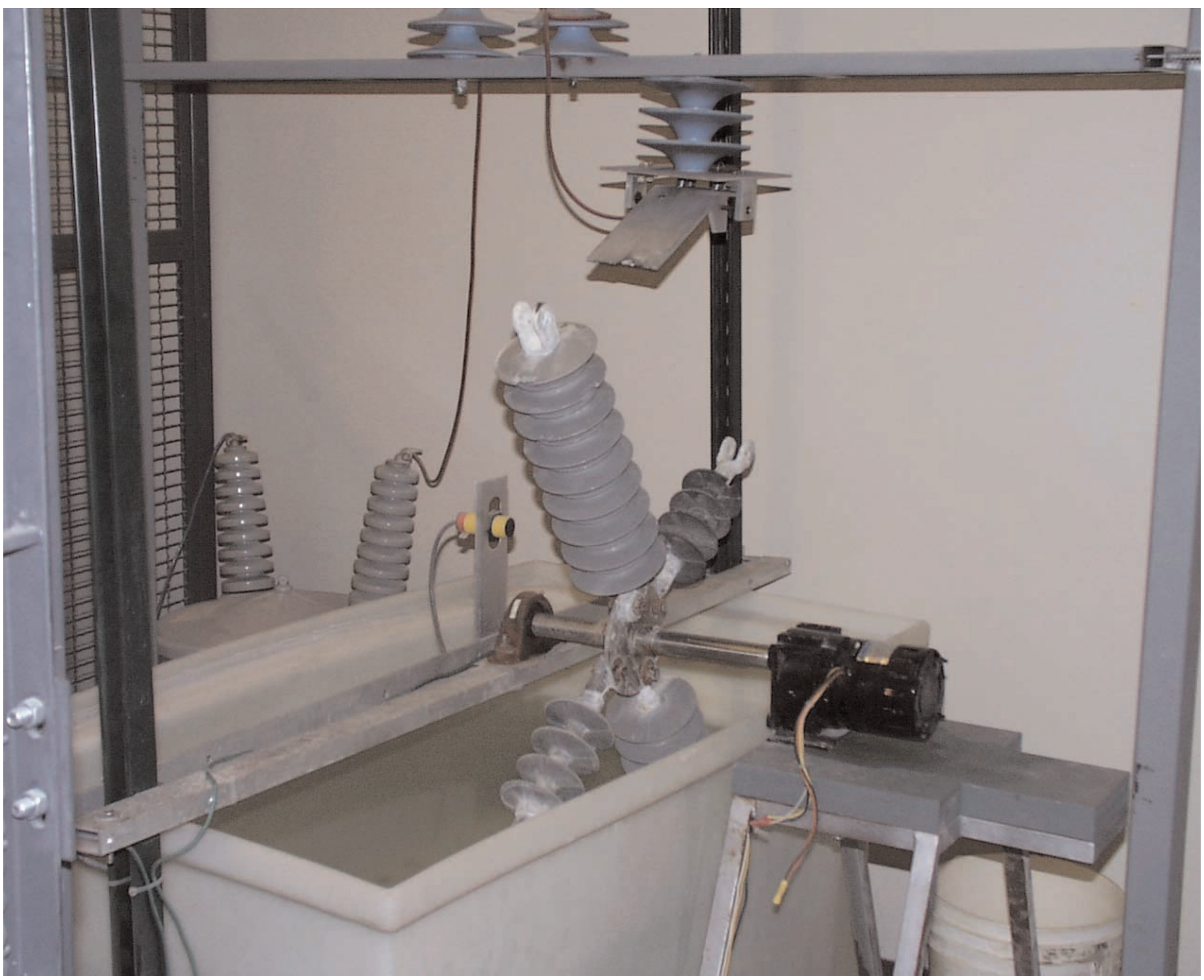
Performance Prediction of Polymer Insulators for Distribution

Technical Report



Performance Prediction of Polymer Insulators for Distribution

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Final Report, January 2001

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REPORT SUMMARY

This report describes accelerated laboratory tests conducted to evaluate performance and life expectancy of four available polymer insulator designs.

Background

Polymer insulators are used extensively in the United States in distribution overhead lines. Many utilities specify polymer insulators exclusively and have moved away from traditional porcelain. Since many manufacturers offer polymer insulators, it has become an attractive economic choice. Available polymer insulators differ in their construction details and external housing composition. In addition, continuing manufacturer improvements lead to changes in their composition and makeup. Utilities, naturally, are interested in the life expectancy and performance characteristic of these new polymer insulators. However, there has been no field or laboratory data to suggest that these new polymer insulators will work satisfactorily for their life expectancy. To correct this lack of data, accelerated laboratory tests were conducted to estimate polymer insulator performance.

Objective

To estimate the performance and life expectancy of available polymer insulator designs.

Approach

This project team examined insulators from four different manufacturers. By combining data from accelerated testing techniques with aging data from several insulator types already in the field, the team was able to estimate future performance and life expectancy. Fog chamber testing methods developed in a previous EPRI project (TR-106322) and a rotating wheel test specified in the IEEE/ANSI 1024 document were the laboratory tests. Fourier Transform Infra-red Spectroscopy (FTIR) was the principal tool for assessing changes due to field and laboratory aging of the insulators. The method for determining life expectancy was based on the Arrhenius model, which relates a change in a physical property with time.

Results

Project results include the following:

- All insulator types evaluated are expected to perform satisfactorily for a 30-year period, provided there are no defects during manufacture and installation.
- Only minor differences in leakage current and discharge activity occurred on insulator surfaces in the high conductivity fog chamber test and rotating wheel test. These differences were attributable to experimental conditions in the tests.

- Both laboratory methods used for accelerated aging—the fog chamber and the rotating wheel—showed consistent ranking of insulator performance.
- The Arrhenius plot for the change of polymer functional groups during accelerated aging has been demonstrated to be a satisfactory tool for useful life estimation. "Useful life" is the time during which satisfactory operation is likely and not the time after which the device will fail.

EPRI Perspective

Polymer insulators for distribution were introduced in the late 1950s and represented the first viable alternative to traditional porcelain insulators. These first generation polymer insulators encountered many problems in the very early stages of service. With a housing made from bisphenol epoxy resin, the insulators exhibited UV radiation damage, moisture ingress, and tracking and erosion due to electrical discharge activity. To correct these problems, individual insulator manufacturers have continually improved their own material formulations and manufacturing methods. Consequently, current polymer insulators differ in their construction details and external housing compositions. Until this research project, there had been no field or laboratory data to evaluate whether the current selection of polymer insulators would work satisfactorily for their expected 30-year service life.

Keywords

Reliability
Distribution
Maintenance
Insulation
Aging (materials)
Electrical insulators

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1
INTRODUCTION

Polymer insulators for distribution were introduced in the late 1950s, and represented the first viable alternative to traditional porcelain insulators. Several problems, chiefly, the poor quality of raw materials, extensive manufacturing facilities and energy needed for production, forced many US suppliers to look for alternative materials and technology for outdoor insulators. The first generation polymer insulators encountered many problems in the very early stages of service itself. These insulators had a housing made from bisphenol epoxy resin. The material exhibited damage from UV radiation of sunlight, moisture ingress, tracking and erosion due to electrical discharge activity that occurs in the presence of moisture and contamination on the insulator surface. The premature problems forced many utilities to revert back to porcelain insulators.

Insulator manufacturers in the meantime had made significant progress in material formulation and manufacturing methods. In addition, much was learnt regarding the requirements for outdoor high voltage use. Laboratory test methods were developed for screening materials and other components for insulator use. All of these factors contributed to significant improvement in insulator quality and performance subsequently. Currently, a majority of polymer insulators in use for distribution have some common features in their construction, namely:

1. A central fiber glass rod made from E-glass fibers and bonded by either epoxy, polyester or vinyl ester resins, the latter being more common due to lower cost.

2. An external housing made from silicone rubber (SR), ethylene propylene diene monomer (EPDM) rubber, or a blend of SR and EPDM.

3. Metal end fittings that are crimped on to the rod.

4. The external housing that is injection molded to the rod in a one shot process.

2
INSULATORS EVALUATED

Insulators from 4 different manufacturers were evaluated and were supplied by the participating utilities. The color of the housing was different for each insulator, this could be simply due to the coloring agent and/or major differences in material composition. The important features of these insulators are listed in Table 2-1. The letteer identification used to designate these insulators in the graphs contained in this report is shown in parenthesis. All the insulators were rated for 15 kV (line to line voltage) application.

Table 2-1
Description of insulators evaluated

Manufacturer-(ID)	Housing Material	Remarks
K-Line (A)	Silicone rubber	Aluminum end fittings
Sediver (B)	EPDM 1	Light gray housing
Victor ©	EPDM 2	Dark gray housing
Hubbell-Ohio Brass (D)	EPDM+ SR blend	Dark gray housing

In addition to the above insulators that were supplied in the new condition, limited number of insulators of type B and D that had been in service for about a 5 year period were also made available. The insulators had no visible signs of degradation when they were received.

3
LIFE ESTIMATION METHODS

The methods used presently for life estimation are all based on chemical degradation theory proposed by Dakin in his 1948 AIEE paper titled "Electrical insulation deterioration treated as a chemical rate phenomena". The Arrhenius chemical reaction rate model forms the basis of Dakin's paper. The reaction can be expressed by the equation:

$L = A \exp(-BT)$, where L= life of insulation under a single stress, A and B are calculated constants, and T is the absolute temperature. The use of this model led to the 10-degree rule, whereby it is postulated that with every 10 ^{o}C rise in temperature, the life of insulation will reduce by a factor of 2.

In this model, the electrical, mechanical and environmental aging are assumed to have no real impact on the life of the insulation. We know that this is not true, especially for outdoor insulation. Many researchers have tried to improve the method proposed by Dakin by including other relevant stresses that the insulation experiences in service. However, not much significant improvement has been achieved with the result that life estimation especially for outdoor insulators relies heavily on service experience, and ill-proven accelerated aging tests.

In previous EPRI sponsored projects at ASU, the relation between accelerated aging tests and field experience was demonstrated. The findings have been published in EPRI reports and IEEE papers [1,2,3]. The laboratory tests chosen were the Fog chamber tests and the rotation wheel test. Periodic measurement of weathershed aging obtained in the field and in the laboratory of identical insulators and cable terminations enabled us to develop an acceleration factor for the laboratory tests. The primary measurement technique used in the project for assessing aging was FTIR (Fourier Transform Infra-red) Spectroscopy. We established that a 500 hour aging in the fog chamber under relative low water conductivity would be equivalent to a 30 year exposure in service in most parts of the USA. Excluded were sites with extreme contamination, such as in the immediate vicinity of major chemical plants.

The purpose of the present project was to subject insulators of interest to the Southern Company to laboratory tests developed in the previous project, and develop estimates of useful life for the insulator types supplied.

As a side goal, we wanted to evaluate other methods of measurement such as resistance, leakage current and weight loss for their ability to predict useful life.

4
DETAILS OF LABORATORY AGING TESTS EMPLOYED

(a).Fog Chamber: Fig. 1 shows the arrangement of insulators in the fog chamber at ASU. It is made from stainless steel sheets and its dimensions are 3.6X3.6X2.5 m high. There are 4 nozzles, one on each wall of the chamber. These nozzles details are as per IEC 507. Water of the required conductivity is made by adding NaCl to deionized water. The saline solution is recycled and changed daily, in order to limit the increase in the conductivity to <10% of the initial value.

The high voltage supply is provided by a 0-100 kV, 40 kVA transformer. The insulators were installed in the vertical position. To facilitate leakage current measurement, a 100 Ω precision resistor was inserted in the ground path of the each insulator. The voltage drop across this resistor was monitored by the data acquisition system, which was developed based on the LABVIEW package.

The accelerated aging tests were performed at two levels of water conductivity; a relatively low value of 300 μS/cm and a moderately high value of 2000 μS/cm. These levels were chosen based on previous extensive testing at ASU. The lower water conductivity is capable of evaluating the leakage current suppression capability and the tracking and erosion resistance to moderate discharge activity. The higher water conductivity evaluates the tracking and erosion resistance to intensive surface discharges.

The insulators were exposed to electric stress and fog for periods ranging from 12-16 hours. During the remainder of the day (12-8 hours) the fog was switched off. At each level of water conductivity, the insulators were tested for a total of 500 hours of exposure to electric stress and fog. This test duration was found to be sufficiently long to obtain a relative ranking of the insulators evaluated.

Figure 4-1
Photograph of Fog Chamber

(b) Tracking Wheel: This set-up was built as per the IEEE/ANSI 1024 standard, and a picture is shown in Fig. 2. There are 4 insulators that can be tested at any one time. These insulators are subjected to energization, rest, dipping and run-off positions cyclically. Each of these position lasts for 30 sec, making a total of 2 minutes for each complete cycle. The specified test duration is 30,000 cycles. The voltage source is a 25 kV, 15 kVA transformer. The insulators are energized with 10 kV, which is slightly higher than the nominal service voltage (8.66 kV). The water conductivity specified is 2200 μS/cm.

The leakage current during the test is monitored by a LABVIEW based data acquisition system. The integral of the leakage current, average and peak currents are recorded for each insulator.

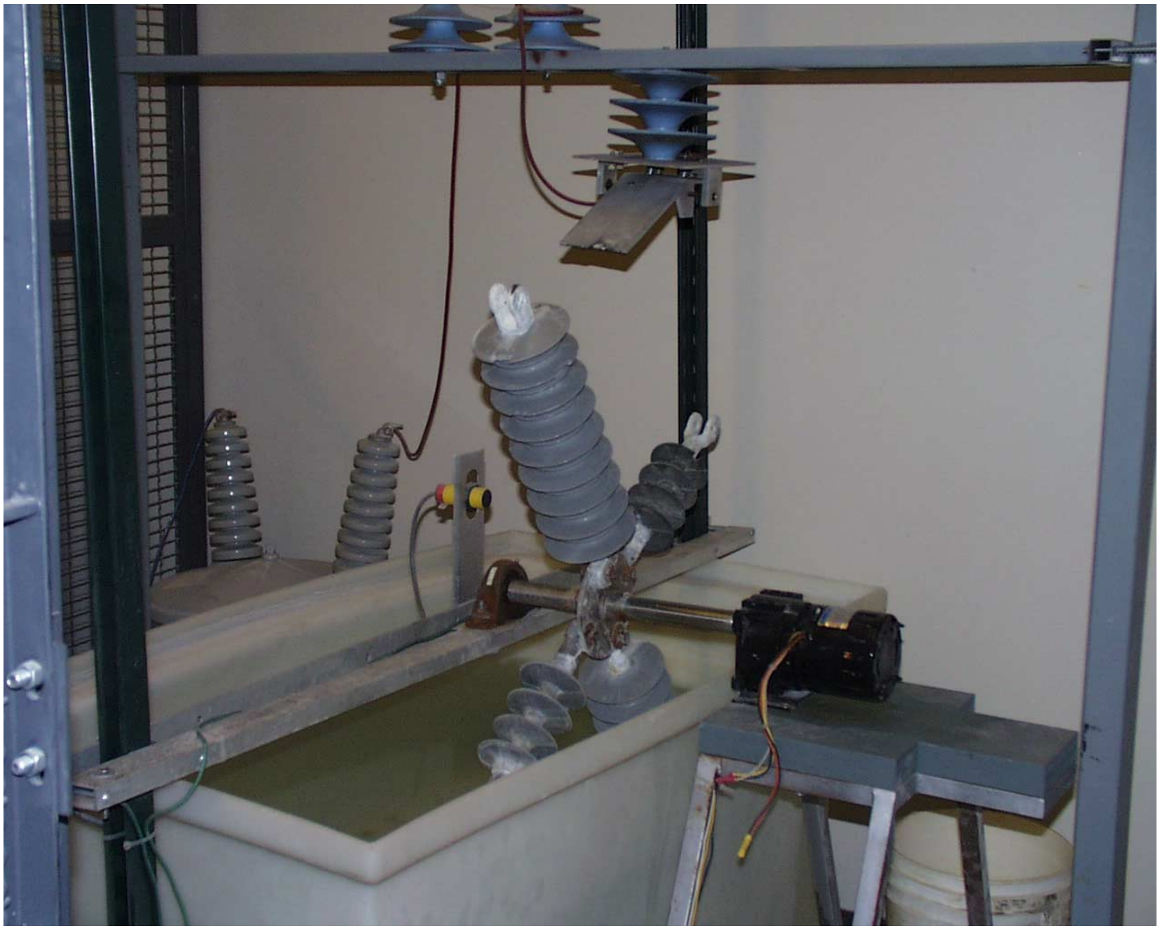

Figure 4-2
Photograph of Rotating (Tracking) Wheel

5
RESULTS

None of the insulators, new and previously field exposed, failed during any of the laboratory aging tests. The difference in leakage current between the new and the previously exposed was minimal and limited to the first 50 hours of the laboratory test exposure. All insulators underwent limited amount of permanent changes during the laboratory test exposure. The changes observed were mostly superficial. For insulators B, C and D which utilized EPDM based rubber, the surface hydrophobicity that was existing when new was lost within the first 50 hours of exposure to the laboratory tests and was lost permanently.

Figures 5-1 through 5-3 show the cumulative charge of the insulators evaluated. It can be seen that only in the low conductivity fog test, the silicone rubber insulator showed better performance (lower charge) than the rest. In the high conductivity fog test and the rotating wheel test, the cumulative charge of all the insulators was not significantly different. Such differences in the performance have been well analyzed and accounted for in earlier EPRI reports and technical papers.

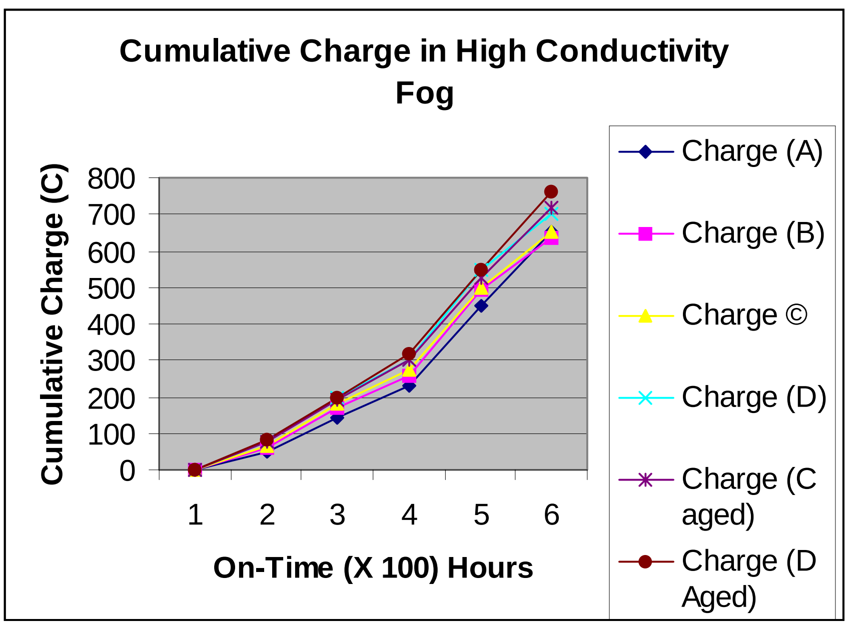

Figure 5-1
Cumulative charge of new and field aged samples in the high conductivity fog chamber test

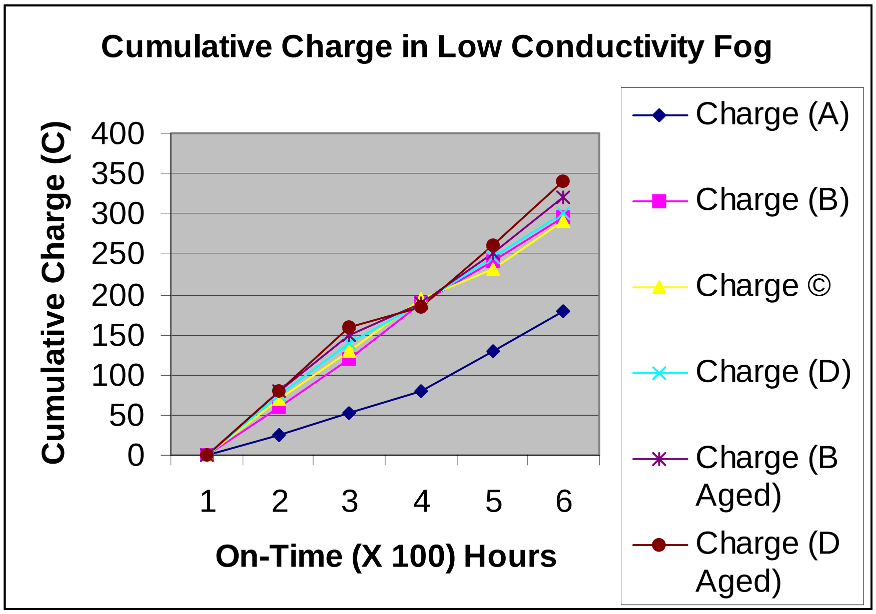

Figure 5-2
Cumulative charge of new and field aged samples in the low conductivity fog chamber test.

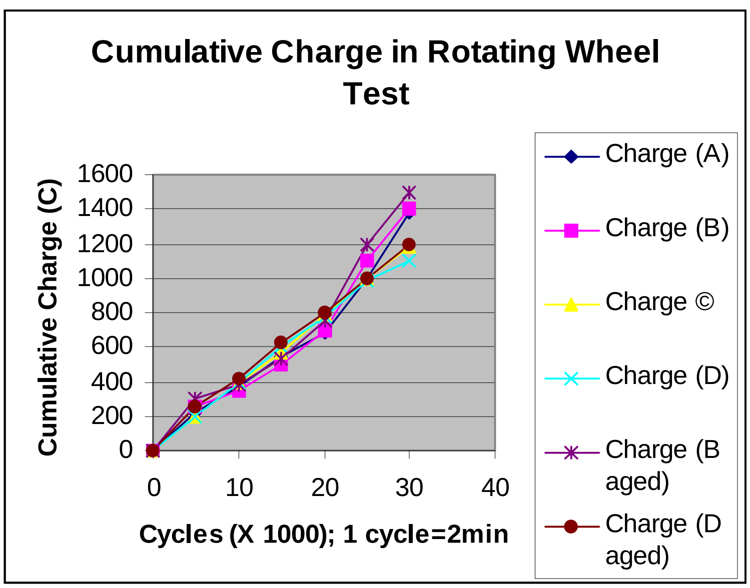

Figure 5-3
Cumulative charge of new and field aged samples in the rotating wheel test

6
PERFORMANCE PREDICTION FROM FTIR ANALYSIS OF FIELD AND LABORATORY AGED INSULATORS

Figures 7-1 through 7-4 show the FTIR plots of the insulators before and after accelerated aging, for the various samples. 4 plots are shown for each sample. Only for insulators B and D, field aged samples were available. The plots essentially show that:

1. The extent of changes experienced by the B and D insulators in the 5 years of field aging is minimal.
2. The changes experienced after the rotating wheel and fog chamber test is significant only if the samples are not cleaned, but on cleaning the changes almost vanish. This pattern is more due to the fact that the depth of material analyzed by this technique is only a few microns (i. e., the thickness of the contaminant), than due to any permanent changes occurring in the material.
3. The difference in the aging produced on a new insulator and a field-aged insulator is negligible.

Estimation of life expectancy: It was assumed that the 50% reduction of the significant peaks would be the indication for end-of-life, although there is no real data to support this assumption. Besides the FTIR data, other parameters, such as reduction in surface resistance with aging, increase in leakage current and weight loss were tried for estimation of life expectancy. Limited data for insulators B and D were obtained from a recently completed EPRI project (TR-111515-V1, 1999), but not for the other insulators. In any case the data was not suitable for performance prediction.

Arrhenius plots were generated showing the reduction in the IR peak on the Y-axis and time of aging in hours on the X-axis (both on a linear scale). The reduction in peak after 500 hours of rotating wheel test and fog chamber tests were used. Values of the FTIR peak after every 100 hours was obtained but the change from the virgin sample was only minimal.

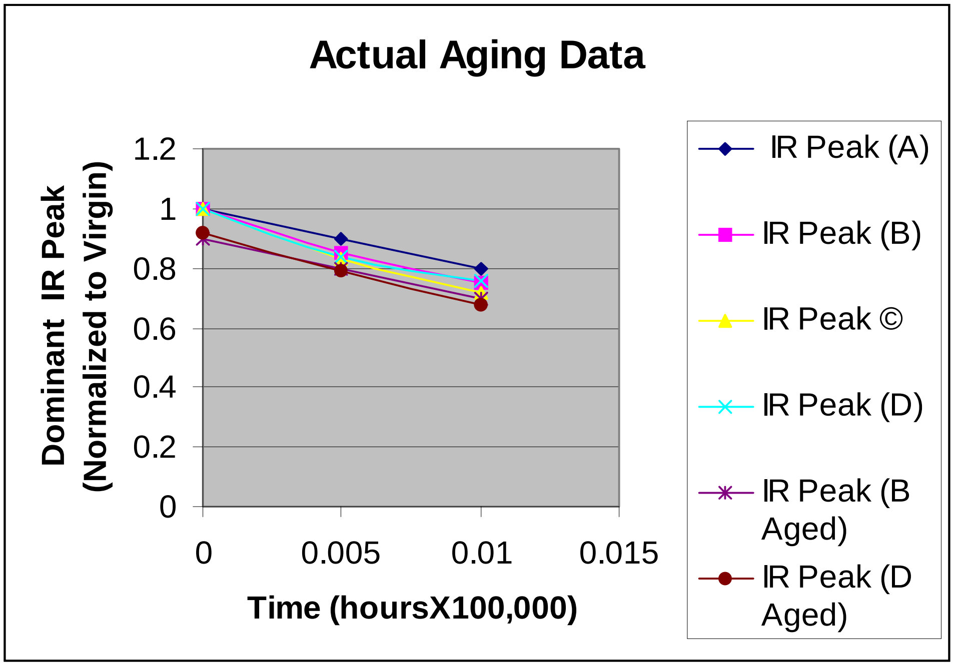

Figure 6-1
shows that the actual aging data from the 500 hour low conductivity test and 1000 hour (30,000 cycle) rotating wheel test.

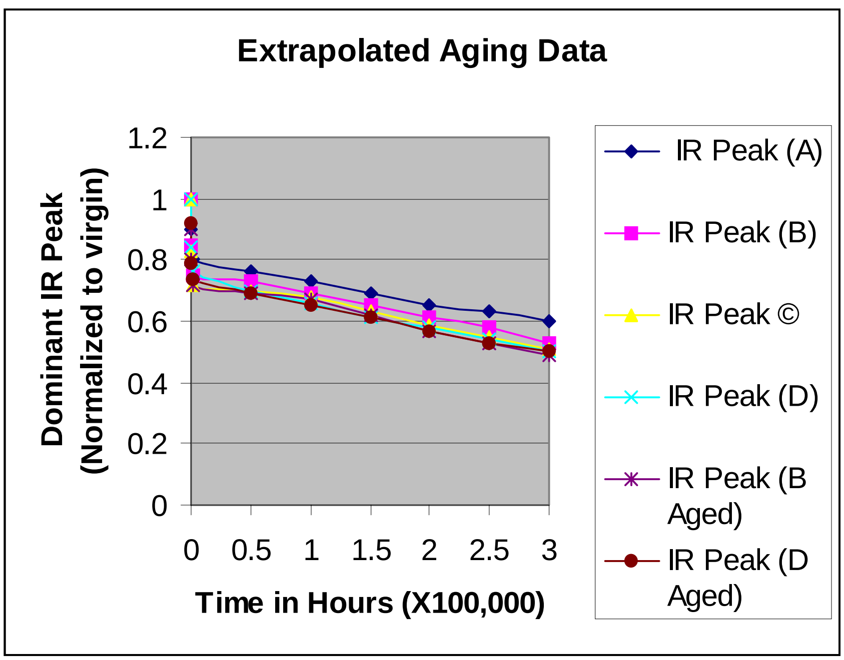

Figure 6-2
shows the extrapolated graph based on the actual data. Acknowledging the risks of extrapolation based on limited testing, the figure nevertheless indicates that the insulators can be expected to perform satisfactorily over a 30 year (262,000 hours) life.

Similar plots were tried with other data such as leakage current, surface resistance and weight loss. All of these parameters gave unreasonable estimates such as 1000 years, or < 1 year. Hence it was concluded that none of these parameters are suitable for estimating useful life.

7 CONCLUSIONS

The conclusions of the project are:

1. All of the insulator types evaluated can be expected to perform satisfactorily for a 30-year period, provided there are no defects during manufacture and installation.
2. There are only minor differences in the leakage current and discharge activity occurring on the insulator surface in the high conductivity fog chamber test and rotating wheel test. This should be attributed to the experimental conditions used in these tests.
3. Both the laboratory methods employed for accelerated aging, the fog chamber and the rotating wheel, showed consistent ranking of the insulator performance.
4. The Arrhenius plot of the change of polymer functional groups during accelerated aging test has been demonstrated to be a satisfactory tool for <u>useful life estimation</u>. The underlined phrase should be understood as the time for which satisfactory operation can be expected, and NOT the time after which the device will fail.

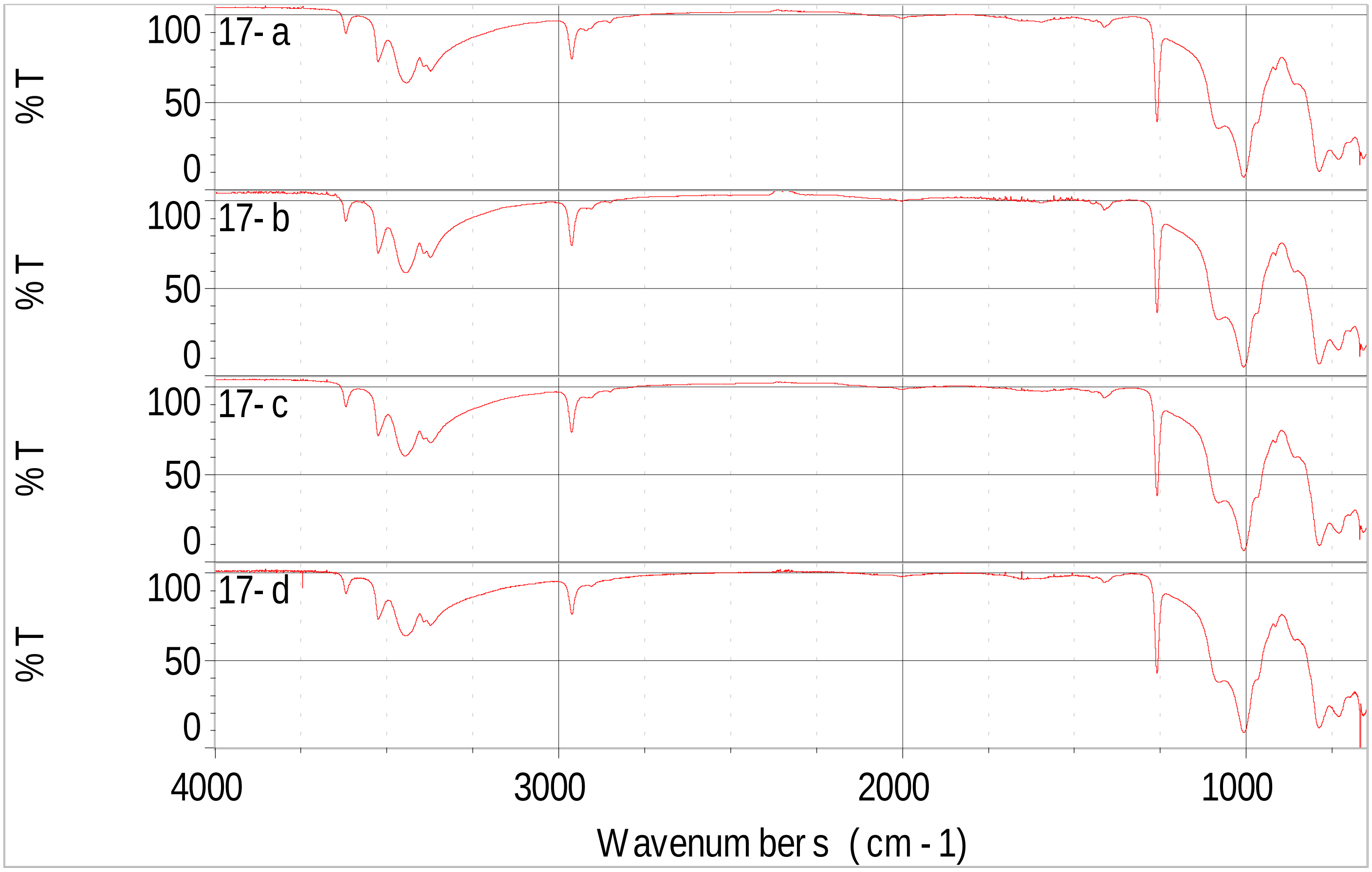

Figure 7-1
FTIR Plots for Silicone rubber insulator A.

Plot 17-a: Virgin insulator

Plot 17-b: After low conductivity fog chamber test. The samples were analyzed after 1 week of test completion to allow for any recovery phenomena. Notice that the changes are negligible.

Plot 17-c: After rotating wheel test. The samples were analyzed after 1 week of test completion to allow for any recovery phenomena. Notice that the changes are negligible

Plot 17-d: After high conductivity fog chamber test. The samples were analyzed after 1 week of test completion to allow for any recovery phenomena. Notice that the changes are still negligible.

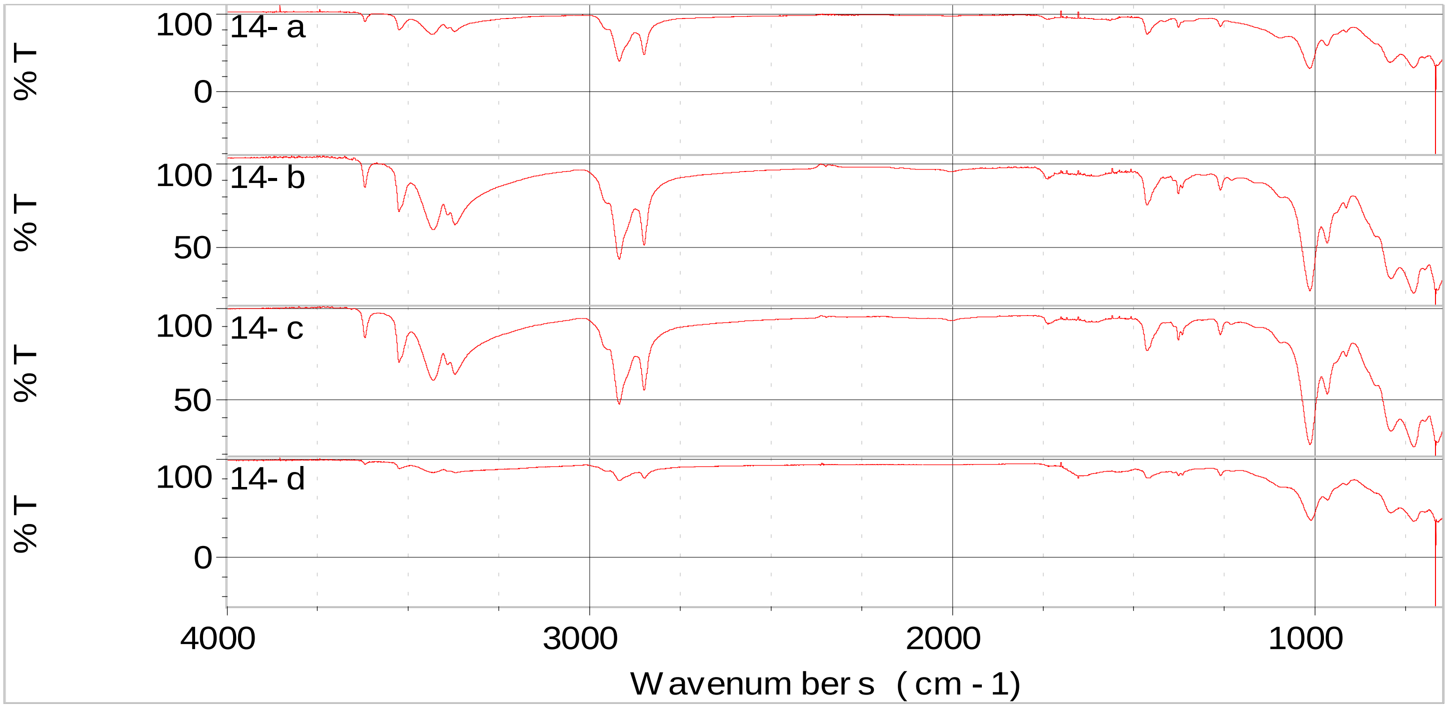

Figure 7-2
FTIR plot for EPDM insulator B.

Plot 14-c: Plot for virgin insulator.

Plot 14-a: After rotating wheel test on a new insulator without cleaning the insulator. Notice that the changes are noticeable, but when the insulator was cleaned the spectrum was very similar to the virgin sample.

Plot 14-b: As received from the field after 5 years. Note that the changes from the virgin are negligible.

Plot 14-d: After rotating wheel test of a field aged insulator without cleaning the insulator. Notice that the changes are noticeable, but when the insulator was cleaned the spectrum was very similar to the spectrum b in the as-received condition.

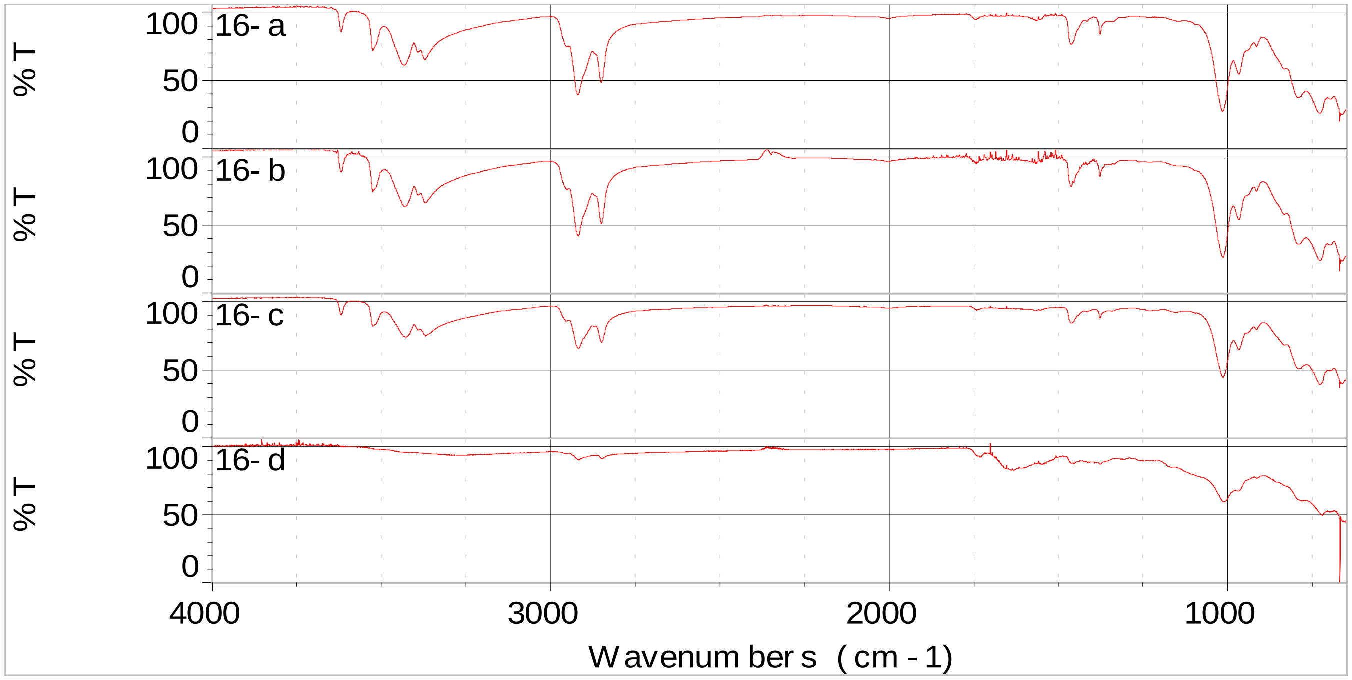

Figure 7-3
FTIR plots of EPDM insulator C.

Plot 16-a: Plot of a virgin insulator.

Plot 16-b: After rotating wheel test. The insulator was cleaned prior to the analysis. Notice that the changes from the virgin sample are negligible.

Plot 16-c: After rotating wheel test. The insulator was not cleaned; hence the large changes from the virgin sample.

Plot 16-d: After high conductivity fog chamber test. The insulator was not cleaned; hence the large changes from the virgin sample.

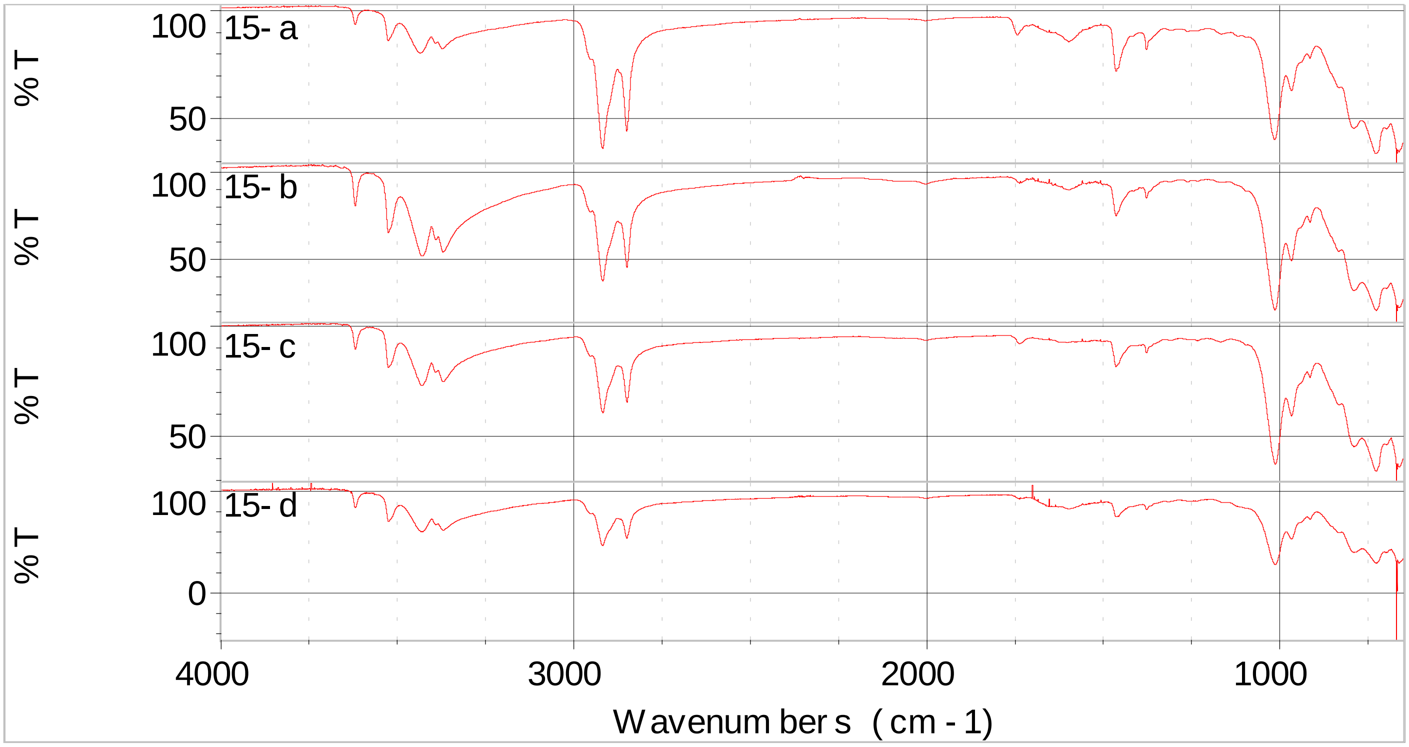

Figure 7-4
FTIR plots of EPDM-silicone rubber blend insulator D.

Plot 15-b: Plot of a virgin insulator.

Plot 15-a: After rotating wheel test of a new insulator. The insulator was not cleaned prior to the analysis. Notice that the changes from the virgin sample are noticeable, but vanish after the insulator is cleaned.

Plot 15-c: After rotating wheel test of a field aged insulator. The insulator was cleaned, the changes from the virgin sample are noticeable.

Plot 15-d: After high conductivity fog chamber test of a new insulator. The insulator was not cleaned; hence the large changes from the virgin sample.

Target:
Distribution Systems

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