tip (mm)
R_0 : Outer radius of cable insulation (mm)
r_0 : Inner radius of cable insulation (mm)

k_f is the stress enhancement factor.

$$k_f = 1 - (1/\alpha)\{(1/2) \cdot \ln(\lambda_0 + 1)/(\lambda_0 - 1) - \lambda_0/(\lambda_0^2 - 1)\} \quad \cdots\cdots (3)$$

$$\alpha = (1/2) \cdot \ln(\lambda_0 + 1)/(\lambda_0 - 1) - 1/\lambda_0 + \{1/(K - 1)\}\{1/(\lambda_0 (\lambda_0^2 - 1)\} \quad \cdots\cdots (4)$$

$$\lambda_0 = 1/\sqrt{1 - R/a} \quad \cdots\cdots (5)$$

$$K = \varepsilon_{r(BTT)}/\varepsilon_{r(XLPE)} \quad \cdots\cdots (6)$$

R : radius of curvature at water tree tip (µm)
a : long-axis radius of spheroid simulating water tree (1/2 of water tree length) (µm)
$\varepsilon_{r(XLPE)}$: specific permittivity of XLPE (2.3)
$\varepsilon_{r(BTT)}$: specific permittivity of water tree

The specific permittivity of water trees is considered as a complex permittivity $\varepsilon_{r(BTT)} = \varepsilon'_{r(BTT)} - j/\omega\varepsilon_0\rho$ (ω: angular frequency of AC field, ε_0: permittivity of vacuum, ρ: electrical resistivity of water tree [inverse of conductivity]). It is highly likely that the electrical resistivity of water trees is reduced due to oversaturated moisture and other factors. Therefore, a trial calculation was made assuming that the following holds in the equation above: $\varepsilon'_{r(BTT)} \ll 1/(\omega\varepsilon_0\rho)$.

A pre-breakdown discharge detection test was conducted to detect defects that initiate breakdown, using cables subjected to the new accelerated, water tree aging test method. The radii of curvature of water tree tips detected in this test were between 20 and 50 µm. The electrical resistivity of water trees that matched the breakdown field was between 6.0×10^8 and 1.0×10^9 Ω·cm. Based on these results, a calculation was conducted to determine the water tree length at which breakdown occurs in a 66 kV or 77 kV in-service electric field, setting the radius of curvature of water tree tips to 20 µm and the electrical resistivity of water trees to 6.0×10^8 Ω·cm, 8.0×10^8 Ω·cm, and 1.0×10^9 Ω·cm, as illustrated in Table 3.

The trial calculation results are well consistent with the water tree length distribution range of the removed cable survey cases plotted in Fig. 5. Thus, it is highly probable that estimation for actual 30-year installation can be made using an extension of the results obtained by the new accelerated, water tree aging test method established in this paper, thereby enabling long-term TR performance to be evaluated.

Table 3. Water tree lengths at which breakdown occurs in a 66 kV or 77 kV cable's in-service electric field

Electrical resistivity of water trees [Ω·cm]	6.0×10^8	8.0×10^8	1.0×10^9
Water tree length at which breakdown occurs due to in-service electric field [mm]	1.4	2.3	5.0

3-4 TR performance criteria

Regarding the pass or fail criteria for TR performance used with the new accelerated, water tree aging test method, it should be appropriate to establish a threshold (harmful water tree length) according to the calculation results for such water tree lengths that result in breakdown in about 25 to 40 years in the cable's in-service electric field, as described in the previous section, at the most challenging electrical resistivity. Accordingly, pass or fail criteria for TR performance were established as given in Table 4. In addition, Table 4 shows harmful water tree lengths for the 154 kV class, as calculated based on the same idea.

Table 4. Harmful water tree lengths with the new accelerated water tree aging test method

Voltage class	66 kV / 77 kV	154 kV
Harmful water tree length [mm]	1.4	1.0

4. Development of TR Insulation for Offshore Wind Power Generation

4-1 TR insulation development concept

For the development of an insulation material for no-water-barrier submarine cables for offshore wind power generation, utilizing the new accelerated, water tree aging test method established in this paper, material performance requirements should include a low dielectric loss factor (tanδ), as well as TR performance, with future use of higher voltages in mind.

Figure 6 shows example relationships between electricity transmitted through power transmission cables and dielectric loss. The calculated values are based on the values of dielectric loss factor of 0.1% and 0.5%, the former being specified for insulation made of XLPE as set out in IEC 60840, an international standard for power transmission cables, and in IEC 63026, an international standard for submarine cables rated at 66 kV or less, and, in the case of 66 kV, the latter being specified for XLPE containing special additives. The dielectric loss is proportional to the square of voltage and the magnitude of the dielectric loss factor. Accordingly, in the case of enhancing the capacity by raising the voltage, the amount of dielectric loss increases. In particular, the increase becomes significant when the value of the dielectric loss factor is high. Furthermore, the initial dielectric loss factor of no-water-barrier cables should be held lower than that of cables with water barriers because the dielectric loss factor of no-water-barrier cables increases due to degradation resulting from water submersion and voltage application in some cases.

Because it is difficult to completely remove the cause of water treeing, which is micro-foreign matter, from cable insulation, it is a convenient way of rendering TR performance to add a water treeing retarder to the insulation. It is necessary to closely look into additives used as a water treeing retarder because they come with varying polarity, which affects the dielectric loss factor. Sumitomo Electric has discovered additives that have small dielectric loss factor and are effective in retarding water treeing. Candidate composition B, based on XLPE, and candidate composition C, based on a non-crosslinked insulation material, were evaluated.

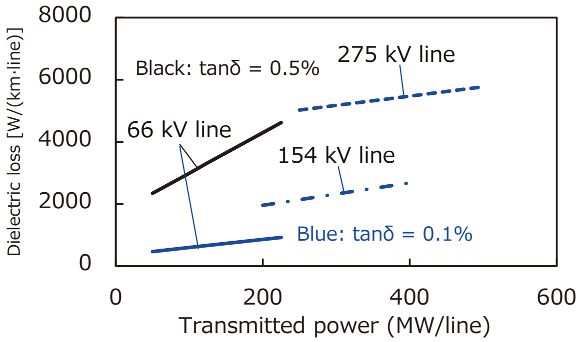


Fig. 6. Example relationship between electricity transmitted through transmission cables and dielectric loss

4-2 TR insulation consideration

(1) TR performance evaluation using sample sheets

To look into TR insulation, pressed sample sheets were prepared by sandwiching a semiconducting layer material used in transmission cables between insulating materials made of candidate compositions, as illustrated in Fig. 7, and the samples were evaluated as to water treeing properties by means of water aging testing. To give an equivalent level of oversaturated moisture to that occurring in the new accelerated, water tree aging test method, the samples were submerged in seawater and subjected to HCs consisting of three days of 60°C to 70°C and then returning to room temperature. Voltage was applied to the high-voltage side, or the semiconducting layer material, and the maximum water tree length was investigated at certain prescribed intervals of voltage endurance days. The test electric field was set to 4 kV/mm, assuming an in-service electric field in the 66 kV class, and also to 8 kV/mm as an evaluation taking application to the 154 kV class (in-service electric field: 5 kV/mm) and 275 kV class (in-service electric field: 7 kV/mm) into consideration.

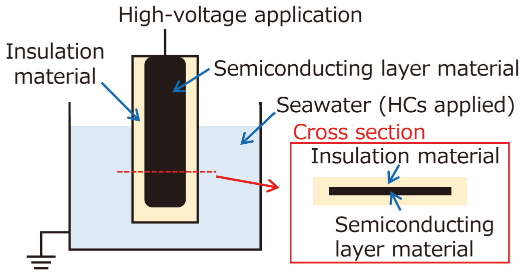


Fig. 7. Sample sheet and water aging test system

This water aging test was conducted for 180 days. The maximum water tree length shown by each candidate composition and Sumitomo Electric's general-purpose insulation in this test is presented in Table 5. The maximum water tree length is known to be generally constant irrespective of the magnitude of the electric field.(14) This finding is also consistent with the results produced by this test. An example of studying long-term properties based on the above results is shown in Fig. 8, in which performance degradation ratios (with the initial breakdown strength being 1) are organized in terms of test period ratios (with the design service life being 1). Candidate composition A

Table 5. Maximum water tree lengths of different candidate

Test electric field	Sumitomo Electric's general-purpose insulation	Candidate composition A	Candidate composition B	Candidate composition C
4 kV/mm	0.46 mm	0.43 mm	0.21 mm	0.37 mm
8 kV/mm	0.46 mm	0.39 mm	0.20 mm	0.38 mm

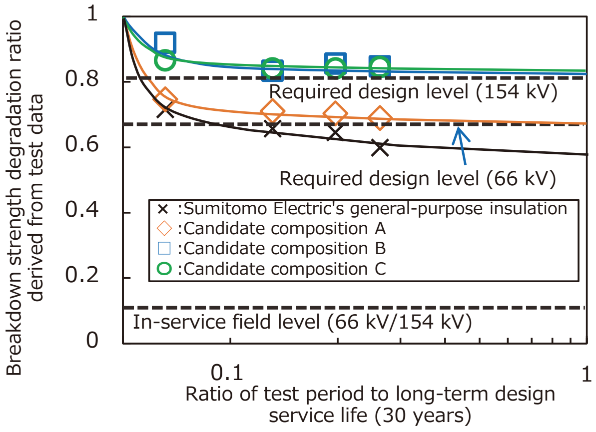


Fig. 8. Results of studying long-term properties using sample sheets

underperformed the required design level regarding the 154 kV class. In comparison, candidate compositions B and C exhibited higher TR performance than that of candidate composition A, suggesting that they meet the required design level within the design service life period, up to the 154 kV class.

(2) Dielectric loss factor

The dielectric loss factors of candidate compositions were measured with an automatic Schering bridge, using sample sheets 0.2 mm in thickness at a measurement temperature of 90°C and an applied field of 8 kV/mm. The results are listed in Table 6. Candidate compositions B and C produced favorable results, with the dielectric loss factor being low as compared with that of candidate composition A.

Table 6. Dielectric loss factors of different candidate compositions

Composition	Candidate composition A	Candidate composition B	Candidate composition C
Dielectric loss factor	0.22%	0.05%	0.04%

4-3 Progress of evaluation using the new accelerated, water tree aging test method

Using a prototype cable made of candidate composition C, a TR performance evaluation was conducted by the new accelerated, water tree aging test method. The test field was set to 4.2 kV/mm, which is the in-service electric field of the 66 kV class, and a cable consisting of a 200 mm^2 copper conductor and 3 mm thick insulation was tested as well as another cable consisting of a conductor and insulation differing from the above in conductor size and insulation thickness. Figure 9 presents the relationship between the number of water aging days and the maximum water tree length along with long-term water tree length estimates based on the relationship. The test results revealed that the water tree length estimate for 30-year-old candidate composition C is shorter than the harmful water tree length for the 66 kV class, which is the pass or fail criterion for TR performance. In addition, assuming that the maximum water tree length is independent of the applied electric field, the estimate is shorter than the harmful water tree length for the 154 kV class, with the result representing possibly favorable TR performance.

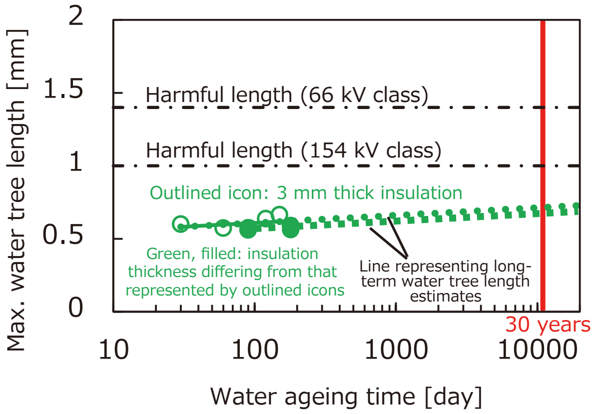


Fig. 9. Results of the new accelerated water tree aging test method applied to candidate composition C

Based on the evaluation of sample sheets as to water treeing properties, as described in 4-2, it is highly probable that candidate composition B will produce favorable results at a similar level to candidate composition C. Therefore, we will evaluate prototype cables using the new accelerated, water tree aging test method.

5. Conclusion

We have been studying no-water-barrier submarine cables with superb manufacturability, cost efficiency, and ease of installation for offshore wind power generation increasingly introduced in Japan and abroad. This report demonstrated that the new accelerated, water tree aging test method provides test conditions for causing water treeing degradation within a practical period and enables the long-term TR performance of actual 30-year installation to be evaluated. It also presented discovered materials provided with high TR performance and a low dielectric loss factor to be in line with future use of higher voltages. Going forward, we will evaluate the TR performance of prototype cables made of candidate composition B, using the new accelerated, water tree aging test method. At the same time, we will test candidate compositions B and C as to various properties that different standards require of cables.

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