EVALUATION OF AGING DEGRADATION OF 6KV CV CABLE (THREE-LAYER CO-EXTRUDED STRUCTURE)

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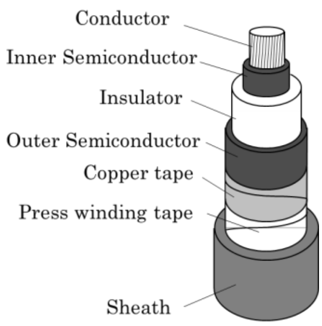
ABSTRACT

Distribution equipment is newly constructed and replaced along with the equipment faults and with the economic activities, so it was naturally updated in the high economic growth period from 1950's to 1990's in Japan. However, in recent years, because of the decrease in manufacturing defect failure by the improvement of equipment quality and decrease in construction volume by the sluggish economic growth, opportunities for updating decreased. As a result, we are in the situation of holding a large amount of high aging equipment. In order to maintain a safe and stable power supply under this situation, it is important task to update the high aging equipment at an appropriate time.
Thus, we are working to grasp the degradation status of each equipment by sampling surveys of the major distribution equipment from the actual fields for the purpose of verifying the equipment update timing.
This paper reports the surveyed results on Three-layer co-extruded structure 6 kV CV cables.

INTRODUCTION

In Chubu Electric Power Co., Inc., power cable (6.6 kV class) used for distribution system is cross-linked polyethylene insulated PVC sheathed cable (CV cable) which uses cross-linked polyethylene having superior electrical and thermal characteristics for an insulator. They are adopted since the 1960s, and today, as a result, all the cables in the field are CV cables.
As for the CV cables which we adopted, structure has changed several times (show in Figure 1). Because the structure of first adopted CV cables (hereinafter referred as T-T cable) was constituted of the tape-winding inner and outer semiconductive layer and the steam cross-linked insulator, there were the microvoid in insulators and irregularities (such as micro projection) between insulators and semiconductive layer. Therefore water trees were generated and extended, resulting to insulation degradation in the long term.
Thus, the CV cable structures has changed to inner semiconductive layer and insulator co-extruded since 1975 (hereinafter referred as E-T cable) and has changed to three-layer co-extruded including outer semiconductive layer since 1985 (hereinafter referred as E-E cable). In addition, dry cross-linked method for insulator and strict management of foreign substance has been introduced.
E-T cable is recommended to be replaced within 15-30 years from the survey of durability of long-term used cables under various installation environments [1]. Meanwhile, the E-E cable is expected to have a longer insulation lifetime at design stage, and has reached 30 years after its adoption. Therefore, we surveyed various performances of removed E-E cables. In this paper, we researched the degradation phenomenon caused by cohesion solids in the semiconductive layer that occurred with the E-E cable and report the results of evaluation of the degradation characteristics of the removed E-E cables and accelerated degradation cables.



Introduced year		1960 - 1974	1975 - 1984	1985 -
Type		T-T cable	E-T cable	E-E cable
Structure		Single-layer extruded	Two-layer co-extruded	Three-layer co-extruded
Manufacturing method	Inner Semiconductor	Tape wrapping	two-layer co-extrude	Three-layer co-extrude
	Insulator	exclude		
	Outer Semiconductor	Tape wrapping		
	Cross-linked method of the insulator	Steam cross-link		Dry cross-link

Figure 1. Structure of each 6kV CV cable

1. DEGRADATION PHENOMENA OF E-E CABLE

1.1 DC leakage current measurement

We regularly implement DC leakage current measurements that can detect the degradation condition of insulator easily and accurately on site, so that cables can be appropriately updated by obtained degradation signs. In this measurements, failures with leakage current occurred in 2 to 5% of the E-E cable even which took intensive countermeasures against water tree degradation. However, under high-humidity environments, non-defective cable may be judged as defective due to an increase and disturbance phenomenon of leakage current occurring from corona discharge or creepage leak current at the cable terminal.

For this reason, the cables which judged as defective were re-measured under the environment excluding increase and disturbance of leakage current. As show in Table 1, it turned out that the degraded E-E cables were manufactured by specific manufacturers (hereinafter referred as Specific cable).

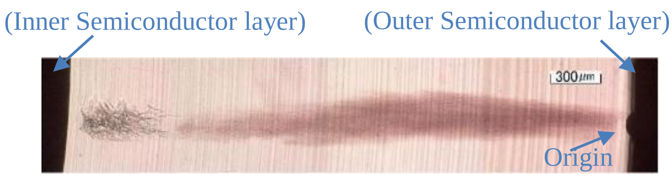
Table 1. Defective ratio of leakage current test

	Specific cable	The Others
No. of test cable : a	6,833	7,363
No. of defective cable : b	352	51
Defective ratio (%) : b/a	5.2%	0.7%
No. of re-defective cable*1 : c	303	0
Re-defective ratio (%) : c/b	86.1%	0.0%

*1 Re-defective refers to a cable that was determined as defective even re-measured in the laboratory.

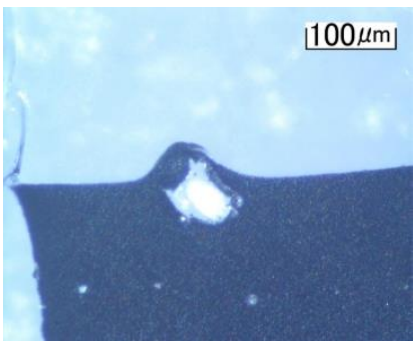
1.2 Survey of Specific cable

The specific cables judged as defective were studied by magnification observation and elemental (EDX) analysis. As a result of magnification observation, as shown in Figure 2, it was confirmed that a water tree originating from the outer semiconductive layer interface of insulator was generated. In addition, there was micro projections in the outer semiconductive layer at the original point of the water tree, and white cohesion solid existed inside the projection. From EDX analysis of this cohesion solid, it was investigated that the solid was magnesium oxide used as a compounding agent. These features were confirmed in all cables examined, although there were some differences.

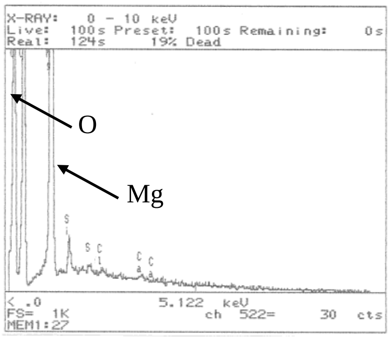


<Picture of origin of water tree>

- Cable 6.6kV 150mm2
- Size of a projection 40×180μm
- Length of water tree 2730μm



<Picture of a projection cross section >



<Elemental (EDX) analysis >

Figure 2. Result of Specific cable survey

Furthermore, in order to investigate the relation between the water tree and the micro projection, total 7,700 pieces of 0.5 mm thickness slice were taken from the defective cable. Thus the height of the projections, the existence of cohesion solids and water tree were observed for projections with a height of 20μm or more. As shown in Figure 3, water trees occurred only when the projection height was 40μm or more with existence of cohesion solids. Water tree did not occur in other cases.

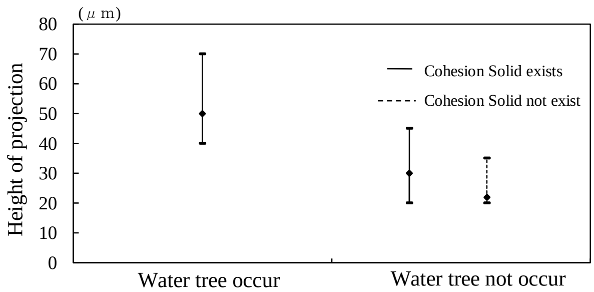


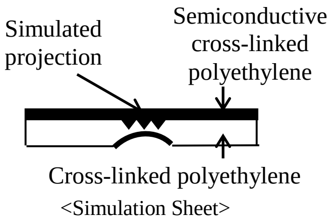
Figure 3. Projection height and water tree occurrence

It is noteworthy that water trees occurred even with a 40μm height projection, and existence of cohesion solids. Regarding the size of the projection, the height of the projection is regulated to 250μm or less according to Japanese Electrotechnical Committee JEC-208 (High voltage test method of cross-linked polyethylene cable of extra high voltage (11 to 77 kV) (1980)), and the size of 40μm is not especially large projection.

1.3 Simulation tests

Assuming from the above results, it was considered that the existence of cohesion solids affected in occurrence of the water tree. Therefore the relationship between the existence of cohesion solids and water tree degradation was investigated. Research on the effect of impurity ion to water tree extension, experiments have showed that cation with smaller atomic weight extended more water trees [2]. Since the cohesion solid which became the core of the projection of the defect part has cation Mg 2+ (atomic weight 24) equivalent to that of Na + (atomic weight 23) which is considered to have large effect to water tree extension in the reference [2], it is assumed that ionization occurs in the presence of moisture and the water tree occurred due to this effect.

Therefore, using two type of sheet samples, submergence and voltage charging test was conducted. One has artificially simulated projection with magnesium oxide powder (purity 98%, average particle diameter 5µm) cohesion as its core, and for comparison the other has simulated projection formed only with semiconducting material.



◆Charging voltage AC20kV (8kV/mm)
◆Temperature of water 60℃
◆Charging time 1000h、2000h 3000h、6000h

Figure 4. Test condition

As shown in Table 2, water trees occurred (occurrence probability is around 50%) only with the samples having a height of 40µm or more projection with magnesium oxide cohesion as its core. Water tree did not occur when the projection height was less than 40µm even if it contained cohesion of magnesium oxide.
Consequently, it was confirmed that water trees occur and extend by diffusion of magnesium cation into insulator. This happens only when the cable had a projection with a height of 40µm or more at the insulator interface with cohesion solids of magnesium oxide as its core in the outer semiconductive layer, and also when the cable was used in moisture environment.

Table 2. Result of simulation test

MgO core	Added				Not Added			
Charging time (hour)	1000	2000	3000	6000	1000	2000	3000	6000
Projection: Less than 40µm (No.)	0/8	0/5	0/2	0/5	0/4	0/3	0/7	0/8
Projection: Over 40µm (NO.)	**3**/5	**2**/4	**3**/6	0/0	0/6	0/1	0/4	0/4

1.4 Countermeasures against Specific cables

Magunesium oxide is added to the semiconductive layer for the purpose of inhibiting discoloration of the shielding copper tape, and it was manufactured by two specific manufacturers from 1985 to 1996.
Since newly purchased E-E cable has changed their semiconductive layer to material without cohesion solid as described above, there is no problem concerning newly installed ones. Meanwhile, the all Specific cables installed at the field are planned to be replace by 2023 as same countermeasures to the T-T cables and E-T cables.

2. AGING DEGRADATION CHARACTERISTICS OF E-E CABLE

2.1 Sampling survey

The defect caused by aging degradation of the E-E cable is assumed to be a ground fault due to insulator breakdown of the cross-linked polyethylene used for the insulating layer. The greatest degradation factor affecting the insulation lifetime of cross-linked polyethylene is water tree degradation [3]. In the report [4], it is confirmed that the water trees grow by aging, and the AC breakdown voltage tends to decrease.
Therefore, in order to grasp aged degradation characteristics other than the above-mentioned specific events, some of the E-E cables installed as a distribution facility were removed and a survey were conducted.
<Test samples>
16 removed cables and 32 accelerated degradation cables were used as samples. The cable size was 250 and 400 mm^2 (insulator thickness: 3.5 mm) (see Table 3).

Table 3. Number of Sample [No.]

Type	Installation year (years)	Cable size (mm^2) 250	Cable size (mm^2) 400	Total
Removed	18 - 27	7	9	16
Accelerated degradation	33 - 48	18	14	32

※For accelerated deterioration, the installation years equivalent to the acceleration magnification.

2.2 Water tree extension

The existence of water tree of the removed cables and its tree length were investigated and AC voltage breakdown tests were conducted.
In addition, accelerated deterioration cables which were some parts of the removed cables were produced by frequency acceleration, and water tree investigation and AC voltage breakdown tests were also conducted to them.

2.2.1 Test procedure

(1) Water tree observation
Test pieces were prepared by slicing the insulator of the samples to a thickness of about 1 mm. 10 test pieces were prepared for each sample, and a water tree with a length of 100µm or more was observed using an optical microscope. The observed water trees were classified into the inner semiconductor water tree, the outer semiconductor water tree and the bow-tie tree, and the maximum length were measured.

(2) AC voltage breakdown test
AC voltage of 5kV / 60Hz was applied between the conductor and the shielding layer of the sample, and the breakdown voltage was measured by increasing the voltage by 5kV steps every 5 minutes.

(3) Accelerated deterioration test
The removed cable which its part of the sheath was peeled off, was submerged. Water was also injected into the inside of the conductor from the end cable. The water was tap water at room temperature. In this state, AC voltage of

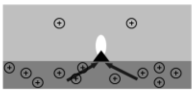
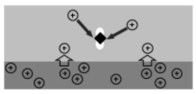
3.8kV / 1,800Hz (acceleration rate: 30 times) was applied between the conductor and the shielding layer. After applying for a particular period of time, observation of the water tree and AC voltage breakdown test were carried out.

2.2.2 Test Result

(1) Types of water tree

The water trees in the cables is roughly classified into inner and outer semiconductor trees and bow-ties tree (see Table 4).

Table 4. Type of water tree and its characteristics

Type	Inner and Outer semiconductor trees	Bow-ties tree
Characteristics	Extension from the interface between the inner / outer semiconductive layer and the insulator	Extension inside the insulator
Supply of moisture and cations	Insulator Semiconductive layer 	Insulator Semiconductive layer 
	• Supplied infinitely from semiconductive layer	• contained in the insulator from the beginning • Dissolving and diffusing from the outside into the insulator (limited)

Examples of the confirmed water tree is shown in Figure 5. Inner semiconductor tree and the bow-tie tree occurred, though we could not confirm the outer semiconductor tree. The inner semiconductor trees were confirmed with 7 samples. In addition, the bow-tie trees were confirmed in all samples (see Table 5)

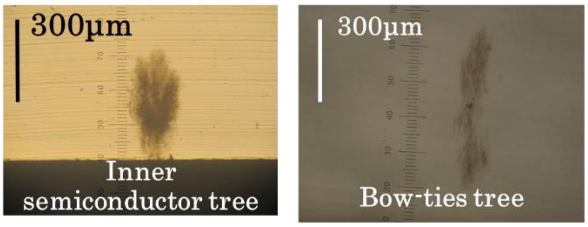


Figure 5. Picture of each water tree

Table 5. Number of samples with water tree [No.]

Type	Types of water tree		
	Inner semiconductor tree	Outer semiconductor tree	Bow-ties tree
Removed	3	0	16
Accelerated degradation	4	0	32
Total	7	0	48

(2) The length of water tree

The length of the each water tree, inner semiconductor tree and bow-tie tree which confirmed by above observation were measured. Figure 6 shows the relationship between each tree length and the installation year. The length of inner semiconductor tree and bow-tie tree tends to extend by aging. The extension characteristics of the inner semiconductor tree and the bow-tie tree are assumed to be different [5]. However, it was not possible to confirm clear differences in the respective extension characteristics. From the future works, in addition to the survey on the extension characteristics of conventional bow-tie tree, it is important to implement the survey focus on the inner semiconductor tree.

Furthermore, a sample which is bridging the insulating layer was not confirmed, the maximum tree length from the removed cables was 1,340μm (24 years; Inner semiconductor tree), the maximum tree length from the accelerated deterioration cables was 1,940μm (47 years; Bow-tie tree). Assuming that the extension characteristic of the water tree length is linear with the time it was installed, the maximum extension speed of all samples is 55.8μm / year. Thus, assuming that the lifetime is the time when the insulating layer (thickness: 3.5 mm) bridges, the insulation lifetime is 63 years.

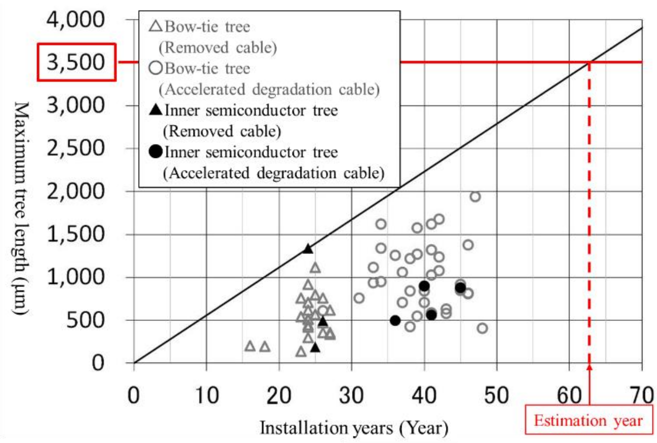


Figure 6. Relationship between installation years and maximum water tree length

(3) AC voltage breakdown test

Figure 7 shows the aging characteristics of the AC breakdown voltage. The result varied much and it was impossible to confirm the influence of aging only with this test result. It is considered that the reasons for the variation are that the influence of the existence of micro contamination substances in the insulating layer which is much lower than the manufacture control value, projections at the interface between the semiconductive layer and the insulating layer, the temperature and humidity of the installation location and submerged status etc. The minimum value of AC breakdown voltage was 35 kV (25 years of removed cable, 41 years of accelerated deterioration cable), which was sufficiently large compared with the working voltage (ground voltage 3.8 kV).

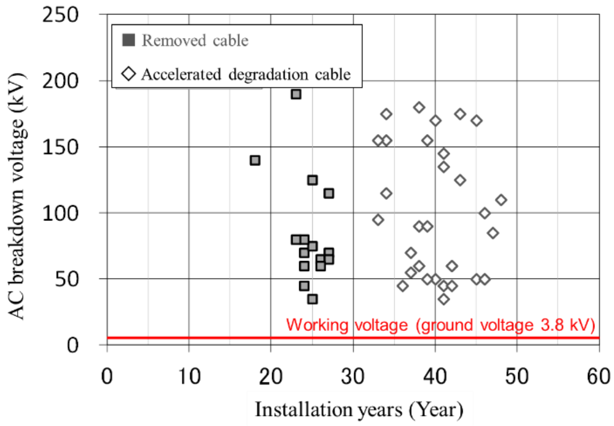


Figure 7. Relationship between installation year and AC breakdown voltage

2.3 Future works for E-E cable

The insulation lifetime is assumed as 63 years from this survey of water tree length, E-E cable replacement cycle more than E-T cable.
However, since the consideration of aged degradation of this research is assumed from limited samples, we will continue to grasp the degradation phenomena, investigate the removed cables and accelerated degradation cables, and to grasp the ageing degradation characteristics in detail. In addition, if the lifespan of the terminal integrated with the high-voltage cable is shorter than the lifespan of the cable itself, it becomes the bottleneck of the lifespan of the whole cable. So, we are proceeding to evaluate the degradation characteristics and to estimate the lifespan of the integrated terminals of outdoor cables.

3. CONCLUSION

In this paper, we evaluated the degradation of E-E cable which has reached 30 years after its adoption. Such evaluation on degradation plays an important role in maintaining public safety and stable power supply.
It is necessary to develop effective and efficient maintenance measures for increasing aged facilities as future tasks. In addition to the degradation evaluation, we are trying to improve the accuracy of the future prediction by recording and accumulating the defect events at the fields and analyzing the trend of the occurrence situation.

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