Development of Composite Insulators for Overhead Lines (Part 2)

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ABSTRACT Furukawa Electric's composite insulators are characterized by a hermetically sealed structure made by integral molding with a silicone rubber sheath that covers up to the end fittings. Exposure tests on full-size insulators were carried out in Okinawa at 77 kV over a 5-year period to evaluate them under the usage conditions prevailing in Japan. No deterioration was observed, nor was any deterioration observed in accelerated aging tests carried out on full-size insulators in accordance with IEC 61109 Annex C, demonstrating ample reliability. Service life of the composite insulators was estimated by charged exposure tests and accelerated aging tests with leakage current as the parameter. A figure of not less than 34 years was arrived at as the period within which slight deterioration would occur under the severe sea-salt contamination occurring in Okinawa, thereby confirming a sufficiently long period of resistance.

1. INTRODUCTION

The materials used in insulators for overhead transmission lines have been ceramics and glass. Both offer good insulation characteristics and excellent weather resistance, but they also have several disadvantages--they are heavy, have poor resistance to impact, and suffer major deterioration in terms of the voltage withstand characteristics under contamination. To overcome these problems insulators have been proposed and adopted having a composite structure--a sheath of silicone rubber, which is weather resistant and has excellent voltage withstand characteristics when contaminated, and a core of glass fiber reinforced plastic (FRP) to bear the tensile force. They have not been in general use in Japan, with the exception of special applications such as interphase spacers or experimentally for purposes of research.

Interest in composite insulators has, however, increased in recent years as they become more widely used overseas and social conditions favor attempts to reduce costs. In response the Electric Technology Research Association has established an investigative committee with a view to conducting specialized studies, and its report [1), while recognizing the cost advantages realized by the use of composite insulators overseas and offering no objection to their use, points out that no method has been established for estimating their service life.

Since the development of Furukawa Electric's composite insulators, which are characterized by a watertight end fitting structure, research has brought about successive improvements in their electrical and mechanical reliability. Part 1 of this paper described the process of developing composite insulators for overhead transmission lines and the results of performance tests [2)], and in Part 2 we report on our on studies of their long-term reliability.

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2. STRUCTURE OF COMPOSITE INSULATORS

Composite insulators comprise a core material, end fittings and an outer sheath of rubber. The core is made of FRP to provide mechanical strength against tensile force. The end fittings transmit tension from the lines to the tower and are made of forged steel, malleable cast iron or aluminum alloy. The outer sheath is made of silicone rubber, which offers superior electrical insulation properties and weather resistance. The silicone rubber used in the sheaths is particularly high in tearing strength so that it will not break when damaged during construction or otherwise. The end fittings and the FRP are joined by compression. Since electrical fields are concentrated at the tips of the end fittings making corona discharge more likely, the design is optimized by electrical field calculation to relax field stress. Once the end fitting has been compression joined to the FRP, the silicone rubber sheath is applied over the end fitting to form an integral unit. In a structure that is unique to Furukawa Electric, surface finishing is applied to the end fittings to improve their adhesion to the rubber, and the boding length is sufficient to prevent the entry of moisture from the end fittings along the FRP interface. Figure 1 shows the structure of a typical composite insulator.

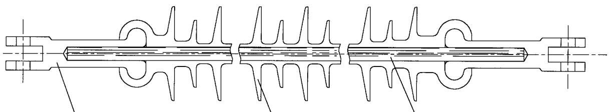

Figure 1 Structure of composite insulator.

3. LONG-TERM RELIABILITY OF COMPOSITE INSULATORS

Composite insulators for overhead lines typically are used in a severe natural environment and are constantly subjected to tensile loads and electrical stress. Thus it is essential that they have mechanical properties such that the joints between the end fittings and the FRP have long-term integrity, without slippage. Electrically it is essential that they withstand problems associated with organic materials, involving erosion due to dry-band localized arcing and corona discharge occurring under conditions of contamination or humidity.

3.1 Deterioration Phenomena

The factors influencing deterioration of composite insulators may be electrical, mechanical or a combination. The main ones are as follows:

Electrical factors include tracking, erosion, puncture of sheds, cracking, etc., while mechanical factors include long-term degradation of tensile strength and degradation of strength due to repetitive bending and twisting.

As combination factors we may note brittle fracture, in which the glass fiber of the FRP core becomes corroded by acid so that it fractures under comparatively low levels of strain. It is thought that brittle fracture is caused by nitric acid that is generated when there are problems at the interface between the end fittings and the silicone rubber outer sheath, resulting in corona or partial discharge at those points where moisture penetrates to the FRP. In this respect Furukawa Electric's composite insulators have a hermetically sealed structure in which the silicone rubber sheath is molded to cover the interface between the fittings and the FRP, to improve reliability against brittle fracture.

3.2 Methodology for Evaluating Reliability

There are currently a large number of organizations doing research on the phenomenon of the deterioration of the outer sheath in composite insulators. Among internationally recognized standards, IEC 61109 Annex C establishes a method for accelerated aging tests by means of environmental stress, and IEC 60587 and IEC 61302 give tests for specific outer sheath materials.

Since long-term sheath deterioration varies with environmental stress, the ideal method of determining the reliability of composite insulators would be by prolonged exposure to the usage environment, but much time and money would have to be expended before a result could be obtained. Accordingly evaluation is accomplished by concentrating and accelerating the environmental stress factors impacting deterioration. Silicone rubber--the most commonly used material for the outer sheaths--is characterized by outstanding properties of weather resistance together with a level of hydrophobicity that gives high voltage withstand characteristics under contamination. In addition, if hydrophobicity declines it recovers again, complicating the evaluation.

For this reason it is appropriate to estimate service life by conducting accelerated tests, while comparing usage conditions. Based on this philosophy, Furukawa Electric has proceeded to evaluate the reliability of composite insulators by conducting accelerated aging tests, as described below, at the Okinawa Charged Exposure Test Site.

4. RELIABILITY EVALUATION TESTS

4.1 Measuring Leakage Current

The deterioration that most generally affects composite insulator with a silicone rubber outer sheath of suitable mechanical design is caused by flows of leakage current on the surface in contaminated environments and by the erosion resulting from thermal and electrical factors. As erosion proceeds the silicone rubber sheath becomes corroded exposing the FRP, and this can lead to insulation breakdown and brittle fracture. It is thought that leakage current is the most suitable parameter by which to evaluate this erosion deterioration.

To obtain a clear picture of erosion deterioration by long-term reliability tests, the leakage current resulting from dry-band localized arc discharge was classified in terms of waveform characteristics using the method described below and designated as intermittent current, and this was distinguished from continuous current, which is the resistance component current[3].

(1) Definition of continuous current (resistance component current): A current which continues for a period longer than one sine-wave current cycle and of which the duration below the threshold value at the zero cross-over is 3 msec or less (Figure 2).

(2) Definition of intermittent current (dry-band localized arcing current): A current which continues above the threshold level for 1 msec or more, and of which the duration below the threshold value at the zero cross-over is 3 msec or more (Figure 3).

4.2 Exposure Testing [4)~6)]

Since 1995 77-kV line-to-ground charged exposure tests have been carried out at a test site located approximately 300 meters from the seacoast in Okinawa Prefecture, a region of high temperatures, severe salt contamination and comparatively frequent typhoons, providing continuous monitoring of the contamination and deterioration properties of the composite insulators.

(1) Insulators tested:
In order to investigate the influence of unit charge stress (V/mm), an important parameter in the withstand-voltage design against contamination, we made use of silicone rubber composite insulators having the same structure but different values of surface leakage distance. Porcelain insulators were also tested for comparison. Table 1 shows the specifications of the insulators tested.

(2) Results of observation:
(a) External visual inspection: After 5 years of testing the composite insulators showed satisfactory characteristics, and there was no observable erosion or tracking deterioration despite the severe levels of salt contamination at the test site.

(b) Equivalent salt deposition density: ESDD was measured by absorbing 200 ml of distilled water into a dust-free wipe Bencot and wiping down the surface of the composite insulator.

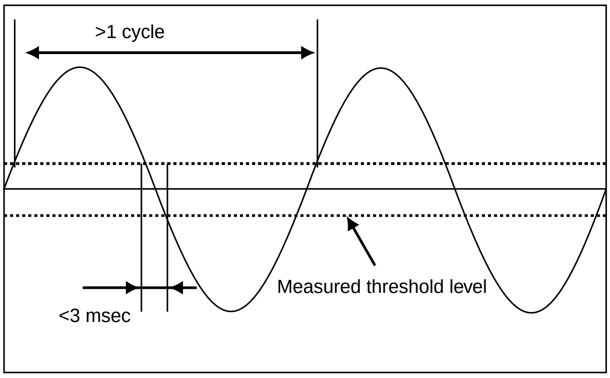

Figure 2 Definition of continuous current.

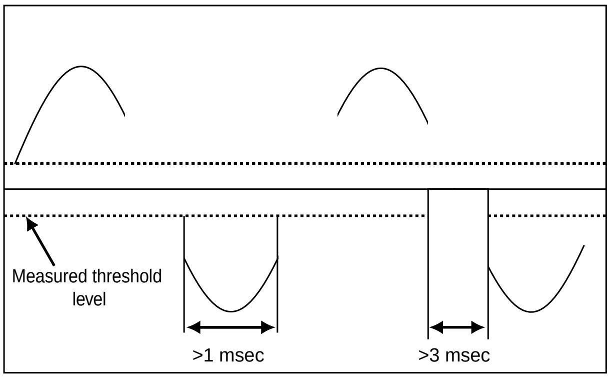

Figure 3 Definition of intermittent current.

Table 1 Specifications of sampleinsulators in exposure tests.

Sample	Section length	Effective distance	Number of sheds	Electrical stress
A	1359 mm	1107 mm	31	24.2 V/mm
B	1488 mm	1237 mm	35	21.5 V/mm
C	1618 mm	1367 mm	39	19.4 V/mm
D	1813 mm	1560 mm	45	16.9 V/mm

Measurements at 1-month intervals over the course of four years shows that the 50% cumulative ESDD was not particularly high--0.015 mg/cm^2--but maximum values in the aftermath of typhoons reached as high as 0.30 mg/cm^2 This shows that the test site suffers from severe contamination under the abnormal conditions presented by typhoons.

Figure 4 shows the results of investigations of volumetric trends in contamination of composite insulators. It will be noted that the values of ESDD measured for samples exposed for 1, 3, 6 and 32 months show a tendency to saturate, demonstrating that accumulation of contaminants on the surface of the silicone rubber sheath does not occur.

(c) Hydrophobicity: Hydrophobicity was measured every year by cutting out of the same insulator a specimen 5 mm square, and using a contact angle gauge, taking as the static contact angle the contact angle obtained by dripping 4 μl of distilled water for 1 minute, then applying 8 μl of distilled water, and taking as the receding contact angle the contact angle 1 minute after 8 μl suction.

Table 2 shows the results of an investigation of the contact angle of water droplets at the surface of the outer sheath as a measure of the hydrophobicity of the insulators tested. For all of the test samples the static contact angle showed values higher than the initial hydrophobicity. The receding contact angle, on the other hand, although on occasion higher than the initial value, showed results that, depending on the sample, were as much as 14 degrees lower than the

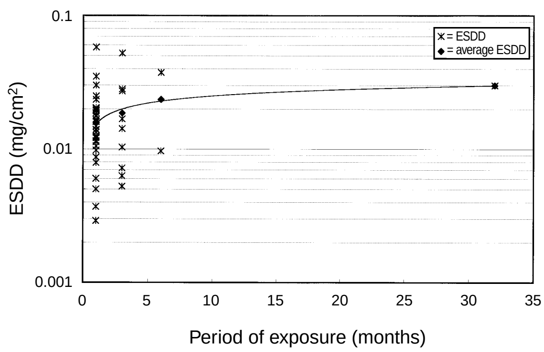

Figure 4 ESDD during exposure test.

Table 2 Surface hydrophobicity of test samples.

Sample	Static contact angle (deg.)			Receding contact angle (deg.)		
	Period of exposure (months)			Period of exposure (months)		
	29	41	53	29	41	53
A	128.0	130.4	132.9	103.8	94.9	97.8
B	112.3	123.1	114.7	79.1	88.1	74.0
C	121.1	130.8	136.8	88.9	99.4	102.9
D	112.0	105.9	111.6	82.4	70.9	68.5
Original	99.6			82.0		

Table 3 Four-year cumulative current charge at test site.

Sample	Cumulative current charge		x / (x + y)
	Intermittent (x)	Continuous (y)	
A	0.81 mAh	55.20 mAh	1.4%
B	2.26 mAh	62.05 mAh	3.5%
C	0.36 mAh	49.85 mAh	0.7%
D	0.64 mAh	38.69 mAh	1.6%

Table 4 Specifications of sample insulators in accelerated aging tests.

Sample	Section length	Effective distance	Number of sheds	Electrical stress
A	1359 mm	1107 mm	31	24.2 V/mm
E	1748 mm	1495 mm	43	17.6 V/mm

initial value. Furthermore the year-to-year changes in hydrophobicity were not only declines; recovery also occurred. Examining the effects of electrical stress, we may say that there is no correlation with hydrophobicity.

(d) Leakage current: Table 3 shows cumulative results for leakage current charge over a period of 4 years from 1995, classified for continuous and intermittent current. Almost all of the leakage current occurring at this exposure test site was of the continuous type, with only a few percent consisting of the intermittent current that is thought to influence sheath deterioration in composite insulators. Furthermore, the three typhoons that passed through the area during the test period accounted for approximately 50% of the intermittent current charge and about 95% of the continuous current charge. Thus we can state that virtually all instances of leakage current flow at the test site were concentrated during typhoon periods. Despite the reversal of continuous current charge between the A and B samples, Table 3 reveals a loose correlation with charge stress. For intermittent current, on the other hand, no correlation was observed between charge stress and electrical charge within the range of stress examined.

4.3 Accelerated Aging Tests [4), 5)]

Equipment was constructed capable of accelerated aging tests as stipulated in IEC 61109 on samples of the same size and at the same voltage (77 kV AC to ground) as are being tested at the Okinawa site, and tests were conducted [4)].

(1) Test methodology:

The test conditions were as follows:

- Charge voltage: 77 kV AC (voltage to ground)
- Test chamber dimensions: 4.4 x 4.4 x 3.3(ht) m
- Tension: 20 kN

Since these tests involve continuing the daily cycle

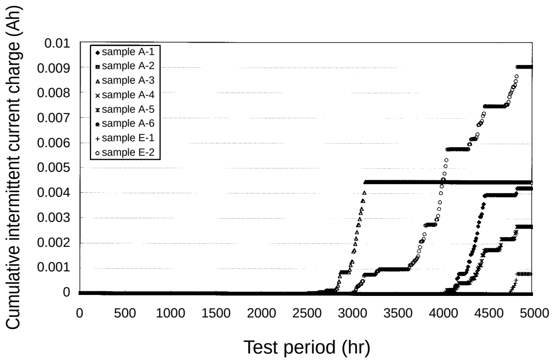

Figure 5 Transition of intermittent current.

shown in IEC 61109 Annex C for 5000 hr, a considerable time is required. To make the conditions even more rigorous, tests without rainfall cycles were also conducted to eliminate the washing effect of rainfall in the test cycle of Annex C.

(2) Insulators tested:

Table 4 shows the specifications of the test samples. The insulators used for the regular accelerated test cycle were A samples, which had the most severe stress at the Okinawa test site, and the E samples for high-contamination applications. For the test without rainfall, only A samples were used.

(3) Test results:

(a) General: It has been reported in earlier work [1), 2)] that no erosion or tracking deterioration was observed. In the present research we carried out a test specific to the test apparatus used, applying a tension of 20 kN, as a means of verifying the water-tightness of the end-fittings, which has an impact on brittle fracture, even though no such test is provided for in IEC 61109 Annex C. However no peeling or other problems with the end fittings occurred.

Tests were also conducted on insulators (identical to the A samples) on which scratches 20 mm in length and 1 mm in depth were inscribed reaching to the core at right angles to the length of the insulator at the end of the outer sheath and around the body, but no advance of tracking or erosion at the scratches was observed.

In the test which omitted the rainfall portion of the artificial weather cycle as a means of increasing the severity of the conditions, erosion did occur on the outer sheath of the composite insulators. This suggests that the washing action of the rainfall in IEC 61109 Annex C lightens the deterioration conditions with respect to the insulators.

(b) Leakage current: Table 5 shows the time course of change in the intermittent leakage current charge during accelerated aging tests. Major deviations can be observed in the leakage current charge, and it can be seen that even after the elapse of 5000 hr there

Table 5 Measurements of cumulative charge. (after 5000 hr)

Test condition	Cumulative current charge		x / (x + y)
	Intermittent (x)	Continuous (y)	
Rainfall excluded	41.47 mAh	0.81 mAh	97.9%

are some insulators in which hardly any leakage current occurs. Further virtually no intermittent leakage current occurred in the initial stages of the test, demonstrating the sound hydrophobic properties of the composite insulators. After the elapse of a further period there was a tendency toward sudden flows of intermittent leakage current, and considerable difference in onset times was seen among samples. This shows that because these tests were conducted using actual insulators there were individual differences, in that the drop in hydrophobicity in the length direction of the insulators could hardly be expected to occur generally within the same test chamber, and may be attributed to the nature of accelerated aging tests using full-size insulators.

(c) Erosion in intermittent leakage current: Table 5 shows the leakage current charge for samples showing erosion in the test omitting rainfall, measured after 5000 hr, and Photo 1 shows the occurrence of erosion

The process by which erosion occurred in the test omitting rainfall was as follows: First of all, erosion was found by visual observation at two points on the center portion of the insulator sheds 2550 hr after the start of the test, at which time the intermittent current charge was 18.98 mAh. When the test was then continued to 5000 hr the number of points of erosion increased to five and the intermittent current charge was 2.2 times greater, or 41.47 mAh [5]. This showed that erosion deterioration of actual insulators is not necessarily concentrated at a single point, but occurs in a random manner.

Furthermore, since no erosion was found during four years of testing at the Okinawa site despite the fact that the continuous current charge accumulated was in excess of 60 mAh (more than three times greater than the intermittent current charge of about 19 mAh at which erosion was confirmed in the accelerated aging test), we may conclude that continuous current charge does not contribute significantly to erosion. [2]

5. ESTIMATING SERVICE LIFE OF COMPOSITE INSULATORS

Since erosion was confirmed in the accelerated aging test conducted without rainfall, estimates were made of the service life of the silicone rubber outer sheath from the results of measurements at the Okinawa test site and of the accelerated aging tests.

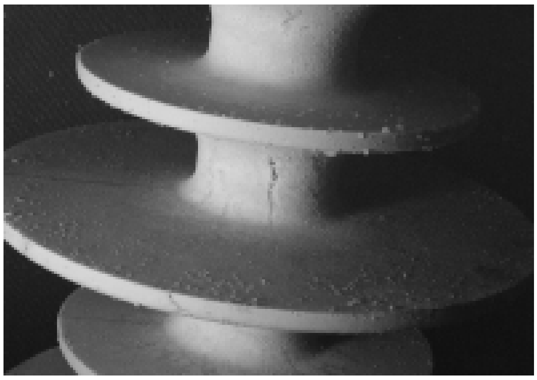

Photo 1 Occurrence of erosion.

The estimates were based on the following assumptions:

- That since it was the intermittent current charge that impacted erosion of the silicone rubber sheath, the intermittent charge current values measured at the Okinawa test site and in accelerated aging tests would be used;
- That the cumulative intermittent current charge occurring up to the onset of composite insulator erosion were the same for both test environments (Okinawa test site and accelerated aging test).
- Assuming that final sheath life for use as an insulator is the condition in which the transmission voltage can not be withstood, the limitation by the IEC 61109 standard is when erosion reaches the core. At the present stage, however, to be on the safe side, slight erosion of the sheath was considered to be the first stage of erosion.

Based on the above assumptions, a comparison was made between the intermittent current charge at the onset of erosion in the accelerated aging test without rainfall (18.98 mAh) and the value obtained in the exposure test at the Okinawa site for B samples, which had the highest intermittent current charge among the insulators tested (2.26 mAh). The number of years to the onset of erosion under the conditions at the Okinawa test site were calculated according to the equation

$$18.98 \text{ mAh} \ / \ (2.26 \text{ mAh} \ / \ 4 \text{ yr}) = 34 \text{ yr} \qquad (1)$$

In this way it was estimated that the time required for slight erosion to occur on the surface of a composite insulator under the conditions of the passage of typhoons and rapid contamination such as can occur at the Okinawa test site was 34 years.

This service life is the result of considering the point at which erosion would occur on the surface of a composite insulator. In actuality if, once erosion has begun on the insulator surface, the silicone rubber sheath were to be attacked by corrosion that penetrated to the core, this would be a fatal condition as far as a composite insulator was concerned. In general the silicone rubber sheath of the insulator has a thickness of 3 mm or more at the stem, so that it would require an even longer time for this fatal condition to be reached.

6. SUMMARY OF TEST RESULTS

In long-term charged exposure tests carried out over the more than five years since 1995 in the severe salt-contamination of the Okinawa test site, Furukawa Electric's composite insulators for phase spacer applications and transmission applications exhibited no deterioration.

Furthermore, large-scale accelerated aging testing equipment was constructed capable of combining the accelerated aging test conditions and tension loads specified in IEC 61109 Annex C. Full-size composite insulators were charged at 77 kV and were subjected both to the regular accelerated aging cycle and to a test cycle with the washing effect of rainfall omitted. In the regular accelerated aging cycle there were no problems--no penetration of salt or moisture into the ends and no deterioration of the silicone rubber outer sheath. In addition, to simulate damage that could occur during construction, standard accelerated aging tests were also conducted with the silicone rubber sheath cut back to expose the FRP. Due to the superior bonding at the interface between the outer sheath and FRP of Furukawa Electric's insulators, there were no electrical problems due to the entry of moisture and it was confirmed that even if damage were to occur, it would not immediately result in breakdown or failure.

Since it is possible in the course of the accelerated aging test without rainfall to induce erosion artificially in the center trunk portion of an insulator, such accelerated aging tests may be considered effective not in confirming the quality of composite insulators, but as a means of promoting deterioration. From the accelerated aging test without rainfall and the charged exposure test in Okinawa, estimates of the service life of composite insulators using the cumulative intermittent current charge occurring during discharge as the parameter affecting insulator deterioration, results were obtained that give a figure of 34 years or more--highly satisfactory for practical purposes--even in an area of severe salt contamination like Okinawa.

These investigations, however, are based on comparative data assuming salt contamination, a major factor in insulator design. Further investigation would need to be done before these results could be applied to areas with special conditions such as high humidity or severe industrial pollution.

7. CONCLUSION

Because of thoroughgoing quality control and a unique watertight structure for the end fittings, Furukawa Electric's composite insulators have exhibited high reliability in electric power transmission lines. They have been used without problems overseas for over 20 years as suspension insulators [7], and in Japan for 10 years as interphase spacers and about four years as strain insulators.

This paper has reported on two types of tests carried out on composite insulators: charged exposure tests at a test facility in Okinawa Prefecture and accelerated aging tests conducted indoors. The use of silicone rubber in transmission lines had been considered problematic, but it has been confirmed that it has ample service life.

ACKNOWLEDGMENTS

The charged exposure tests in Okinawa and the accelerated aging tests were carried out at the behest of the Tokyo Electric Power Company as part of research on evaluating the service life of organic interphase spacers. We are grateful for the cooperation of Prof. Higashimori and Mr. Iha of the Dept. of Electrical Engineering, Faculty of Engineering, Ryukyu University in obtaining measurements for the charged exposure tests. We would also like to express our thanks to others too numerous to mention.

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Manuscript received on April 28, 2001.