Development of Composite Insulators for Overhead Lines

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ABSTRACT The United States is leading a world-wide trend toward replacing ceramic and glass insulators with composite insulators that are lighter in weight, as well as being superior in pollution withstand voltage characteristics and resistance to impact (to counter vandalism). In the early 1990s, Furukawa Electric developed composite insulators for use as 66/77-kV inter-phase spacers, and subsequently has extended applications to include 275-kV inter-phase spacer insulators and 154-kV and 66/77-kV class transmission line suspension insulators. The IEC, an international standards organization, has tested this kind of composite insulators for electrical and mechanical performance and has confirmed their reliability, but the use of organic material as the insulating material has aroused reservations about long-term aging. Accordingly work has been going forward on outdoor long-term loading cycle exposure tests and indoor accelerated aging tests.

1. INTRODUCTION

Overhead power transmission lines require both cables to conduct the electricity and insulators to isolate the cables from the steel towers by which they are supported. The insulators have conventionally been made of ceramics or glass. These materials have outstanding insulating properties and weather resistance, but have the disadvantages of being heavy, easily fractured, and subject to degradation of their withstand voltage properties when polluted. There was therefore a desire to develop insulators of a new structure using new materials that would overcome these drawbacks.

The 1930s and '40s saw the appearance of the first insulators to replace inorganic materials with organic, but these suffered problems of weather resistance, and their characteristics were unsatisfactory for outdoor use. In the 1950s epoxy resin insulators were developed, but they were heavy, suffered from UV degradation and tracking, and were never put into actual service. By the mid-1970s a number of new insulating materials had been developed, and the concept of a composite structure was advanced, with an insulator housing made of ethylene propylene rubber (EPR), ethylene propylene diene methylene (EPDM) linkage, polytetrofluoro ethylene (PTFE), silicone rubber (SR) or the like, and a core of fiber-reinforced plastic (FRP) to bear the tensile load.

Since these materials were new, however, there were many technical difficulties that had to be remedied, such as adhesion between materials and penetration of moisture, and the end-fittings, which transmit the load, had to be improved. Since the 1980s, greater use has been made of silicone rubber due to its weather resistance, which is virtually permanent, and its hydrophobic properties, which allow improvement in the maximum withstand voltage of pollution, and this had led to an explosive increase in the use of composite insulators.[1)]

In 1980, Furukawa Electric was engaged in the development of inter-phase spacers to prevent galloping in power transmission lines, and at that time developed composite insulators that had the required light weight and flexibility. In 1991 the first composite insulators having a silicone rubber housing were used as inter-phase spacers for 66-kV duty, and in 1994 their use was extended to 275-kV service with a unit 7 m in length--the world's largest.

Thus as composite insulators have established a track record in phase spacer applications and their advantages have been recognized, greater consideration has been given to using them as suspension insulators with a view to cutting transportation costs, simplifying construction work and reducing the cost of insulators in order to lower the costs of laying and maintaining power transmission lines.

Recently Furukawa Electric developed composite insulators for suspension and delivered, for the first time in Japan, 154-kV tension insulators and V-type suspension insulator strings. Subsequently they were also used on a trial basis as tension-suspension devices in 77-kV applications. Work is also under way on the development of composite insulators for 1500-V DC and 30-kV AC railway service.

This paper presents an overview of the process of developing composite insulators for suspension and tension, and of service life prediction.

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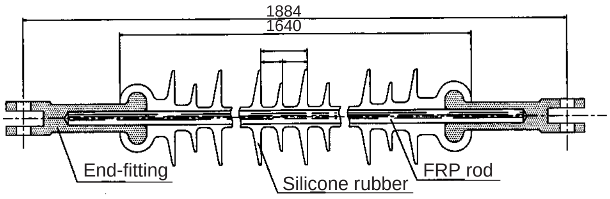

Figure 1 Structure of composite insulator

2. DESIGN OF COMPOSITE INSULATORS

2.1 Structure of Composite Insulators

Typically a composite insulator comprises a core material, end-fitting, and a rubber insulating housing. The core is of FRP to distribute the tensile load. The reinforcing fibers used in FRP are glass (E or ECR) and epoxy resin is used for the matrix. The portions of the end-fitting that transmit tension to the cable and towers are of forged steel, malleable cast iron, aluminum, etc. The rubber housing provides electrical insulation and protects the FRP from the elements. For this reason we at Furukawa Electric have adopted silicone rubber, which has superior electrical characteristics and weather resistance, for use in the housing. Figure 1 shows the structure of a composite insulator.

2.2 Designing Composite Insulators

An important feature of the composite insulators developed here is that the design of the shed configuration is extremely free, owing to the use of silicone rubber for the housing. Based on past experience, IEC 60815 "Guide for the selection of insulators in respect of polluted conditions" was adopted.[2)] Electrical and mechanical characteristics were designed to satisfy the requirements set forth in IEC 61109 "Composite insulators for a.c. overhead lines with a nominal voltage greater than 1000 V: Definitions, test methods and acceptance criteria".

With regard to pollution design, it has been suggested that because of the hydrophobic properties of silicone rubber, composite insulators can be designed more compactly than in the past, but because of the absence of adequate data it was decided in principle to provide as great or greater surface leakage distances. The design value for leakage distance was referenced to the value per unit electrical stress as determined in IEC 60815, adjusted upward or downward according to customer requirements.

Tensile breakdown strength was determined by applying a safety factor to the long-term degradation in tensile breakdown strength.

The rubber and FRP of the housing were required not only to have sufficient mechanical adhesion but to be chemically bonded, so as to prevent penetration of water at the interface. And because in general a large number of interfaces may result in electrical weak points, Furukawa Electric has adopted a composite insulator design in which the sheds and the shank are molded as a unit, resulting in higher reliability.

The end-fittings comprise three elements, and have the greatest effect on insulator reliability. Specifically the penetration of moisture at this point raises the danger of brittle fracturing of the FRP and the electrical field becomes stronger. For this reason the hardware is of field relaxing structure and the silicone rubber of the housing is extended to the end-fitting to form a hermetic seal. The end-fitting is connected to the FRP core by a compression method that maintains long-term mechanical characteristics.

Table 1 Main specifications of composite insulators

Product number	H154-120-1880CC
Overall length (mm)	1884
Number of sheds (lrg/sml)	26/25
Shed diameter (lrg/sml) (mm)	117/83
Effective length (mm)	1640
Surface leakage distance (mm)	5400
Weight (kg)	10
Electrical characteristics	
Power-frequency withstand voltage (kV)	440
Lightning impulse withstand voltage (kV)	835
Switching impulse withstand voltage (kV)	635
Mechanical characteristics	
Tensile strength (kN)	120
Bending breakdown strength (MPa)	294

The design requirements for composite insulators for 154-kV service are set forth below.

• Overall performance

(1) To have satisfactory electrical characteristics in outdoor use, and to be free of degradation and cracking of the housing.
(2) To be free of the penetration of moisture into the interfaces of the end-fitting during long-term outdoor use.
(3) To possess long-term tensile withstand load characteristics.
(4) To be free of voids and other defects in the core material.
(5) To be non-igniting and non-flammable when exposed to flame for short periods.

• Electrical performance (insulator alone)

(1) To have a power-frequency wet withstand voltage of 365 kV or greater.
(2) To have a lightning impulse withstand voltage of 830 kV or greater.
(3) To have a switching impulse withstand voltage of 625 kV or greater.
(4) To have a withstand voltage of 161 kV or greater when polluted with an equivalent salt deposition density of 0.03 mg/cm^2.
(5) To have satisfactory arc withstand characteristics when exposed to a 25-kA short-circuit current arc for 0.34 sec.
(6) Not to produce a corona discharge when dry and under service voltage, and not to generate harmful noise (insulator string).

Table 2 Test Items and applicable test standard

1	Overall performance
1.1	UV durability (ASTM G53)
1.2	Ozone durability (JIS K 6301)
1.3	Composite insulator durability (IEC 61109) (paragraph reference)
(1)	Test of interface and connection of the end-fitting (5.1)
(2)	Load-time test of core (5.2)
(3)	Tracking and erosion tests of the housing (5.3)
(4)	Core material tests (5.4)
(5)	Flammability test (refer to IEC 60707) (5.5)
(6)	Mechanical load-time test and test of the tightness at the interface between end-fitting and insulator housing (6.4)
(7)	Adhesion strength test between end-fitting and insulator housing seal (7.4)
2	Electrical performance of the insulator
2.1	Power-frequency wet withstand voltage (IEC 60383) (6.2)
2.2	Lightning impulse withstand voltage (IEC 60383) (6.1)
2.3	Switching impulse wet withstand voltage (IEC 60383) (6.3)
2.4	Maximum withstand voltage of pollution (JEC 170)
2.5	Arc-withstand characteristics (IEC SC36B (Secretariat) 116)
2.6	Corona characteristics (RIV) (refer to IEC 60437 (reference test) 6.5)
2.7	TV interference test (V-string insulator only)
3	Mechanical performance of the insulator
3.1	Tensile breakdown strength (IEC 61109, JIS C 3801)
3.2	Tensile withstand load (IEC 61109)
3.3	Bending characteristics (JIS C 3801)
3.4	Bending breakdown strength (JIS C 3801)
3.5	Proof test for breakage of one of two strings (reference test)
3.6	Vibration fatigue characteristics (reference test)
(1)	Longitudinal vibration fatigue test (reference test)
(2)	Transverse vibration fatigue test (reference test)
3.7	Torsional withstand load (reference test)
3.8	Repetitive torsional strength (reference test)
3.9	Swing characteristics (V-string insulator only)

• Mechanical performance (insulator alone)

(1) To have a tensile breakdown load of 120 kN or greater.

(2) To have a bending breakdown stress of 294 MPa or greater.

(3) To show no abnormality at any point after being subjected to a compressive load equivalent to a bending moment of 117 N•m for 1 min.

(4) To show no insulator abnormality with respect to torsional force producing a twist in the cable of 180°.

(5) To be for practical purposes free of harmful defects with respect to repetitive strain caused by oscillation of the cable.

Table 1 shows the characteristics of an insulator designed to satisfy these specifications.

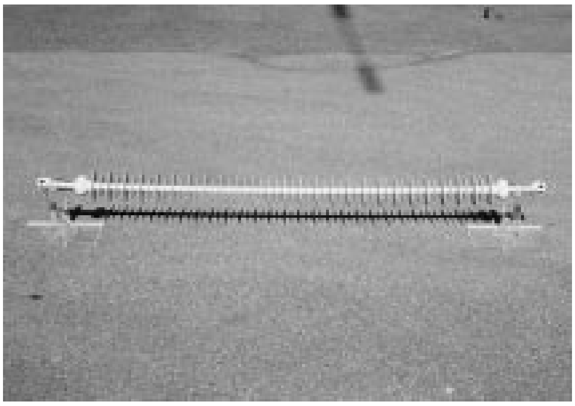

Photo 1 Composite insulator under test

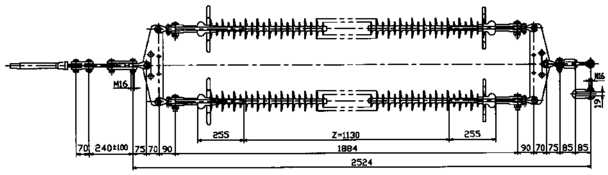

Figure 2 Composite insulator string for tension tower

2.3 Testing to Confirm Performance

In order for the composite insulators to be used as insulator strings, tests were also conducted to confirm their performance as V-string suspension devices or tension devices. These test items are shown in Table 2. Photo 1 shows an insulator under test, and Figure 2 shows a composite tension insulator string.

2.4 Representative Test Results

The main tests for confirming the performance of the composite insulators are (from Table 2):

1.3 Composite insulator durability, (1) Test of interface and connection of the end-fitting;

2.5 Power arc-withstand characteristics;

3.3 Bending characteristics; and

3.6 Vibration fatigue characteristics: (1) Longitudinal vibration-fatigue test

These will be dealt with in turn below.

2.4.1 Test of Interface and Connection of the End-fitting

The interface adhesion between the housing rubber and the FRP core in the vicinity of the end-fitting is considered one of the most crucial aspects of composite insulator manufacture, and as a means of verifying its suitability, the following procedures set forth in the design test in IEC 61109 were implemented:

1) nitial dry power-frequency flashover voltage test

2) Sudden load release test (30% of SML* -20 to -25°C)

3) Temperature-mechanical test (50% of SML* +50 to -35°C)

4) Water-immersion test (42 hr, boiling water, NaCl 0.1% weight)

5) Verification tests

a) Visual inspection (for cracking or other abnormality)

b) Steep-front impulse voltage test

c) Dry power-frequency voltage tests
- Flashover test (to check for drop from initial conditions)
- 80% of FOV for 30 min (to check for temperature rise in insulator shank)

* SML = specific mechanical load

The following test results were obtained:

a) Visual inspection: no cracking or separation of the housing rubber was observed.

b) Steep-front impulse voltage test: The insulators tested were separated into two sections and 1000 kV/ µs (positive- and negative-polarity) was applied 25 times to each. All underwent external flashover, but no puncture of the housing rubber or core occurred.

c) Dry power-frequency voltage tests: Table 3 shows the results of five repetitions of average flashover voltage, but all of the test specimens held 90% or more of initial flashover voltage. Next 80% of average initial flashover voltage (328.9 kV x 0.8 = 263 kV) was applied to the lower end-fitting for 30 min and the temperature rise was measured immediately. All test specimens satisfied the standards, with a temperature rise of less than 20 K.

2.4.2 Power Arc-withstand Characteristics

Since the housing is made of organic material, the extent of damage to the insulator due to power arcing and the voltage withstand characteristics after testing were confirmed by the method described below.

A copper wire fuse was attached to the end-fitting on both ends of an insulator fitted with arcing horns, a short-circuit current of 25 kA was applied for 0.34 s, and the condition of the housing rubber and of arc movement was investigated. The arcing horn was then removed and a wet impulse withstand voltage test was carried out. Figure 3 shows the setup for the power arc withstand test, in which the angle α of the insulator from the horizontal was 6°. The test showed that the arc moved between the horns, and fusing of the horns was observed. There was some discoloration of the insulator portion (housing rubber) but it was confirmed that the sheds were not chipped or damaged, and there was no fusing of the end-fitting. Photo 2 shows a composite insulator after application of the power arc. To investigate residual strength after the test, the tensile breakdown load was determined by applying SML for 1 min and then applying load until breakdown occurred.

Table 4 shows the results of the switching impulse withstand voltage test. As can be seen, there was no drop from the initial value.

2.4.3 Bending Characteristics

Since FRP is used in the core of the composite insulator, it is necessary that permissible bending load is not exceeded either during laying or in later service. Bending

Table 3 Results of flashover voltage test (adjusted to standard atmospheric conditions)

	Initial (kV)	After boiling (kV)	Change (%)
Sample #1	326.4 kV	334.2 kV	+2.38%
Sample #2	327.6 kV	335.2 kV	+2.32%
Sample #3	332.6 kV	326.4 kV	-1.90%
Average	328.9 kV	331.9 kV	+0.93%

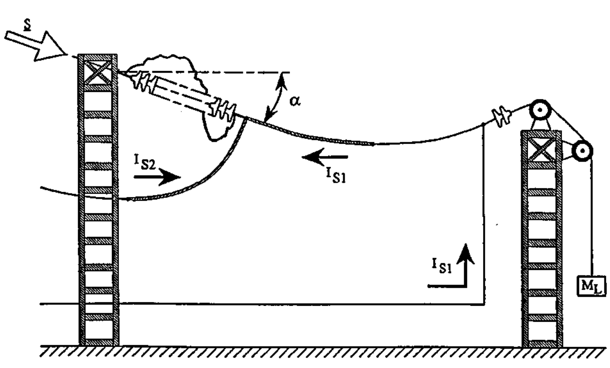

Figure 3 Setup for power arc test of composite insulator

Photo 2 Composite insulator after application of power arc

Table 4 Results of switching impulse withstand voltage test

	Initial	After power arc test
Withstand voltage (kV)	635	667

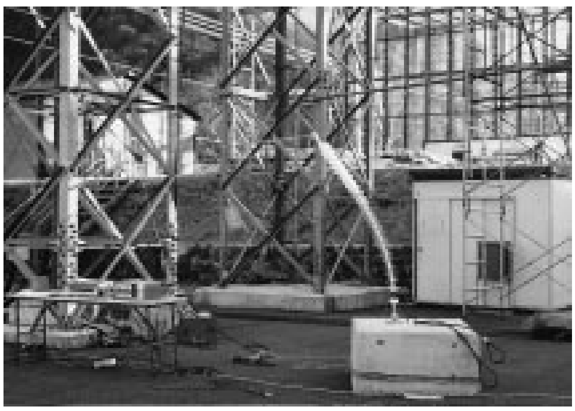

Photo 3 Setup for bending breakdown test

Photo 4 Composite insulator installed on working transmission line

characteristics tests were therefore carried out.

The tests were performed in accordance with Section 7.2.2 of JIS C 3801 "Insulator Test Methods". One end of the unit to be tested was held stationary and a bending stress of 294 MPa (30 kgf/mm^2) was applied for 1 min. Since no abnormality was observed, bending moment was increased until breakdown, which occurred at 539 MPa (55 kgf/mm^2). Photo 3 shows the setup for the bending breakdown test.

2.4.4 Longitudinal Vibration-fatigue Tests

In consideration of the galloping oscillation, sleet jumping and aeolian vibration that occur in actual service, longitudinal vibration fatigue tests were carried out. A horizontal tensile testing machine was used to apply a repetitive fluctuating tension of 32±12 kN.

The tests showed that after 2 million repetitions of the mechanical load, there was no pullout of the core or fracture of the end-fitting, or separation between the silicone rubber and the hardware, thereby demonstrating that mechanical reliability was sufficiently high.

2.4.5 Summary of Test Results

The results of some of the test items covered in Table 2 were described above. It was also confirmed that there were no problems with respect to any of the remaining items.

Photo 4 shows a composite insulator installed on a working transmission line.

3. PREDICTING SERVICE LIFE

The service life of a composite insulator involves both electrical and mechanical aspects. Electrical aging involves damage from erosion or tracking due to the thermal or chemical effects of discharge occurring when the insulation material is polluted or wet, and may even result in flashover.

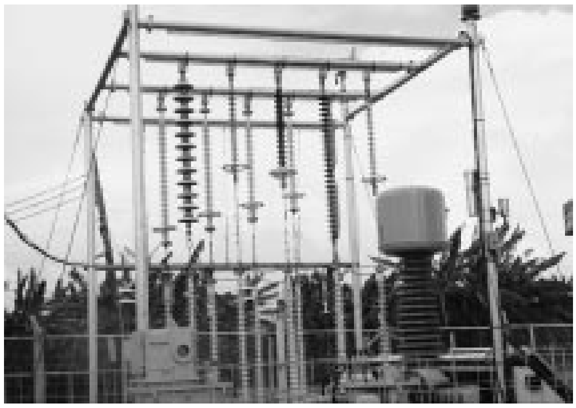

Photo 5 Facility for loading exposure testing in Okinawa

Mechanical aging includes long-term drop in the strength of the core material or in the holding force of the end-fittings, as well as brittle fractures of the core material, and can on occasion result in breakage of the insulator string. A drop in core strength or holding force of end-fitting can be countered by adopting an appropriate safety factor and using a reliable method of compression. Brittle fractures, on the other hand, occur mostly near the interface between the insulation material and the end-fitting, and provided this area has been properly manufactured, the probability of their occurrence will be lower than that of electrical aging.

To estimate service life from the electrical aspect, actual-scale composite insulators were exposed to electrical stress, and were subjected to an exposure test under a natural environment. A test chamber simulating environmental stress was also constructed, and accelerated tests were carried out according to international standards (IEC 61109 Annex C). Further, by comparing leakage current waveform and cumulative charge, which may be characterized as electrical aging, evaluation of composite insulator service life was carried out.

Furthermore, since in Japan, a drop in insulation performance due to rapid pollution during typhoons is a familiar phenomenon, an investigation was made based on the characteristics of leakage current obtained during a typhoon into the effect of rapid pollution on electrical aging in composite insulators. [4)–7)]

3.1 Okinawa Loading Exposure Testing Facility

Japan's position surrounded by the ocean means that salt pollution is a common problem, necessitating an understanding of aging and decreased insulation performance due to surface discharge when polluted or wet. Accordingly a facility for loading exposure testing was constructed in Okinawa, the prefecture where contamination is most severe and typhoons most frequent.

The facility is sited on the Pacific Ocean coast at Nakagusuku Bay. It is exposed on the east to winds off the ocean and is about 300 m from the shoreline in an area of severe salt pollution. Photo 5 shows the testing facility.

To determine the effect of unit electrical stress (V/mm), which is the most important design parameter for pollution resistance, it was decided to use as test specimens composite insulators of the same material and structure but different surface leakage distances, together with ceramic insulators as a reference. [5)~7)]

In an effort to determine the electrical behavior of insulators, the test facility monitors weather information (air temperature, humidity, wind direction and velocity, and precipitation) and carries out continuous measurement of leakage current and equivalent salt deposition density (regularly and during passage of typhoons). These results are currently being tabulated, and will be presented in a subsequent report.

3.2 Accelerated Aging Tests

The method designated by IEC 61109 for accelerated aging tests of the housing material of composite insulators specifies evaluation of short specimens that satisfy unit electrical stress levels. In this case, however, to examine the effect both of the material and of the structure, the procedures used in the loading exposure tests being carried out in Okinawa were followed for both the test specimens and the voltage (77 kV AC (to ground). To serve as a suitable site for these tests, a large fog chamber was built measuring 4.4 m square by 3.3 m in height. [7)]

In order to be able to investigate the temperature change, humidification, precipitation, salt exposure and UV irradiation set forth in IEC 61109, at the same time as performing accelerated aging tests on the adhesion of the end-fitting and terminal portion of the housing rubber, this facility is provided with equipment for applying a steady load of 20 kN.

Table 5 shows the test cycle of IEC 61109 Annex C.

This method of acceleration provides a test that promotes electrical degradation by simulating, reproducing in a short period of time, and then repeating the stress caused by changes in weather under electrical stress. Photo 6 shows the setup for the accelerated aging test.

Evaluation of the test results was carried out by continuous measurement of leakage current, regular measurements of the hydrophobicity of insulator surfaces, and analysis of surface conditions after the completion of the tests using scanning electron microscopy (SEM) and X-ray photoelectron spectrometry (XPS).

As Photo 7 shows, hydrophobicity was adequately maintained after the specified period of 5000 hr, despite a minor decline from the initial conditions.

Visual observation of insulators after test completion revealed a certain degree of gray discoloration, but SEM results showed no difference from the initial conditions. XPS observation of coupling energy also showed no change from initial rubber coupling, thus confirming that no aging occurred.

Thus we see that in actual-dimension accelerated aging tests conducted in accordance with IEC 61109 Annex C, the composite insulators showed no great leakage current and no tracking or erosion of the insulator surface. Tests of withstand voltage characteristics conducted separately also showed satisfactory results. It was accordingly concluded that these insulators would satisfactorily stand up to use at the ordinary level of pollution prevailing in Japan.

Table 5 Accelerated Aging Test Cycle

(hours)	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24
Humidification			■					■				
Heating		■	■				■	■				■
Salt spray				■	■				■	■		
Artificial rain	■											
UV irradiation	■	■				■	■				■	■
Loading weight	■	■	■	■	■	■	■	■	■	■	■	■
Voltage application	■	■	■	■	■	■	■	■	■	■	■	■

4. CONCLUSION

Composite insulators are light in weight and have demonstrated outstanding levels of pollution withstand voltage characteristics and impact resistance, and have been widely used as inter-phase spacers to prevent galloping. They have as yet, however, been infrequently used as suspension insulators. The composite insulators for suspension use that were developed in this work have been proven, in a series of performance tests, to be free of

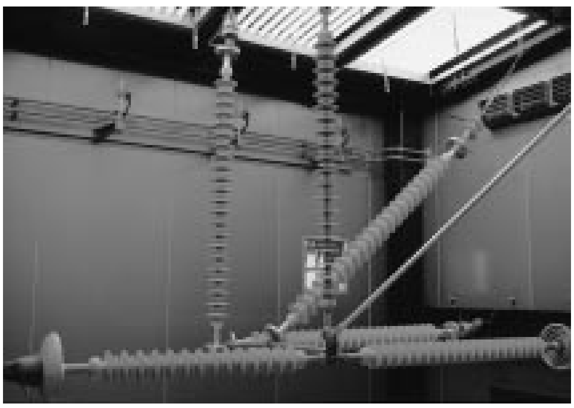

Photo 6 Setup for accelerated aging test

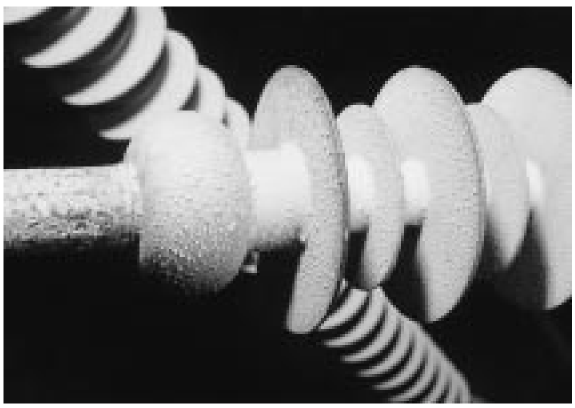

Photo 7 Surface of composite insulator after 5000 hr testing according to IEC 61109, Annex C

problems with regard to commercial service, and in 1997 were adopted for the first time in Japan for use as V-suspension and insulators for a 154-kV transmission line.

To investigate long-term degradation due to the use of organic insulation material, outdoor loading exposure tests and indoor accelerated aging tests are continuing, and based on the additional results that will become available, work will continue to improve characteristics and rationalize production processes in an effort to reduce costs and improve reliability.

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