

LABORATORY INVESTIGATION
INTO THE RADIO INTERFERENCE PRODUCED BY ARTIFICIALLY
POLLUTED 22 KV DISTRIBUTION LINE INSULATORS

By

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SYNOPSIS

Although it is known that polluted power line insulators can, under certain conditions, cause interference with radio communication networks, there is little useful practical data as to the extent of the problem. This is mainly due to the difficulties associated with quantifying and measuring this interference.

There are various test procedures to measure radio noise characteristics of hv insulators, set out in recommendations published by the International Electrotechnical Commission (IEC). These however, only apply to clean and dry conditions. The IEC has also recommended methods for the laboratory simulation of natural pollution conditions in insulator flashover tests. This project involved combining the two techniques into a laboratory procedure for measuring RN produced by artificially polluted insulators.

The investigation was concentrated on 22 kV line insulation and RN in AM frequency bands. Initial tests were done to develop a repeatable pollution simulation method based on the IEC 507 clean fog artificial pollution test. This method was then combined with the IEC 437 RN measurement test circuit to form the basis of two different types of test procedure.

The first test procedure was a prolonged or constant voltage method. It consisted of monitoring the insulator RN with time while it was subjected to a pre-determined pollution condition

and a constant voltage for the test duration. This is representative of the field situation but makes it a very time consuming process to obtain interference values over a range of test voltages. The second, accelerated type, procedure was to record RN as the voltage was varied within any one test run. This is not representative of a practical case where large voltage variations are rare, but it did have time saving implications.

The accelerated procedure generally gave lower RIV values than those indicated by the prolonged procedure at the same voltage and pollution severity. Nonetheless, it was concluded that, by paying particular attention to wetting rates and voltage step durations, the accelerated procedure could also be further developed into a standard polluted insulator RN test.

Two different insulator types - a porcelain line post insulator and a glass disc insulator - were used in 153 clean fog test runs. The results showed that clean, or polluted but dry insulators, operating at practically used specific creepages, produce insignificant levels of interference. Only at impractically low specific creepage were unacceptably high ranges of RN emitted. When the insulators were polluted and dampened with the clean fog, the RN increased rapidly with voltages above 1 kV. For the line post insulator the curve reached a knee point at about 8 kV, beyond which very little or no RIV increase with voltage was observed up to 18 kV. For the glass disc units, although the slope of the curve decreased at the higher voltages the same knee point was not so evident. For both insulators, except at very low voltages, little variation in RN level with pollution severity at fixed voltage was observed.

These results are in general agreement with the conclusions of previous work. It would be useful to further refine the test methods, both to develop a RN measurement standard and to obtain more data pertaining to specific insulator types. A standard procedure would also permit investigating the correlation of both polluted insulator leakage current and the practical nuisance value of the RN, with laboratory measured RIV values.

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1. INTRODUCTION

1.1. Background And Rationale

Any electrical discharge occurring on an overhead power line, whether that discharge be partial or complete, can give rise to high frequency electromagnetic energy, which is likely to be conducted along and radiated out from the line [1],[2]. The general terms radio noise (RN) and radio interference (RI) are used to describe this phenomenon. It is an undesirable effect as it tends to disrupt the proper functioning of radio communications equipment.

Despite extensive research having been conducted into the general phenomenon of power line noise, it is not yet fully understood in all aspects. Furthermore, specific data on the extent of the problem in varied pollution conditions and at different voltages is not complete. One aspect of the problem is RN produced from polluted line insulators. This thesis describes an investigation into the laboratory simulation and measurement of RN produced by polluted insulators on power lines rated up to 22 kV.

Although Eskom (the South African national electricity supply authority) annually receives many complaints of radio and television interference from its power lines, relatively few of these can be traced to polluted insulator sources. Where such sources have been found, they have tended to be in regions under marine pollution conditions. Most of these occurrences have been at sites in the Natal coastal areas, such as in the Richards Bay

vicinity, where very severe marine pollution conditions are known to exist. In the last few years, however, there have been some two or three interference complaints investigated by Eskom's Engineering Investigations Division in the greater Johannesburg area, where industrially polluted insulators were suspected to be the cause.

This particular project arose from an enquiry relating to a Post Office high frequency (HF) communications link that was to be established at Bredasdorp, which is close to the coast in the Southern Cape. Some concern was expressed that polluted insulator interference might affect the link, but it was found that insufficient data existed on which to base an accurate prediction of this. Thus, this project was initiated both to add to the knowledge of the phenomenon in general and, in particular, to obtain some data on the extent of the problem in local South African conditions.

In general, power line RN has been found to occur at all voltage levels, from 4 kV to 800 kV and above, and has been reported to emanate from numerous sources of spark and corona discharges that occur on these lines [3],[4]. Furthermore, depending on the particular situation, the frequency spectrum of the RN may extend into the Gigahertz range [4],[5],[6].

Although it is known that polluted outdoor insulation can be one of these RN sources, this is one of the areas where the data is incomplete. Furthermore, there is no standard test procedure specified for performing RN tests on polluted insulators in the laboratory. It is not easy to specify such tests due mainly to

difficulties in obtaining reproducible experimental results. Factors such as the amount and distribution of solid pollution on the insulator surface, the wetness of the insulator, the ambient conditions, and the voltage stress across the insulator, all affect the resulting RN level. As a result, practical pollution conditions are not easy to quantify or to accurately or repeatedly simulate in the laboratory. Furthermore, since the electrical discharge processes by which the RN is produced are statistical, this introduces a greater spread in results, even under identical test conditions. The only RN test for which there is a standard procedure, is in the clean, dry insulator situation [7]. Then the insulator surface and ambient conditions can be well defined and are easily reproducible, not only in any one laboratory, but also in any number of laboratories.

The lack of data on polluted insulator RN is largely attributable to the world wide trend towards increasingly higher transmission voltages of 200 kV and above. This has caused power line research in general to focus on these EHV and UHV situations, in which conductor corona is by far the major contributor to the line noise level. Thus other noise sources, such as spark gap discharges and polluted insulators, have been less studied as they are encountered more often at lower voltages, where conductor voltage gradients tend to be below the corona inception level.

Polluted insulator RN, however, may in the future become an important design criterion in South Africa. This is due to the increasing level of rural electrification that is occurring in the country, which in turn can be expected to result in a great

proliferation of 22 kV networks. For such lines, there is plenty of information available to ensure that conductor corona as a RN source is eliminated at the design stage. Furthermore, hardware sparking interference sources can be identified and avoided by following good construction practices [8]. However, since pollution interference is a natural phenomenon, the designer has very little other than past experience to guide him. As more lines are built, so it becomes increasingly more difficult to avoid RN problems by merely routing lines well away from any sensitive radio installations. Instead, more attention needs to be paid to designing lines with acceptably low RN levels in all situations, and this will require more accurate and complete information than is presently available.

1.2. Objectives And Limitations Of The Investigation

The overall aim of this study was to make a contribution towards increasing knowledge in the area of power line RN involving polluted insulation and to provide some data pertinent to local conditions. Thus, a valid and reproducible laboratory test procedure for obtaining RN characteristics of polluted insulators was to be developed. Power line RN is usually measured either in terms of the strength of the electromagnetic field radiated out by the noise source, or as a quantity called the radio influence voltage (RIV). These can both give an indication of the amount of electromagnetic energy produced at a particular frequency by the electric discharges on a power line.

In this investigation, RN was measured in terms of RIV. In

determining the best test procedure to use, some useful local data on insulator RN variation with pollution severity and voltage was obtained. It should be noted that the investigation was done at an altitude of approximately 1500 m above sea-level. Thus, implicit in the data obtained, is the effect of reduced air density, as compared with other published data that has been obtained at altitudes much closer to sea-level. Although it is not possible to isolate this effect, it could be significant since it is known that in general the inception of electric discharge activity does depend on the relative air density [9].

Two problems had to be overcome before RN characteristics could be measured. Firstly, the production of RN by polluted insulators had to be simulated in the laboratory in a manner representative of the insulator RN production on a service line in natural pollution conditions. Secondly, either the RIV or some other quantity, representative of the RN emanating from the polluted insulators, had to be measured. Existing techniques were adapted for the pollution simulation and RIV measurements.

The investigation was specifically limited to reticulation class insulators for lines of 22 kV and lower voltages. Only two types of insulator used on such lines in South Africa were considered in the study, a glass disc insulator and a porcelain line post type. Although the tests on the disc insulators used only one-disc long strings - as typically used on 11 kV reticulation lines - it may be possible to extrapolate the results to longer strings at higher voltages where similar specific creepage distances, i.e. total insulation creepage length per unit system voltage, are used. The RN performance of these insulators was to

be measured in conditions varying from normal unpolluted, to the most severe polluted conditions likely to be encountered by local 22 kV lines.

The study was further limited to the HF portion of the frequency spectrum, with all readings being taken at the specific frequency of 1 MHz. Since there is some general data available on the shape of the frequency spectra of different RN sources , it was felt that it would be more useful to record RN over a wider range of pollution conditions, rather than over a greater frequency range [10]. The frequency range can be extended further into the HF range, with only minor changes to the test circuit. To extend this to the very high frequency (VHF) range, i.e. the FM and TV broadcast ranges above 30 MHz, however, will require major changes to the test procedure. Indeed, the conducted RN measurement method which was used, is only specified for frequencies up to 2 MHz [7].

1.3. An Outline Of The Investigation

The project was begun in March 1986 and was completed in four basic stages in the period to September 1988. The first two phases were done at the University of Cape Town during 1986. The latter two phases, which included the main body of the experimental work, were done at two different laboratories in the Transvaal. The initial setting-up and calibration of the test circuit was done in the high voltage laboratory of the South African Bureau of Standards (SABS) at the National Electrical Test Facility (NETFA) near Pretoria. The rest of the experiments

that involved artificially polluting insulators, were done at the Council for Scientific and Industrial Research (CSIR) laboratories in Pretoria.

1.3.1. Literature Review

The first phase of the project involved familiarisation with the general problems of power line RN. Of particular concern was the previous work that has been done in the field of polluted insulator RN. Existing techniques for measuring power line RN both in the field and in the laboratory and methods for performing natural and artificial pollution tests on insulators in the laboratory were reviewed in the literature. However, no well defined or standardised procedure for combining the RN measurements with pollution tests to specifically record RN characteristics of polluted insulators were found. Consequently the need to establish a procedure and to obtain some specific data was identified.

As revealed in the literature, the critical condition for pollution RN arises when the pollution produces a conductive layer on the insulator surface. There are two categories of method already established to simulate this field occurrence in the laboratory. These are respectively labelled clean fog and salt fog pollution test methods. In the clean fog method a layer of solid pollution, which is either naturally or artificially applied, is wet by a mist of water vapour generated in the laboratory. The salt fog method instead subjects a clean insulator to a laboratory-produced salt fog environment. Two problems arise when implementing these methods. The first is the

accurate reproduction of the pollution condition from one experiment to the next. The second is the quantification of severity of an artificial pollution condition in relation to a severity of a natural condition.

1.3.2. Implementing The Artificial Pollution Method

The first practical phase of the project involved the implementation of an artificial pollution test method in the laboratory. A clean fog type method was chosen in which the pollution condition was simulated by pre-depositing a layer of dry, solid pollution on the insulator, which was subsequently wetted with a clean water mist. The solid layer consisted of a mixture of Kaolin and common salt.

The alternative was to use a salt fog type test method where the pollution condition is simulated by a conductive fog applied to an initially clean insulator. The clean fog approach however, was preferred as this type of pollution mechanism occurs more frequently in local operating conditions. Conductive or salt fogs are relatively uncommon in South Africa except in some coastal areas, while the majority of the country's power lines operate inland where prolonged dry spells are common. During dry periods solid pollution deposits accumulate on the insulators. Later, when these deposits are made wet by, for example, the first rains at the end of a dry season, typical clean fog type insulator pollution situations arise.

The aim was to develop a suitable procedure to be able to repeatedly reproduce an artificial pollution condition of

specified severity. The severity was to be indexed by the normal clean fog test severity parameter, i.e. the density of the salt deposit on the insulator surface. This can be measured as a quantity called the equivalent salt deposit density (ESDD) [11]. Inherent in the ESDD measurement is the assumption that the pollutant is uniformly distributed over the insulator surface.

Therefore, to repeatably attain a given pollution severity on an insulator, would imply the application of identical pollution layers of Kaolin and salt. The layer was applied as a slurry of the solid components mixed in distilled water with a fixed volume ratio of Kaolin and a variable ratio of salt to give different ESDDs. The slurry was sprayed onto the insulator which was then left to dry to complete the process.

Thus, this phase involved repeatedly preparing artificially polluted insulators and then measuring the resultant ESDD and visually assessing the uniformity of the pollution layer. Eventually a suitable procedure was established by which an insulator could be artificially polluted, within acceptable limits, to a pre-specified severity. In doing this however, it was confirmed that the ESDD was directly related to the salinity of the pollution mixture. Therefore, this salinity could rather be used as the severity index, eliminating the need to measure the ESDD of every insulator on every test run. This had significant time saving implications.

1.3.3. Implementing The RIV Measurement System

The third phase of the investigation involved setting up the test

circuit and calibrating the RIV measurement system. This was done at NETFA from April to September in 1987. The test circuit was based on the recommendations of the International Electrotechnical Commission (IEC) Publication 437 and the International Special Committee on Radio Interference (CISPR) Document 18.2 [7],[12]. These recommend a conducted interference measurement method for interference in the HF ranges up to 2 MHz. The method uses a radio receiver to measure the interference current at a particular frequency generated by a noise source in an hv circuit. Radiated measurements at VHF ranges using an antenna and radio receiver were also considered. However, these were found to be impractical as a result of the low levels of radiated interference produced and the distorting effects of the laboratory environment on these measurements.

Two problems arose in the application of the RIV measurement system. Firstly, it had to be ensured that a reading encompassed all of the interference current generated by the test object, while excluding any discharge current generated by other sources in the circuit. Since the system measures the interference current as a voltage (the RIV) across a series resistance, the second problem involved the correct interpretation of the RIV values, i.e. what was the resistance value and how can the readings be compared with published data.

To overcome these problems, a series of calibration tests were performed on the circuit. These consisted of injecting a known value of HF current (at the measurement frequency) into the test circuit to simulate the radio frequency (RF) interference current generated by the test insulator. This was done by connecting a

signal generator as a current source across the test object in accordance with the CISPR recommendation [12]. The meter reading was then compared with the reading expected for the calculated injected current value. In this way the effects of the various circuit parameters on the measured RIV values were investigated. Once the system had been shown to be operating satisfactorily, a final run of current injection tests was done to determine the correction factor according to the CISPR recommendations [12]. This factor was added to the RIV value indicated by the receiver, so that the RIV could be expressed as the voltage, in decibels relative to 1 microvolt, due to the RF current flowing through a 300 ohm resistance.

1.3.4. The Polluted Insulator RN Tests

Once the test circuit was successfully commissioned and calibrated, the insulator RN tests were completed at the CSIR in Pretoria. These tests involved recording voltage and RIV values against time, while subjecting the insulators to a variety of ambient conditions. The conditions varied from the clean and dry state to a heavily polluted and wet state. The wetting of the dry, polluted insulators was achieved by introducing steam into a pvc canvas walled enclosure or fog chamber, in which the insulator was mounted.

Two series of tests were done, each using a different type of ceramic insulator commonly used on 22 kV power lines. The first set of tests used a Cullinan porcelain line post type insulator (EP303) and the second used a Pilkington glass disc (U70BL) insulator. The line post tests were done from October 1987 to

April 1988 and the disc insulator ones from April to August 1988. The results of a total of 153 test runs on the two insulators, using various procedures for the voltage and wetting applications, indicated a strong dependence of the RIV versus time curve on the procedure used. Despite this dependence, the results demonstrated the expected effect of much higher insulator RN being produced under wet, polluted conditions than in the dry state. This higher value however, tended to exhibit a saturation effect against both voltage and pollution severity.

1.4. Development Of The Dissertation

The dissertation is presented in seven main chapters followed by a concluding chapter. The first of the main chapters, Chapter 2, gives a review of the relevant literature and defines the investigation in detail. The subject of polluted insulator RN is reviewed from both radio interference and insulator pollution aspects.

The following three chapters then give a detailed description of the experimental techniques used in the investigation. Existing artificial pollution tests and RN measurement techniques are reviewed, and a description is given of how these methods were adapted for use in this particular study.

In Chapter 6 the various procedures implemented, for the series of tests on the artificially polluted line post and disc type insulators, respectively, are covered. It considers the dependence of the resulting RN levels on the different voltage

and fog application procedures.

In Chapter 7 the main findings of the investigation are presented. The detailed results are recorded in an appendix, and in Chapter 7 they are presented in summarised, graphical form. They are analysed and discussed in terms of the insulator RIV versus voltage and pollution severity characteristics and the effects of the test procedure variations. These results are also compared, where possible, with findings that have been previously recorded in the literature. The final conclusions and some general discussion of the investigation are covered in the last chapter. This chapter also discusses various possibilities for taking the work further in a subsequent study.

2. BACKGROUND TO AND DEFINITION OF THE INVESTIGATION

The purpose of this chapter is to explain how the project was defined. To do this it is first necessary to define the overall problem of power line RN and to review the work that has been done in the field to date. The first section of this chapter describes power line RN and in particular how it may emanate from polluted insulators. The second section reviews the main findings of power line RN and pollution research to date and then shows how the investigation is defined against this background.

2.1. A Background To The Problem Of Power Line RN

2.1.1. Definition And Origin Of Power Line Interference

The phenomenon of power line interference is just one aspect of a broader problem that may be called electromagnetic spectrum pollution. The section of the spectrum of interest is that used for the electromagnetic relaying of information, i.e. upwards from the lowest radio frequencies towards the Gigahertz range. Pollution occurs when an unintended electromagnetic signal interacts with an information carrying signal in such a way as to degrade that information. Thus, power line interference refers to the phenomenon whereby overhead power lines impress upon the environment such polluting electromagnetic signals. There are several different processes by which this can occur. With one exception, that of so called "ghosting interference", they all have their origins in various electric discharge phenomena.

Ghosting occurs when a power line reflects a broadcast signal. Since the reflected signal is delayed, it may interfere with the directly incident broadcast signal at the receiving antenna, and will result in a distorted signal being received.

Although there are many different electric discharges that can occur on power lines, their basic process is always the same, i.e. a normally insulating medium becomes conductive to some extent, due to ionisation of the medium by an electric field. Not all of these discharge processes will necessarily produce electromagnetic interference [13]. All those that do, however, characteristically cause a pulsative loss current to flow in the line conductors. This is fundamentally a 50 Hz current which has superposed on it a wide spectrum of RF components which give it its pulsative nature.

These RF currents are conducted along the line in both directions from the discharge source. Although they are normally rapidly attenuated, they may propagate for a distance of several kilometers down the line. Therefore, the total RF current at any point on a line is the vector summation of the contributions from all the different discharge sources along that line. [14],[8]. As the current wave travels down the line, the conductors act as antennae to the HF components resulting in HF electromagnetic fields being radiated out from the line. These are the so called RN fields, and become "interferences" if they are incident on some susceptible equipment - usually some form of radio or television receiving equipment.

generation of corona RN [15] and depends on the type of corona that occurs, which in turn is determined by the field strength and polarity [13].

Despite the polarity dependence, positive and negative pole corona discharges do have many similarities. In general, for both types the current will either be pulsative or continuous, dependent only on the magnitude of the electric field. At the initial corona inception field value, a pulsative current flows as determined by the relaxation processes occurring to produce the discharge. As the field is further increased, at some stage the discharge nature changes to a continuous or "glow" type discharge, characterised by steady, non-pulsative current waveform. If the field is increased beyond this, towards the breakdown strength, the pulsative nature returns as pre-breakdown streamers begin to develop. The final stage is a complete breakdown, or gap type discharge.[13].

For a gap discharge to occur from a hv element, another oppositely charged or grounded surface must exist within the critical field contour. The electron avalanches or streamers then form a complete conductive path between the two electrodes, resulting in the well known arc or spark-over phenomenon. In this gap discharge phase a pulsative current also flows. Once a streamer has bridged the gap, it presents a low resistance path across the gap and a current flows between the two electrodes as their potential difference is discharged. As this difference collapses, at some stage it falls to below the critical value for avalanche formation and as a result the discharge cannot be sustained and is extinguished. Therefore, the current can no

longer flow, the potential difference builds up again and the process repeats itself, giving the current its pulsative nature.[5].

2.1.3. Corona And Gap Discharge Sources On Power Lines

Corona discharges can occur around any live hardware, so long as the corona inception field strength is exceeded at the surface of that hardware. Thus, corona typically occurs around line conductors, on spacers and dampers and at the live ends of insulator assemblies and bushings. A gap discharge on the other hand, may occur between any two oppositely charged surfaces under the influence of the line electric field. There are two different cases, sometimes referred to as spark and micro-spark gaps respectively [16].

A spark gap discharge occurs between any two metal surfaces not firmly bonded together electrically. Such gaps typically occur where corrosion forms an insulating layer between two normally bonded metal parts, such as ground wires and clamps, loose washers and nuts and the cap and pin of consecutive insulators in a string. A micro-gap discharge takes place between a metal and an insulating surface, for example between an insulator tie wire and the insulator groove.

Another source of gap type discharge is the one of particular interest to this project, namely discharges over the surface of polluted insulators. Under certain conditions, the surfaces of line insulators may become conductive, resulting in spark type discharge activity developing on the surfaces. To fully

understand the phenomenon of polluted insulator RN, it is necessary to consider in greater detail how pollution causes such spark type discharges.

2.1.4. The Pollution Mechanisms

The basic requirement for discharge activity to occur on a polluted insulator is that a surface or leakage current must flow over it. This will occur if the insulator has a high voltage applied across it and its normally insulating surface becomes conductive due to the pollution condition. There are basically two different pollution conditions that may cause a conductive surface layer on an insulator. These are:

- a) An initially dry insulator becomes covered by a film of conductive moisture, when the insulator is subject to a salt spray or fog, as may happen in coastal areas, or when industrial air pollution may cause a conductive fog.

- b) A dry pollution layer accumulates on the insulator surface - eg salt residues that dry on the insulator after a salt fog, dust, industrial smoke, or soot from veldt fires. This layer may contain soluble substances that when wetted (by fog, dew, drizzle etc) dissolve, and cause the layer to become conductive.

Once the leakage current due to the conductive layer is flowing, the degree of the resulting discharge activity depends on two, oppositely interactive, processes that occur on the insulator surface. Both of these are very variable and depend on the

composition and distribution of the contamination on the insulator.

Consider the case of an insulator covered with a deposit of dry pollution. While dry the solid layer has a very high resistivity, i.e. the insulating capability of the surface is unimpaired. However, if some moisture is applied to the dry surface, any soluble components in the layer begin to dissolve, and a film of ionic liquid gradually covers the insulator surface. Since ionic liquids are in general conductive, the insulator surface resistivity decreases as the liquid film develops. If the insulator has no voltage applied across it, this surface resistivity continues to decrease to a minimum value. If the wetting continues, this minimum value is maintained until sufficient liquid has collected on the insulator, for it to begin dripping off the edges. As the conducting ions are thus washed off the insulator, so the surface resistivity increases again. This wetting and washing, with the consequent changes in surface resistivity, is the first interactive process that occurs.

If the insulator is energised during the wetting, then the second process also occurs. As the wetting starts and the surface resistivity falls, the applied voltage causes a leakage current to flow in the conductive layer. The magnitude of current is directly proportional to the surface conductivity and its effect is to cause localised heating, proportional to the square of the current density. The heating tends to dry the surface in opposition to the applied wetting. This is the second interactive process. Depending on the wetting rate and on the distribution and amount of soluble contaminant on the insulator, a complicated

transient phenomenon will occur as the two processes interact.

As the leakage current drying progresses it may cause a completely dry area - a "dry band" - to form. Such an area will not be conductive and so no surface, resistive current flows across it. This results in a potential difference build up across the dry band. If this becomes sufficiently high, the electric field strength may be large enough to initiate an electric discharge or arc across the dry band. If the gap remains dry, the discharge process is repeated and a repetitive pulse type current flows in the hv circuit with the resulting interference-producing capabilities.

If the pollution takes the form of a conductive fog rather than the above example where a pre-deposited dry layer is made wet the situation is similar. Then however, the leakage current depends on the conductivity of the wetting agent, and not on the rate of wetting of a solid layer. Nonetheless once the initial conductive film has been set up, and leakage current is flowing, similar interactive wetting and drying occurs and RN can again result.

Thus, the study of polluted insulator RN requires an understanding of two totally different aspects of power line engineering. Firstly, it is necessary to be aware of the general effects of pollution on power line insulation and the mechanisms by which they arise. These pollution problems include insulation flashover and hardware corrosion, as well as RN. Secondly, one must be familiar with the overall problem of power line RN and the mechanisms by which it is produced and propagated to cause interference.

2.2. State Of The Art And Definition Of The Investigation

In the preceding sections the different sources of power line RN were described with particular emphasis on the mechanisms by which polluted insulator RN is produced. It is now useful to consider the relative importance of each of these aspects of power line RN, according to the research that has been published to date. This then will lead to a definition of the objectives and scope of the present investigation.

2.2.1. History Of Power Line RN And Pollution Research

A search of the literature revealed that both RN and pollution problems on power lines were identified in the 1920's on some of the early hv lines [9],[17]. However, it was only in the late 1940's that research into the field of power line RN was initiated. Corona discharges on overhead lines had been theoretically studied for some 25 years before that, but from the point of view of the corona power loss only.[9]. Research into the pollution problems of power lines began in the 1930's with the establishment of a test site at Croyden in the United Kingdom [18]. This research was, however, aimed principally at the pollution flashover problems experienced on the first 132 kV and higher voltage lines. For many years research in the two fields (power line RN and insulator pollution) developed quite separately, as the problem of polluted insulator RN was not identified. It was only in the early 1970's, with research on UHV transmission lines at voltages above 500 kV, that attention was paid to this particular problem [10].

It was not studied before this because on the earlier, lower voltage lines, there were so many other prevalent noise sources, both gap and corona, that until then the relatively infrequent occurrence of polluted insulator RN remained unnoticed. Although Warburton claimed in 1969 [16] that noise free lines could be built up to 115 kV, there were still many kilometers of old line in operation with numerous sparking sources.

Furthermore, from about 1947, when research was begun into using the 345 kV and higher transmission voltages with higher conductor surface voltage gradients than earlier lines, conductor corona became the principle noise source of concern [19]. At these higher voltages, even using bundle conductors, which were introduced partly to reduce conductor RN levels, corona inception field strengths are often exceeded. Once voltage levels rose above 500 kV however, insulator RN began to receive some attention because the interference from these lines tends to be so great that every effort has to be made to minimise all possible sources [20].

2.2.2. Prediction Of The RN Level Of An Overhead Line

Despite many years of research into gaseous discharge phenomena, no analytical formula exists to predict the onset of corona on a hv element. Nonetheless various empirical formulae have been found to apply to specific electrode geometries.[13]. For an electric discharge to form in air at atmospheric pressure, a field strength of about 30 kV/cm is required. Thus these empirical formulae really only describe the variations from this value that occur as atmospheric conditions change and as the

uniformity of the field is affected by any particular electrode geometry.

Some of the first investigations into RN revealed that conductor corona, on practical lines, often occurs at significantly lower gradients than those predicted by empirical relationships [4],[19]. This was found to be due to imperfections on the conductor surface. These imperfections occur in the form of physical marks, such as nicks or scratches on the conductor, or as air borne solids that affix themselves to the conductor, such as bird droppings, insects or various forms of air pollution. Stranding of the conductors also causes an irregular cross-section which further reduces the conductor corona inception level. These all effectively cause localised areas of enhanced electric field strength at the conductors. The corona inception may thus be exceeded even when the smooth conductor surface voltage gradient is too low for corona. This effect is accounted for by a surface state coefficient, which can only be estimated from experimental results or experience.[9].

By the early 1970's considerable experience had been gained on the corona performance of overhead lines [9]. Based on many field and cage experiments, various empirical and semi-empirical formulae have been developed to predict the RN level of a line under any given atmospheric conditions. Examples of some of the more commonly used ones are given in reference [9]. These formulae are based on the known (measured) RN level of a reference line. They define how the RN level of another line, will differ from the reference line level when the physical or meteorological parameters of the line are changed. The main

physical parameters involved are the number, diameter and spacing of sub-conductors, the phase spacing and the conductor height. Atmospheric pressure and relative humidity are the most important meteorological factors that affect the RN generation.

In addition to the empirical RN pre-determination formulae, there are also other methods of a more analytical nature [9]. These are considerably more complicated methods and are based on the excitation function theory. This involves the prediction of the radiated noise fields using electromagnetic wave propagation theory and considering each individual discharge on the line as a HF current source. In a simplified form the excitation function is a measure of the HF current obtained from a statistical combination of all the individual discharge source currents. This usually has to be measured in simulated cage tests and so even these so called "analytical" formulae have an experimental component.

With the availability of these prediction formulae and past experience, conductor corona becomes a design criterion. When a line is to be built, a maximum allowable RN level for the energised line is specified. Many countries base this specification on the CISPR recommendations for the setting of RN limits [12]. The formulae then permit a proposed design to be checked against the limits before construction begins. If gap or other non-conductor corona sources exist on a line however, they will in practice add significantly to the theoretically calculated line noise level. Since the formation of gap discharges is so variable - they can occur between any two electrically insulated surfaces - there are not even empirical

formulae to predict the level of noise they will produce. However, according to the interference co-ordination principle described by Gary et. al. [21], if the noise from such sources is 10 dB less than the conductor corona noise alone, then these sources will increase the overall line noise by less than 0.5 dB.

2.2.3. Differences In Corona And Gap RN

Apart from verifying empirical formulae, the results of RN research have also yielded other important findings. They have shown that, on 132 kV and higher lines, the most repeatable RN level is that attained during conditions of heavy rain. This level is some 15 to 30 dB higher than the average fair weather levels determined from long term recordings.[22]. Immediately after a shower of rain, once the conductors are dry again, another fairly well defined level occurs, which is also usually when the lowest level occurs. This is because the rain washes contaminants off the conductors so that when they are dry again, the number of potential corona sources is likely to be a minimum.

Another important finding is that conductor corona usually only causes interference in the AM broadcast band. Its spectrum typically falls off rapidly with frequency above 10 MHz and so seldom gives rise to any television interference (TVI) [8]. Gap type discharge noise fields however, are more likely to cause TVI than are corona discharges. These fields typically have much lower amplitudes than conductor corona RN fields in the AM bands. Their spectra however, have much higher cut-off frequencies. Thus, a gap discharge noise amplitude that is lower than a corona produced noise at HF ranges may, in the VHF ranges, be greater

than the corona noise. For this reason TVI is more likely to have spark gap origins than corona origins. With artificial gap sources on a line, RN has been measured right through the television frequencies into the Gigahertz ranges [5].

Since TVI is most likely to come from localised gap sources, once a source has been located, it can usually be rectified by a maintenance crew. Much effort has been spent by utilities worldwide to develop means of detecting such sources [3]. These methods mainly employ directional antennae with a suitable radio receiver to pin-point the exact position of the problem, which is most often at a tower. Once an operator is experienced in this work, using existing techniques and equipment, it is fairly easy to locate and rectify most TVI problems.

Thus, corona RN is more a design stage problem, while most gap type interference is minimised and controlled by ensuring good workmanship in the building and operation of hv lines. The only source of RN that is not so easily dealt with is polluted insulator RN. The problem is that this noise occurs largely due to natural phenomena over which neither design nor maintenance engineers have any control. Once a problem area has been identified however, it can be combatted by such measures as increasing the insulation creepage distance, or by periodically greasing or washing the insulators.

2.2.4. The Development Of Polluted Insulator Research

Over the years, research into the power line pollution problem has been focussed mainly on the reduced withstand capability of

polluted insulation. The aims of this research have been to both understand the physical mechanisms of the pollution flashover process and to compare the performance of different insulator types in different pollution conditions.

Early studies involved observations of the performance of insulators subjected to natural pollution conditions, either in service or in specially built test sites.[18]. Such tests however, take a long time to yield any significant data. Furthermore, if a new line route is being investigated, it can be very expensive to set up a natural test site [17]. Therefore, laboratory tests, which could obtain more accurate data, very much more quickly, were required. These tests are referred to as artificial pollution tests.

Since the problem was first tackled in the 1930's, many different laboratory test methods have been used with varying success. They all have one common feature - the main condition to be simulated is the conductive surface layer that the pollution causes on the insulator. An IEC Publication, IEC 507, and a NGK Insulators paper sum up the most important of these methods [23],[24]. At present, however, only two types of pollution test are recognised internationally as being both representative of natural pollution conditions and able to produce repeatable results. These are the clean fog and salt fog tests respectively. They are the basis of the polluted insulator test procedures that the IEC and CIGRE are working towards standardising.[25]. These methods however, only describe procedures for determining voltage withstand capabilities of polluted insulators and do not cover the measurement of RN that is also generated under these conditions.

2.2.5. RN Tests On Polluted Insulators

Although there are IEC standard procedures recommended both for the simulation of the pollution conditions in which insulators may operate (IEC Publication 507 [23]) and for the measurement of RN from high voltage insulators (IEC Publication 437 [7]), there is no standard procedure to combine these to measure RN produced by polluted insulators. The IEC 507 recommendations are only given with respect to measuring polluted insulator withstand or flashover voltages. The RN measurements recommended in IEC 437 on the other hand, are only applicable to clean and dry insulators. That document does however, also note that wet and polluted conditions may influence the RN performance of insulators and that it may therefore be necessary to develop a test to simulate this.

The IEC 507 pollution simulation methods cannot be directly applied to RN tests because different measurements are required for the two tests. For a withstand test, a voltage level and pollution severity are assigned to the test. It is then merely noted whether the insulation under test withstood the condition or if a flashover occurred. For the RN test it is not a question of whether or not RN occurred, but rather a question of how much RN was produced.

The difficulty in measuring this RN arises because the RN producing current only flows during the transient stages of the interactive wetting and drying processes on the insulator. Therefore, a very variable and complicated transient process has to be repeatedly simulated exactly from one occasion to the next.

If the wetting rate is reduced, a steady state where the fog wetting is equal to the leakage current drying could be reached. The question then is whether this gives the maximum RN level that could occur in practice. It is unlikely to do so since the equilibrium will probably be reached before the surface resistivity is minimum, i.e. before the leakage current is maximum, when maximum RN is expected. If this is so, a better approach is to ensure that the wetting rate is higher than any drying that may occur, so that washing will ultimately result. Then at some stage of the transient interaction, the point of maximum conductivity should be passed, and the maximum value of RN recorded on such a test run, should be the maximum possible for the given test pollution severity.

Most of the studies into the measurement of RN characteristics of polluted insulators over the last twenty years have been done either in Japan or under CIGRE Working Group WG 36-01. The study reported by Bernadelli et. al. [26], was aimed at making a contribution towards the problem of whether a pollution test should be specified, in addition to the clean dry RN test of IEC 437. The conclusion was that there was no correlation between the dry and polluted condition RN performances of insulators and so another test is necessary.

Similar studies have been done in Japan to provide data on the RN performance of polluted insulators. Sawada et. al. [20] report on a laboratory study that was done to obtain noise design data for 1000 kV and higher voltage insulator strings. Fujimura et. al. [27] did a similar set of experiments for artificially polluted insulators under hvdc. Both studies note the great complexity of

the phenomenon and resulting measurement difficulties, due to the RN being determined by the electrical properties of the surface layer, which change with time.

A paper published in 1987 by Sub-Committee C of CISPR summarises the majority of the CIGRE WG36-01 findings on polluted insulator interference [28]. It uses these findings to review the effects of varied insulator surface and ambient conditions as indicated by available data. It then makes recommendations for polluted insulators to determine if they will cause the RN level of a line to exceed its specified, admissible RN limit. These test recommendations are made based on the assumption that for conductor surface voltage gradients greater than $12 \text{ kV}_{\text{rms}}/\text{cm}$, the insulator RN level should be so low that it does not increase the overall line level by more than 0.5 dB. At lower gradients however, insulator RN is expected to be the main factor in determining the line RN level. The overall admissible level is then the insulator limit to be aimed for. The final recommendation is that the test procedures as outlined in CISPR 18.2 and IEC 437, are adequate for insulators polluted from light to medium levels, provided a 10 - 18 dB margin between the corona and insulator noise is maintained. In heavy pollution there is no satisfactory test available, but high noise values can be expected.

2.2.6. The Objectives And Scope Of This Investigation

It was against this background that the project was initiated, with the aim of making a contribution to the knowledge of the RN performance of polluted insulation. It was felt that, since very

high levels of RN have been reported to emanate from polluted insulators, it is necessary to have a standard test to perform this measurement. Thus, the main objective of the project was to implement a repeatable method, based on existing techniques, to measure the RN performance of polluted insulators in the laboratory. The two aspects of the test procedure, including the simulation and quantification of the pollution severity and the measurement of the RN, were to be covered. In establishing such a method, some local data on 22 kV type insulators was to be obtained. The local data could then be compared with the findings of the CIGRE and Japanese experiments previously mentioned. As explained in the introduction, the investigation was limited to voltages up to 22 kV with the RN readings being taken at 1 MHz.

The clean fog pollution test method was chosen with the conducted RIV measurement technique of CISPR Publication 18.2 [12]. The clean fog method is recognised as being representative of pollution conditions where the solid pollution is first deposited as a dry layer and then wetted. South Africa typically has long dry spells, during which large, dry deposits accumulate on insulator surfaces. This is followed by wet conditions with the onset of the rainy season, when extensive discharge activity may arise. Thus, although some salt fog situations do occur along the South African coast, Macey feels that the clean fog case is representative of the majority of insulator pollution situations that occur in this country [17]. In the clean fog method a layer of pollution is applied to the insulator, usually as a slurry of Kaolin and common salt. This is then dried before the unit is mounted and energised in a test chamber into which clean fog is introduced.

The pollution severity in a clean fog test is measured by a quantity called the equivalent salt deposit density (ESDD) of the dry pollution deposited on the insulator. This is a measure of the mass (per unit area) of soluble components in the pollution deposit on the insulator. It is however, both a very time consuming measurement to perform, and it has to be done after the fog test since it involves washing all the solid pollution material off the insulator and collecting it in a known volume of distilled water. This also can be misleading as some of the pollutant may be washed off during the fog test before the ESDD measurement is done. For these reasons the severity index was the first aspect of the procedure investigated.

In the course of this work, the idea was to develop a procedure for artificially polluting insulators such that the resulting ESDD could be determined by the salinity of the pollutant slurry. Then the salinity, which requires no measurement other than the mass of salt and volume of water in the slurry, can be used as the severity index.

For the interference measurement, the conducted RIV technique was chosen in preference to the radiated one as it is more suited for laboratory experiments. Radiated readings in an hv laboratory can suffer serious distortions if standing wave situations occur due to reflections from the walls and other equipment in the laboratory. The conducted method involves a direct measurement of the noise-producing current and so is more easily done.

The approach to developing the overall procedure was based on the assumptions that the degree of discharge activity on the

insulator surface increases with the leakage current and that both the degree and nature of the discharge activity determines the RIV. It is known that if the wetting rate is high enough, the surface conductivity increases with the wetting from virtually zero in the dry state, to a maximum [29]. Then, as the fog washes off the pollutant, so the conductivity decreases again.

For the tests to yield useful information they must simulate the most severe conditions. Therefore, the maximum interference level produced for given voltage and severity is the figure of interest, rather than the time variation of the RIV. As a result the object was to record values of RIV when the surface conductivity was maximum for any given test condition. Two approaches were investigated.

Firstly, for each test run at a given severity, the voltage was held constant and the RIV values were recorded against time as the wetting was applied. Readings were taken as the RIV increased with the initial wetting until it subsequently fell. Care had to be taken to ensure that the decrease was due to washing and not as a result of the drying causing such wide dry bands that all discharge activity ceased.

The second method was an accelerated one to obtain the RIV value for more than one voltage from each run. The idea was to know when the insulator conductivity was around its maximum value and to then take readings of RIV at a number of different voltage values. The difficulty was to ensure that when the next reading is taken it is not being influenced by the previous readings' voltage level, i.e. readings must be taken under approximately

steady state conditions but these are expected to be voltage dependent.

The constant voltage approach is most representative of natural service conditions and so should provide the most valid data. However, if the accelerated procedure can be shown to yield the same results then it has a big advantage for use as a standard laboratory test. This advantage is the time saving possible if a complete RIV versus voltage characteristic can be obtained in just one test run as opposed to doing a separate run for each test voltage level as required for the constant voltage method.

3. POLLUTED INSULATOR TEST TECHNIQUES

As mentioned in Chapter 2, polluted insulators are either tested in the field under natural pollution conditions or in the laboratory using either naturally or artificially polluted insulators. By whatever method the tests are done, they must yield results that can be validly applied, so as to understand and predict the pollution performance of insulators in practical operational situations. Since the collection of pollution on insulators is a natural phenomenon, and a very variable one, it is difficult to precisely define those conditions to be simulated in pollution tests [29]. Artificial tests can be exactly defined but may not always be very realistic and so are hard to relate to practical situations. Natural tests on the other hand are more realistic but less precise [30].

Of the two generally accepted test methods, the clean fog method can be used on both naturally and artificially polluted insulators. The salt fog method on the other hand, is only applicable as an artificial test method since it requires the test insulators to be initially clean and unpolluted.

In the first part of this chapter brief descriptions of these two types of pollution test method are given. Although only the clean fog method was used for this investigation, the salt fog method is also briefly covered for comparative purposes. In the remaining sections the implementation of the clean fog test for this investigation is described.

3.1. Pollution Test Techniques

3.1.1. Salt Fog Methods

In salt fog type tests the insulators are thoroughly cleaned and then mounted in a test chamber into which artificially produced conductive fog is admitted. The fog is generated by atomising a solution of household salt into a very fine spray. The severity of the pollution condition is quantified by the fog conductivity which is usually given in terms of the salinity of the spray water in kilograms per liter. Under these conditions the test insulator is energised and its performance with respect to the parameter of interest, i.e. RN or flashover, is monitored as required. Although this does accurately represent the field occurrence of a salt fog pollution condition, it is difficult to relate the salinity severity to a natural pollution site severity where the insulators may not initially be clean. It also has the practical disadvantages of requiring special spray equipment to atomise the salt solution, and of the corrosion problems due to the salt spray environment in the laboratory.

3.1.2. Clean Fog Or Pre-Deposit Methods

For clean fog type tests a layer of solid, dry pollution is fixed to the insulator surface. This is either done artificially in the laboratory or by field exposure to natural pollution conditions. In the laboratory, the layer is then dampened with either a clean water spray or with steam. This dissolves the layer's soluble components and results in a film of conductive solution covering the insulator.

When the pollution layer is an artificial one, it is first applied in liquid form and is then dried onto the insulator surface before being subjected to the fog. Various methods including spraying, dipping and flow-coating are used for the layer application. The liquid is prepared as a slurry in water and contains household salt and a clay based binding substance such as Kaolin. The salt provides the soluble components, while the non-soluble Kaolin helps the mixture to adhere to the insulator surface.

The severity of the pollution condition in this type of test is most commonly given by the equivalent salt deposit density (ESDD). This value is expressed in milligrams of salt per unit surface area of polluted insulator. The detailed procedure to measure ESDD is given in Appendix A, but basically it involves washing all the solid pollutant off a known area of insulator into low conductivity distilled water. The conductivity of the resulting solution is measured and then the concentration of salt solution that would give the same conductivity is determined from standard tables [31]. From this the equivalent mass of salt on the insulator and hence the salt deposit density can be calculated.

Since the ESDD of a naturally polluted insulator is as easily measured as that of an artificially polluted one, this gives a simple standard by which to compare naturally and artificially polluted insulators. The difficulty, however, is to assess the validity of this comparison. By measuring a certain value of equivalent mass of salt from a naturally polluted insulator one obtains an ESDD value. However, the "salt", i.e. the conductive

components, may not have been uniformly distributed over the insulator area. When this same ESDD is artificially simulated in the laboratory, every effort is made to ensure that the required amount of salt is applied as uniformly as possible over the insulator surface. Although the ESDD's are the same, the salt distribution is different which, it has been found in some studies, may affect the flashover performance [32].

Other than being able to directly correlate (within the above limitation) artificial and natural pollution severities, the clean fog method also has other practical advantages. The most important of these is its simplicity and lower cost to implement than the salt fog method [33]. It also avoids the corrosion problems of the salt-fog method.

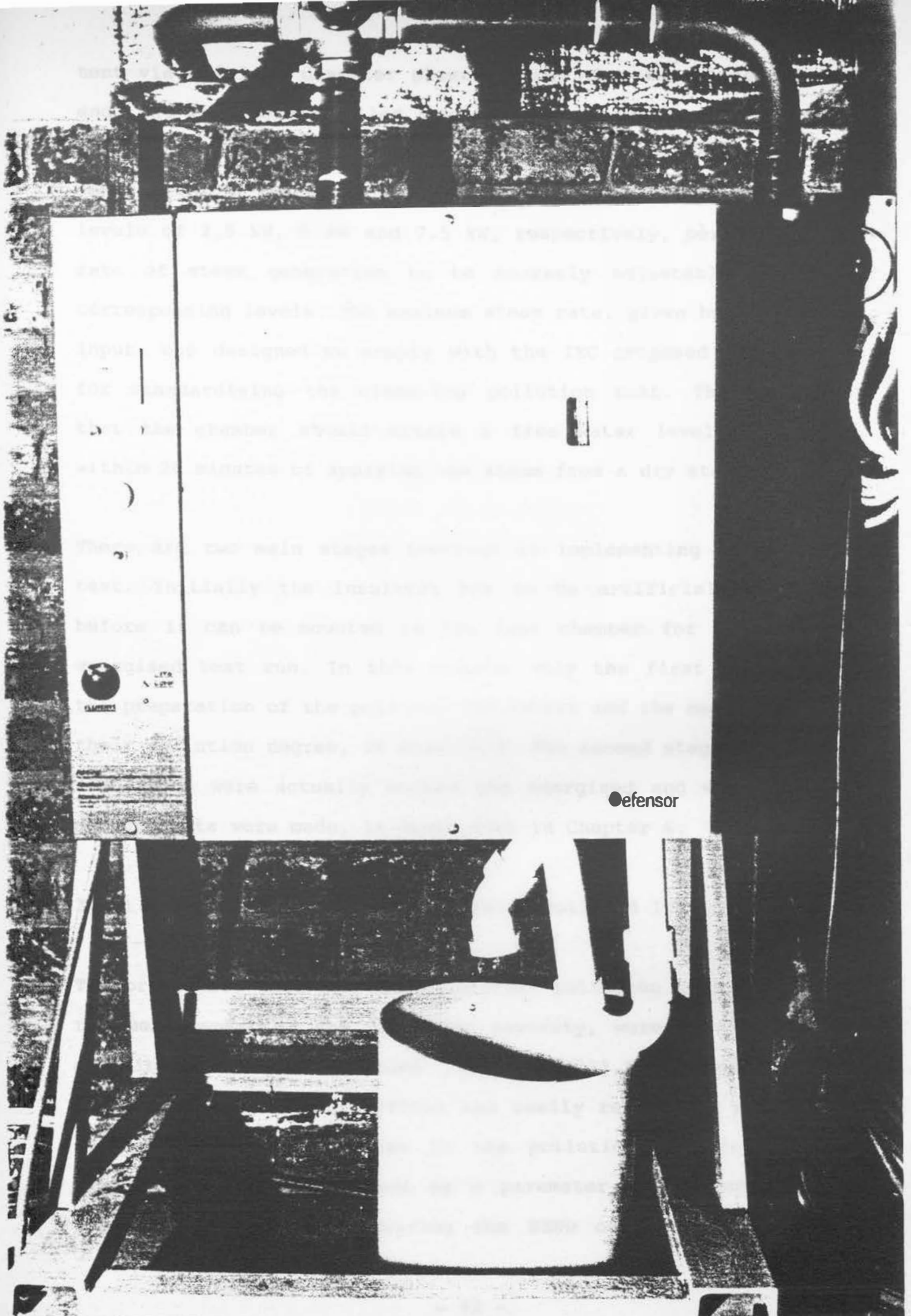
3.2. Implementation Of A Clean Fog Test Method

For this investigation a clean fog method was used with artificially polluted insulators. Apart from its practical advantages over the salt fog method, there were two main reasons for adopting this approach. Firstly, as mentioned in Chapter 2, this type of method was felt to best represent the prevalent pollution conditions in South Africa, where the majority of power lines are situated inland well away from the sea. Also, this country typically has long dry spells during which contamination deposits build up on the line insulators. When these deposits become wet, RN and flashover problems are expected, via similar mechanisms to those that occur in a clean fog test.

Secondly, since the laboratory in which the tests were done was already fitted out for clean fog testing, there was also a further practical consideration in the decision. The test facility was part of the CSIR hv laboratories at Pretoria. It was established in 1986 [33] to comply with proposed IEC recommendations for a standard clean fog test method for determining flashover voltages of polluted insulators. Only its main features and characteristics are described here.

The main requirements for a clean-fog test facility are a chamber which can be filled with water vapour and into which a hv lead can be taken in order to connect a test object to the hv supply. In the CSIR laboratory the chamber consisted of a 4 m x 5 m x 5 m high polyester reinforced pvc tent, suspended from the inner steel structure of the building in which it was housed. The tent had a zip-up door in one vertical wall and a bushing arrangement in another wall, through which the hv lead was introduced. The bushing consisted off a 2 m x 1.2 m perspex sheet, through the centre of which ran an aluminium fitting, with suitable connectors both on the inside and outside of the tent. According to Prak, the bushing had been tested under wet conditions to withstand 200 kV [33], whereas for this project only voltages below 30 kV were used. In the centre of the tent roof there was a hole, of approximately 1 cm diameter, through which a steel cable ran from a hand operated winch mounted on the laboratory wall. This was used to suspend test objects in the chamber.

A humidifier, which is illustrated in photograph 3.1, provided the water vapour to simulate the fog. It generated a mist condition by boiling tap water and feeding the steam into the



PHOTOGRAPH 3.1 THE "CLEAN FOG" GENERATOR

tent via a 2.5 cm diameter plastic pipe, that was closed at one end, but with holes drilled into its length inside the tent. The pipe ran across the chamber floor from one corner to roughly the centre point. The humidifier had three selectable input power levels of 2.5 kW, 5 kW and 7.5 kW, respectively, permitting the rate of steam generation to be coarsely adjustable to three corresponding levels. The maximum steam rate, given by the 7.5 kW input, was designed to comply with the IEC proposed requirement for standardising the clean-fog pollution test. This requires that the chamber should attain a free water level of 3 g/m^3 within 20 minutes of applying the steam from a dry start.[33].

There are two main stages involved in implementing a clean fog test. Initially the insulator has to be artificially polluted before it can be mounted in the test chamber for the wet and energised test run. In this chapter only the first stage, i.e. the preparation of the polluted insulators and the measurement of their pollution degree, is described. The second stage, where the insulators were actually wetted and energised and where the RN measurements were made, is dealt with in Chapter 6.

3.2.1. The Preparation Of Artificially Polluted Insulators

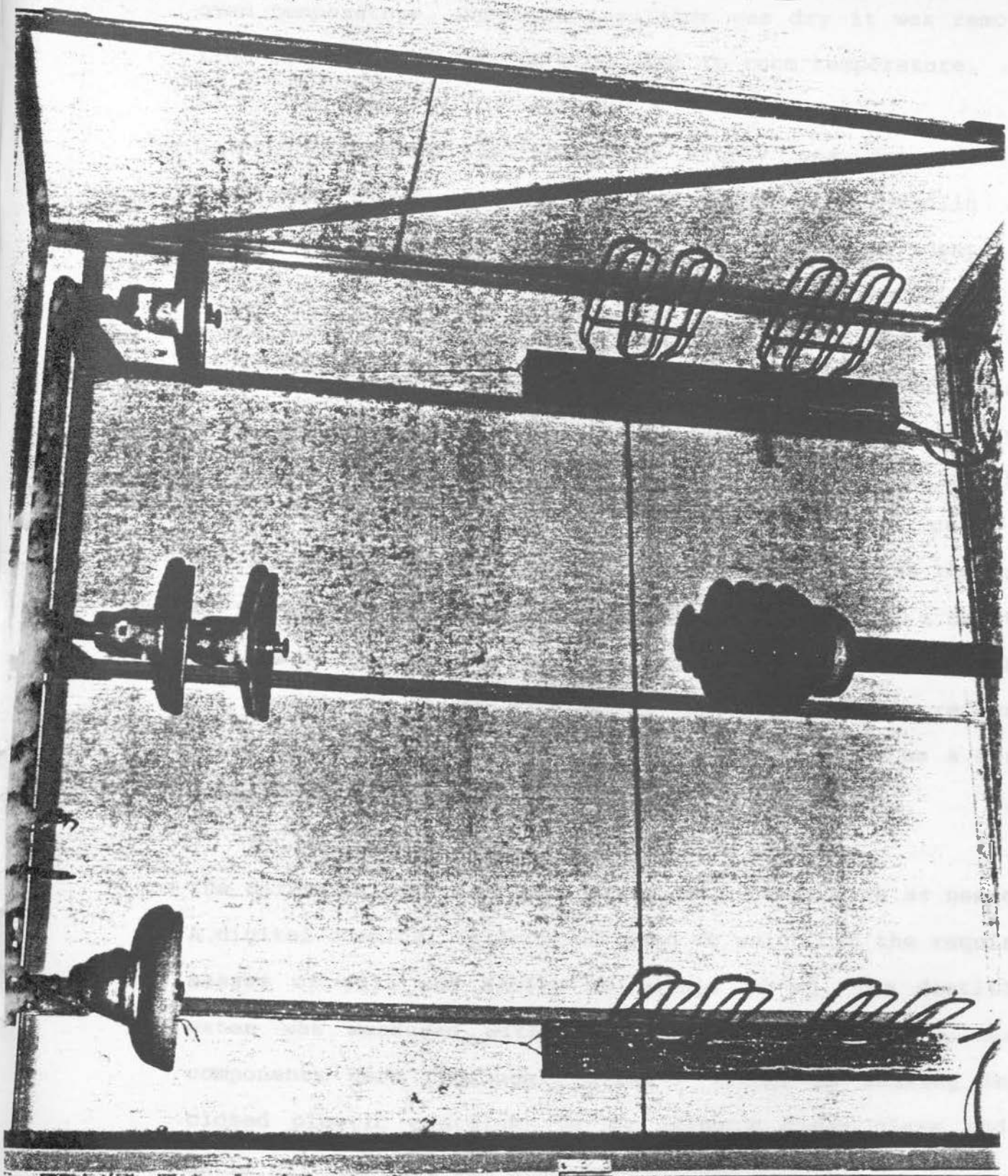
The procedures used for the artificial pollution application and the measurement of the resulting severity, were based on those described in the literature [11],[23],[32],[25]. Emphasis was placed on using a well defined and easily repeatable method. In this way the uncertainties in the pollution severity values, which were to be specified by a parameter of the application procedure instead of measuring the ESDD of each insulator as

tested, were minimised. The procedure used to apply a pre-specified contamination layer to an insulator is described below.

- a) First the insulator was thoroughly washed to remove any previously deposited solid pollution and also to eliminate any oily substances on the insulator. Even a very thin film of oil or grease, as might be deposited by touching the insulator with bare hands, was unacceptable. The reason is that oil on the surface causes it to be hydrophobic. Therefore, when the pollution slurry is applied, it does not adhere to these areas, resulting in an unrepeatable and non-uniform deposit. Hence, it was very important to ensure that, at no stage during the preparation of a polluted insulator, was its surface touched by the bare hands.

The insulators were washed with tap water and Teepol industrial soap using a cotton cloth. They were then thoroughly rinsed with distilled water. Any greasy patches were likely to become evident at this stage as areas not easily wetted when the insulator was rinsed. Such areas had to be re-washed until they disappeared and the clean insulator could be easily wetted all over by the rinse water.

- b) Once an insulator was properly washed and rinsed it was dried before the artificial pollution was applied. It was dried in an asbestos enclosure with four electric heating elements. As shown in photograph 3.2, the insulators were either suspended vertically in the drying chamber or else placed on a stand on the chamber floor. For the two types of insulator used drying



PHOTOGRAPH 3.2 THE DRYING CHAMBER

(2) When the washed and dried insulator had cooled down to room temperature, it was ready for the artificial pollution

took from 10 to 20 minutes depending mainly on the initial oven temperature. Once the insulator was dry it was removed from the oven and left to cool down to room temperature.

c) In the meantime the pollution slurry was prepared. It consisted of a mixture of household salt, Kaolin and distilled water. The different slurries used were identified by the concentration of salt in the slurry expressed as the number of grams of salt per liter of water added to the slurry. Various values of salt concentration in the range from 5 g/l to 80 g/l were used. A standard amount of 40 g/l of Kaolin was used in all the slurries. In the rest of this thesis an identifier of the form 40:x is used to differentiate the various slurries. The 40 indicates the mass of Kaolin in the slurry, (always 40 g/l) while the x denotes the amount of salt in the solution in grams per litre. Thus for example, a slurry with 5 g/l of salt added, is referred to as a 40:5 mixture and one with 80 g/l of salt as a 40:80 mixture.

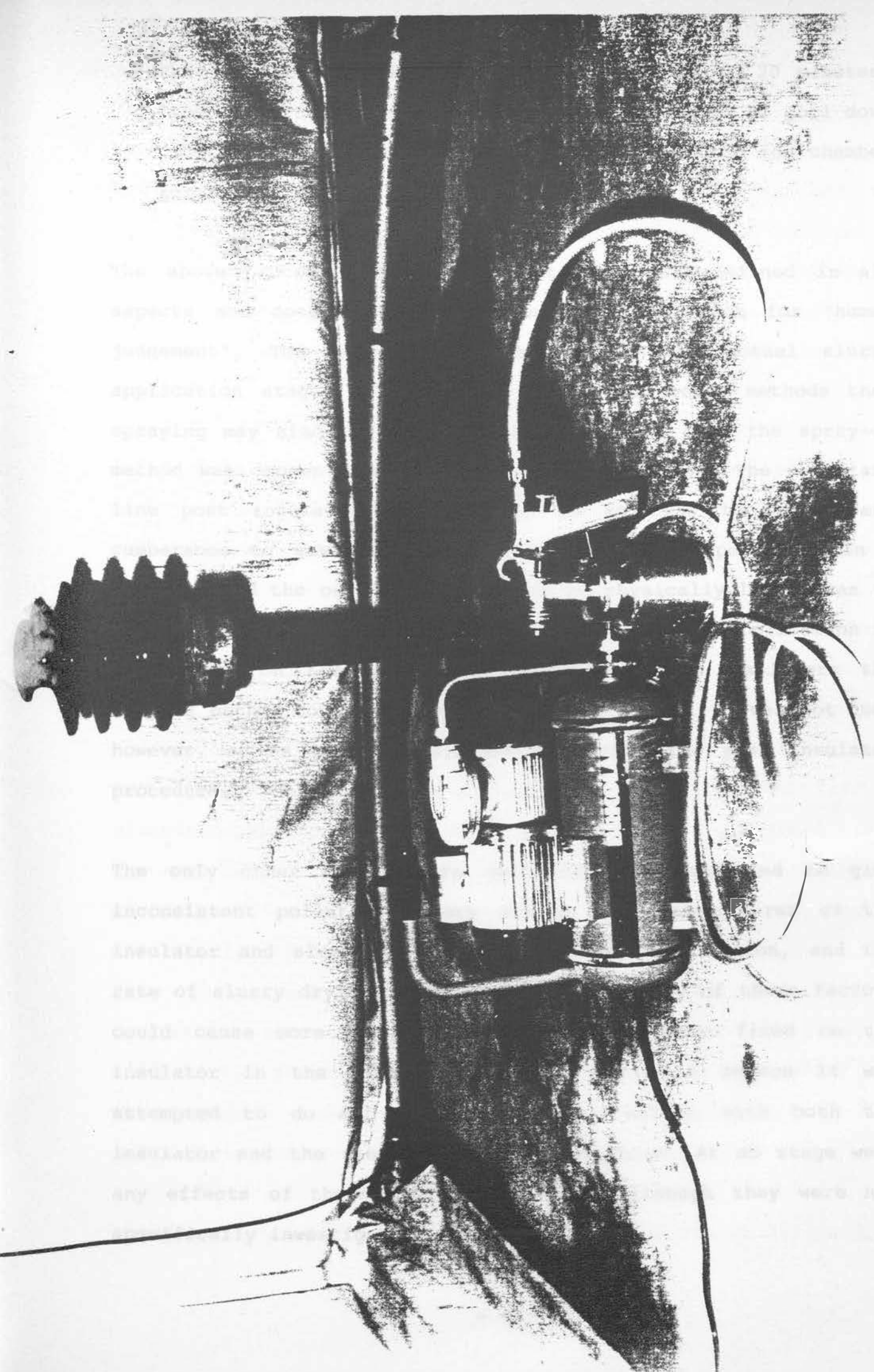
The different slurries were mixed in 2 litre lots as needed. A digital chemical balance was used to weigh out the required masses of salt and Kaolin to within 10 mg. The distilled water was measured with a measuring cylinder. The three components were thoroughly mixed - either by shaking in a closed plastic container or by using a clean glass rod - until all the salt was dissolved.

d) When the washed and dried insulator had cooled down to room temperature, it was ready for the artificial pollution

application. The slurry was applied using a spray-on method with the small air compressor shown in photograph 3.3. The spraying was done inside the fog chamber to confine the salt spray and so to minimise its corrosive effect in the laboratory. During spraying, the insulators were either placed on the stand as seen in photographs 3.2 and 3.3, or hung vertically from the roof in the case of the glass disc insulators.

The spraying was done following a fixed procedure. First an initial spray was done over the whole top and bottom surfaces ensuring that the insulator became wet all over. If large areas were found to remain dry they were inevitably due to grease patches on the surface indicating that the sample had not been properly washed. In those cases the test had to be abandoned and the washing stage repeated.

If however, the wetting appeared to be satisfactory over the entire surface the process continued. The insulator was then tilted and rapidly sprayed all over until the liquid flowed freely and evenly off the insulator surface. While spraying the pollution on, the spray gun was continually shaken to ensure that the slurry was always homogeneously mixed. When it was judged that a uniform liquid layer covered the insulator, spraying was stopped and the insulator kept in the tilted position for any excess liquid to drip off it. As drops formed at the insulator shed edges, they were flicked off with a finger nail. After about one minute, when rapid dripping had ceased, the insulator was put to dry again.



PHOTOGRAPH 3.3 THE AIR COMPRESSER AND SPRAY GUN

e) The insulator was left to dry for about 10 to 20 minutes. Once dry, it was removed from the oven and left to cool down to room temperature before being mounted in the fog chamber for a test run.

The above procedure is clearly not very well defined in all aspects and does leave a certain amount of room for "human judgement". The main uncertainty is in the actual slurry application stage. As previously mentioned, other methods than spraying may also be used for this. In this case the spray-on method was chosen for a practical consideration. The porcelain line post insulator which weighs 13 kg, was too heavy and cumbersome to easily handle during a dipping operation. In a spray method the only time it had to be physically lifted was to move it in and out of the oven. During the actual application it was rested on the stand. For the glass disc insulators the dipping method could have been more easily used. It was not used however, so as to be consistent with the line post insulator procedure.

The only other areas where variations are expected to give inconsistent pollution layers are in the temperatures of the insulator and slurry prior to the slurry application, and the rate of slurry drying. It is surmised that any of these factors could cause more or less pollutant to remain fixed on the insulator in the final dry stage. For this reason it was attempted to do all the slurry applications with both the insulator and the slurry at room temperature. At no stage were any effects of these factors observed, although they were not specifically investigated.

3.2.2. Measurement Of The Pollution Severity

To measure the pollution severity in terms of ESDD, as described in appendix A, involves washing all the solid pollutant off the insulator surface. Therefore, the measurement can only be done on a test insulator after it has undergone its clean fog test. However, during the fog test some of the pollutant may have been washed off, so giving a lower ESDD value than it had before the test.

An alternative is to prepare two insulators in a similar way for each test on one insulator. One insulator is tested in the fog and the other is used for the ESDD measurement. This however, introduces another uncertainty in the test severity. It relies on the two insulators being prepared to the same ESDD, by following the same preparation procedure, but there is no means of checking this.

Using ESDD as the severity indicator also has two further disadvantages. The first is that, as mentioned in section 3.1.2., the ESDD value inherently assumes that the pollutant is uniformly distributed, whereas in reality it may well not be. The second disadvantage is that ESDD measurements can be very tedious and time consuming to perform. In addition the actual ESDD measurement process is susceptible to other errors. The major difficulties are to ensure that all the pollution is washed off the insulator and that no conductive particles, not from the polluted insulator, enter the wash solution.

The time factor can be reduced by only washing the pollutant from

a small area of the insulator and assuming that the deposit is uniform over the rest of the area. It is however, better to cover the entire area. Then at least an accurate figure for the total mass of soluble substances on the insulator is obtained, irrespective of how uniformly it may have been distributed over the surface.

Another possible severity index is the insulator surface conductivity during the fog test. This is probably the best parameter to correlate both RN and flashover performances with, as it directly determines the leakage current which both these phenomena depend on. The difficulty in using this conductivity parameter however, is to measure it. It can be determined from the leakage current but once dry band discharge activity begins, this current has a very erratic form. This makes it a very difficult quantity to measure accurately. This again can be partly overcome by using two insulators for each test run. Both insulators are mounted in the fog chamber, with one subjected to the hv test while the other is unenergised and its surface conductivity is monitored. The monitoring is done by applying regular voltage pulses (of approximately 600 volts rms) across the insulator and observing the current waveform as the voltage across a series resistance.

This has similar disadvantages as the two insulator ESDD method. A further complication however, is that even if both insulators are identically polluted and subjected to the same wetting, their instantaneous surface conductivities will not necessarily be the same. Differences are expected to arise due to the heating effects of the leakage current on the hv energised test

insulator. This may cause the test insulator conductivity to be lower than the values measured on the other unit.

In this investigation a third method, where the pollution degree is specified in terms of the composition of the artificial pollution slurry, was used. This method is based on an assumption that the severity of an artificially polluted insulator in terms of its ESDD, depends directly on the amount of salt in the applied pollution slurry. If such a relationship could be found, then the severity of an artificially polluted insulator could be directly specified by the slurry salinity, without having to perform any further special measurement.

The main advantage of the proposed method is a considerable time saving, especially when a large number of tests are to be run. This method had been previously used by Macchiaroli [34], but it is recognised that the exact relationship between ESDD and slurry salinity may vary both with the method of application and also possibly from one operator to another. The accuracy of the measurement relies only on the accuracy with which an insulator can be repeatedly prepared to the same ESDD from the same composition slurry. There is no further uncertainty in an actual severity measurement after the pollution application. Thus, the proposed method of using the pollution slurry salinity as severity index, was preferred for its relative simplicity and time saving advantages, with no sacrifice of accuracy as compared with other methods.

Thus, the artificial pollution procedure was to pollute the insulators by spraying the slurry onto the insulators. The

severity of the insulator pollution was given as the salinity of the slurry. The salinity severities then had to be related to ESDD values so that test results given in terms of the two different severity units can be compared. Therefore, a series of tests was done where insulators were repeatedly polluted with various salinity slurries and the resulting ESDD values were measured after each application. These tests are described in the next section.

3.3. The ESDD Versus Slurry Salinity Tests

3.3.1. The Aims Of The Tests

These tests were done for both the insulator types used in the main interference tests (porcelain line-post and the glass disc insulators) and had two aims. Firstly, it had to be shown that using a given slurry, an insulator could be repeatedly artificially polluted to the same ESDD by the method of section 3.2.1. This might not be easy to do mainly because there was no way to precisely control the amount of salt that adhered to the insulator during the spraying operation. Using the spray-on method it was not expected to obtain better than about 15 % agreement in the ESDDs of similarly polluted insulators.

The second aim of the tests was to determine how the ESDDs on the two insulator types would vary with the slurry salinity. This would enable slurry salinity to be used as the pollution severity in the RN tests, while also permitting the results to be compared with others given in terms of ESDD. However, as cautioned in a

paper by CIGRE Working Group 33-04 [32], "values obtained with one procedure should not in principle be compared with those related to another technique". Although theoretical relationships between different severity parameters can be developed, the Working Group found poor agreement in practice. They therefore suggested that for each severity parameter, values be established to correspond to a fixed range of practical severities defined to cover from light or no pollution to very heavy or severe levels. Different sets of results can then be compared on this basis.

Thus, the aim of this section was to establish, for the two insulator types, an approximate range of salinity values corresponding to the same ranges of pollution severity from light to heavy as defined by the ESDD parameter. The range of pollution severities is usually divided into at least 4 levels. The levels suggested by CIGRE Working Group 33-04 [32] and the Transmission Line Reference Book [35] are illustrated in table 3.1 and are the ones considered here.

Natural Pollution Level Classification	ESDD Ranges (mg/cm ²)	
	Cigre WG33-04	Transmission Line Reference Book
No significant pollution	0.0075 - 0.015	
Very light pollution	0.015 - 0.03	0 - 0.03
Light pollution	0.03 - 0.06	0.03 - 0.06
Average/moderate pollution	0.06 - 0.12	0.06 - 0.10
Heavy pollution	0.12 - 0.48	>0.10
Very heavy pollution	>0.48	

Table 3.1 : Pollution Severity Ranges Quantified By ESDD

3.3.2. ESDD Test Procedure And Results

The first series of tests was done on the glass disc insulator. Fifteen ESDD measurements were done in all on 3 different discs. One measurement was done on each disc for 5 different slurries ranging from 40:5 to 40:80. The second series of tests was done on the line post insulator. It included 20 measurements all on the same unit and covered a similar range of slurry concentrations. This range was chosen to cover the light to heavy pollution conditions described in table 3.1.

For each individual test the insulator was artificially polluted according to the method of section 3.2.1. and then its ESDD was subsequently measured. In most of the tests this measurement was done immediately after the polluted insulator had been removed from the drying chamber and cooled down to room temperature. In some cases however, the ESDD was only measured after the artificially polluted insulator had been subjected to a fog condition in the fog chamber. The ESDD measurements were done following the procedure set out in Appendix A. The conductivity meter readings were all automatically corrected to 25 °C. Thus, as described in Appendix A, it was not necessary to take any temperature readings.

For the glass disc insulator the masses of salt deposited on the top and bottom surfaces were determined separately. This was done by first swabbing off the top area into 500 ml of distilled water and then the bottom area using a fresh lot of distilled wash water. Thus, the top and bottom ESDD values were independently measured but an overall ESDD figure could also be calculated.

The line post insulator was also swabbed down in a number of discrete areas. These areas were the top of the insulator to the end of the tie wire groove, from there to the end of the top edge of the first shed, then the three areas including the bottoms and the tops of each consecutive pair of sheds and finally the bottom of the fourth shed including the stem going into the metal end fitting. In the following these areas are respectively referred to as surfaces numbered 1 to 6, while the whole surface is numbered 7. Two different swab procedures were used.

The first procedure was to swab off different areas separately into different 500 ml wash solutions. The conductivity of each solution was measured individually to determine the mass of salt on each surface. Each of areas 3 to 6 were done separately, while areas 1 and 2 were treated together. First area 2 was swabbed off into the wash solution and the conductivity was recorded. Then area 1 was swabbed off into the same solution and the new conductivity was recorded. The sizes of the 6 areas are such that, in some cases when using 500 ml of distilled water, the conductivities of the wash solutions were so low that the resistivity values exceeded the ranges of the tables from which the equivalent masses of salt were obtained. Thus, estimates had to be made by extrapolating the resistivity versus concentration curve.

To overcome this problem, the second procedure was used. This, instead of using a different swab solution for each surface, used the same one for all 6 measurements. Thus, first the top was washed and the resulting conductivity measured. Then the area between the first and second sheds was washed into the same

solution and the new conductivity measured. The mass of salt deposited between the first and second sheds could then be calculated as the difference between the two masses indicated by the two conductivity readings. This process was repeated for all 6 areas so that at the end, the swab solution conductivity represented the total mass of salt deposited over the whole insulator surface.

There was a further variation in some of the line post insulator tests. In some of them the ESDD was only measured after the insulator had undergone a test period in the fog chamber with steam present. Of the 20 line post insulator tests, 11 were done using the first procedure. Of these 7 were done immediately after the pollution application without the pollution layer having been disturbed at all. The other 4 were all done after a fog test during which the pollution layer could have been partially washed off. The other 9 tests were done using the second swab procedure. Of these only 3 were done directly and 6 after a fog test.

The results of these tests for the glass disc and the line post insulators are given in tables 3.2 and 3.3 respectively. Given in the tables are the conductivity readings, and the calculated equivalent masses of salt and ESDD values for each insulator surface swabbed. The masses of salt are calculated from the conductivity measurements using the tables and formulae as detailed in Appendix A. Thus, they are an accurate representation of the masses of salt in the wash solutions subject to the limitation of the accuracy of the conductivity meter. This, according to the meter specifications, is better than 1 %.

Disc	Pollution Mixture	Conductivity at 25°C (μS/cm)		Equivalent Mass of Salt (mg)			Estimated ESDD (mg/cm ²) Top = 642 cm ² Bottom = 917 cm ²		
		Top	Bottom	Top	Bottom	Total	Top	Bottom	Total
1	40:80	423	578	102.0	140.3	242.3	0.159	0.153	0.156
2		429	539	103.5	130.6	234.1	0.161	0.142	0.150
3		421	531	101.5	128.7	230.2	0.158	0.140	0.148
1	40:40	167	232	39.72	55.34	95.06	0.062	0.060	0.061
2		215	286	51.23	68.45	119.7	0.080	0.075	0.077
3		219	274	52.19	65.54	117.7	0.081	0.071	0.076
1	40:20	100	130	23.58	30.74	54.32	0.037	0.034	0.035
2		90	148	21.20	35.16	56.36	0.033	0.038	0.036
3		107	151	25.32	35.66	60.98	0.040	0.039	0.039
1	40:10	50.2	76.1	11.77	17.90	29.67	0.018	0.020	0.019
2		48.9	79.9	11.46	18.80	30.26	0.018	0.021	0.019
3		55.7	81.4	13.07	19.16	32.23	0.020	0.021	0.021
1	40:5	29.6	44.6	6.92	10.45	17.37	0.011	0.011	0.011
2		29.0	44.8	6.78	10.50	17.28	0.011	0.011	0.011
3		29.2	45.8	6.82	10.73	17.55	0.011	0.012	0.011

Table 3.2 : Glass Disc Insulator ESDD Test Results

Test No.	Slurry Type D - Direct T - Fog Tested		Conductivities ($\mu\text{S}/\text{cm}$)					
			Area 2	Area 1+2	Area 3	Area 4	Area 5	Area 6
1	40:40	D	185.0	224.0	285.0	256.0	316.0	115.0
2	40:40	D	137.5		213.0	153.6	44.8	26.2
3	40:40	T	67.0		144.0		76.0	10.0
4	40:40	T	77.0	98.0	161.0	110.0	66.0	20.0
5	40:20	D	159.6		219.0	212.0	239.0	88.0
6	40:20	D	158.0	177.0	233.0	235.0	229.0	87.0
7	40:10	D	52.0		94.0	105.0	92.0	40.0
8	40:5	D	34.3	39.4	34.9	29.3	40.9	11.3
9	40:5	D	22.0	29.0	33.0	32.0	39.8	17.1
10	40:5	T	22.7	29.8	34.8	209.0	20.2	8.9
11	40:5	T	7.4	9.3	17.9	16.0	14.8	8.6

Table 3.3a : Line Post Insulator Conductivity Readings
From ESDD Tests 1 - 11

Test No.	Slurry Type D - Direct T - Fog Tested		Cumulative Conductivities ($\mu\text{S}/\text{cm}$)						
			Area 0	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
12	40:15	D	8.1	23.6	85.9	206.0	325.0	480.0	533.0
13	40:15	T	10.3	27.3	97.2	223.0	337.0	466.0	516.0
14	40:15	T	9.5	26.6	87.6	222.0	296.0	361.0	394.0
15	40:5	D	10.1	20.0	47.1	86.6	125.6	176.2	193.8
66	40:5	D	8.9	16.7	40.4	84.0	122.1	174.0	193.6
17	40:5	T	9.9	15.7	39.0	80.1	126.2	185.4	211.0
18	40:5	T	9.5	15.0	30.6	64.5	102.0	138.4	155.6
19	40:5	T	7.3	12.2	28.1	64.5	100.6	136.1	156.4
20	40:5	T	9.4	41.2		78.5	113.5	153.5	174.8

Table 3.3b : Line Post Insulator Conductivity Readings
From ESDD Tests 12 - 20

Test No.	Equivalent Masses of Salt							
	Area 1	Area 2	Area 1+2	Area 3	Area 4	Area 5	Area 6	Area 7
1		44.0	53.4	68.2	61.2	75.8	27.2	285.8
2		32.5		50.7	36.4	10.5	6.1	136.2
3		15.7		34.1		17.9	2.5	70.2
4		18.1	23.1	38.2	26.0	15.5	4.7	107.5
5		37.8		52.2	50.5	57.0	20.7	218.2
6		37.5	42.0	55.6	56.1	54.6	20.5	228.8
7		12.2		22.2	24.8	21.7	9.4	90.3
8		8.0	9.2	8.2	6.9	9.6	2.8	36.6
9		5.1	6.8	7.7	7.5	9.3	4.0	35.3
10		5.3	7.0	8.1	4.9	4.7	2.2	26.8
11		1.9	2.3	4.2	3.8	3.6	2.2	16.0
12	3.7	14.6	18.3	28.8	28.9	38.0	13.1	127.4
13	4.2	16.3	20.5	30.2	27.6	31.6	12.4	122.3
14	4.1	13.8	17.9	32.7	18.0	15.8	8.1	92.5
15	2.5	6.2	8.7	9.3	9.2	12.2	4.2	43.6
16	2.0	5.4	7.4	10.3	9.0	12.5	5.5	44.7
17	1.4	5.4	6.8	9.7	11.0	14.2	6.2	47.9
18	1.4	3.6	5.0	8.0	8.9	8.7	4.1	34.6
19	1.2	3.6	4.8	7.4	8.6	8.5	5.5	36.3
20			7.4	8.8	8.4	9.5	5.0	39.1

Table 3.3c : Line Post Insulator Calculated Equivalent Masses Of Salt

Test No.	Slurry Type D - Direct T - Fog Tested	ESDD (10^{-4} mg/cm ²)							
		Area 1	Area 2	Area 1+2	Area 3	Area 4	Area 5	Area 6	Area 7
1	40:40 D	537	1170	969	1080	995	1250	853	1049
2	40:40 T		864		802	592	173	192	534
3	40:40 T		418			295	78	275	
4	40:40 T	286	481	419	604	423	255	146	394
5	40:20 D	1050		826	821	939	649	856	
6	40:20 D	257	997	762	880	912	900	643	840
7	40:10 D		324		351	403	357	293	354
8	40:5 D	69	213	167	129	111	158	80	134
9	40:5 D	94	133	123	122	122	154	125	130
10	40:5 T	95	141	126	129	79	77	69	99
11	40:5 T	26	49	42	66	62	59	670	59
12	40:15 D	211	388	332	456	470	626	411	437
13	40:15 T	240	434	372	478	449	521	389	449
14	40:15 T	231	367	324	517	293	260	495	340
15	40:5 D	140	165	157	148	150	201	132	160
16	40:5 D	113	143	134	164	146	206	172	164
17	40:5 T	80	144	123	153	179	234	216	176
18	40:5 T	77	96	90	127	145	143	129	127
19	40:5 T	69	96	87	117	140	140	182	133
20	40:5 T			135	139	137	157	157	144
Surface Area (cm ²)		175	376	551	632	615	607	329	2724

Table 3.3d : Line Post Insulator Calculated ESDDs

The ESDD values however, which were obtained by dividing the masses of salt by the insulator surface area, have an additional unknown error. Since these areas are not given as a specification of the insulators, the values were calculated from scale drawings of the insulator profiles and measurements of their actual dimensions. Since the insulators are not of simple geometry, the dimensions could not easily be measured and the areas had to be calculated by approximating them to simple shapes. These calculated values are indicated in the result tables 3.2 and 3.3. No other figures could be found with which to compare these values and so their accuracy is open to question.

This means that the ESDD values given in the tables may be somewhat inaccurate. Nonetheless, they are still useful for establishing a possible relationship between slurry salinity and ESDD. Since the area error will be the same for each measurement on the same insulator type, it will merely scale all the values up or down the severity axis by the same amount. Also the severity categories are not necessarily rigidly defined and are also quite wide. Therefore, a fairly large area error can be tolerated without affecting the classification of a particular salinity value in terms of light to heavy pollution severity.

3.3.3. Analysis And Conclusions Of The ESDD Test Results

From table 3.2 of the glass disc insulator ESDD results the mean ESDDs were calculated for each of the top, bottom and total surfaces at the 5 test slurry concentrations. The individual readings were all found to agree to within 10 % of the mean in each case except for the 40:40 slurry. Table 3.2 shows that the

first of the 3 tests done with that slurry gave conductivity readings for both the top and bottom surfaces that were much lower than the values from the other 2 tests. This resulted in the maximum deviation from the mean of 16.6 % occurring for the 40:40 top reading. For the total surface value the deviation from the mean value was slightly lower at 14.5 %.

Table 3.2 also shows that neither the top nor the bottom readings were consistently higher or lower than the total readings. Further, at each point the top and bottom mean values all agreed to within 5.5 % of the total surface ESDDs. The total surface ESDD values were plotted against the slurry salt concentration in the graph of figure 3.1. The graph suggests that there is a direct straight line relationship between the glass disc ESDD and the applied slurry salt concentration for the tested range up to 80 g/l. The line drawn on the graph was fitted to the mean ESDD value at each point.

This however, is not expected to be a definitive relationship since, as described in section 3.2.1 the slurry application procedure is not precisely defined in all aspects. If however, the results are considered in comparison with the pollution severity scales of table 3.1, the classifications of table 3.4 are derived. This shows that the slurry range from 40:5 to 40:80 gave pollution severities from very light to heavy as was desired.

Table 3.3 of the line post insulator ESDD test results shows that for 3 of the 5 slurry concentrations - 40:10, 40:15 and 40:40 - only 1 direct ESDD reading was taken. For the 40:5 and 40:20

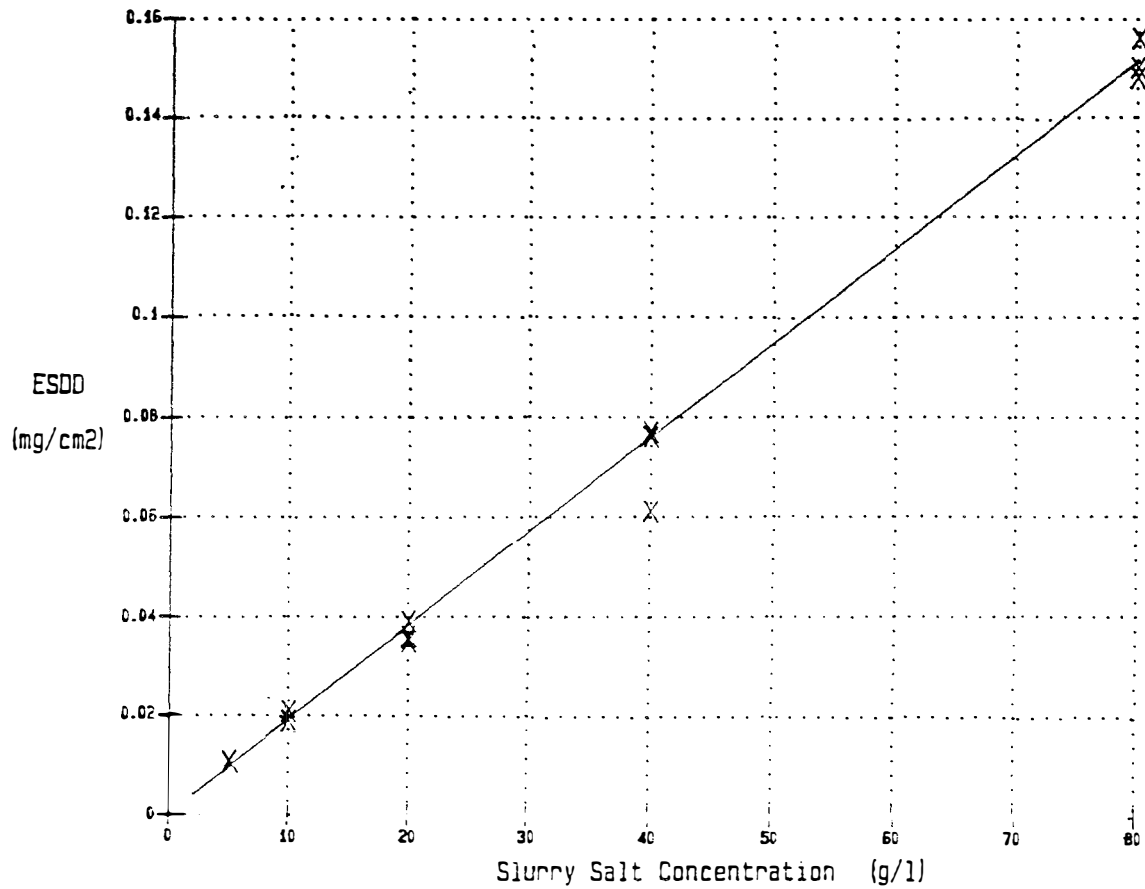


Figure 3.1 : Glass Disc Insulator ESDD Versus Slurry Concentration

Slurry Mixture	Mean Glass Disc ESDD (mg/cm ²)			CIGRE Pollution Category (From Table 3.1)
	Top	Bottom	Top	
40:5	0.0110	0.0113	0.0110	No significant pollution
40:10	0.0187	0.0207	0.0197	Very light pollution
40:20	0.0357	0.0370	0.0367	Light pollution
40:40	0.0743	0.0687	0.0713	Moderate pollution
40:80	0.159	0.145	0.151	Heavy pollution

Table 3.4 : Classification Of Slurry Concentration As Pollution Severity Index

slurries 4 and 2 readings were obtained respectively. From this relatively small amount of data mean values cannot be calculated and plotted as was done for the glass disc results. Nonetheless, the few data points that there are do show a similar increasing trend of ESDD with slurry concentration as was found for the glass disc insulators. Although the values from the 40:20 slurry fall into a higher pollution severity than did the glass disc 40:20 values, overall the classifications of table 3.4 should also be applicable to the line post insulator. Thus, a 40:5 slurry can be assumed to represent a very light pollution severity on the line post unit, which increases to a heavy pollution condition for slurries of 40:40 and higher salt concentrations.

The 4 direct readings with the 40:5 slurry are seen to have an average ESDD value of 0.0147 mg/cm^2 and an 11.6 % dispersion about this mean. This indicates that, as for the glass disc insulator, it should be possible to prepare the line post insulator to a pre-specified ESDD with a better than 15 % repeatability.

For the other readings recorded in table 3.3, i.e. those ESDD values measured on the insulator after a fog test, since neither the length nor the rate of steam generation were recorded, no numerical conclusions can be drawn from them. It can merely be seen that in some cases the post-test ESDD severity was definitely much lower than that expected from the other results. This was most marked for the 3 ESDD readings done on 40:40 polluted insulators after different fog tests. There the resultant ESDDs were only approximately half the expected values,

giving severity levels similar to those expected from a 40:15 or lower slurry concentration.

In summary, from the results of the ESDD tests it was concluded that, by using the same slurry mixture, a number of similar insulators could be artificially polluted to have the same ESDDs to within 15 % accuracy. Furthermore, the ESDD of the artificially polluted insulators would be directly related to the concentration of salt in the pollution slurry. Thus, in the rest of the thesis slurry concentration, given in the 40:x form as described in section 3.1.2, is used as the pollution severity index. For comparison purposes, this index will be taken to be related to the CIGRE defined pollution severity ranges according to table 3.4.

4. RN MEASUREMENT TECHNIQUES AND THE TEST CIRCUIT

Once the conditions under which polluted insulators can cause RN had been simulated and quantified in the laboratory, the second part of the problem was to measure the RN levels. There are in general three methods available for assessing the RN levels emitted by hv equipment. These are visual observations of corona activity on the equipment, field measurement of the radiated noise field, and laboratory measurement of the RIV or radio frequency current. Visual observations can be photographically recorded but the field and laboratory measurements can be done more precisely with a radio noise meter or a spectrum analyser. Readings from these instruments are related to the degree of interference of an unwanted signal, either by providing an absolute value of the noise strength or by providing a signal to noise ratio.

In this study, the RN emitted by polluted insulators was investigated by performing laboratory RIV measurements using a standard RN meter. This chapter therefore, discusses the general characteristics of RN meters and how they are used to measure power line RN> this is followed by a description of the type of laboratory RN measurement system recommended by the IEC and a version of which was used in this investigation. The discussion only covers the principle of operation of the measurement system and its particular requirements, given by the IEC, to ensure the accuracy of the RN data that it provides. How the system was implemented and used to measure RIV produced by insulators in clean fog tests, is described in the following chapter.

4.1. Characteristics Of RN Meters

Radio noise meters have been compared to "selective voltmeters characterised by a certain pass band and which can be tuned to a centre frequency" and "calibrated radio receivers that function as RF voltmeters" [9],[36]. These meters have the facility to measure and display the strength of RF signal in a given bandwidth at the receiver input. The value indicated by any receiver in response to a given input signal depends on the electric response characteristics of the receiver. These receiver characteristics will be given as a specification for any RN meter but will not be the same for all meters. Therefore there are two possible approaches to performing RN measurements. Either the measurement receiver is chosen to have the same characteristics as the receiver that is being interfered with, or else a meter with specified, standard characteristics is used.[36].

The advantage of using a receiver similar to the system under assessment, is that it gives a direct indication of the interference effect of the noise to that particular system. By comparison the use of a standard set yields well-defined, absolute values that permit different sets of independently obtained data to be compared. For research purposes it is essential to use the standard receiver approach so that published results can be unambiguously interpreted. For this reason, bodies such as CISPR and American National Standards Institute (ANSI) have drawn up specifications for the characteristics of receivers to be used for RN measurements [37],[38]. Since the measurement method may also affect the results, this is also covered by the standards.

For practical measurements, the meter input signal is usually a series of pulses, which contain a spectrum of HF components. The meter reading then is an indication of the magnitude of those HF components that fall in the receiver bandwidth centred at the tuned frequency. Although the meter reading is usually calibrated against a pure sine wave, its output response is related to some value (eg peak, average or rms) of the input pulses.

In a RN meter the input pulses are processed through a number of stages to derive the final meter indication [12]. The first stage is a RF amplifier, which amplifies a portion of the pulse spectrum centred around the receiver tuned frequency. This RF amplifier output, which is a series of oscillating pulses, is then converted to an intermediate frequency (IF) before passing into an IF amplifier. The train of pulses at the IF output then goes to the detector circuitry. This rectifies the pulses and detects the envelope of the rectified pulses. The envelope then passes to some weighting circuitry that determines the response type of the meter. It weights the voltmeter output indication to be a function of either the peak, or the average, or some other intermediate value of the detected pulse envelope.

Thus, the meter reading depends both on the receiver bandwidth, which is fixed by the narrower of the RF and IF amplifier bandwidths, and on the type of weighting circuit used. The most commonly used weighting circuit is the quasi-peak one which forms the basis of both CISPR and ANSI specifications. This basic circuit, which consists of a charging capacitor with specified charge and discharge time constants, is shown in figure 4.1. Figure 4.2 shows how the voltage at the output voltmeter is less

than the peak value of the pulse envelope, as the train of rectified pulse envelopes successively charges and discharges the capacitor, i.e. it is a "quasi-peak" value. The charge and discharge time constants determine how close to the peak value it actually is.

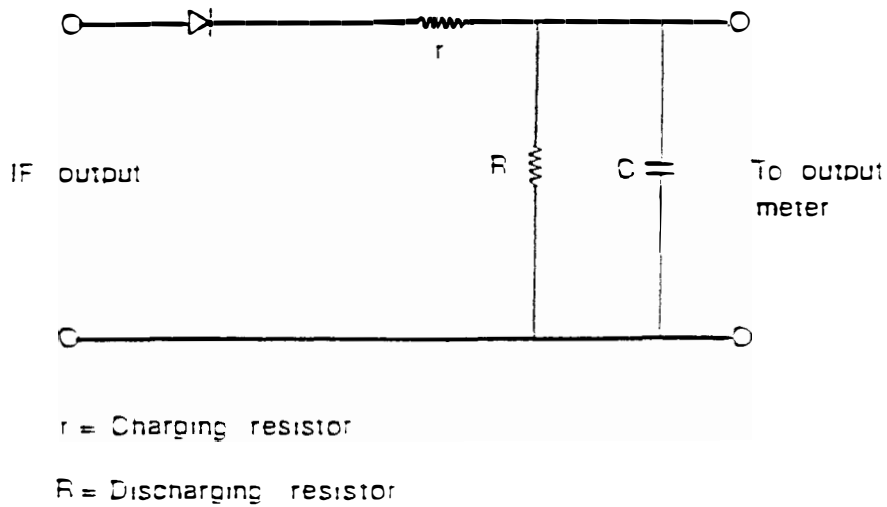


Figure 4.1 : The Quasi-Peak Detection Circuit

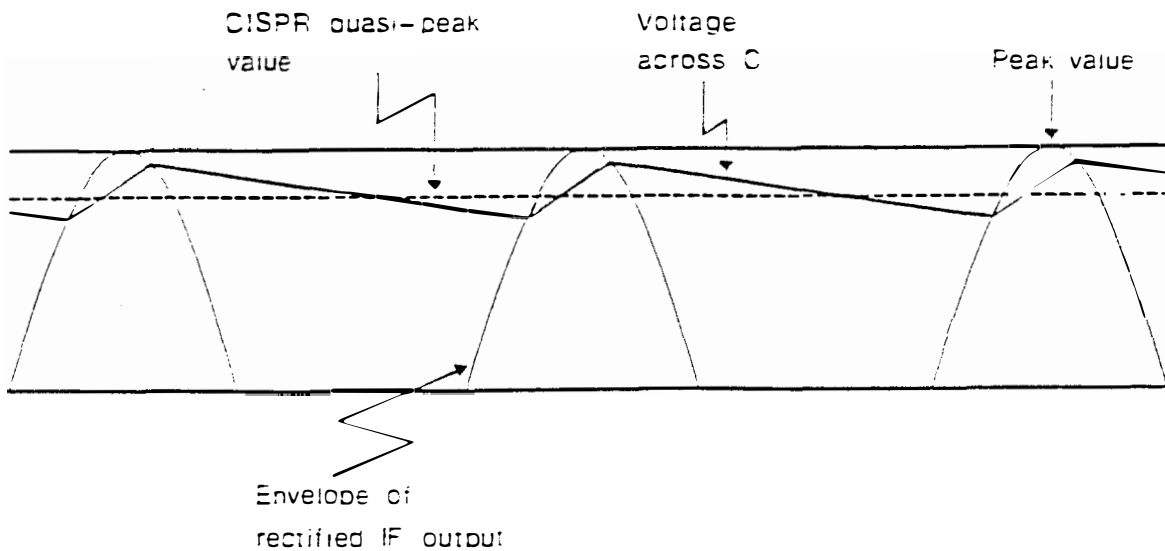


Figure 4.2 : Derivation Of The Quasi-Peak Value

The quasi-peak meter response is specified by both CISPR and ANSI because its indication is dependent, not only on the meter bandwidth and time constants, but also on the noise pulse

repetition rate (prf). This is desirable as it has been found that the nuisance value of any noise is dependent on both its pulse peak amplitude and its prf.[9]. Table 4.1. lists the main CISPR and ANSI quasi-peak meter specifications for the range from 0.15 MHz to 30 MHz. The table shows that CISPR requires a wider bandwidth and ANSI a longer discharge time, but both use the same charge times. These two differences cause CISPR meters to indicate 2 dB lower than ANSI receivers for the same input noise signal [9]. The bandwidths are chosen to be similar to those of typical AM receivers that operate in that frequency range. At higher frequencies, the specifications are changed to cover the higher bandwidths of FM and TV receivers (of the order of 120 kHz and 10 MHz respectively).

	CISPR	ANSI
Bandwidth	9 kHz	5 kHz
Charge time constant	1 ms	1 ms
Discharge time constant	160 ms	600 ms

Table 4.1 : Quasi-Peak RN Meter Specifications For
150 kHz To 30 MHz

4.2. Using Noise Meters To Measure Power Line RN

In the context of measuring power line RN, the problem is to get the signal to be measured from its source to the instrument. As described previously in Chapter 2, power line noise manifests

itself as both a pulsative current flowing in the line conductors and as a broadband radiated electromagnetic wave. Thus two measurement possibilities arise. Firstly, one can couple the receiver to the hv line and directly measure the conducted current, by diverting it to flow through the receiver. Secondly, one can use an antenna to pick up the radiated noise signal and feed that to the receiver. In both cases the measurement process will to some extent distort the absolute value of the noise being measured. Thus, the difficulty is to interpret how accurately the measured quantity represents the generated noise, in either absolute terms, or in terms of the nuisance or interference, to a particular communications system.

Therefore, not only must the response characteristics of the receiver be known, but also the effects on the indicated value of the total measurement system. These effects include attenuation of the noise signal, either in the coupling circuitry or in the radiation path, reflections due to circuit mismatches and stray capacitance effects. Further measurement inaccuracies may arise from unwanted background noise sources.

For this particular project the requirement was to measure the RN produced from hv insulators in the laboratory. Although radiated measurements may be possible in the laboratory, the conducted current measurement was preferred here. Since the levels to be measured may be very low, to perform such radiated measurements accurately indoors, requires an electrically screened room to keep background signals as low as possible. Also other large equipment in the laboratory, such as the test transformer and even the laboratory walls, are likely to distort and reflect the

radiated signals making reliable readings difficult to obtain.

The measurement system and procedure used was based on IEC Publication 437, which covers the IEC recommendations for radio interference tests on hv insulators [7]. According to IEC 437 however, the method is only applicable for clean and dry test objects, and specifically excludes polluted insulators. CISPR Publication 18.2 also notes that "generally standards and normal practice" are limited to tests on clean and dry objects as other test conditions are hard to reproduce [12]. Nonetheless, it does also state that the basic measurement method, i.e. the CISPR 18.2 method on which IEC 437 is based, should also be valid for wet and polluted conditions, although no recommendations as to how these conditions should be simulated in the laboratory are made.

By choosing the conducted measurement system of IEC 437, the measurement frequency was limited to the range 0.5 MHz to 2 MHz. Higher frequency ranges are not covered because, as the wavelength becomes shorter, so the measurement circuit distortion tends to increase resulting in less accurate readings. By paying careful attention to matching in the circuit and by keeping all leads and components as short and small as possible, measurements in the VHF range, above 30 MHz, can be performed. In recent years Janischewski [39] has developed a circuit that is able to measure very high frequency discharge pulses, up to the Gigahertz range. Such measurements were, however, beyond the scope of this project and noise readings were taken at 1 MHz only, using the methods described in IEC 437 and CISPR 18-2.

4.3. The Standard IEC 437 RIV Measurement Circuit

4.3.1. Principle Of Operation

According to the IEC recommendations, the test circuit is as shown in figure 4.3 [7]. The principle of operation of the system is to directly measure a particular frequency component of the HF current that flows in the hv circuit when discharge activity occurs on the test object. It achieves this by diverting that particular current component to flow to ground through a known value of resistance. A RN meter is then used to measure the voltage - called the radio influence voltage or RIV - developed across the resistor by this current. Since the resistance value is known, the reading can also be converted back to its original current form. This may be required when radiated field calculations are done using the excitation function theory.

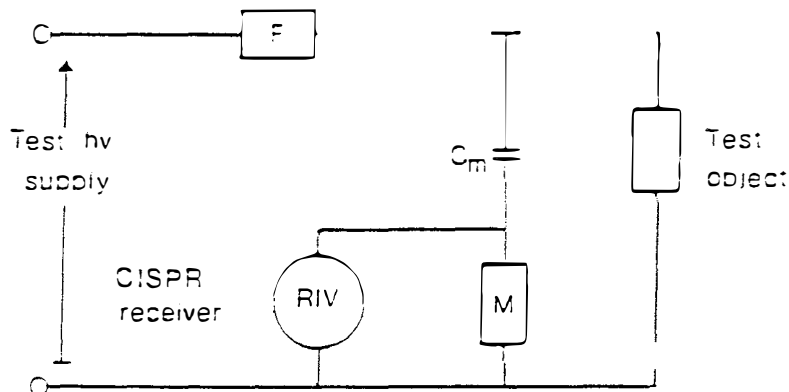


Figure 4.3 : The IEC 437 RIV Measurement Circuit

The system operation is best explained by considering the test object in figure 4.3 to be a broadband RF current source. Current flowing from this source can in general follow 3 different paths.

It can flow through the coupling capacitor C_m to the measurement termination M , through the filter F back to the supply, and to ground through the circuit stray capacitance C_s . Thus, only that portion of the total current that flows through M will be measured by the receiver, while the rest that flows through F and into C_s causes an error in the measurement.

The circuit is designed so that the path through C_m and M has a low impedance for the desired frequency current component. The other 2 paths are made to have much higher impedances to this current. The impedance through to the power supply is increased by inserting F between the supply hv terminal and the test object and C_m . F is a parallel LC circuit with resonant frequency tuned to the measurement frequency. Thus, at this frequency, this route has a high impedance while at other frequencies, in particular the 50 Hz of the power supply, the impedance is relatively low. The stray capacitance path impedance is inversely proportional to C_s . Although no specific precautions are taken to lower C_s , its effect on the RIV measurements can be minimised by using a sufficiently large value for C_m . The current is split between C_m and C_s roughly in proportion to their respective magnitudes.

Once the chosen frequency component of the interference current has been diverted to M , other currents with the same frequency and originating from other background sources, have to be prevented from distorting the RIV readings. This is partly achieved by F since it blocks any background currents that originate on the supply side of F from flowing to M . Other background noise, generated on the test object side of F , cannot be selectively attenuated in the same way. Instead steps have to

be taken to eliminate or at least minimise these sources.

These steps include using suitably large diameter, smooth hv connectors and taking care in connecting the circuit. The hv connections should all be made very firmly and should not have any unnecessary sharp points. Induced HF currents in the ground connections are prevented by making all earth leads as short as possible and by ensuring that there are no earth loops.

The measurement termination M consists of a parallel LR circuit. The inductance of L is chosen to provide a high impedance to the measurement frequency but a low impedance to the mains frequency. This is a protective measure to keep the 50 Hz voltage across the RN meter as low as possible without shunting the interference current away from it. The RIV is then the voltage that the interference current develops across the resistor R and is measured with a suitable type of RN meter. The readings are given in decibels referred to 1 microvolt. Since it is the current rather than the voltage across R, that produces the interference, the value of R also needs to be specified. However, so that different measured RIV values can be directly compared with one another, they are routinely corrected to the equivalent voltage across a 300 ohm resistance.

4.3.2. The IEC RIV Measurement Circuit Requirements

For the test circuit to give accurate readings of the interference current and for the circuit to simulate the practical situation of interference generation on a service line, there are a number of specifications set out in the IEC documents

IEC 437 and CISPR 18.2 that should be met [7],[12]. These are mainly to do with the hv power supply and the impedance of the test circuit as seen by the interference generator, i.e. the test object.

The power supply specification is that it should comply with the recommendations for hv test transformers given in IEC Publication 60.2 [40]. The most important of these recommendations are that, for pollution testing the source voltage must have a sinusoidal waveshape with both half cycles "closely alike", a frequency of between 40 Hz and 60 Hz and a ratio of peak to rms values of $\sqrt{2}$ to within 5 %. A minimum short circuit current capability is also specified for the supply. It is given as a function of the ratio of the transformer series resistance to reactance. This minimum capability is particularly important for pollution flashover testing. For those tests, if the supply is not strong enough, i.e. its short circuit current is too low, the voltage drop due to the discharge leakage current could cause a partial arc not to develop to a full flashover. With a stronger source on the other hand, (eg in a practical case on a hv power system) the same arc might well develop to a flashover.

The main circuit impedance requirement is that the impedance at the measurement frequency between the live conductor and earth, as seen by the noise source, should be 300 ± 40 ohms with a phase angle of less than 20 degrees. This is so that the test object sees an impedance similar to what it would see in practical service conditions. Most often the impedance seen by hv line equipment will be the surge impedance of the line, which will be of the order of 300 ohms. However, as noted in the CIGRE corona

effect guide [9], for non-terminal insulators, (as were being tested here) the impedance seen will only be half of this. This is because the HF current flows in both directions down the line away from its source point.

Although the nominal value of 300 ohms is specified, the CISPR document 18.2 [12] does note that as long as this impedance value is between 100 ohms and 600 ohms, the interference current generation should not be affected. Then readings can be directly, proportionally converted to the standard value of 300 ohms.

So that the measurement part of the system does not distort the interference current, there are 3 further specifications governing the measurement termination and the coupling capacitor. Firstly, the receiver is connected to the circuit using shielded co-axial cable. To avoid reflections at the ends of this cable, it should be matched with its characteristic impedance. The second requirement is that, to successfully divert power frequency currents away from the receiver, the value of inductance L in the measurement termination should be greater than 1 mH at the measurement frequency of 0.5 MHz. This gives 0.314 ohms impedance at 50 Hz and 3140 ohms at the measurement frequency. The third requirement is that, to minimise stray capacitance errors, the coupling capacitor must be considerably greater than C_s . Provided it is at least 5 times bigger, the error due to C_s will be less than 2 dB [9].

The other CISPR recommendation for the test circuit concerns the blocking filter F . This recommendation is that F must attenuate signals at the measurement frequency by at least 35 dB. This is

to ensure that the error due to the interference current flowing back to the supply is negligible. This level of attenuation also prevents background discharges on the supply side of F from affecting the RIV readings.

5. THE TEST CIRCUIT CONNECTION AND VERIFICATION

For this project the IEC standard RIV measurement circuit was connected up at the CSIR clean fog test facility in Pretoria. The circuit was used to measure the interference levels produced by artificially polluted insulators during clean fog type tests. This chapter gives a detailed description of the implementation of this RIV measurement system. In addition to giving details of the equipment used, the description also covers the calibration tests that were done in accordance with CISPR requirements.

5.1. The Test Circuit Equipment

The standard IEC RIV test circuit was connected as shown in figure 5.1. The hv supply was provided by a single phase, 120 kVA regulator and hv step up transformer set. The regulator was an auto-transformer with its input supplied between 2 phases of the laboratory 380 V mains supply. Its output was thus adjustable from 0 to 380 V and provided the primary input to the step up transformer. The transformer had 2 primary and 4 secondary windings. These could be connected in various combinations (via external terminals) to supply 0 to 15 kV, 30 kV, 60 kV and 120 kV nominal secondary voltage ranges for the 0 to 380 V primary voltage range. For all the RIV tests, the 0 to 60 kV connection was used. The regulator and transformer units were placed inside the laboratory next to the fog tent.

The filter F consisted of a parallel LC circuit. It was made up

from ordinary low voltage components, since they were not required to develop any high 50 Hz voltage drop. The inductor was a coil of resin insulated copper wire wound on a ferrous core. The capacitance consisted of two capacitors in parallel. One was variable so that the filter could be tuned within a range of approximately 20 % around the 1 MHz measurement frequency.

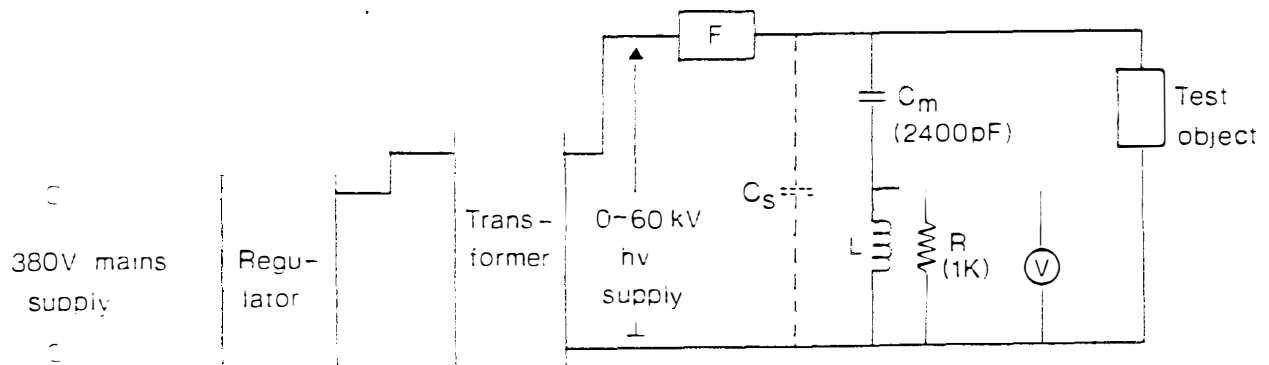


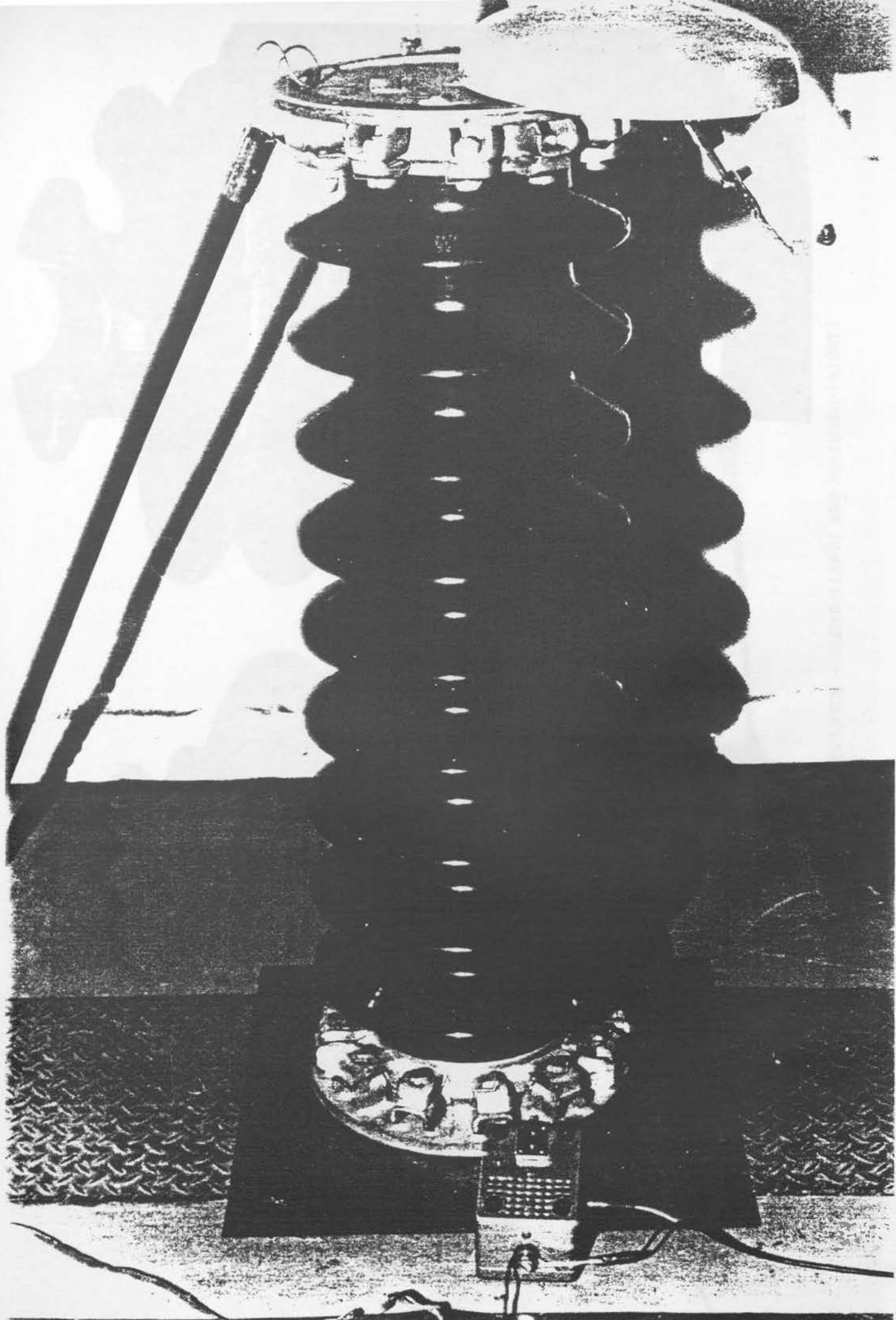
Figure 5.1 : Connection Of The Test Circuit

Although various smaller values of coupling capacitor were initially tried, for the final test circuit a 2400 pF, 100 KV test capacitor was used. The measurement termination, comprising the coil L and measurement resistor R, was a unit made by Messwandler-Bau. It consisted of a 1 kilohm resistor connected in parallel with a coil of 0.660 mH inductance. It also had a protective spark gap connected across it. The measurement instrument was a 80 kHz to 30 MHz tunable Schwarzbeck (Model FSME 1515) radio interference receiver or noise meter. It had a -10 dB to +120 dB measurement range, referenced to 0.32 microvolt on its 50 ohm input. Its response characteristics conformed to the CISPR quasi-peak receiver requirements.[41].

The blocking filter, coupling capacitor and the measurement termination across which the receiver was connected, were positioned just outside the tent beneath the perspex bushing. This arrangement can be seen in photograph 5.1. The hv supply was fed from the top of the capacitor through the bushing onto the test object inside the tent.

Two different types of insulator were used as test objects. These were a EP303 line post insulator and a U70BL glass disc insulator as illustrated in photographs 5.2 and 5.3 respectively. The photographs show the insulators in both clean and artificially polluted states. Different mounting methods were used for the two insulator types. The line post insulator was bolted vertically onto a wooden cross-arm structure as shown in photograph 5.4. The insulator pin was earthed through a 10 ohm resistor, across which the leakage current could be observed on an oscilloscope. The conductor used to make the hv connection from the tent bushing to the insulator, was a 2.5 cm diameter metal pipe, which extended about 1 m beyond the insulator and was terminated in a 30 cm diameter copper sphere. The conductor was either tied into the insulator top groove, using a standard moulded tie wire, or (as explained in Chapter 6) was not tied to the insulator at all, but just left resting on top of the insulator, under its own weight.

The disc insulators were suspended via the steel wire through the middle of the tent roof. They were insulated from the suspending cable by a Bakelite block, but were earthed through a separate, braided copper strip and the 10 ohm resistor. The connection from the tent bushing to the insulator again used the metal pipe and copper sphere. The conductor to insulator connection was made as

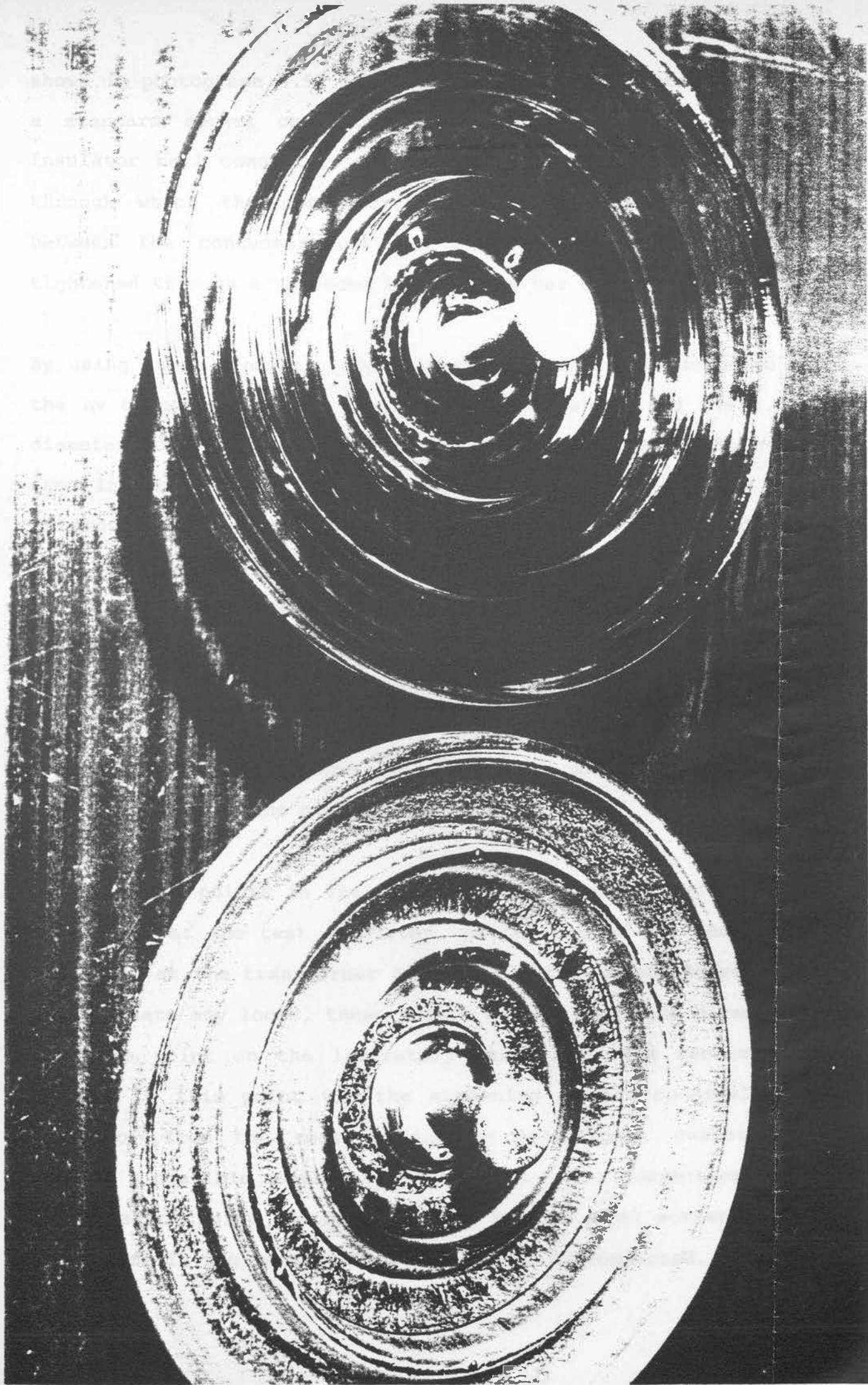


PHOTOGRAPH 5.1 THE COUPLING CAPACITOR, MEASUREMENT TERMINATION AND BLOCKING FILTER



PHOTOGRAPH 5.2 THE LINE POST INSULATOR - CLEAN (LEFT) AND POLLUTED (RIGHT)

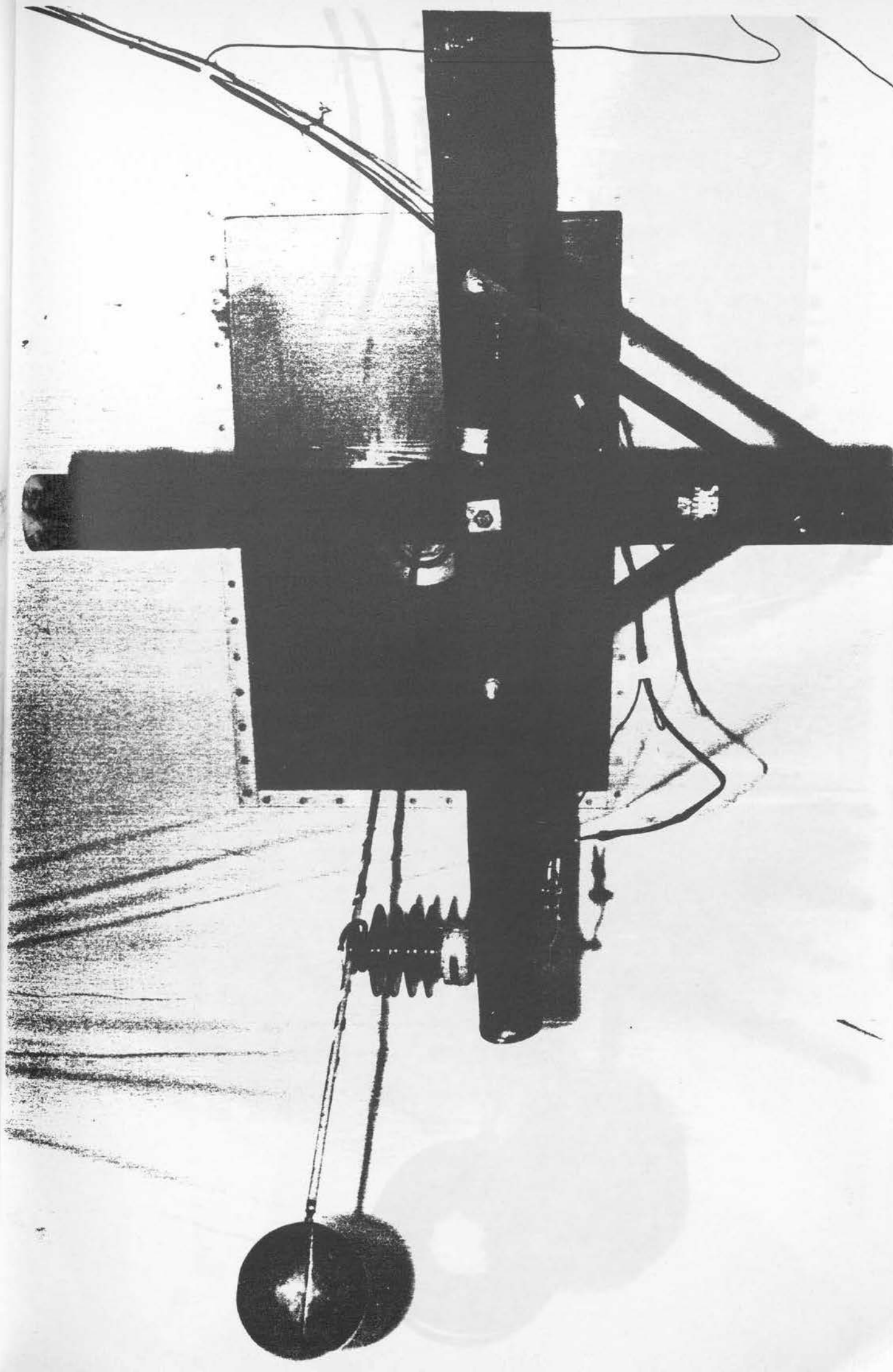
PHOTOGRAPH 5.3 THE GLASS DISC INSULATOR - CLEAN (LEFT) AND POLLUTED (RIGHT)



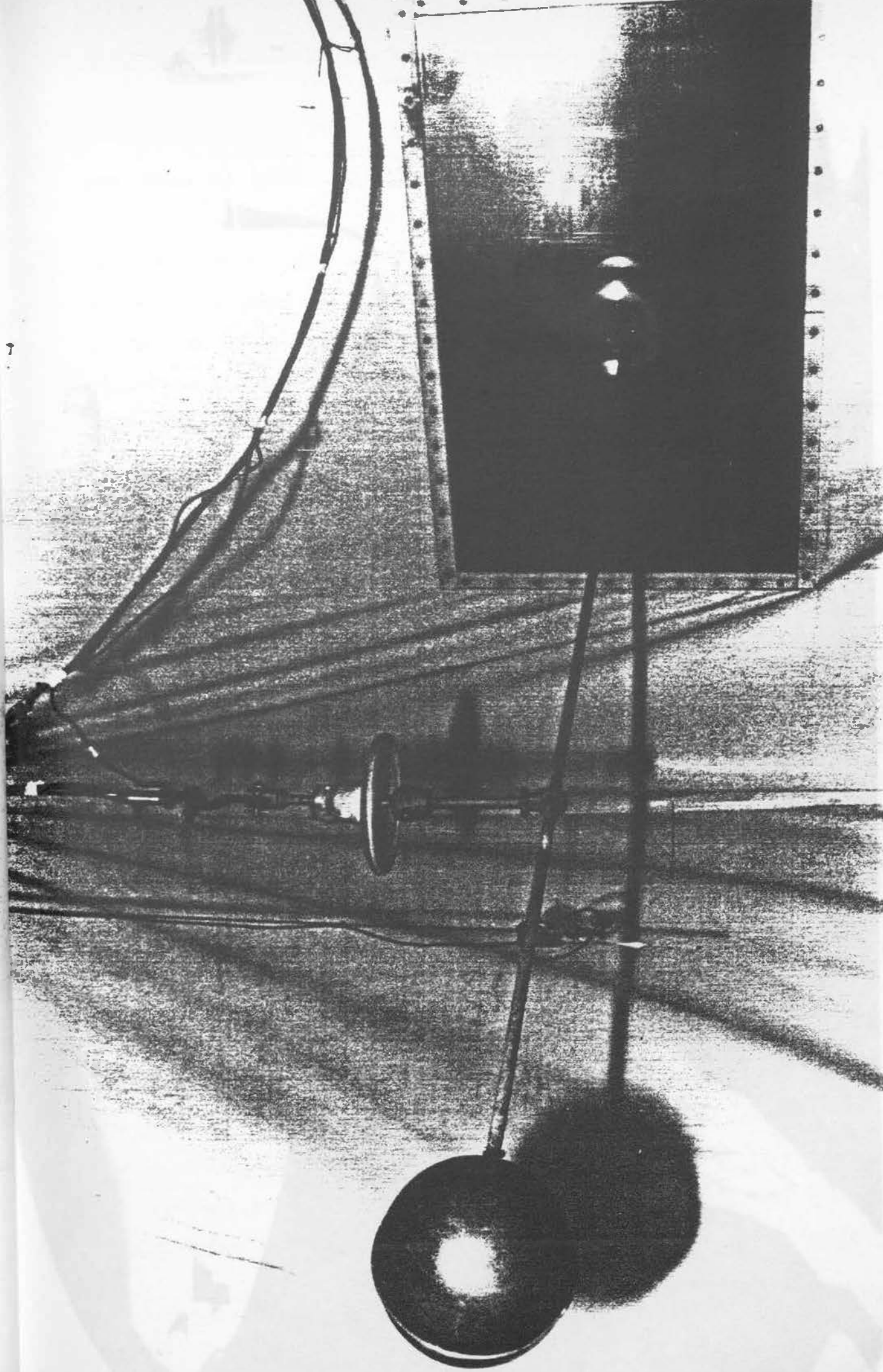
shown in photograph 5.5. It consisted of a solid metal bar, with a standard socket connector on one end, connected into the insulator ball connector. The other end of the bar had a hole through which the conductor passed. To ensure good contact between the conductor and the bar, there was a bolt that tightened through a threaded hole in the bar onto the conductor.

By using large diameter (approximately 5 cm) aluminium pipes for the hv connectors up to the tent window bushing and the 2.5 cm diameter conductor and the copper sphere inside the tent, corona free interconnections were achieved over the test voltage range to above 30 kV. Also, to minimise the circuit background noise levels, the filter was connected as close to the coupling capacitor (on the transformer side and not the test object side) as possible. This was at the top of the capacitor as shown in photograph 5.6. Also shown in the photograph is an aluminium corona shield, that was bolted onto the capacitor, over the filter and its connections, to reduce the possibility of corona from that part of the circuit.

There were 4 points in the circuit where earth connections were required - at the test insulator, at the end of the measurement resistor, at the transformer tank and at the measuring receiver. To eliminate any loops, these points were all earthed directly to the same point on the laboratory earth mat. The receiver was earthed to this point via the screening of the co-axial cable connector from the receiver to the measurement resistor. To prevent a possible earth loop through its mains connection to the common earth point and back through the co-axial screening, the earth wire in the receiver power plug was disconnected.



PHOTOGRAPH 5.4 THE LINE POST INSULATOR MOUNTING METHOD



PHOTOGRAPH 5.5 THE GLASS DISC INSULATOR MOUNTING METHOD

5.2. Description of the Test Circuit

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PHOTOGRAPH 5.6 THE BLOCKING FILTER CONNECTION

5.2. Verification Of The Test Circuit

The rest of this chapter describes how the test circuit was checked against the CISPR circuit requirements and how the system was calibrated. Analysis of the system shows that it did not necessarily meet all the CISPR requirements. Nonetheless, a number of tests were done on the circuit to demonstrate that these shortcomings would not adversely affect the accuracy of RIV readings obtained from the system. This initial setting up and verification of the test circuit was done at the NETFA laboratories. Once the test equipment had been moved to the CSIR laboratory and re-connected there for the pollution tests, the circuit calibration was checked again.

5.2.1. The Test Transformer

With the step up transformer connected for its 0 - 60 kV range, it was checked against the IEC 60.2 recommendations [40]. This was done by connecting the transformer up to the 0 - 380 V supply with a capacitive divider across its hv output. The divider output was then both observed on an oscilloscope and measured using a digital rms voltmeter, as the voltage was increased to its maximum range. These observations showed that the transformer waveshape adequately satisfied the frequency, shape and peak to rms value requirements.

Using this same circuit configuration, the transformer test voltage was also measured as a function of its primary voltage. The results of these measurements are given in the table in

Appendix C where they are also plotted on a graph. The graph enabled the test voltage in the subsequent RIV tests, to be determined by measuring the transformer primary voltage. This obviated the need to connect another instrument in the secondary.

The IEC 60.2 short circuit current requirement was more difficult to check. However, shortly before the transformer was used for this work, it was serviced in the ESKOM workshops at Rosherville. This service included a routine short circuit test being done on the transformer. It consisted of short-circuiting the transformer primary winding and measuring the current when a reduced voltage was briefly applied across the secondary terminals. The applied test voltage was 225.6 V and the measured current was 0.191 A with the result being given as a percentage impedance of 3.94 %. This was calculated from the measured voltage and current values and the transformer rated voltage and KVA capacity according to equation 5.1 as derived below.

$$\begin{aligned}
 \% \text{ impedance} &= \frac{\text{measured impedance}}{\text{rated impedance}} \times 100 \% \\
 &= \frac{\frac{V}{I}}{\frac{KV \times 1000}{KVA/KV}} \times 100 \% \\
 &= \frac{V \times KVA}{10 \times I \times (KV)^2} \dots\dots\dots 5.1
 \end{aligned}$$

where : V = applied test voltage (Volts)

I = measured current (Amps)

KVA = transformer rated KVA

= 120 KVA

KV = transformer rated voltage(kV)

= 60 kV.

This percentage impedance can be seen alternatively in terms of an equivalent circuit as a series impedance Z , given by the measured current divided into the applied voltage,

$$\text{i.e. } Z = \frac{225.6 \text{ V}}{0.191 \text{ A}} = 1180 \text{ ohms.}$$

Using this equivalent circuit and the I_{\max} theory, it can be shown that no unacceptably high voltage reductions were expected to occur during the RIV tests with the polluted insulators. According to the I_{\max} principle for insulator pollution flashover, the highest surface leakage current that flows prior to a flashover, is a function only of the insulator's specific creepage. An equation describing this, as proposed by Verma [42], is shown in equation 5.2.

$$I_{\max} = 650 (V/d)^2 \dots\dots\dots 5.2$$

where : I_{\max} = value of current in the last half cycle before flashover

V = line-to-line system voltage (volts)

d = creepage distance of the insulation (cm).

This can also be written in terms of specific creepage as equation 5.3.

$$I_{\max} = (650 \times 10^{-4} S)^2 \dots\dots\dots 5.3$$

where : S = specific creepage (mm/kV), which is defined by the IEC in IEC Publication 815 according to equation 5.4 as,

•

S = Total insulation creepage length (mm) 5.4.

System voltage (kV line - line)

According to equation 5.3, for the range of specific creepage tested, (7 mm/kV to 202 mm/kV) the corresponding range of I_{max} is 207 mA to 172 A. Since the creepage distance of the insulators tested was fixed, i.e. 280 mm for the glass discs and 525 mm for the line post insulator, the highest values of specific creepage only occurred in the tests done at the very low voltages. At these voltages however, neither of the tested insulators were highly enough stressed to approach flashover, even when severely polluted. Indeed in all the tests at the lowest voltages, below about 5 kV, very little if any discharge activity was observed.

Thus, although the theoretical I_{max} at 202 mm/kV is 172 A, this magnitude of current could not arise since it would represent an impossibly high voltage drop. To limit the voltage drop to an acceptable level of below 10 % at the maximum specific creepage, sets a limit of 127 mA on the leakage current that can flow with the 1180 ohm transformer impedance. Although the actual leakage current values were not measured, at this low voltage, (approximately 1.5 kV to give 202 mm/kV) the current was only expected to be of the order of a few tens of milliamps. This would cause correspondingly lower voltage regulation than 10 %.

At the other end of the range, with the very low specific creepages of around 7 mm/kV, flashover was expected and in some cases did occur. At the 7 mm/kV extreme, the greatest theoretical voltage drop before flashover is 244 V for the calculated I_{max} value of 207 mA and the 1180 ohm impedance. This represents a

negligibly low percentage drop of 1 % at the 22.5 kV required to give the minimum specific creepage of 7 mm/kV on the glass disc.

As the test voltage is decreased from this maximum value, i.e. as the specific creepage is increased, so the theoretical I_{max} values also increase. Therefore, the resulting theoretical maximum percentage voltage drops also increase. However, these I_{max} currents will only flow in tests where flashover conditions are approached. In other tests, with reduced surface discharge activity, the leakage currents will be much lower than the calculated I_{max} values. Thus, the voltage regulation will then also be much lower than the I_{max} indicated values.

For the glass disc insulator, the lowest test voltage at which flashover occurred in any of the tests was 12 kV. This is equivalent to a specific creepage of 13 mm/kV. For the line post insulator, the minimum flashover test voltage was 18 kV corresponding to 17 mm/kV specific creepage. Thus, in these tests where high levels of discharge activity occurred, the maximum percentage voltage drops would be 7.9 % and 7.5 %, for the line post and glass disc insulators respectively, as the corresponding I_{max} values are 1.20 A and 767 mA.

Thus, over the practical range of specific creepages for polluted areas recommended in IEC Publication 815 [43], i.e. 16 mm/kV to 31 mm/kV, the leakage currents were not expected to result in large enough voltage drops to affect the interference generation on the polluted insulators. At the higher specific creepages, i.e. above 31 mm/kV, the leakage currents are expected to be too small to cause significant voltage drops, although the

theoretical values of I_{max} in those ranges could not in fact be supplied by the test transformer. At the lower specific creepage values, the voltage drops would be less than 10 %, due to the higher voltages used and the lower values of I_{max} .

5.2.2. The Measurement Termination And Blocking Filter

If the filter and the step up transformer beyond it are neglected, the impedance seen by the test object consists of the coupling capacitor in series with the measurement termination and the RN meter. The equivalent impedance of this, with the 50 ohm meter input impedance connected directly across the 1 kilohm resistor of the termination, is calculated to be 81 ohms with a phase angle of 54 degrees at 1 MHz. This large difference with the value of 150 ohms however is not expected to cause any great distortion of the RIV results. If the interference producing test object is modeled as a current source, i.e. an emf source with a very high series resistance, then the difference in the current with 81 ohms, or 150 ohms, or even with 300 ohms connected to the source will be negligible. This assumption is not unreasonable since it is also made in the CISPR specified calibration procedure [9].

The receiver connection to the measurement termination was made using 50 ohm shielded co-axial cable. Thus, at the receiver end the cable was correctly terminated in its characteristic impedance, since the receiver input impedance was also 50 ohms. The connection to the test circuit however, was directly across the 1 kilohm resistor. Even if the 0.660 mH of the inductor is considered, this gives an effective 1 MHz terminating impedance

of 805 ohms at that end of the cable. In spite of the mismatch, the calibration tests did not indicate any resulting error in the meter RIV readings.

The name-plate value of 0.660 mH for the inductance L in the termination gives 0.21 ohms impedance at 50 Hz and 4147 ohms at the measurement frequency of 1 MHz. These impedance values therefore, comply with those from the CISPR recommended value of 1 mH for L at 0.5 MHz. Although the test circuit stray capacitance was not actually measured, it is not expected to have been large enough to cause significant error. The value of C_m of 2400 pF is 2.4 times the value of 1000 pF recommended by CISPR as being likely to satisfy the requirement that $C_m > 5C_s$. Once again, the circuit calibration tests would have brought any large stray capacitance error to light if it had existed.

Although there was no equipment available to directly measure the component values of the parallel LC blocking filter at 1 MHz, its effectiveness was demonstrated by measuring its insertion loss as suggested in CISPR 18.2 [12]. The calibration tests also served to confirm that the filter attenuation was high enough to prevent the hv source shunting the interference current away from the measuring receiver.

According to CISPR 18.2 the filter insertion loss is estimated by connecting up the complete test circuit but with the power supply switched off. A signal generator is connected to the circuit via a series resistor of at least 20 kilohms so that it appears as a current source to the test circuit. The connection is made on the supply side of the filter and the signal generator is set to

deliver a current in the range of 50 to 200 microamps at the measurement frequency. The receiver indication is then noted both with the filter connected in the circuit and with it shorted out. The difference in these two readings gives an indication of the filter attenuation at the measurement frequency.

In this case a sine-wave signal generator with a 33 kilohm series resistor was used. It was set to inject a 170 microamp, 1 MHz current into the circuit. The variable capacitor of the filter was then adjusted for minimum receiver indication with the filter connected. The highest loss that could be achieved was 23.5 dB. Although this value is somewhat less than the 35 dB recommended by CISPR, the calibration tests showed it to be sufficient.

5.3. The Calibration Tests

These calibration tests are required to ensure the accuracy of the RIV measurements being performed. The basic principle is to inject a known value of RF current into the measurement circuit and observe the meter reading. The standard CISPR RIV value for this current can be calculated and the difference between it and the meter value is the calibration or correction factor (CF). This factor actually consists of two components. Firstly, the measurement circuit may attenuate the interference current and some of the current may flow to the supply and into the stray capacitance. Therefore, there is a circuit attenuation component. Secondly, there is what CISPR 18.2 calls the "resistance network factor" [12]. This accounts for the fact that the RN meter RIV reading is not necessarily measured across 300 ohms and nor is it

always referenced to 1 microvolt.

According to the test circuit of figure 5.1, the effective measurement resistance was the 1 kilohm termination resistor in parallel with the 50 ohm input resistance of the receiver, i.e. 47.62 ohm. Also, as given in the meter specifications, when using the meter's 50 ohm impedance input, it displays the voltage readings in decibels relative to 0.32 microvolt. Therefore, the resistance network factor to correct the displayed readings to CISPR standard values, referred to 1 microvolt across 300 ohm can be calculated as follows.

If the interference current to be measured is i microamp, then the desired RN meter reading is,

$$RIV = 20 \log(i \times 300) \quad \text{dB/microvolt 300 ohms.}$$

The actual Schwarzbeck meter reading V_q , however will be,

$$V_q = 20 \log[(i \times 47.62)/0.32] \quad \text{dB,}$$

if zero circuit attenuation is assumed.

Then the resistance network factor (RNF) is given by,

$$\begin{aligned} RNF &= RIV - V_q \\ &= 20 \log[(300 \times 0.32)/47.62] \quad \text{dB} \\ &= 6.09 \text{ dB.} \end{aligned}$$

The total correction factor CF to be added to the receiver readings then will be given by,

$$CF = 6.09 + A \text{ dB} \dots\dots\dots 5.5$$

where : A = circuit attenuation factor.

As will be shown later, in the calibration tests no distinction was made between the two components of CF. It was instead determined in one direct measurement, by injecting a known magnitude of interference current into the circuit and comparing the resultant receiver indication with the CISPR RIV value calculated from the current magnitude. It is still useful to calculate the RNF separately as it gives an indication of the size of CF to expect. It also enables one to determine the circuit attenuation value A and to thus estimate the effectiveness of the measures taken to minimise it.

Two different calibration tests were done. The first one used only the measurement termination and receiver to confirm that the effective measurement resistance was 47.62 ohms and that the meter indication was referenced to 0.32 microvolt. It also served to confirm the accuracy of the current source, where the injected current is given as the signal generator voltage divided by the series resistance. The second calibration test was done on the complete test circuit to determine the overall calibration factor.

5.3.1. The Measurement Termination Calibration Test

The first calibration test used the circuit of figure 5.2. The signal generator was used to inject a 1 MHz current into the test circuit measurement termination. The test object was included since that was the configuration to be used in the other main circuit calibration test. The RIV across the 1 kilohm resistor was recorded as the current was varied from approximately 0.5 to 500 microamps. The current was adjusted by adjusting the signal

generator output voltage V_{gen} . The results of the test are indicated in table 5.1.

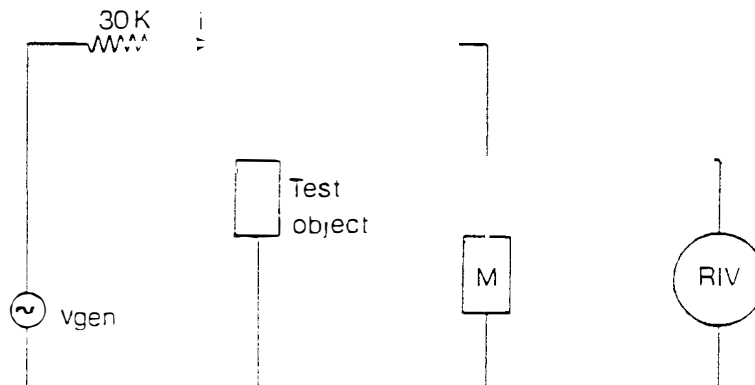


Figure 5.2 : The Measurement Termination Calibration Test Circuit

RIV Set Value (dB)	Vgen Source Voltage (mV 0-pk)	Calculated Value V_q (dB)
33	13.0	33.2
35	16.4	35.2
40	29.05	40.16
45	51.65	45.16
50	91.4	50.12
55	165.0	55.25
60	293.0	60.24
65	519.5	65.21
70	856.5	69.55
75	1210	74.57
80	2880	80.09
85	5125	85.09
90	8895	89.88
95	15800	94.87

Table 5.1 : The Measurement Termination Calibration Test Results

The procedure was to start with the signal generator output set to its lowest value, (10 mV) which gave a meter reading of about 31 dB. The voltage was then increased until the receiver reading was 33 dB. These values of V_{gen} and RIV were then recorded. The

voltage was then increased to give the next value of RIV as shown in the result table of table 5.1 and the new set of readings was recorded. This was repeated until the generator was at its highest output voltage. A second set of readings was then taken, for the same RIV values, as Vgen was wound down to its minimum value again.

Included in the result table are the calculated values (Vq) of the RIV voltage. These were calculated from equation 5.7 as follows.

Injected current i is given by,

$$i = V_{gen}/30 \text{ K}$$

Therefore, the voltage across the measurement termination,

$$V_q = i \times R_m \quad \text{where } R_m = \text{effective measurement resistance}$$

$$V_q = V_{gen} \times \frac{1 \text{ K} // 50}{30 \text{ K}} \quad = 1 \text{ K in parallel with } 50 \text{ ohm receiver input impedance}$$

$$= 47.62 \text{ ohm.}$$

(The impedance of the termination inductance is so high at 1 MHz that it can be neglected. If it is included the effective measurement impedance becomes the 47.62 ohms resistance in parallel with the 0.660 mH inductance. This gives a resultant impedance of 47.61 ohms with a phase angle of 0.06 degrees.)

Since the meter displays this voltage in decibels relative to 0.32 microvolt the readings Vq will be given by,

$$V_q = 20 \log(V_{gen} \times 47.62) \dots\dots\dots 5.6$$

$$\quad \quad \quad (0.32 \times 10^{-6} \text{ V} \times 30\text{K})$$

$$V_q = 20 \log(3.508 \times V_{gen}) \dots\dots\dots 5.7,$$

where Vgen is read off the signal generator display in millivolts

as the zero-to-peak value of the generated sine value. As can be seen from the results given in table 5.1, the measured values agreed to within 0.5 dB over the full range from 30 dB to 95 dB. Better accuracy could not be obtained since the receiver could only be read to an accuracy of 0.5 dB. From this result it was concluded that the accuracy of the current source was quite satisfactory to be used to calibrate the RIV test circuit.

5.3.2. The Main Circuit Calibration Tests

The main calibration test was done with the complete test circuit set up as in figure 5.1. The signal generator was again connected across the test object and a similar set of readings (of RIV as a function of V_{gen}) to those taken in the other calibration test were recorded.

The procedure again was to adjust V_{gen} to give pre-set values of RIV, with two readings being taken for each RIV value. Two runs of this test were done - one each with the line post and glass disc insulators connected as the test object. For the second test, on the glass disc, a 33 kilohm source resistor was used in place of the 30 kilohm one used in the other calibration tests. The results are recorded in tables 5.2 and 5.3 respectively, where the V_{gen} values are the averages of the two readings at each RIV setting.

In the tables the RIV values are the experimental readings and the V_q values were calculated. The calculation, as shown in the following, gave the standard CISPR RIV values for the known (calculated) value of injected current.

As before, the current i is given by,

$$i = V_{gen}/R_s \quad \text{where } R_s = \text{current source resistance (30 or 33 kilohms).}$$

Therefore, the CISPR value is given by,

$$\begin{aligned} V_q &= 20 \log[(i \times 300)/1 \times 10^{-6} \text{ V}] \text{ dB} \\ &= 20 \log[(V_{gen} \times 300)/(R_s \times 1 \times 10^{-6} \text{ V})] \end{aligned}$$

i.e. $V_q = 20 \log(212.1 \times 10^3 V_{gen}/R_s) \dots\dots\dots 5.8$

where V_{gen} is again the zero-to-peak generator voltage measured in millivolts.

RIV Set Value (dB)	Vgen Source Voltage (mV 0-pk)	Calculated Value Vq (dB)	Calibration Factor CF (dB)
15	1.705	20.80	5.80
20	3.22	26.32	6.32
25	5.83	31.48	6.48
30	10.40	36.50	6.50
35	18.5	41.51	6.51
40	32.55	46.41	6.41
45	58.15	51.45	6.45
50	99.5	56.15	6.15
55	179.0	61.22	6.22
60	315.5	66.14	6.14
65	561.5	71.15	6.15
70	996	76.13	6.13
75	1770	81.12	6.12
80	3250	86.40	6.40
85	5765	91.38	6.38
90	10165	96.30	6.30
94	16185	100.3	6.30

Table 5.2 : Line Post Insulator Calibration Test Results

Also in the tables are given the calibration factors (CF) calculated at each measurement point as the difference between the CISPR calculated values V_q and the actual meter readings RIV. The results gave average calibration factors of 6.3 dB and 5.8 dB respectively, for the line post and glass disc insulators. However, since the RN meter could not be read to greater accuracy than 0.5 dB for both insulator types, the factor was rounded off

to 6 dB. This is the value that will be used in subsequent chapters to correct the meter readings from the RIV tests, that are recorded in Appendix B.

RIV Set Value (dB)	Vgen Source Voltage (mV 0-pk)	Calculated Value Vq (dB)	Calibration Factor CF (dB)
33	12.45	38.89	5.89
35	15.75	40.94	5.94
40	27.95	45.92	5.92
45	49.65	50.91	5.91
50	88.2	55.90	5.90
55	158.5	60.99	5.99
60	281.5	65.98	5.98
65	499.5	70.96	5.96
70	827.5	75.35	5.35
75	1465	80.31	5.31
80	2775	85.85	5.85
85	4945	90.87	5.87
90	8670	95.75	5.75
95	15500	100.8	5.80

Table 5.3 : Glass Disc Insulator Calibration Test Results

As shown earlier in this chapter, the RNF part of the correction was 6.1 dB. Then since the total factor was only 6 dB, it shows that the circuit attenuation to the 1 MHz interference current was almost negligible. This shows that the filter F in particular must have been functioning correctly and suitably attenuating the desired measurement current component. It also indicates, as described in Chapter 4, that the circuit stray capacitance was suitably small and that the circuit mismatch between the receiver and measurement termination had no serious effect on the meter indication.

6. THE POLLUTION TEST PROCEDURES

This chapter describes how the clean fog test and RIV measurement techniques were combined in various test procedures to measure the RI from artificially polluted insulators in the laboratory. It begins with a section on the rationale behind the different test procedures investigated. It then describes how the effect of circuit background noise on the test results was assessed in a preliminary set of tests. The last two main sections systematically list and detail the specific procedures used for each individual test. They cover the dry state tests and the clean fog ones, done in the main investigation on the two different insulator types, both when clean and artificially polluted. Each section respectively covers the complete set of tests related to one insulator type.

6.1. Adaptation Of The IEC 437 RN Test Procedure

As described previously, since no applicable standard test exists, the aim of the investigation was to establish a suitable RI laboratory test procedure for polluted insulators. The starting point was IEC Publication 437, entitled "Radio Interference Tests on High-Voltage Insulators", which only covers the case of clean and dry insulators and excludes polluted and wet ones.

According to the IEC recommendation, the procedure entails mounting the insulator and applying the maximum test voltage for

5 minutes. The voltage is then stepped down to 30 % of this value, raised again in steps to the maximum value and finally stepped down to the 30 % value again. Readings of RIV are taken at each step voltage and the values recorded in the final decreasing run are taken as the RI characteristic of the insulator.[7].

If this method was applied directly in a clean fog artificial pollution test, the problem would be to determine when and how the fog should be applied in relation to the timing of the voltage steps, and the recording of the RIV readings. This problem arises from fundamental differences in the predominant RI producing mechanisms on a clean or dry insulator and on a wet and polluted one.

In the clean and dry insulator cases, RI is produced by partial electric discharges (corona) at areas of the insulator where the electric stress is sufficiently high. During these tests the insulator surface state is well defined and stable, i.e. it does not change during the test as a result of the applied test conditions. Therefore, the RI produced at any instant depends only on the test voltage across the insulator at that instant and not on the test conditions in the preceding test period. For this reason similar test conditions can be accurately repeated from one test run to another, irrespective of the voltage range to be covered. This makes it possible to precisely define the test procedure of IEC Publication 437 to provide valid and repeatable dry insulator RI data.

In the wet and polluted insulator situation, the RI production is

more complicated and variable. Although the same corona discharges may still occur, the predominant RI source is spark type discharges across dry bands on the insulator surface. As described earlier, in Chapter 2, the dry bands result from complex, transient interactions between the fog wetting the insulator and the drying effect of the resultant surface leakage current. Consequently the RI does not only depend on the instantaneous test conditions, i.e. the applied voltage and the wetting rate. It is further strongly influenced by how these conditions have been controlled in the preceding test duration.

Apart from the voltage and fog applications, the other factor which was expected to affect the clean fog test results, but which could not be so easily controlled, was the initial insulator surface temperature. In a steam-produced clean fog situation, insulator wetting can occur both by condensation and impingement. Therefore, the insulator surface temperature affects the wetting rate, as the condensation rate depends on the difference between the steam and the insulator surface temperatures.

Thus, if the steam has the same temperature for all tests, ideally they should each be started with the insulator surface at the same temperature. Although the surface temperature can be measured, with for example a thermocouple, it is more difficult to control, if it is not equal to room temperature. Thus, for each test, after the insulator had undergone its final drying period in the oven, it was first cooled down to room temperature before being mounted for a test. Although this temperature was not the same in all cases, this constraint did at least ensure

that the insulator surface was in thermal equilibrium with its ambient at the start of each test. For the line post insulator the initial temperature varied from 21.5 °C to 28 °C, and for the glass disc insulators from 14 °C to 24 °C.

To develop a suitable procedure for measuring RI characteristics of polluted insulators (RIV values that would depend only on pollution severity and voltage for any particular insulator type) two basic types of test procedure were investigated. These were both based on the IEC 437 method for dry insulators, but included variations to account for the not entirely predictable, transient nature of the RI produced by a wet, polluted insulator. This development was based on one main assumption - for given insulator pollution severity and applied voltage, there exists a defined maximum RI level that the insulator can generate. Whether this level is being attained depends primarily on the amount of moisture on the insulator surface. It was further assumed that, if the amount of moisture on a polluted insulator were to steadily increase, from an initially dry state, the insulator pollution layer would eventually become saturated. Saturated here implies that the application of further moisture would result in liquid, containing both some soluble and some insoluble components of the pollution solids, dripping off the insulator, i.e. the pollution would begin to be rinsed off the insulator.

If an unenergised, polluted insulator were subjected to sustained wetting this saturation and ensuing washing effect would result. If however, the insulator was energised at the same time to some high voltage, the result could be different. As the pollution layer absorbs moisture, its soluble components begin to dissolve

and form a conductive layer over the insulator. This permits a resistive leakage current to flow through the layer and the resultant heating produces a drying effect in opposition to the wetting. Thus, for washing to eventually occur, the wetting rate needs to be high enough to overcome the maximum heating rate that can be produced. This maximum heating will arise at maximum surface conductivity (as the leakage current will then be maximum). This in turn is expected when the insulator surface is near saturation.

By this reasoning, if sufficiently rapid wetting is applied to an initially dry, polluted insulator for long enough, with the insulator energised at a constant voltage, "washing" must eventually result. In that case, at some stage during the process, the maximum attainable RIV value (that was assumed to exist) must have been attained since all possible levels of wetness between the dry and saturated states have been covered. This was the rationale for adopting the first test procedure labeled the "constant voltage" or "prolonged" test procedure.

For this test procedure, a pre-polluted and initially dry insulator was energised at constant voltage for the whole test duration. Then, as the fog was applied at the maximum rate, the RIV level was monitored against time from before the first fog application to the dry insulator until the test end. The RIV was first expected to increase in time from a low value, to a maximum as the insulator was wetted. Later it should have decreased again as, either "washing" began or the leakage current heating dried the insulator faster than the steam could wet it, if the wetting rate was too low. The idea was that the wetting rate should

always be high enough to eventually cause the washing condition to arise. Then, if for fixed voltage and pollution severity, in a number of similar such test runs, the maximum RIV value recorded in time was found to be repeatable, it would be assumed to be characteristic of that voltage level and pollution severity.

This test procedure on its own could provide all the data necessary if such characteristic values are found. However in practice, the procedure was found to be very time consuming which would limit its usefulness. Each test run, which it was found could last for over 90 minutes, only provided one RIV value, pertinent to only one particular voltage for the given pollution severity. This could often be sufficient data, since an insulator may only need to be tested at its proposed working voltage or specific creepage, i.e. only one characteristic RIV value is needed for each insulator at each pollution severity. However for this information to have wider use, RIV variation with specific creepage for the different insulators is also required. This information would be useful to indicate to what extent the variation of specific creepage can be used to reduce excessive interference levels produced by polluted insulators. Thus it was proposed to develop a second procedure whereby, in a single test run, of similar duration to a constant voltage test, a more complete set of RIV versus voltage values would be obtained. Given the uncertainty about how RI may vary with local meteorological conditions, eg temperature and RH, to obtain a complete curve under unrecorded but unchanged conditions may also be advantageous. Thus a second procedure, labeled the "accelerated procedure", was proposed.

The rationale for this second procedure was based on the assumption that the curve of RIV versus time (for a test with sufficiently high wetting for eventual washing) would be flat around the RIV maximum. This was observed to be the case in many of the prolonged procedure tests. They showed that most often the RIV would increase rapidly from a very low level, as the initially dry insulator became wet. The curve would then level off at around or just below its maximum value. After some very variable length of time, the RIV would then decrease again but at a much slower rate than the initial increase.

This could permit a number of characteristic RIV values to be determined in one test, by varying the voltage, while the insulator surface conditions were optimal. Care would need to be taken to ensure readings were taken before the decreasing RIV phenomenon due to washing was significantly advanced.

For this procedure the test insulator was first placed in the fog chamber in the dry state. The wetting steam was then applied and a pre-conditioning period would follow before any readings were recorded. Various pre-conditioning procedures, which involved using different (fixed) level applications of wetting and voltage to the test insulator during this time, were tried. At the end of the pre-conditioning, the insulator would be energised at the first desired test voltage. From that moment on the RIV was monitored against time. For the remaining test period the voltage was varied over a given range, with RIV readings being regularly recorded against time. The voltage was varied in a step manner, with each voltage step value being held for a pre-determined length of time. This step time was also varied between runs to

try and establish an optimum length. If it was made too short, the characteristic RI value might not be read, as the insulator could still be in a transient stage from the previous step. If the steps were too long, there would be no advantage over the prolonged test. The validity of this test was to be judged by comparing the results it produced with the RIV characteristics obtained by the prolonged procedure.

In a total of 153 individual test runs, different versions of the two test procedures were investigated. These included both wet and dry state tests on both clean and polluted insulators. The exact details of the procedure adopted for each individual test run are given in the last two sections of this chapter. The detailed results of each test are then listed in Appendix B. For the wet tests they are recorded as tables of applied voltage and RIV readings with the time after the beginning of the test at which each reading was taken. For the dry tests the times are not recorded and the tables just give the voltage and measured RIV values. The voltage values were set according to the transformer primary voltage, with the corresponding hv being obtained from the graph or table of Appendix C. The RIV values were read directly off the noise meter connected across the measurement resistive termination.

The RIV meter indications were seldom very steady, but instead tended to have large instantaneous fluctuations. Where these variations occurred, readings were taken by observing the needle deflection for some 5 to 10 seconds around the reading instant. The recorded value was then either given as the two extremes of the observed deflection or as an estimated middle reading with

limits of the variations noted from this value.

The RIV values were recorded assuming that the total measured RIV was being produced by the insulator as a result of the applied insulator pollution conditions. It was possible however, that other noise sources - background noise sources - could affect the readings. Therefore, before the main set of polluted insulator tests were run, a preliminary set of background noise tests were done. These are described in the next section before the last two sections that give the precise details of the main pollution tests.

6.2. Preliminary Background Noise Level Measurements

There are two possible sources of background interference that the noise meter might measure in addition to, but independent of, the interference it is desired to measure, i.e. that produced by the test object. These are sources external to and sources internal to the energised test circuit (other than from the test object itself). Examples of external sources would include any transmitted or other rf signals from whatever source, incident on the test circuit. Internal sources would occur at localised areas of enhanced electric field on the test circuit connections, (such as may occur at loose connections or sharp points) where corona or even complete electric discharges result. Those noise sources would be detrimental in the test circuit if they combined with the RIV produced by the test object and caused unacceptably high errors in the readings. This section shows how this effect on the RIV readings was assessed and found to be negligible.

The assumption is made that the RIV measuring instrument has a rms type response and that the background noise signal is independent of the required signal to be measured. Then, by simple algebra, it can be shown that for a 10 dB or greater difference between these 2 signals (if they could be measured independently) when measured together, the measurement error due to the background signal will be 0.41 dB or smaller.

For the lowest measured signal of about 10 dB, provided the background level was at least 10 dB lower, i.e. ≤ 0 dB, the maximum background noise error would be 4 %. Considering the nature of the experiments, this was an acceptable degree of error. In most cases where the measured signal was greater than 10 dB, up to above 100 dB, (provided the 10 dB difference was achieved) the 0.41 dB error would represent a much lower percentage than this 4 %.

In the course of the investigation, the background noise levels were checked by energising the circuit without any test object connected and noting the RIV indication on the receiver. A reading was first taken of the ambient or external background level, i.e. with the circuit test supply off. The supply was then switched on and further RIV observations were made, with the voltage initially set to zero and then as it was increased through the test range to 30 kV.

With the final arrangement of the test circuit, under normal test ambient conditions, all background interference was found to be too low to measure on the available noise meter, i.e. below 0 dB uncorrected meter indication or 6 dB/microvolt 300 ohms. This was

checked both with and without the fog condition being applied. It was however, only achieved after various precautions had been taken to eliminate internal circuit background noise sources. These included using large diameter hv connectors in the circuit and ensuring all hv connections were firmly secured and shielded where they presented sharp points. Occasional bursts of background noise of up to 20 dB and higher were observed but these could be linked to temporary outside disturbances. In particular nearby thunder activity and operation of the high voltage impulse test set in the adjoining open air laboratory were seen to cause these high background levels in the test circuit.

Thus, in the subsequent tests, with the test insulator mounted in the circuit, wherever readings of 16 dB/microvolt 300 ohms or greater were recorded, the error due to circuit background noise would have been less than 0.41 dB. This implies a maximum background noise error of 3 % which as mentioned above, was within acceptable limits. Therefore, no correction or any other allowance, needs to be made to any of the RIV values recorded in the main RIV tests, to account for the effects of circuit background noise. Instead, any measurable levels of RIV recorded in the tests could be confidently quoted as coming from either the test insulator itself or from the insulator connections to the hv conductor. The remaining two sections of this chapter now respectively describe the line post and glass disc insulator test procedures used to obtain the results as listed in Appendix B.

6.3. The Line Post Insulator Tests

A total of 67 test runs were carried out on the EP303 line post insulator. These covered surface conditions from clean to artificially polluted with a 40:80 pollution slurry, equivalent to a heavy pollution ESDD level. The same insulator unit was used in every one of these runs as it was the only undamaged unit available. The tests were done using variations of the constant and variable voltage procedures, and using the two different methods of connecting the hv conductor to the insulator.

The first 40 test runs used the moulded tie wire connection. These ties had rubber coverings over the section that was in contact with the insulator. When discharge activity occurred during these tests, it was found to cause burn marks through the rubber at points where the discharges were initiated. For this reason and because the continued re-use of a tie tended to deform its shape, no tie was used for more than 6 tests before it was replaced. For the remaining 27 tests, the other connection method was used, whereby the conductor was rested on top of the insulator. In these cases, the surface of the conductor was smoothed with sand paper before each test, to eliminate any marks on the conductor that might initiate coronas, and to give the best contact possible with this method.

These tests were done chronologically in the 4 stages. The first stage consisted of stepped procedure tests, the next two of constant voltage ones and the final stage was done using stepped tests again. The procedures for each of these phases are outlined below.

6.3.1. Line Post Insulator Accelerated Tests 1 - 5

For these a stepped voltage procedure similar to the IEC 437 method was used. The procedure is illustrated in figure 6.1. Initially the steam generator was set to warm up at maximum power, while the steam was delivered outside the laboratory and not into the tent. During this period a set of readings of the dry insulator RIV was recorded, as the voltage was stepped down from 13.5 kV to 1.5 kV in 1.5 kV steps. The regulator was then wound up to 13.5 kV again and the power switched off.

Once the steamer had been on for 20 to 25 minutes, the steam was then switched in to the tent with the unit still on maximum power. After 20 minutes of fog application, the steamer was switched to its lowest power level of 2.5 kW. Five minutes later the voltage was switched back on at 13.5 kV.

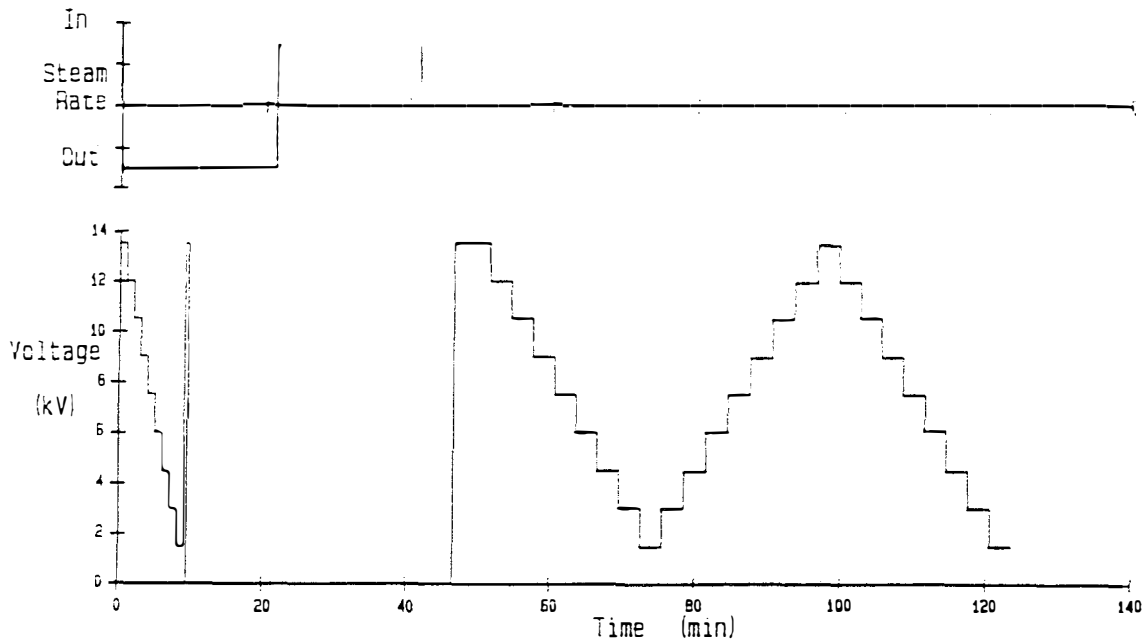


Figure 6.1 : The Stepped Procedure Of EP303 Tests 1 - 5

The IEC procedure was then followed, where the voltage was held constant at this value for 5 minutes and then stepped down, up, and down again through the voltage range. As in the initial dry run, the voltage steps were 1.5 kV, and 8 steps down to 1.5 kV were used. Each step voltage was held for about 3 minutes, except for the maximum value at the end of the increasing run, which was held for 5 minutes again. At least two readings were taken at each voltage step - one at the beginning of the three minute period and one at the end. In some cases further readings were taken in between the two end readings.

Of the five tests, three were done with a 40:5 pollution severity and the other two with a 40:20 severity. Although the basic procedure was the same for all five tests, in the last three slight variations in terms of voltage range, step size and step time were used. Test 3 also differed in that it was done as a re-run of test 2 without re-applying a new pollution layer. At the end of the second test procedure the fog generation was stopped. After 30 minutes, when the insulator had partially dried, the third test procedure was carried out. For this reason no dry readings were recorded in test 3.

In Appendix B the initial dry state results are recorded in separate tables to the wet state results. In the wet state result tables, the time zeroes have been taken as the moment when the power was first applied to the already wet insulator and not as the zero shown in figure 6.1.

6.3.2. Line Post Insulator Constant Voltage Tests 6 - 40

For these tests the constant voltage and constant fog rate procedure was used. This general procedure is outlined in figure 6.2. It gave values of RIV for the polluted insulator when dry at varied voltage and when wet at fixed voltage. Timing was started when the circuit was switched on at zero volts, once the insulator had been mounted in the chamber, with the steamer off. The voltage was raised to 22.5 kV and the steamer then set to maximum power, but with the steam being directed outside the laboratory.

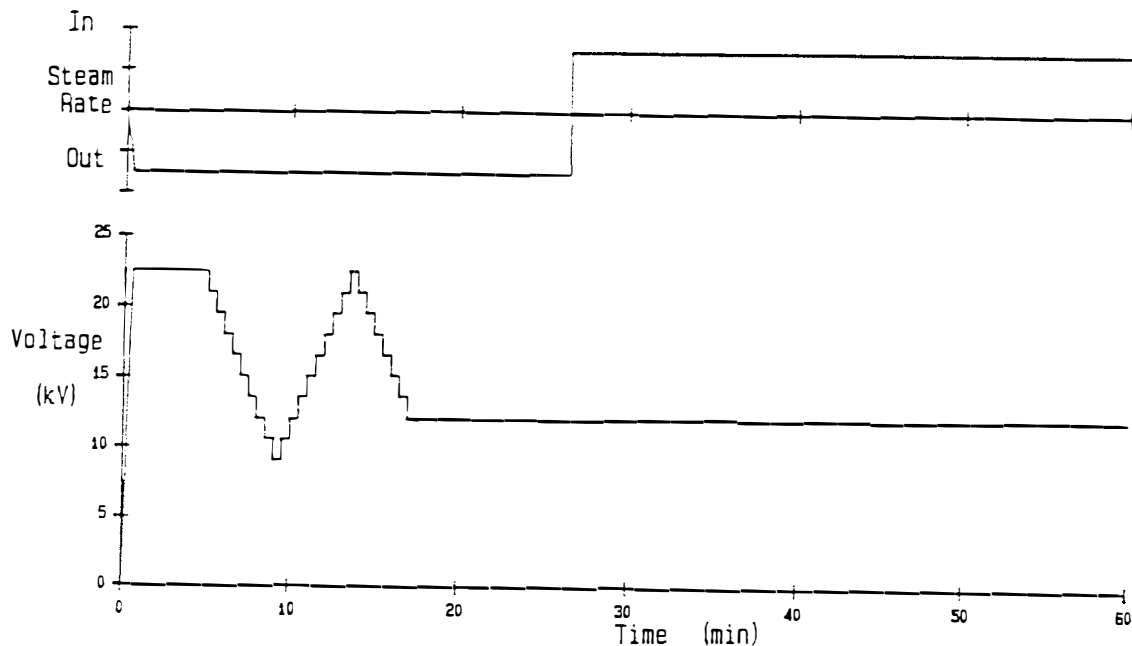


Figure 6.2 : The Prolonged Procedure Of EP303 Tests 6 - 40

The voltage was held at 22.5 kV for approximately 5 minutes, during which time the RIV was monitored on the RN meter. The voltage was then lowered in 1.5 kV steps (in no particular time) taking one reading at each step, until the RIV reading had fallen to the circuit unenergised background level, i.e. a meter indication of less than 10 dB. The voltage was then similarly

stepped back up to 22.5 kV and then down to the required test voltage, which was always less than 22.5 kV, except for one clean state run done at 25.5 kV. From thereon the voltage was held constant at that value till the end of the test.

After this constant voltage had been held for 5 minutes, the steamer was switched to deliver steam into the tent at its maximum rate. For the first 11 runs this time was anywhere between 20 and 60 minutes after the test start, depending on how long it took to obtain the dry state readings. For the rest of the tests however, once the procedure had been well established, this time was invariably 26.5 minutes after the start. The maximum fog application was also maintained for the duration of the test. From the moment the final test voltage level was set, till the end of the run, RIV readings were recorded, usually at half minute intervals, but occasionally at 1 minute or longer time lapses. The temperature inside the tent was also read at the time of the fog application and at the end of the test. It was also noted at other times during the run, when the tent was entered to make visual observations of the surface discharge state of the test insulator.

In all tests the RIV level was seen to rise from the initial level at fog application to a maximum value in 10 to 20 minutes. This maximum was not always well defined as the meter indication tended to be very variable especially when there was intense discharge activity occurring on the insulator. The level would then, after a variable length of time, fall off again. A test run would be stopped any time after it was judged that the maximum RIV level had been passed. Thus, the total test time, between

switching the circuit on and ending the test, was typically anywhere between 1 and 2 hours.

There were occasional deviations from this procedure as can be seen in the detailed results in Appendix B. These deviations were either due to some interruption during the test or else occurred where, after the main test run was complete, further readings at different voltages were also recorded.

The pollution severities and test voltages for the 35 tests in this batch were as indicated in table 6.1. Although the tests are numbered 6 to 40 they were not necessarily performed in that order.

Test Number	Severity	Voltage (kV)
6	40:5	9.0
7 - 9	40:5	18.0
10 - 12	40:20	9.0
13 - 16	40:20	12.0
17 - 20	40:20	15.0
21 - 25	40:20	18.0
26 - 28	40:40	9.0
29 - 32	40:40	12.0
33	40:40	15.0
34	40:40	16.5
35 - 36	40:40	18.0
37 - 38	Clean	15.0
39	Clean	18.0
40	Clean	22.5

Table 6.1 : Pollution Severities
And Voltages Of EP303
Tests 6 - 40

6.3.3. Line Post Insulator Constant Voltage Tests 41 - 62

Here the test procedure was very similar to that for the previous batch of tests, 6 to 40. A constant voltage and fog application procedure was still used, only the insulator surface pre-conditioning differed and the conductor to insulator connecting tie wire was not used. Instead the alternative connection was used, where the conductor was rested on top of the insulator in its tie groove.

As shown in figure 6.3, the steamer was initially switched on to its maximum power, with the steam delivered outside the laboratory. This was done before the insulator was even mounted. The timing was begun when the steamer was first switched on. Once the insulator had then been mounted in the chamber, the voltage was switched on at zero. The time to voltage switch on was variable from 7 to 30 minutes but was most often 10 minutes. The voltage was then raised as rapidly as possible to 22.5 kV and thereafter stepped down, at half minute intervals, by 1.5 kV to the required test voltage. At each step level a dry state RIV reading was recorded. Once the test voltage had been set, the steam was switched into the tent and the test proceeded as for tests 6 to 40. The pollution severities and voltage levels for these 21 tests were as shown in table 6.2.

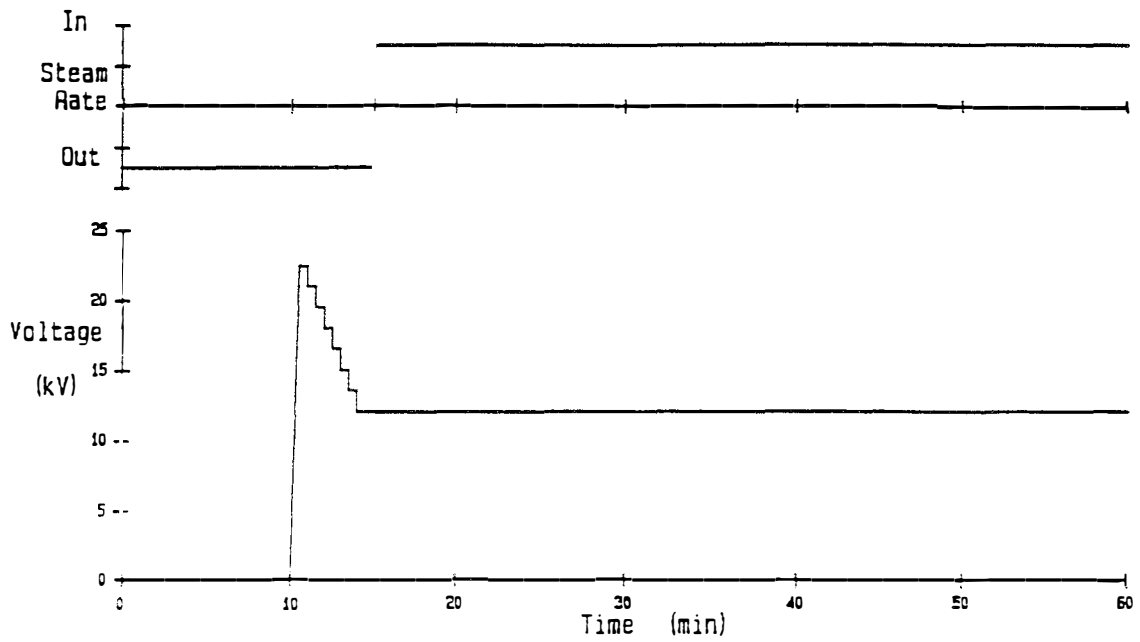


Figure 6.3 : The Prolonged Procedure Of Tests 41 - 62

Test Number	Severity	Voltage (kV)
41	40:5	1.5
42 - 43	40:5	3.0
44	40:5	4.5
45	40:5	6.0
46	40:5	7.5
47	40:5	18.0
48	40:20	1.5
49	40:20	3.0
50	40:20	7.5
51 - 52	40:40	1.5
53	40:40	2.3
54 - 55	40:40	9.0
56	40:40	18.0
57	40:80	1.5
58	40:80	3.0
59	40:80	18.0
60	40:10	3.0
61 - 62	Clean	22.5

Table 6.2 : Pollution Severities
And Voltages Of EP303
Tests 41 - 62

6.3.4. Line Post Insulator Accelerated Tests 63 - 67

For the last five tests, a reduced fog generation rate and a stepped voltage procedure was used. The procedure is illustrated in figure 6.4. Initially, while the power to the test circuit was off, the steamer was warmed up for 10 minutes at maximum boiling rate. After 10 minutes the steam was introduced to the tent for a further 15 minutes at full power, with the voltage still off. Thus, no dry state readings were taken in these tests. The steamer was then switched to its lowest power level of 2.5 kW and left there for the rest of the test.

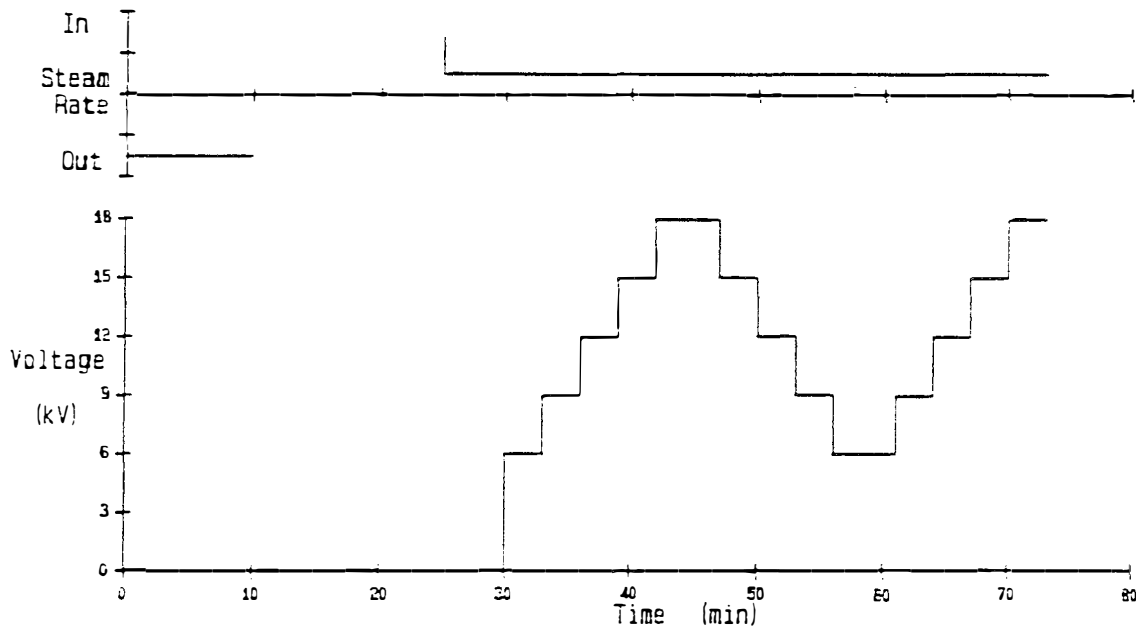


Figure 6.4 : The Stepped Procedure Of EP303 Tests 63 - 67

The circuit power was switched on at zero voltage 5 minutes after the steamer was set to 2.5 kW. The voltage was then rapidly raised to 6 kV and thereafter increased to 18 kV in 3 kV steps at three minute intervals. The top 18 kV level was held constant for 5 minutes before being reduced again to the initial 6 kV level, in similar size steps. It was then held there for a further 5 to 6 minutes, before being increased in 3 minute steps to 18 kV

again. At each step where the voltage was held constant for 3 to 6 minutes, RIV readings were taken at half minute intervals. The first two of these tests were done with 40:5 pollution severities, while the other three were performed with 40:10, 40:20 and 40:80 severities respectively.

6.4. The Glass Disc Insulator Tests

These tests were only done after the line post insulator tests had been completed and made use of the same basic procedures. As with the line post insulator, the glass discs were only mounted in the test chamber in either their clean or artificially polluted state, once they had reached room temperature after the final oven drying. For the glass disc tests however, the steamer was kept on maximum power for the entire duration of all tests. Both the constant and stepped voltage procedures were again used for the wet state tests.

One major difference for the glass disc tests however, was in the initial period before the steam was admitted to the tent. In the case of the line post tests, since only one unit was available for testing, the minimum time between any two test runs was about 2 hours. Thus, by the time the insulator was mounted in the tent for the next test, all the steam from the previous one had either condensed on the tent walls and floor or else it had moved out of the tent. As a result, when the insulator was energised before any steam was re-admitted to the tent, the insulator was still completely dry.

For the glass disc tests, three units were used, although only in two clean, dry tests were more than one unit ever tested together. Thus if, for example, all three units were ready to be tested at the same time, one test could follow immediately after the other. In practice there was usually approximately 15 minutes between any two such tests. Thus, when subsequent tests were carried out after the first one, the tent atmosphere was already quite wet at the start of the later tests. This meant that, unlike for the line post tests, initial readings before the fog application could not be used as dry state test data. It also resulted in the wet test time being shorter as it took much less time for the fog to saturate the chamber atmosphere again when the steam was re-admitted.

Using the three discs, 86 test runs were done covering a range of pollution severities from clean up to 40:80, i.e. heavy pollution, and a range of voltages from 1.5 kV to 22.5 kV. As for the line post tests, the detailed results are given in Appendix B. Here the main points of the different test procedures are given. The procedures followed for these tests are also grouped into 4 stages. The first stage consisted of only clean state runs, while the second and final stages both used stepped voltage procedures. The third stage consisted of a series of constant voltage type tests on polluted and wet insulators.

6.4.1. Glass Disc Insulator Dry And Clean State Tests 1 - 8

These were all done with the insulator washed clean and the first seven were only run in the dry state. Only in the last one was steam introduced into the tent. The first four clean dry state

tests were done on single discs with the voltage stepped through the range 7.5 kV to 28.5 kV, using the IEC 437 type procedure. The remaining three dry tests followed a similar procedure only they each used strings of two disc units. For the one clean and wet test, a single disc was used and the voltage was held constant at 22.5 kV for the duration of the wetting condition.

6.4.2. Glass Disc Insulator Accelerated Tests 9 - 18

These tests were done using step type procedures, over various voltage ranges. In all cases the procedure was to switch the steam into the tent (which was in most cases already at quite high humidity from a previous test) at maximum power and immediately thereafter to switch the voltage on and rapidly raise it to 12.0 kV, except for test 14 which started at 3 kV. This initial value was held for approximately 15 minutes (varied between 13 minutes and 20 minutes) before the step procedures were begun. These were not the same for all 10 tests.

The first five tests, i.e. tests 9 - 13, were all done at a 40:10 severity and followed exactly the same procedures. The voltage was first stepped from its initial value at 12 kV up to 15.0 kV. It was then stepped down to 6 kV and then back up to 15 kV again in 1.5 kV steps. All step durations were between 2 and 3 minutes, with at least three RIV readings being taken at each step.

Test 14 was also a 40:10 severity one. The initial voltage however, was set to 3 kV after which it was increased in 3 minute and 3 kV steps to 9 kV. It was then stepped down to 3 kV again before going up to 22.5 kV.

Of the remaining 4 tests, 2 each used 40:20 and 40:80 severities. Using various voltage step sizes, they covered the range from the initial 12 kV down to 3 kV. The step times were also varied between 3 minutes and 10 minutes. The precise details of all these tests can be seen from the result tables of Appendix B.

6.4.3. Glass Disc Insulator Constant Voltage Tests 19 - 82

These tests all used a constant voltage procedure, with the steamer also constant at its maximum heating rate for the test duration. Timing began with the insulator already mounted when the steamer was switched on to maximum power, but with the steam being fed outside the tent. The test voltage was then switched on at zero volts and quickly increased to the required test level where it remained for the constant voltage test duration.

At some time later, which varied from test to test, the steam was then switched into the tent. RIV readings were taken at various intervals (usually 1 or 2 minutes) from the time the test voltage was first switched on until, as for the line post constant voltage tests, it was judged that the maximum RIV for the particular test had been recorded. These test times however, were usually much shorter than the 1 to 2 hours taken for the line post tests.

Occasional variations of this procedure, as shown in Appendix B, were also used. These consisted of taking further readings at step voltage levels after the main constant voltage test readings had been completed. The pollution severities and voltages for the 64 tests in this batch covered the ranges from 40:5 to 40:80 and

from 3 kV to 15 kV respectively, as indicated in table 6.3.

Test Number	Severity	Voltage (kV)	Test Number	Severity	Voltage (kV)
19 - 21	40:5	3.0	54	40:40	3.0
22 - 24	40:5	6.0	55 - 57	40:40	6.0
25 - 27	40:5	9.0	58 - 62	40:40	9.0
28 - 30	40:5	12.0	63 - 66	40:40	12.0
31 - 33	40:5	15.0	67 - 72	40:80	3.0
34 - 35	40:20	3.0	73 - 77	40:80	6.0
36 - 38	40:20	6.0	78 - 80	40:80	12.0
39 - 46	40:20	9.0	81	40:10	9.0
47 - 51	40:20	12.0	82	40:10	12.0
52 - 53	40:20	15.0			

Table 6.3 : Pollution Severities And Voltages Of
U70BL Tests 19 - 82

6.4.4. Glass Disc Insulator Accelerated Tests 83 - 86

These 4 tests were all run to identical stepped voltage procedures with a constant steam rate. The procedure is illustrated in figure 6.5. At the start of each test, the steamer was already warmed up from a previous test. Timing was begun, when the insulator had been mounted in the fog chamber, at the moment the steamer was switched on at maximum power setting. The steam was initially directed outside the laboratory. Immediately after switching the steamer on, the voltage was also switched on and raised to 3 kV.

After 15 minutes the steam was re-directed into the tent. The voltage was held at 3 kV for a further 15 minutes before the step procedure was started. The voltage was first stepped up in 3 kV levels to 21 kV at 6 minute intervals, after which it was stepped back down to 3 kV in 4 minute intervals. Readings of the

interference level were taken at 2 minute intervals throughout the test duration. One test was done at each of the 4 severities 40:5, 40:10, 40:20 and 40:40.

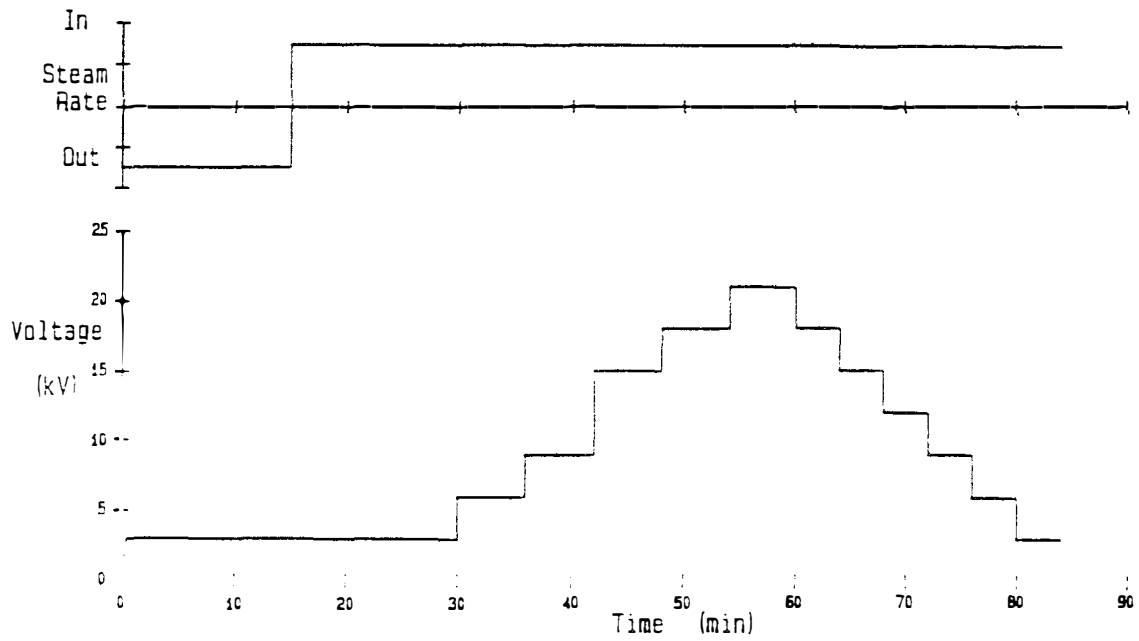


Figure 6.5 : The Stepped Procedure Of U70BL Tests 83 - 86

7. ANALYSIS AND DISCUSSION OF RESULTS

In this chapter the results of the tests described in Chapter 6 are analysed and discussed. Initially some observations are noted on the general nature of the results and some of their limitations are mentioned. The remaining main sections then deal with the dry and wet state results in greater detail. The first of these sections covers the dry state tests, while the prolonged and accelerated procedure tests are covered in the other two main sections. Within each of these three sections the line post and glass disc insulators are treated separately, although some comparisons between the two are made.

7.1. General Observations

The tests were done on the two insulator types over a range of line to ground test voltages from 1.5 kV to 22.5 kV. This corresponds to a range of specific creepage from 202 mm/kV to 13.5 mm/kV for the line post insulator and 108 mm/kV to 7.2 mm/kV for the glass disc insulator. These values were calculated according to the IEC Publication 815 definition of specific creepage which was given previously as equation 5.4.

IEC Publication 815 includes recommendations for the selection of line and station insulators to be used on three phase systems up to 525 kV in polluted environments. It recommends using specific creepages ranging from 16 mm/kV to 31 mm/kV to cover from light to very heavy pollution conditions. Thus, the range of specific

creepages investigated in this study greatly exceeds that normally used in practice. The results over the extended ranges are still of interest however, to add to the general understanding of the phenomenon of polluted insulator RI.

It was shown in section 2.2.5 how the transient interactive wetting and drying processes are expected to result in an inverted U-shaped curve, for the variation of RIV with time for a polluted insulator, while being energised and wetted at constant levels. Theoretically, the maximum RIV value of the U-curve is representative of a particular test, if at the end of the test, insulator washing has occurred. As washing occurs conductive material is removed from the insulator surface and as a result its conductivity should decrease. Thus, when washing begins, the state of maximum surface conductivity, i.e. also maximum RIV, should have been reached. This was demonstrated in 1972 by the Institut de Recherche de l'Hydro-Quebec (IREQ) in a series of experiments done to investigate the fog parameters of artificial pollution tests [44]. They measured the surface resistivity of polluted insulators while being wetted in a steam fog chamber.

If washing has not occurred, then either the test has not been run long enough for the fog to saturate the pollution layer, or the leakage current drying exceeds the applied fog wetting. In the second case, the excessive drying will prevent the surface from becoming saturated even with prolonged wetting. Then, the maximum possible conductivity (and RIV) for that pollution severity will not be reached. Thus, the maximum value recorded in such tests, will not be characteristic of the given test ESDD severity as it will also depend on the wetting rate.

In the interference tests of this study, however, even when they were run until washing was observed, a corresponding decrease in RIV (for constant voltage) was not always noted. Furthermore, in the flat regions of the U-curves and in the initial increase of the RIV, the readings did not follow an even, smooth curve. Instead, although the long term trend was to follow the U-shape, the instantaneous values tended to be very variable and unsteady.

The fact that no RIV decrease had occurred by the end of some tests, when washing was observed, was probably because those runs were terminated at the first sign of washing. This was taken to be when the first water droplets were seen dripping off the insulator shed edges. At this stage it is likely that, although the solid layer is saturated, insufficient conductive solution has been washed off to affect the insulator surface conductivity. The RIV is then also still in its flat, maximum region.

In those tests that ran until the RIV decreased, the time for which the maximum level was maintained was extremely variable. This variation however, did not seem to be related to either of the two test parameters of pollution severity or voltage. It could have been related to the steam rate, which may have varied between tests. This rate was not actually measured, but it was attempted to keep it constant by using the same heater power setting on the steam generator for all similar tests.

The variability of the instantaneous RIV values was noticed at all voltages and severities, although it was particularly marked at the higher voltages and severities. In these cases large variations are expected due to the higher values of leakage

current that flow. A higher leakage current causes greater drying on the surface and so wider dry bands can be expected. The overall result is a far more violent and variable interaction of the various processes, leading to extremely variable leakage current and hence RIV. This agrees with findings published by Bernadelli in 1972 [45]. He found that in fog tests on polluted insulators, there was usually a basic level of interference about which there were frequent, rapid fluctuations.

The effect of leakage current drying was well demonstrated in some tests, where it was observed that the RIV would initially have a fairly steady value. A short period of intense discharge activity would then suddenly occur, as indicated by the audible and visible effects of the discharges as well as sudden, large, variable and erratic increases in the RIV. This activity would then abruptly cease and the RIV would decrease by 15 to 20 dB below the initial level. Visual observations at these times, showed much larger dry areas on the insulator surfaces than when a more steady RIV level prevailed. This would be due to the excessive heating of the sudden large discharge currents. With these dry bands being too wide for significant leakage current to flow, the insulator then gradually becomes wet again and the discharge activity builds up once more as the dry band sizes decrease.

In some cases the discharge activity was high enough to cause a flashover on the test insulator. Table 7.1 shows the voltages and pollution severities at which this occurred. It shows the lowest voltage at which the line post insulator broke down was 18 kV, whereas it is intended for use at 12.7 kV (22 kV system voltage).

The glass disc unit however, flashed over at 12 kV for 40:40 and 40:80 severities. This is equivalent to 13.5 mm/kV specific creepage and a moderate to heavy pollution condition. According to IEC 815 such pollution levels (medium to heavy) would require specific creepages of at least 20 mm/kV [43].

Test Number	Pollution Severity	Flashover Voltage (kV)	
EP303	20	40:20	18
	28	40:40	18
	34	40:40	18
	59	40:80	19.5
U70BL	10	40:10	15
	17	40:80	12
	"	"	12.75
	"	"	13.5
	18	40:80	12
	52	40:20	15
	53	40:20	15
	54	40:40	14
	63	40:40	12
	78	40:80	12
	80	40:80	12
	86	40:40	18

Table 7.1 : Summary Of Insulator Flashovers

This limited amount of flashover data indicates, that the line post RIV values, at 18 kV and above for severities of 40:20 and higher, may not be very reliable since they are recorded in regions where unstable discharge activity and even flashover is expected to occur. Furthermore, these results would have no real practical application, since the 18 kV test voltage represents a higher system voltage than would be used in practice. For the glass disc tests the data recorded in 40:80 and 40:40 tests at 12 kV and above and in 40:20 tests at 15 kV and higher have similar limitations.

In the rest of this chapter, the RIV results of the line post and glass disc insulator tests are presented in more specific detail. The dry case tests are discussed first, followed by the two types of polluted and wet tests. In each of these sections the different insulators are considered separately.

It should be noted that the results of all the tests are recorded in Appendix B. The RIV values given there, are the uncorrected values read directly off the noise meter display. All the RIV values tabulated and discussed in this chapter and in Chapter 8, on the other hand, include the 6 dB correction factor that applies according to Chapter 5. Thus, they are corrected CISPR values, representing the RIV measured across a 300 ohm resistance and expressed in decibels referenced to 1 microvolt.

7.2. Dry State Tests

An insulator while dry whether polluted or not, and while clean but wet, at normal operating voltage stresses is not expected to have any significant surface leakage current flowing, as its surface conductivity remains low. Thus, any RI measured in these situations, would be from corona discharges on metal fittings, rather than from the insulator's creepage surface. Therefore, the RIV levels recorded in the dry tests and the wet but clean tests should, for any particular test voltage, be well defined, constant levels that are much lower than the expected levels of the polluted, wet tests. This was the general trend observed. In some of the dry tests, the RIV values were even too low to be accurately measured with the given equipment.

7.2.1. Line Post Insulator Dry Test Results

In the line post insulator tests, nominally dry state readings were taken in the first 5 accelerated tests, as well as at the start of the 57 prolonged procedure tests. Since it is assumed that in the dry state the RIV is time invariant and independent of any solid deposits on the insulator surface, the results of all the dry tests were treated together with no distinction being made as to the test pollution severity. These results have been summed up in table 7.2 of dry state RIV versus voltage. In the table the averages and the maxima of all the readings taken at each voltage, for both decreasing and increasing voltage runs, are given. They were derived from the results recorded in sections B.1.1 and B.1.3 of Appendix B. All values below 10 dB in Appendix B were neglected. These low values are equivalent to the ambient background noise level and could not be accurately measured with the available equipment.

The standard deviations of the average values indicate a very wide dispersion of readings at each voltage level. The standard deviations range from 18.1 % to 30.3 % with an average value of 26.1 %. The wide spread of readings could be accounted for by the fact that the atmosphere may not have been completely dry in all these tests. This follows from the results presented in a summary of all CISPR's findings on polluted insulator RI [28]. The paper shows that, although the exact RIV behaviour varies with insulator type, for relative humidity (RH) between 20 % and about 50 %, the RIV from both clean and polluted insulators, tends to decrease. Decreases of 30 dB and over are reported for some cases.

Voltage (kV)	RIV (dB/ μ V/300 Ω)			
	Average \pm Standard Deviation (%)		Maximum	
	Up	Down	Up	Down
22.5	41.9 \pm 25.5	46.0 \pm 23.5	56	64
21.0	40.3 \pm 27.7	39.5 \pm 28.3	58	56
19.5	38.2 \pm 28.6	38.9 \pm 25.7	53	53
18.0	37.2 \pm 26.6	37.3 \pm 25.3	49.5	52.5
16.5	35.7 \pm 25.8	33.6 \pm 26.9	48.5	47.5
15.0	32.1 \pm 26.6	31.4 \pm 26.8	44.5	46.5
13.5	29.3 \pm 30.3	27.0 \pm 26.6	42.5	42.5
12.0	23.7 \pm 23.7	23.4 \pm 26.0	33.5	36
10.5	21.8 \pm 18.1	21.0 \pm 23.7	30.5	31
9.0			26.5	25

Table 7.2 : EP303 Dry State RIV Versus Voltage

Thus, if the RH was in this range during the dry tests, it could account for the very low values that were recorded as compared with the maximum values at each voltage. The CISPR paper also shows that, above about 60 % RH the RIV can increase very rapidly again as the insulator is then becoming quite wet. It is unlikely however, that any of the "dry" readings were taken at this high RH. At all voltages, the maximum dry RIV values recorded were at least 30 dB lower than the polluted and wet state values, that are presented in the next section.

The values from table 7.2 are plotted in the graph of figure 7.1. In the graph distinction is made between increasing and decreasing voltage values. For both the maximum and average value curves, over the entire voltage range, except for at the 22.5 kV point, both the up and the down values agree to within 3 dB with neither being consistently higher. The curves show the RIV increasing over the entire range of applied voltage. However, since this EP303 insulator is specifically designed to operate at

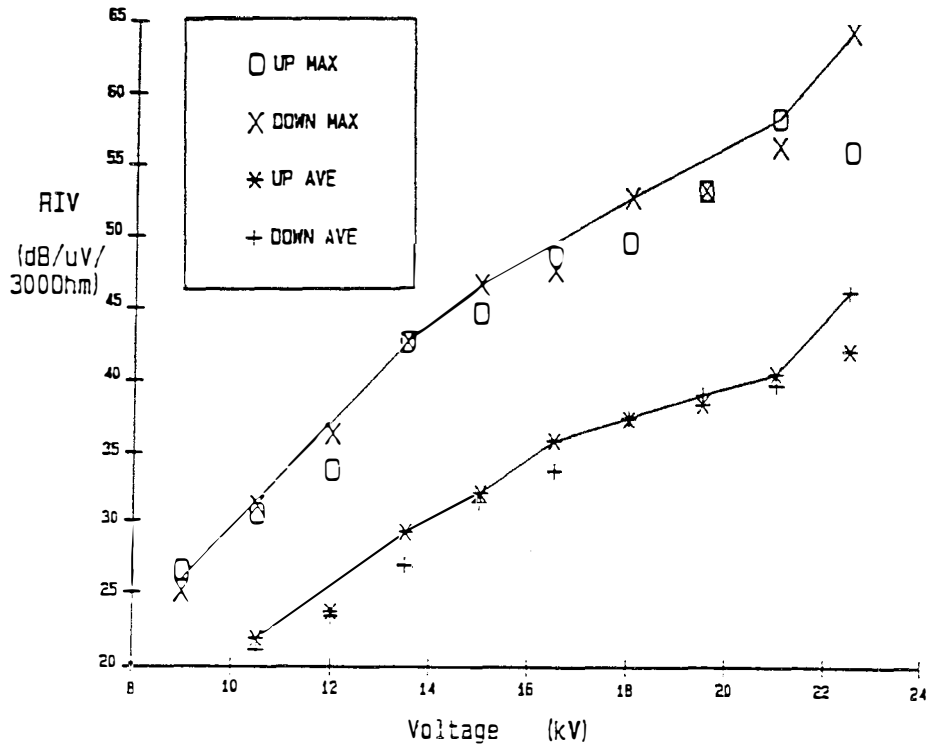


Figure 7.1 : EP303 Dry State RIV Versus Voltage

a single system voltage of 22 kV, i.e. at a specific creepage of 23.9 mm/kV, this is the point of main interest on the graph. The maximum value at 22 kV, i.e. at 12.7 kV test voltage, is 40 dB. As will be seen later, this is around 45 dB lower than the values recorded at that voltage for the polluted and wet cases.

7.2.2. Glass Disc Insulator Dry Test Results

For the glass disc insulator, the only dry state data recorded was in the first 8 tests on the clean insulators. No dry and polluted tests were done. The results of the first 4 tests and test 8, as the voltage was varied through the indicated range, are presented graphically in figure 7.2. As there were considerably fewer readings than for the line post insulator dry state tests, all the individual readings are plotted. The curve

on the graph is drawn to cover all readings at each voltage. The results from the other three tests, i.e. tests 5, 6 and 7, are not included on the graph as they were done on strings of 2 insulators.

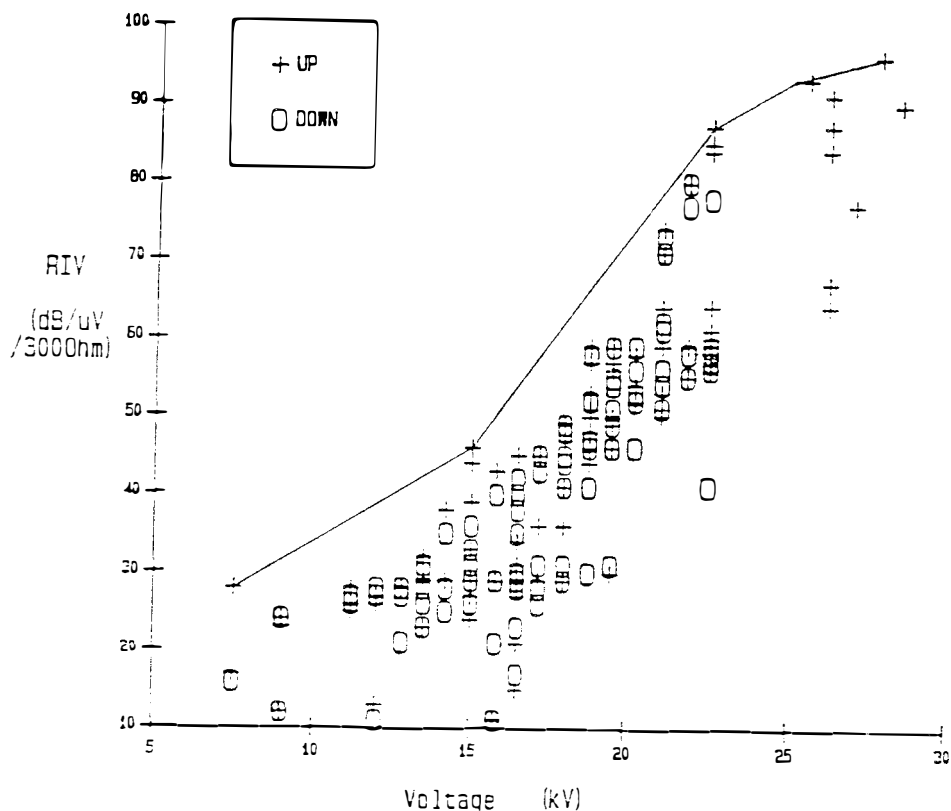


Figure 7.2 : U70BL Dry State RIV Versus Voltage

Figure 7.2 shows a similar wide dispersion of readings at each voltage point as for the other insulator type. Once again this could be due to a decrease in RIV for increased RH. In this case the CISPR results are more directly applicable, since figure 1 of the CISPR paper refers to a single glass disc U120 type insulator unit [28]. This insulator has a similar profile to the U70BL disc but it has an 8 % longer creepage path.

The paper shows that, as RH increases from 20 % to 40 %, the RIV from a single U120 disc falls by approximately 20 dB for applied

voltages in the range from 14 kV to 22 kV. The majority of the values in figure 7.2 fall within 20 dB of the maximum value recorded at each voltage. This, as for the line post unit, is a possible explanation of the wide dispersion in the recorded values as the RH during the tests could have varied by this amount.

As for the line post insulator, the dry state RIV readings for the U70BL disc show a continually increasing trend with test voltage. At test voltages above 20 kV the RIV level exceeds 70 dB going to 96 dB at 27.8 kV. These values of RIV from a clean and dry insulator would be intolerable. However, they should not occur in practice, since those voltage levels represent impractically low specific creepages. Over the IEC 815 recommended range of specific creepage for light to heavy pollution, i.e. 16 mm/kV and higher corresponding to 10 kV and lower test voltages, the RIV levels from figure 7.2 are always below 30 dB. On the graph distinction is made as to whether values were recorded on an increasing or decreasing voltage run. Again no consistent difference between the two directions was evident.

The RIV readings for the two-disc strings, as given in Appendix B, are in general agreement with the single disc results when compared on the basis of specific creepage. Although the two-disc string values fall within the single disc ranges of figure 7.2, they all lie between 4 dB to 20 dB below the single disc maxima. This is not necessarily significant however, as relative to the number of single disc readings, too few two-disc readings were taken at the 3 specific creepages covered.

For the wet test at 22.5 kV on the single disc, the RIV decreased by 24 dB in 27 minutes of fog application. The supposedly dry value before the wetting began was 78 dB. An initial increase up to 85 dB was observed in the first 5 minutes of wetting but thereafter it decreased steadily in time to 54 dB. Had the test been continued it could have dropped further. Although this is an impractically high voltage for a single disc to operate at, the test does show that decreased RIV can be expected from a clean disc insulator when it becomes wet. This is in agreement with the CISPR findings for the case where the insulator is wet by condensation, without large water drops, as in a light fog. The presence of water drops due to rain for example, on the clean insulator surface is reported to increase the RIV level again.

7.3. Constant Voltage Procedure Tests

The constant voltage or prolonged procedure tests are considered before the accelerated ones as their results are taken to be the characteristic values with which the accelerated tests are to be compared. For the tests to provide useful information for design purposes, or for comparing different insulators, each one must provide a RIV value that is representative of that particular test. Furthermore, it must be possible to repeatedly obtain this same representative value in any number of similar tests. Thus, the difficulty was to define how such a value would be determined from the record of RIV versus time for the test, since the instantaneous RIV values were so variable.

After a preliminary analysis of the results, it was decided to

use the maximum RIV value recorded in each individual test. Only the steady maximum values however, and not the fluctuating ones were considered. For example, where readings were recorded in the form $x \pm y$ or $x - x+y$, they were taken to represent a steady interference level of x dB. This means that the maximum possible RIV levels are not necessarily being included. It however, should not affect the practical application of the results, as the higher interference levels were of a burst nature and so would not cause continuous interference. If they are taken as the representative values, a greater dispersion of the results is expected. This is because these burst type maxima were generally very erratic and were seldom maintained for longer than one second. Thus, it was very difficult to record them with any great accuracy by visual observation of the noise meter needle deflection.

The results of the 57 line post and the 64 glass disc constant voltage or prolonged procedure tests are summed up in the graphs of figures 7.3 and 7.5. These are discussed in detail in the following two sections. At this stage however, it should be noted that the lines on the graphs are drawn to cover the maximum values at each voltage level. This may indicate unnecessarily high values but it is the most valid curve that can be drawn. The average values of all the readings at each voltage cannot be used since the same number of readings was not recorded at each voltage. Indeed at many voltages, for the different severity curves, only 1 reading was achieved while at other points up to 6 readings were taken.

7.3.1. Line Post Insulator Constant Voltage Test Results

These results are summarised in the graphs a to d of figure 7.3. They include the results from all of the tests 6 to 62. No distinction is made between the different procedures of tests 6 to 40 and tests 41 to 62. Preliminary analysis of the results showed no difference in the results due to the different methods of connecting the conductor to the test insulator. Therefore, since there was no other significant difference in the two procedures the results were combined.

Graph c of figure 7.3 shows that at the 40:40 severity 5 similar tests were done at 9 kV, 4 at 12 kV and 3 at 18 kV. The 5 at 9 kV and 3 of the 4 at 12 kV all gave results falling within a 3 dB or smaller range. The fourth reading at 12 kV is 15 dB lower than the others. At the 18 kV voltage, although the values all fell within a 6 dB range from 81 dB, they all lie below the level indicated by the line on the graph.

A similar situation was observed at this voltage in the 40:5 and 40:20 severities. For the 40:5 case however, 3 readings were recorded at 80 dB to within 3 dB and the fourth one at 93 dB. It is noted that an 18 kV test voltage is equivalent to 31 kV system voltage, but the insulator is intended for 22 kV applications. If the one reading at 93 dB is ignored, these 18 kV, 40:5 readings show test repeatability to about 7 %, although the values are lower than the trend the other 40:5 results indicated. This could be due to excessive heating at this impractically high voltage with the fixed wetting rate. The readings at 15 kV and 16.5 kV at 40:40 severity also show similarly low values.

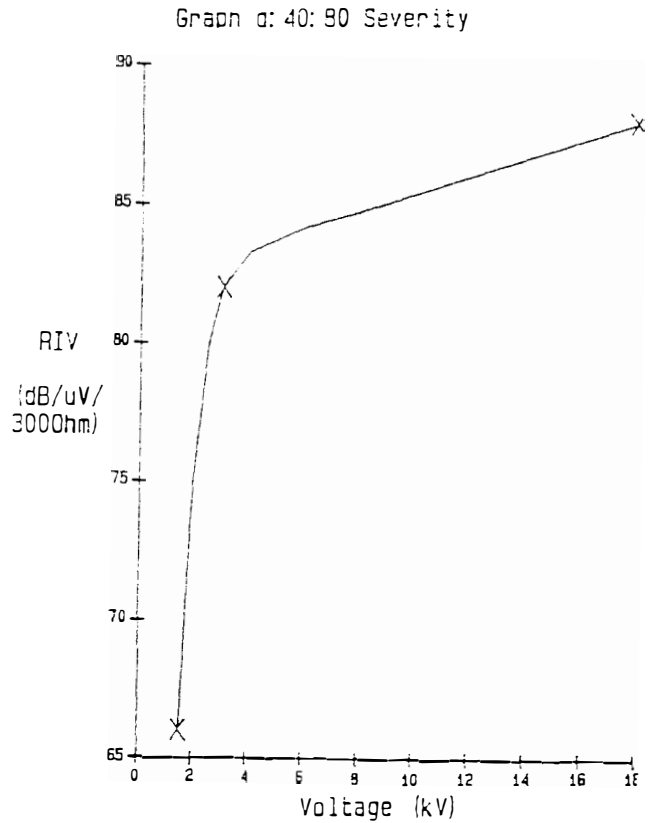
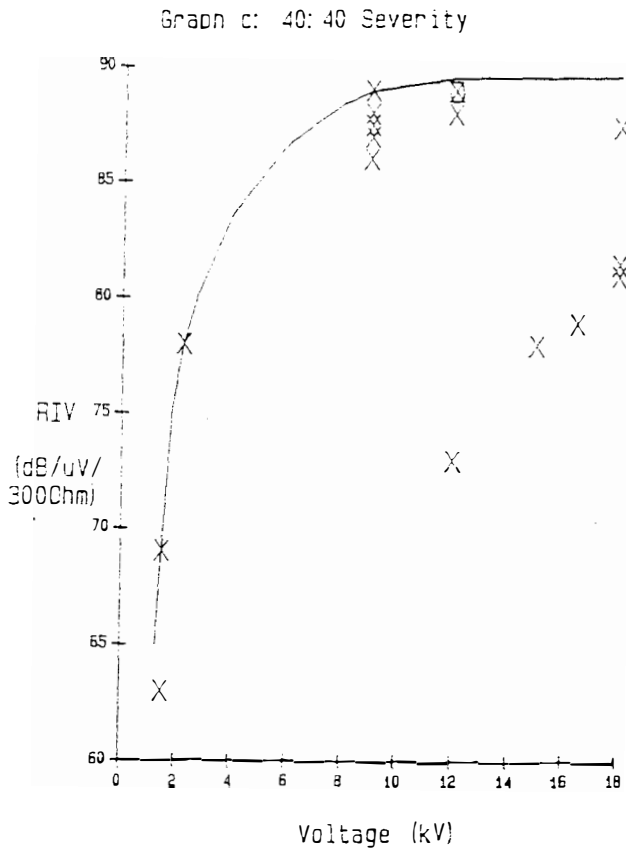
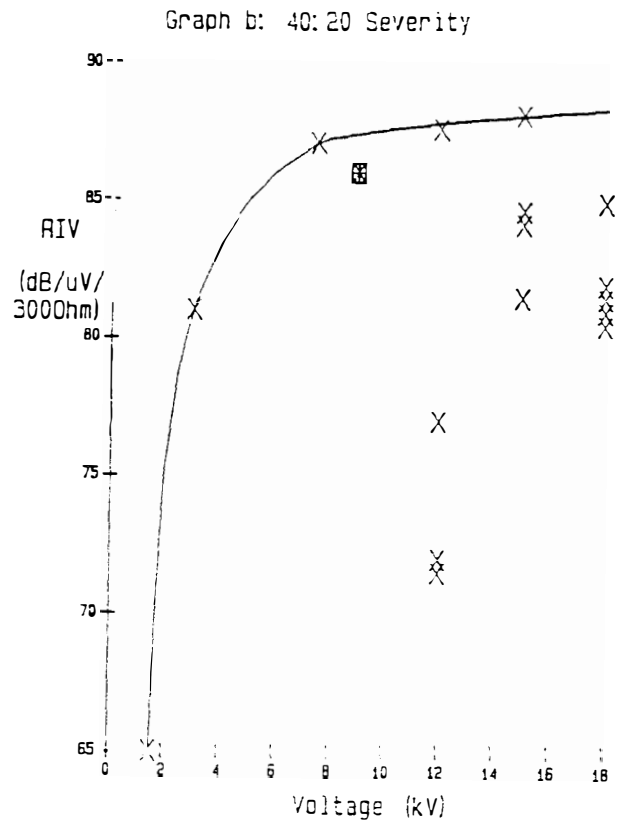
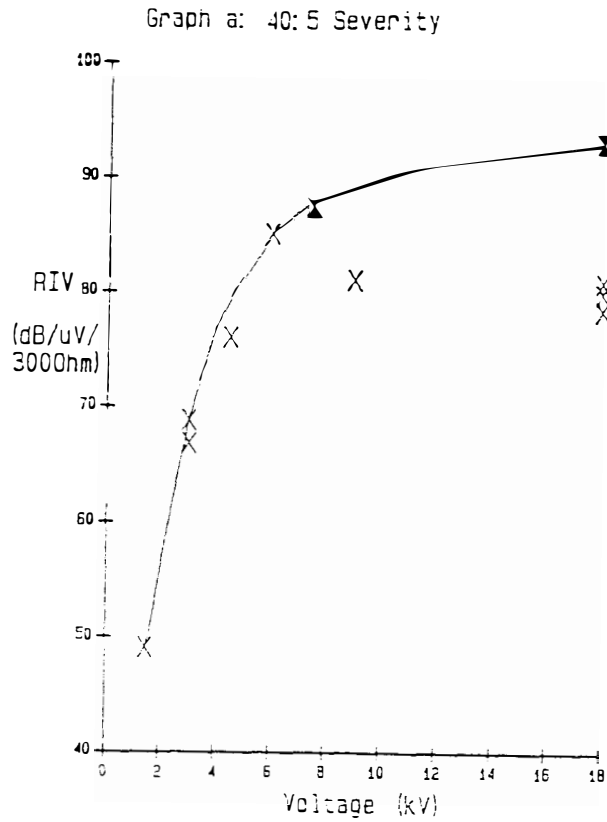


Figure 7.3 : EP303 Prolonged Procedure RIV Versus Voltage

At the 40:20 severity multiple readings were taken at 12 kV and 15 kV. The 4 readings at 15 kV all lie within a 6.5 dB range, but the 4 at 12 kV have a much greater dispersion from 71.5 dB to 87.5 dB. It is interesting to note from the result tables however, that the two lowest values of 71.5 dB and 72 dB were obtained in tests 16 and 14 respectively. For those tests readings were not taken at regular half minute intervals as for the other tests, but instead were taken irregularly at intervals of up to 9 minutes. Thus, higher values could have been attained that were not recorded. If these two tests are neglected the spread reduces from 16 dB to 10 dB which is only 11 % of the value indicated by the maximum line.

For all severities the RIV versus voltage curves showed an initial rapid increase of RIV as the voltage was increased from 1.5 kV. However, by about 8 kV a saturation effect was noticed after which the RIV showed little or no increase with voltage. On the 40:80 curve, of graph d, the knee point appears to be at a lower voltage of 3 kV. This curve however, is derived from only 3 readings - one each at 1.5 kV, 3 kV and 18 kV - and so may be unreliable. For all severities at the nominal 22 kV operating voltage of the insulator, i.e. 12.7 kV test voltage, the curve is well beyond the knee point. This shows that pollution interference from this insulator type cannot be reduced by lowering the line voltage, as the RIV is insensitive to voltage variation in this region.

No other published RI results, relating specifically to this line post insulator could be found. Nonetheless, the above results do agree with general trends reported by CISPR for cap and pin disc

insulators [28]. The CISPR results show similar fluctuations in the instantaneous RIV values, as well as a knee point effect on the RIV versus voltage curves. They also show that, although the interference level is generally higher for wet, polluted insulators than for dry or clean ones, it is relatively insensitive to the amount of pollution on the insulator.

This last result is confirmed for the EP303 line post unit by the graph of figure 7.4. These curves, derived from the graphs of figure 7.3, give the variation of RIV with pollution severity (in terms of the slurry concentration) at various voltages. The curves actually show a slight decrease in RIV with pollution severity to 40:80 for voltages of 6 kV and above. This decrease however, is not significant in light of the questionable reliability of the RIV values at the highest (40:80) severity.

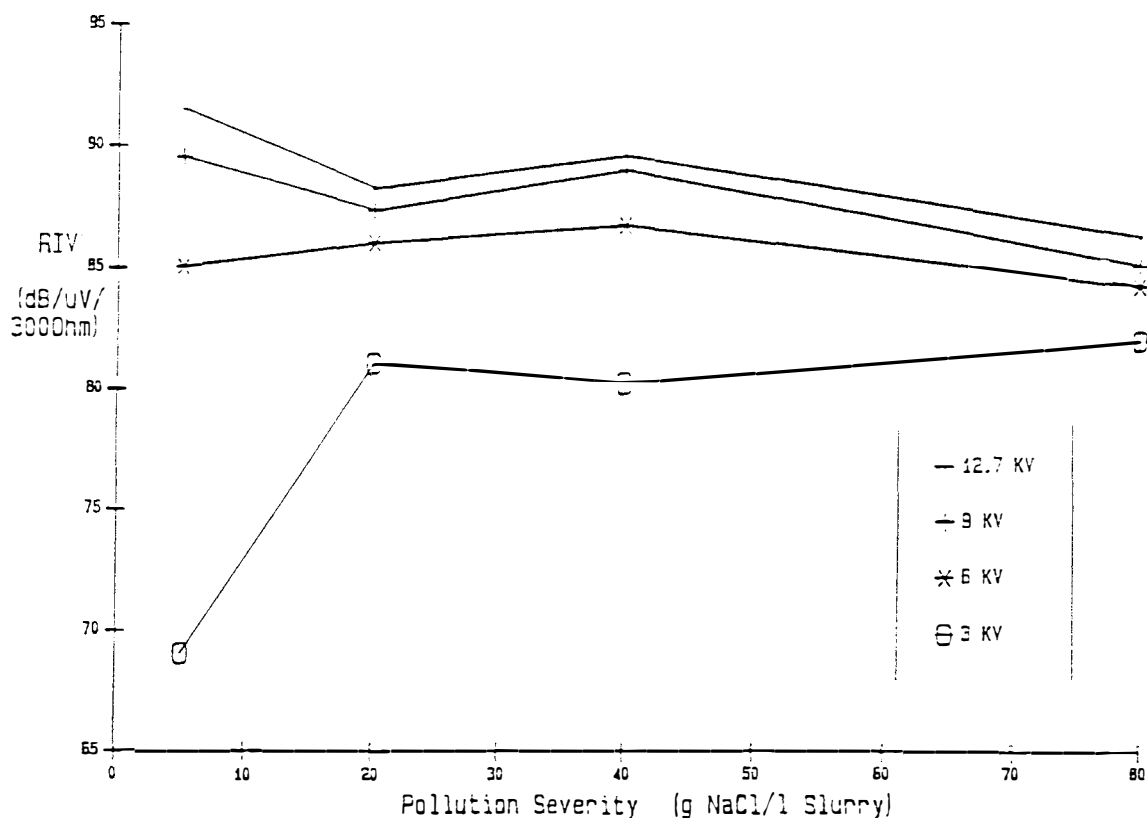


Figure 7.4 : EP303 RIV Versus Pollution Severity

For the 3 kV curve a decrease of 10 dB is shown when the severity goes from 40:20 to 40:5. This result however, is also likely to be variable. At 3 kV the RIV versus voltage curves all have a relatively high slope as they are approaching their knee points. Thus, only a small error in any of these points could have a much larger effect on the RIV versus severity curve for voltages in this region.

7.3.2. Glass Disc Insulator Constant Voltage Test Results

These results are summarised in the graphs a to e of figure 7.5. They include the results of all the glass disc tests 19 to 82. As for the other insulator type, each point plotted represents one complete prolonged test run at constant voltage. Although tests were done at the 5 different severities of 40:5, 40:10, 40:20, 40:40 and 40:80, insufficient data in the 40:10 and 40:80 cases were obtained to draw realistic RIV versus voltage curves. Nonetheless, curves have been drawn in but this limitation should be borne in mind when conclusions are drawn. At the other 3 severities at least 2 and usually more tests were done at each of the 4 or 5 different voltage levels, except for the 40:40 case at 3 kV. There only a single run was done. It should also be remembered that flashovers occurred across this insulator in tests at 12 kV and above for 40:40 and 40:80 severities.

For the 40:5 severity case of graph a, 3 readings were taken at each of 5 voltages covering the range up to 15 kV. The spread of the 3 readings at each voltage varies from 4 dB to 10 dB. This gives a maximum dispersion of 11 % from the mean of the 3 RIV values at each of the 5 voltages. This is not considered to be a

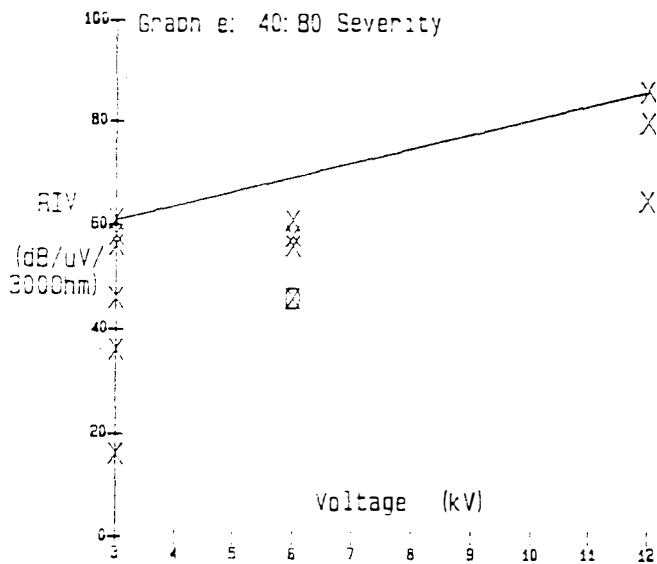
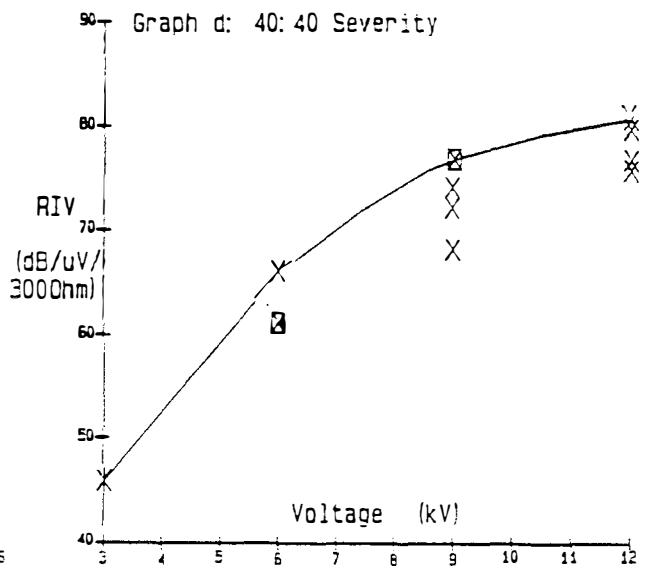
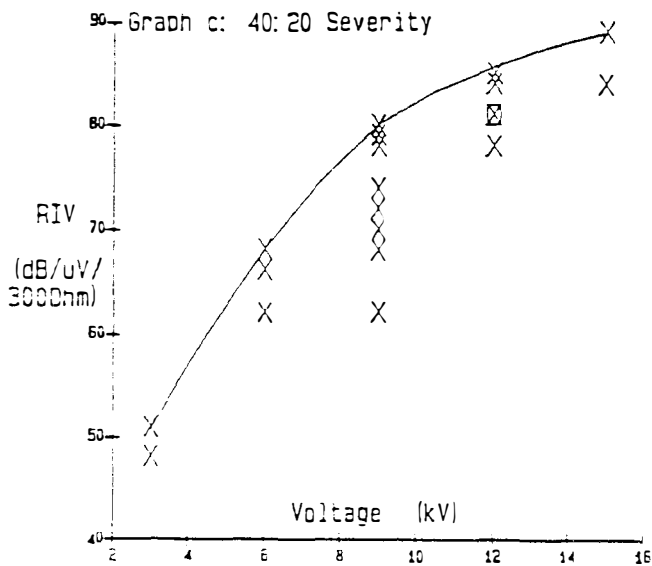
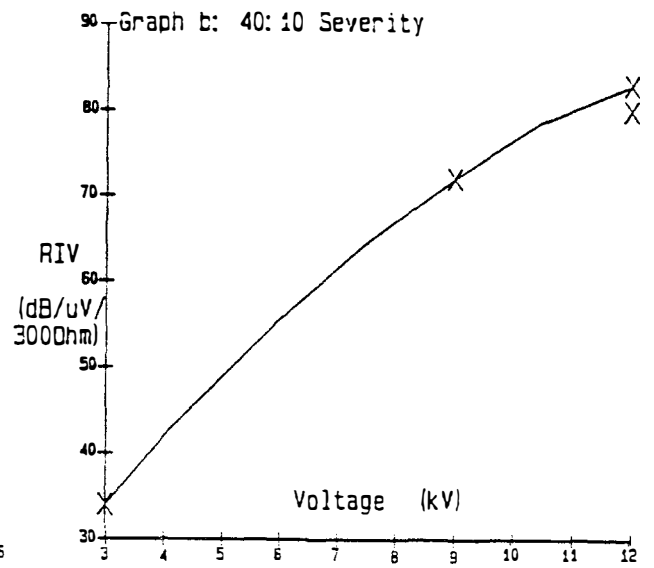
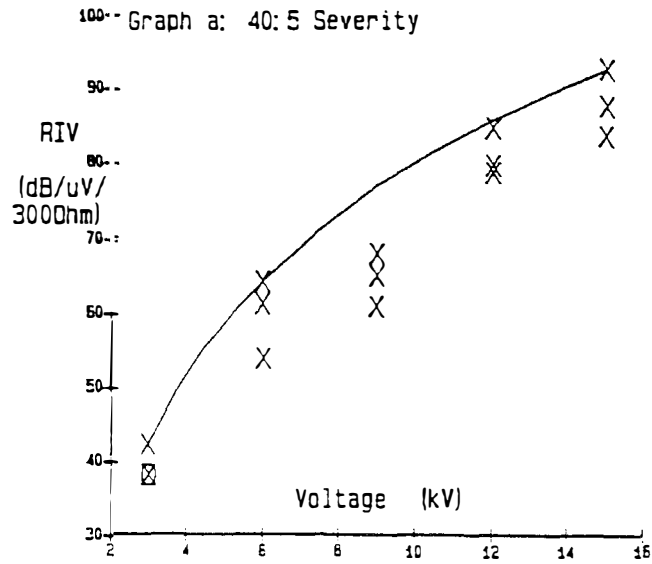


Figure 7.5 : U70BL Prolonged Procedure RIV Versus Voltage

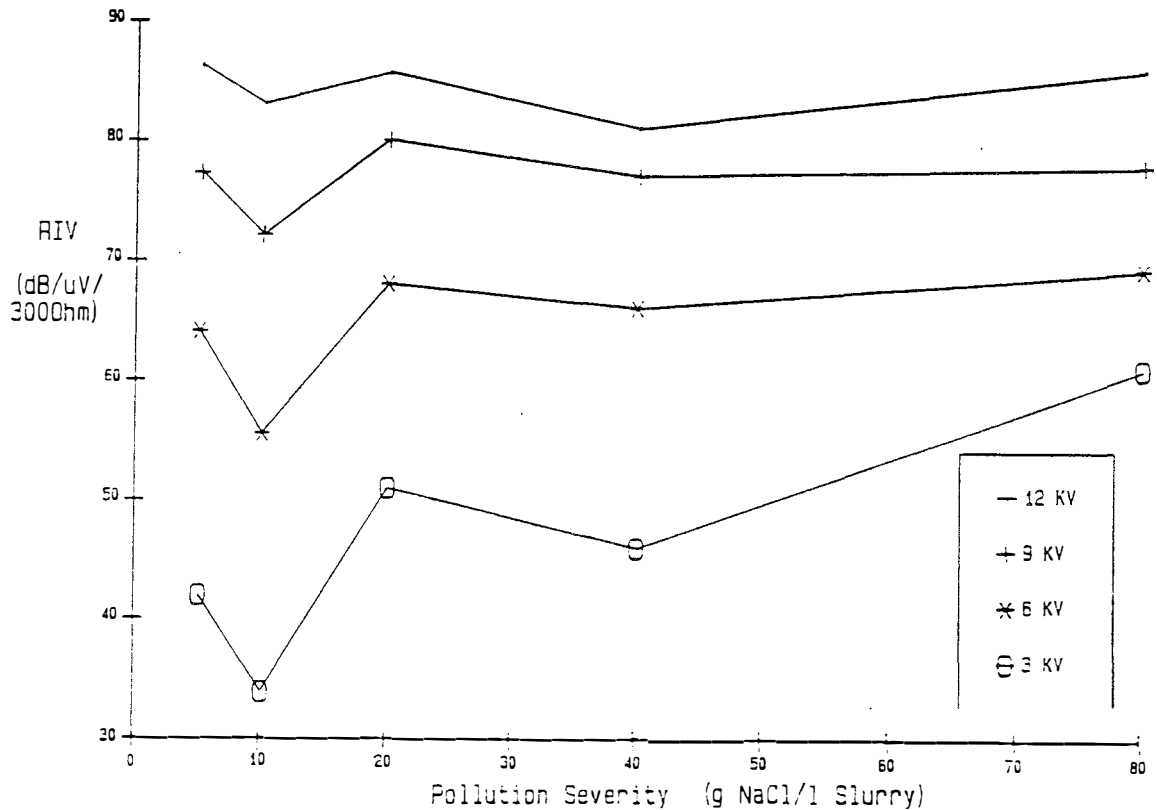
very great dispersion for tests of this nature. When the maximum RIV values at each point, except for the 9 kV one, are joined they form a smooth curve that increases with voltage. The maximum at 9 kV is 9 dB below this curve. Although no marked knee point exists, the slope varies from about 7 dB/kV at the bottom end of the voltage scale to 2.7 dB/kV at the highest voltages.

The 40:20 severity tests also covered test voltages from 3 kV to 15 kV. At 9 kV 8 tests were run and at 12 kV there were 5 values. At the other 3 voltages either 2 or 3 readings were taken. The 8 readings at 9 kV show an 18 dB dispersion with the 3 lowest values being of similar magnitude to the values at 9 kV in the 40:5 case. Apart from these 3 values, the maximum dispersion on the curve occurs for the 5 readings at 12 kV. These are spread over 11 dB or 13 % of the maximum value of 85 dB at 12 kV.

Again the maxima when joined, form a smooth curve over the voltage range up to 15 kV. In this case, towards the upper end of the voltage range, the slope decreases to about 1.5 dB/kV. This suggests that it is approaching a knee point. A 15 kV test voltage however, represents a specific creepage well outside the IEC 815 recommended useful range. The lowest value of 16 mm/kV, recommended for lightly polluted areas, is equivalent to 10 kV across a single disc. Thus, this is the maximum voltage value of practical interest on these RIV versus voltage plots.

For the 40:40 curve the situation is similar, although fewer readings were taken for this severity and only 4 voltage points were covered. The maximum dispersion of 9 dB occurred between the 5 readings at 9 kV. This is 12 % of the maximum value of 77 dB at

that voltage. Again a knee point seems to be appearing at the high voltages beyond the practically useful range.



From the 5 curves of figure 7.5 of RIV versus voltage, values are derived to plot the graph of RIV versus pollution severity shown in figure 7.6. Curves are drawn for 4 different test voltages from 3 kV to 12 kV which gives a range of specific creepage of 13.5 mm/kV to 53.9 mm/kV. The curves show a similar trend to the ones for the line post insulator - namely that the RIV is relatively insensitive to pollution severity, from the light level of 40:5, to the heavy 40:80 pollution severity. In addition, the curves all show a roughly 5 dB to 10 dB dip at the 40:10 severity. This however, is unlikely to be significant for the reasons mentioned earlier, concerning the limitations of the 40:10 data.

7.4. Accelerated Procedure Tests

In the accelerated tests, instead of keeping the voltage constant for the test duration, whilst RIV readings were recorded against time, the voltage was also varied in a step-like manner. In these tests, the RIV was noted to have a transient response at each voltage step. It tended to show rapid, initial fluctuations as the new level of leakage current drying strove towards an equilibrium with the steadily applied fog wetting rate. The manner of this variation depended on whether the voltage step was a decreasing or increasing one.

For a decreasing voltage step, the RIV would fall to below its pre-step value and then in the following time it would increase again but to a lower value than its pre-step level. In the increasing case the opposite would occur. The initial change would be to a higher value, followed by a decrease to some value still above the pre-step value.

In comparing the results with those from the prolonged procedure ones, the values recorded at the end of each voltage step were used. This was because the prolonged procedure results were aimed at giving RIV values representative of the steady state, where a line at constant voltage produces polluted insulator RI. The initial step values would better replicate the RIV levels that would occur if the voltage suddenly changed on a line with polluted and wet insulators. This can happen when a line is switched on, or a voltage regulator undergoes a step change, or possibly under a sudden load change on the line. As was observed here, such (upward) step voltage changes can lead initially to

very high levels of insulator surface discharge activity and hence RIV. These high levels however, are not usually maintained for long, as the initially high discharge currents soon dry the insulator to a degree which reduces the leakage current.

In the prolonged procedure tests, the wetting was always high enough for it to eventually predominate over the leakage current drying and wash the insulator. Thus, it was assumed that readings at the fully saturated, maximum conductivity state were obtained. As long as this condition was reached, it did not matter for how long it was maintained.

In the accelerated procedure cases however, this saturated state needs to be maintained for a longer time, while readings over a range of voltages are recorded. This is expected to be a limitation of the accelerated tests. There is no simple way to ensure that all readings are being taken at this saturated state before washing has caused the surface conductivity to decrease.

In the prolonged case, the test could simply be run until the RIV did decrease and then the maximum value was assumed to represent the saturated state. For the accelerated tests using the line post insulator, to try to prolong and control the available saturated time for taking readings, a pre-conditioning process was used. The insulator was first mounted in the fog chamber with the test supply off but with fog being delivered to the tent at the maximum rate. Then after about 20 minutes, when the insulator was assumed to be at its saturated state, the fog rate was reduced and the test voltage applied. The aim was to reduce the fog rate, so that the wetting and drying would be more nearly

equal thus prolonging the saturated state time. This did however, also mean the opposite situation could occur - the drying could exceed the wetting and so the RIV would decrease again, not as a result of washing, but of excessive heating and drying of the insulator surface.

The results of all the step tests on the two different insulator types, as listed in Appendix B, are presented in summarised form in the remainder of this chapter. Again it is done in 2 sections, with the first one discussing the line post unit results and the second being devoted to the glass disc tests.

7.4.1. Line Post Insulator Accelerated Test Results

The results from the first 5 accelerated tests are summarised in tables 7.3 and 7.4. In table 7.3 the RIV values read at the end of each 3 minute step are shown as the voltage was stepped through the IEC 437 procedure. It also gives the maximum values recorded at any stage of the test at each voltage, as well as the values from figure 7.3 for the 40:5 curve of the prolonged tests.

The table shows that the highest step end values most often arose in the increasing voltage stages of the procedure. These however, were usually not the highest values recorded at each voltage. The result tables in Appendix B show that the highest values were in all cases, except for the tests run at the two lowest voltages, the initial values at each step in the upward runs. The table also shows that the maximum values of all 3 tests, were much lower than those measured in the prolonged tests. They were between 6 dB and 10 dB lower, except for at the lower voltage

RIV (dB/ μ V/300 Ω)											
Voltage (kV)	End Of Step Values									Maxima From All Test 4 & 5 Readings	Fig. 7.3b Prolonged Procedure Values
	Test 1 40:5			Test 2 40:5			Test 3 40:5				
	Down	Up	Down	Down	Up	Down	Down	Up	Down		
13.5	86.0	83.5		80	56	46	81	70.5	-	86	91.7
12.0	82.5	83	77	77	79.5	17	76	79	-	84.5	91.3
10.5	78.5	80	73.5	75	78	6	73	77.5	-	82	90.5
9.0	74.5	77	69	68	74	6	61	73	-	80	89.6
7.5	71	76	65.5	57	71	6	52.5	63	-	78	88.0
6.0	68	71.5	61	62	65.5	6	48	56	-	74.5	85.0
4.5	64	68	58.5	63	62.5	6	40	54	-	69	80.0
3.0	51	52	41	50	51.5	6	42	44	-	52	69.0
1.5	8		20	6			6		-	20	49.0

Table 7.3 : Summary Of EP303 Accelerated Tests 1 To 3

ranges, where the differences were greater. The step end values, on the other hand, which it was reasoned should be most representative of practical polluted insulator RI situations, are 8 dB to 13 dB lower.

As far as repeatability is concerned, these maximum step end values have a less than 13 % maximum dispersion from the mean of the 3 values at each voltage. The exception is for the readings at 13.5 kV where a 20 % dispersion was noted. This is due to the very low value of 56 dB recorded in test 2, whereas the average value of the other 2 tests was 77 dB.

From the detailed tables of results given in section B.1.1, it is seen that when the 56 dB value was recorded, the RIV was rapidly falling and so this certainly was not a steady state value. The wetting rate at that stage was too low and so the insulator was drying out with the corresponding decrease in the RIV level. If the initial value of 81 dB at that voltage step were used, the mean value would become 78.3 dB with only a 10 % dispersion. All 3 tests show the RIV decreasing at all voltages on the final down run. This was also observed to be due to drying and not washing.

Table 7.4 shows the results of 2 similar runs using a 40:20 severity pollution layer on the insulator. These results however, only really serve to confirm that the wetting rate was too low for this procedure to provide very useful results. The maximum RIV values were once again recorded at the beginning of the respective voltage steps in which they occurred. As the voltage decreased from 13.5 kV however, so these maxima became increasingly lower than the prolonged procedure values. Step end

RIV values were only recorded in test 4 over the whole voltage range. Although these values were all less than their respective voltage level maxima, the difference was always less than 4 dB.

RIV (dB/ μ V/300 Ω)								
Voltage (kV)	End Of Step Values						Maxima From All Test 4 & 5 Readings	Fig. 7.3b From All Prolonged Procedure Values
	Test 4 (40:20)			Test 5 (40:20)				
	Down	Up	Down	Down	Up	Down		
13.5	77.5	67.5		67.5			81	88.3
12.0	69.5	65	58.5	59			70	88.2
10.5	62	60.5	39	6			63.5	88.0
9.0	53	52	11				55	87.6
7.5	39	39					39	87.0
6.0	2						6	86.0
4.5								83.4
3.0	4							81.0

Table 7.4 : Summary Of EP303 Accelerated Tests 4 - 5

For test 5 the initial "switch on" step of 13.5 kV was held for 13.5 minutes instead of the usual 5 minute interval. The effect of this is shown by the subsequent decrease of RIV to background levels at 10.5 kV, whereas in test 4 the reading was 56 dB at that step end. The fact that only background RIV was recorded at this 10.5 kV step, indicates that no leakage current could have been flowing for that step duration. This means that excessive drying at the 13.5 kV level must have raised the insulator surface temperature so that, even in the 9 minutes of the 10.5 kV step, the fog wetting caused insufficient cooling for the pollution layer to become wet and conductive again.

The other 5 accelerated tests, 63 to 67, were done after the prolonged procedure line post insulator tests. Although the reduced fog rate was still used, different step procedures and

voltage ranges were used. Since the increasing voltage readings were found to give closest agreement with the prolonged procedure results in tests 1 to 5, for tests 63 to 67 the voltage was started at the lowest values. It was then stepped up to the maximum desired value and thereafter back down again. As before, the steps each lasted 3 minutes except for those at the maximum and minimum voltage levels which were held for 5 minutes. Readings were taken at half minute intervals throughout the test durations.

The voltage range covered was smaller than for tests 1 to 5. The idea was to try and concentrate around the insulator system voltage of 12.7 kV (line to ground) while minimising the required test time. In this case, readings were only taken at 4 or 5 voltage levels on each run instead of the 8 done in tests 1 to 5. The results of these tests, as given in section B.1.4, are summarised in table 7.5. This table gives the RIV values at the end of each voltage step, as well as the maximum value recorded at any stage of the test, for each voltage and the corresponding prolonged procedure values.

Once again before completion of the test, the RIV was seen to decrease. This again was as a result of drying and not washing. For all 5 tests, many of the readings in the second and third down and up steps, were 20 dB to 40 dB lower than either the prolonged procedure values, or the initial up run values. This situation is particularly evident in the 40:80 severity case. There, even on the first up run, the RIV level decreased with voltage over the range 6 kV to 18 kV.

The initial up run, step end values on the other hand, all agreed with the prolonged procedure values to within 7 %, except for the 18 kV values. At that highest voltage agreement ranged from 10 % to 25 %. These percentages were calculated from the values

Voltage (kV)	6.0	9.0	12.0	15.0	18.0
Test 63 Up	85.5	88.5	88	88	79
(40:5) Down	53	55	72	80	
Up		54.5	83.5	83	70
Test 64 Up	86	89.5	88	85	75
(40:5) Down	46	46.5	61	70.5	
Up		50	61	75	70
Test63 & 64 Maxima	86.5	89.5	93	93	92
Prolonged Values(40:5)	85	89.6	91.3	92.3	93
Test 65 Up	86	88	87	87.5	80
(40:10) Down	49.5	50	64	70	
Up		51	56	61	73
Test 65 Maxima	88.5	89	90	93	92
Prolonged Values(40:20)	86	87.6	88.2	88.4	88.4
Test 66 Up	86	89.5	86	82.5	70
(40:20) Down	43	46	54.5	60	
Up		47	46	43.5	39
Test 66 Maxima	88	90	90	91	84
Test 67 Up	88.5	86	83	81	66
Down	53	54	59	62.5	
Up		58	55	11	61
Test 67 Maxima	91	94	94	86	80
Prolonged Values(40:80)	84.2	85.1	86.1	87.1	88

Table 7.5 : EP303 Accelerated Tests 63 - 67

recorded at the ends of the 5 minute intervals for the 18 kV steps. If the values recorded at 3 minutes after attaining 18 kV are used instead, (as was done at the other step levels) the range of agreement improves to between 3 % and 21 %.

Since there is no prolonged curve for the 40:10 severity of test 65, these results are best compared with either the 40:20 or 40:5 severity results. Although this may not be entirely valid, as there is no great difference between the prolonged 40:20 and 40:5 values, 40:10 ones are not expected to differ greatly either.

If the highest values recorded at each voltage, at any stage of the test, are compared with the prolonged results the agreement is closer. Some of these readings even exceed the prolonged curve values. Although these highest values were all measured on the first increasing voltage run of the test, they were not necessarily the first reading recorded at each step level. The range of differences between these values and the prolonged ones is less than 11 % for all voltage levels.

7.4.2. Glass Disc Insulator Accelerated Test Results

These results were obtained from 2 different sets of tests, i.e. tests 9 to 18 and tests 83 to 86. The results of these stepped RIV tests generally showed the same trends as observed for the line post stepped tests. The stepped values were, in most cases, lower than those from the prolonged procedure curves. Again, RIV recorded on up runs, most often exceeded the down run values at the same voltages. The same effects were also noticed for up and down steps, where on an up step the RIV would initially take a

high value and then decrease again towards a steady value, which was higher than the previous step end value. The opposite effect was also observed on down steps.

For these glass disc accelerated tests, the dispersion of RIV measurements at each voltage, tended to be lower than for the corresponding line post insulator tests. This was probably due to the higher wetting rate used in the disc tests. For those tests the fog rate was set to maximum for the whole test duration, whereas in the line post case, a reduced fog rate was used. Thus, even in the final runs of the disc tests, no large drops in RIV due to excessive drying, such as occurred in the line post tests, were observed. Table 7.6 and table 7.7 illustrate the main results of tests 9 to 18. Table 7.6 covers the first 6 tests, which all used a 40:10 pollution level. The first 5 tests of table 7.6 all used an identical up-down-up voltage step procedure covering from 6 kV to 15 kV. The sixth test used a similar step procedure, but it covered a different voltage range.

The values from the 5 identical tests, all had a dispersion of less than 15 % from the average values at each voltage for the separate up and down runs. As for the line post tests, the values recorded on the two up runs were mostly higher than those at the same voltages on the down runs. The up run values also had lower dispersions than the down run values. The errors on the initial up runs from 12 kV to 15 kV were all less than 7 % of the average values. For the next run down from 15 kV to 6 kV, the maximum error was 14 %. The values in the final up run to 15 kV, had a maximum dispersion of 11.5 % of the average values.

Voltage (kV)	RIV (dB/ μ V/300 Ω)														
	Test 9			Test 10			Test 11			Test 12			Test 13		
	Up	Down	Up	Up	Down	Up	Up	Down	Up	Up	Down	Up	Up	Down	Up
15.0	86		85	Trip		80	84.5		85.5	81		83	89.5		90.5
13.8	84			85.5			83.5			81			87.5		
13.5	81	82	82	84	76	74	81	80.5	82.5	82	76	79	86.5	86	86.5
12.8	78			82.5			80			75.5			84		
12.0	73	77.5	78.5	80	73	75.5	78	75.5	78.5	71	73	78	78.5	84.5	83.4
10.5		72.5	75		68	73		72.5	74		70	72		81.5	80.5
9.0		67.5	70		65	67.5		68	69.5		65.5	67.5		77.5	77
7.5		63.5	65		61	64		63	64		61.5	60		73.5	72.5
6.0		57.5			58			57			56			66.5	

Voltage	RIV (dB/ μ V/300 Ω)								
	Test 9 - 13 Averages			Prolonged Procedure Values			Test 14		
	Up	Down	Up	40:10	40:20	40:5	Up	Down	Up
22.5									107
18.0						(98.4)			90
16.5									88
15.0	85.0		84.8		89	93			84
13.8	84.3				87.9	90.4			
13.5	82.9	80.1	80.8		87.6	89.7			
12.8	80.0				86.7	88.1			
12.0	85.1	76.7	78.8	83	85.7	86.2	79		
10.5		72.9	74.9	78.7	83.3	81.9	73	68.5	72
9.0		68.7	70.3	72	80	77.2	52	58	62.5
7.5		64.5	65.1	64.4	74.6	71.4	30	33	
6.0		59.0		55.5	68	64			

Table 7.6 : Summary Of U70BL Accelerated Tests 9 - 14

On comparing the readings of the 6 tests in table 7.6 at 40:10 severity with the prolonged procedure results, it is again noted that they all fall below the prolonged procedure curves. The prolonged curves are given for the 40:5 and 40:20 severities in addition to the 40:10 severity. This is because the 40:10 curve, as stated in section 7.3.2, may not be very accurate, as it is based on considerably less data than are the 40:5 and 40:20 curves. Comparing the 40:10 readings with those recorded for 40:5 and 40:20 severities, although not precisely valid, should still give a good idea of the accuracy of the accelerated tests. This is true for two reasons.

Firstly, as shown in table 3.2, the ESDD severity variation between the glass disc polluted with 40:5 and 40:20 concentration slurries, is only from 0.01 mg/cm² to 0.04 mg/cm². The 40:10 value lies in between at 0.02 mg/cm². These values all represent a relatively light pollution condition. Secondly, in the RIV versus pollution severity curves of figure 7.6, there is little variation of RIV with severity from 40:5 to 40:20. The apparent decrease specifically at the 40:10 severity, can probably be discounted due to the small amount of data from which the 40:10 values are derived.

Despite the doubt existing in the 40:10 prolonged results, the up run average values of table 7.6 agree more closely with these than with either the 40:5 or 40:20 constant voltage values. This agreement is to within 7.5 % over the range of 40:10 prolonged values up to 12 kV. If the 40:5 and 40:20 prolonged values are considered, to cover the range up to 15 kV without extrapolating the 40:10 curve, agreement is still better than 13 %. No values

are available from the prolonged curves with which to compare the values of test 14 at voltages above 15 kV. These voltages however, give specific creepages that are too low to be practically useful and so the results are of limited importance. At 22.5 kV it seems that a sudden, sharp increase in RIV is occurring. This suggests that some interference mechanism other than dry band discharges is beginning. This is expected to be pre-breakdown streamer discharges as the insulator is likely to be close to a flashover situation.

The values in table 7.7 cover tests 15 to 18 of which 2 were done at the 2 severities of 40:20 and 40:80. The values of tests 15 and 16 for the 40:20 case, are again all lower than the corresponding prolonged values at 40:20 severity. For test 15 the step lengths were 3 minutes and the up runs provided the best readings but were still up to 18 % below the prolonged ones. Had more tests been done and average values been calculated, a better result could be expected. In test 16 the few readings taken, show slightly better agreement, (maximum error of 12 %) although they were recorded on down runs. It is noted however, that their step times were 10 minutes and 5 minutes respectively on the 2 down runs, as opposed to the 3 minute intervals of the other tests.

In the 40:80 severity readings, it was attempted to cover the voltage range from 13.5 kV down to 3 kV. The results however, are unreliable as flashovers occurred at voltages of 12 kV and above. This could account for the readings at the lower voltages being very much lower than the prolonged procedure ones. The relatively large amounts of heat, generated in the arc discharges across the insulator, are expected to have heated up the insulator so that

RIV (dB/ μ V/300 Ω)												
Voltage (kV)	End Of Step Values									Figure 7.5 Prolonged Procedure Values		
	Test 15 40:20			Test 16 40:20			Test 17 40:80		Test 18 40:80		40:20	40:80
	Down	Up	Down	Down	Up	Down	Down	Up	Down			
13.5	82.5						81			87.6		
12.8	82						78	78	74	86.7		
12.0	79	78	77.5	85	82		83	82	56	85.7	86	
10.5		71.5	73.5					76	56	83.3	81.8	
9.0		69	70	79			71	67	66	80	77.9	
7.5		63	64						46	74.6	73.5	
6.0		56		66			60			68	69.7	
3.0				57						51	61	

Table 7.7 : Summary Of U70BL Accelerated Tests 15 - 18

Voltage (kV)	RIV (dB/ μ V/300 Ω)											
	Test 83 40:5		Fig 7.5 40:5	Test 84 40:10		Fig 7.5 40:10	Test 85 40:20		Fig 7.5 40:20	Test 86 40:40		Fig 7.5 40:40
21.0	100		(102.6)	98		-	93		-			-
18.0	87	88	(98.4)	93	93	-	93	92	-	Trip		-
15.0	83	83	93	88	87	-	94	90	89	82	80	-
12.0	77	74	86.2	82	81	83	85	83	85.7	73	75	81
9.0	67	64.5	77.2	72	69	72	79	73	80	66	67	77
6.0	42	51	64	59	55	55.5	62	60	68	61	6	66
3.0	19	20	42	33	31	34	42	41	51	46	6	53.5

Table 7.8 : Summary Of U70BL Accelerated Tests 83 - 86

larger dry bands than normal were present. Thus, afterwards at the lower voltages, reduced discharge activity occurred giving the low RIV values of test 18 in particular. Even though 6 minute step sizes were used, this does not appear to have been long enough for the insulator to cool down and to become wet again at the lower voltages.

The results of the last 4 glass disc tests, tests 83 to 86 are summarised in table 7.8. One test was done at each of 40:5, 40:10, 40:20 and 40:40 severities. The table compares each test with its corresponding prolonged procedure RIV values.

The results confirm the findings of previous tests. The up run values were nearly always higher than the down run values and the agreement of the up values with the prolonged ones, was generally better than 15 %. Only at the lower voltage levels in the 40:5 and 40:20 severity cases, were higher errors recorded. In the 40:80 curve test, a flashover occurred at the 18 kV step. This, as for test 18, could explain the background levels measured in test 86 at 6 kV and 3 kV, where readings between 45 dB and 60 dB were expected.

8. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

In this chapter first a brief summary of the whole work is given. This is followed by a discussion of four main conclusions arising from the results of the investigation. The third section of the chapter reviews the test methods that were used to obtain the results. Suggestions are made as to how the methods could be improved for further tests. The chapter ends with a discussion of further work in the field of polluted insulator radio interference that could be useful.

8.1. Summary Of The Work

The broad aim of the investigation was to develop and implement a test procedure to measure the RIV produced by artificially polluted insulators in the laboratory. The results were intended to contribute towards defining a standard laboratory RN test for polluted insulators. This is necessary since at present the existing insulator pollution and RN tests recommended by the IEC only include a polluted insulation, power frequency voltage withstand test and clean and dry state RN tests. The measurements would also provide some data pertaining to the pollution interference performance of two different ceramic insulators used on 22 kV lines in local South African conditions.

The pollution simulation procedure was based on the normal clean fog or pre-deposit method. This involved first drying a layer of solid artificial pollutants onto the test insulator surfaces. The

artificial pollutants consisted of a mixture of Kaolin and household salt. The critical pollution condition, whereby the insulator surface is made conductive, was then simulated by wetting the solid pollution layer. This wetting was done in the laboratory by applying an artificially produced mist condition. The mist was generated by boiling tap water and feeding the steam into an enclosed test chamber in which the insulator was mounted.

The standard IEC clean fog test pollution severity parameter is the ESDD. However, since this involves washing all the solid pollutants off the insulator surfaces into a known volume of distilled water, it is a very time consuming measurement to perform. Its other disadvantage is that the ESDD may change during a clean fog test, as the solids are washed off the insulator by the fog. Therefore, the use of an alternative severity parameter was investigated. This was to use the salinity of the artificial pollution slurry. It was demonstrated that the resulting ESDD on the dry polluted insulator could be made to vary directly with the concentration of salt in the sprayed on solution. Ranges of salinity corresponding to 4 or 5 common pollution severities, described in terms of ESDD from very light to severe pollution conditions, were determined.

The RN produced by these artificially polluted insulators when wet by the clean fog and energised at high voltage was quantified in terms of RIV as defined by the IEC. It was measured using the IEC 437 recommended test circuit. This requires RIV readings to be taken with a standard CISPR radio receiver. The values are quoted in the standard unit of decibels referenced to 1 microvolt measured across a 300 ohm resistance.

The pollution simulation and RIV measurements cannot simply be combined in a test procedure similar to the IEC 437 one, for clean and dry insulators. The difficulty in doing so is that the RI produced by a wet, polluted insulator does not only depend on the instantaneous test conditions, i.e. the applied voltage and the wetting rate. It is also further strongly influenced by how these conditions have been controlled in the preceding test duration. The test procedures were rather based on two assumptions. Firstly, it was assumed that there is a maximum level of RI that an insulator with given pollution severity, energised at given voltage, can produce. The other assumption was that, if the polluted, energised insulator is initially dry and then is steadily made wetter until it becomes saturated, at some stage of the test the maximum RI level will have been attained. It was further assumed that when the polluted insulator was saturated, continued wetting would result in the pollutants being rinsed off the insulator surface.

Two different procedures were used, respectively labelled the constant voltage or prolonged procedure and the stepped or accelerated procedure. In the prolonged procedure the approach adopted was to have the test insulator energised at constant voltage with the steam also applied at a constant rate throughout any one wet test run. The idea was that if the wetting rate was high enough and these conditions applied for long enough, then eventually the completely saturated state will be reached. Since this condition should indicate that maximum RIV had been attained, these prolonged tests were continued until washing of the insulator was observed. It was then assumed that the pollution layer was saturated. The RIV was continuously recorded

8.2. Conclusions To Be Drawn From The Results

There are 4 main conclusions that arise from the results of the 153 test runs. These are summed up in the 4 points below and are then discussed in detail separately in the remainder of this section.

1. Slurry salinity is a suitable parameter to quantify pollution severity in clean fog artificial pollution tests on hv insulators.
2. The prolonged test procedure gave repeatable RIV results to within 15 %, although in many cases the dispersion of results for similar tests was less than 10 %.
3. The accelerated procedure gave consistently lower results than the prolonged procedure. It is nonetheless, a suitable method for further development to form a standard test.
4. In agreement with previously published results, the RIV from the 2 insulator types when artificially polluted, generally increased with test voltage, i.e. with decreased specific creepage, but did not vary significantly with the pollution severity.

8.2.1. Slurry Salinity As Pollution Severity Index

The tests described in Chapter 3 showed that the pollution slurry salinity can be used as a suitable severity index for clean fog pollution tests. For this index to be of practical use however,

it has to be related to the normal clean fog severity parameter of ESDD. The investigation showed that slurry salinities ranging from 40:5 to 40:80, corresponded to a range of ESDDs from about 0.01 mg/cm² to 0.15 mg/cm². These values cover the complete pollution range from light to heavy pollution as commonly defined in terms of ESDD. The advantage of using this salinity pollution severity index was a considerable time saving in the RIV tests as it obviated having to measure the ESDD on the insulators after each clean fog test.

This alternative severity index is applicable to pre-deposit artificial pollution tests in general and not just to RIV tests. Its does however, have one major limitation. Any one operator should be able to consistently achieve the same ESDD from given slurry salinity. The precise relationship though, between salinity and ESDD is expected to vary from one operator to another, even when using ostensibly the same application procedure. This makes the method unsuitable for incorporation into a standard pre-deposit method. However, if the application procedure is precisely defined, the variation might be negligibly small. This would require a purely mechanical dipping process where the operator's subjective judgement would not be required at all. This could lead to a standard relationship between ESDD and pollution slurry salinity. It would greatly simplify the pre-deposit artificial pollution test procedure.

8.2.2. Repeatability Of The Prolonged Test Procedure

Using the prolonged test procedure, the basic nature of polluted insulator interference as described in the literature was

observed. As expected, in the dry and clean cases over the practically useful range of specific creepage, insignificantly low levels of RIV were recorded. In the wet and polluted tests on the other hand, very high and very variable RIV levels were observed. This agrees with the CISPR reported results, where Bernadelli found that the RIV from wet and polluted insulators when energised at constant voltage fluctuates greatly with time. He noted fluctuation levels of +15 dB to -10 dB around a fairly well defined basic level [45].

This is similar to what was observed in the tests on both the line post and glass disc insulators, where fluctuations even greater than 15 dB occurred. It is these "basic levels" that are plotted in the graphs in Chapter 7. The levels of fluctuation were too variable for those maximum values to be used to provide consistent results.

For the dry state tests, the procedure of IEC 437 applies directly and so no prolonged type, dry tests were done on the insulators. However, 121 prolonged procedure, clean fog type wet tests were done on the 2 insulators over a wide range of artificial pollution deposit severities and voltages. The results of these tests showed that it is possible to obtain better than 15 % repeatability in the RIV measurements using this procedure. With further refinement of the procedure and experience in using it, it is believed that the repeatability could be reduced to below 10 %. This would make it a suitable procedure to form the basis of a standard method.

This belief is based on the fact that for the line post prolonged

procedure tests, the dispersion of RIV values from similar tests was often much greater than 15 %. For the glass disc tests on the other hand, the dispersion was generally less than 10 %. For the line post tests, at many points on the RIV versus voltage curves, only 1 reading was taken. At other points more numerous readings were recorded while some tests also included slight variations in the procedure.

The glass disc tests were all done after the line post ones and were done in a far more methodical manner. With the benefit of the experience from the line post tests, in the glass disc series of prolonged tests the procedure was identical throughout. At least 2 readings and usually more, were taken at all but 3 points. This extra care and experience that went into the glass disc tests improved the repeatability by about 5 %. Unfortunately there was insufficient time to repeat the line post tests after the glass disc ones to show that those results could have been improved too.

8.2.3. Comparison Of Accelerated And Prolonged Test Results

The analysis in Chapter 7 of the accelerated test results shows that this procedure can produce results of similar repeatability as can the constant voltage procedure. In the stepped tests the steam generation rate was found to be the most critical parameter. In the first set of accelerated tests on the line post unit, reduced fog rates were used. This was intended to maintain the maximum conductivity state for as long as possible so that a large voltage range could be covered without washing occurring. However, the opposite effect in fact occurred - instead of the

insulator being washed, the wetting rate was so low that the leakage current heating dried out the pollution layer. This resulted in the RIV values falling to virtually the dry state levels at all voltages, within 10 minutes of voltage application to the wet insulator.

Although these low levels are not reproducible, they may be more representative of practical field conditions. In the field the wetting rate may very often be similarly low, so that lower interference levels than the maximum possible for given degree of pollution arise. However, to have a standard, repeatable laboratory test, these maximum possible RN levels would have to be measured. Nonetheless, the tests must simulate field conditions if they are to be used to predict practical performances.

In all the accelerated tests, higher values were recorded on increasing voltage runs than on decreasing ones and the highest values usually occurred at the beginning of a particular step. These highest values however, were unstable and so were not considered as they were not reproducible.

For the line post tests the IEC 437 stepped procedure was at first implemented with the reduced fog rate. This method however, was not suitable as by the final decreasing voltage run, when the characteristic values are supposed to be read according to the IEC 437 procedure, negligible RIV levels were recorded even at the highest test voltages. Even the maximum values recorded, which occurred on the initial increasing voltage runs, were always at least 10 dB below the prolonged procedure

characteristic values. This was probably due to excessive drying occurring with the too low wetting rate.

In the glass disc tests however, where the maximum wetting rate was used throughout, the results agreed far more closely with the prolonged values. The best agreement was again obtained on increasing voltage runs. Test repeatability, taken on initial increasing voltage runs, was obtained to within 10 % of the mean values of a number of similar tests. In these runs, values less than 10 % lower than the corresponding prolonged procedure values were also consistently recorded. This comparison is done on the basis of the maximum curves of the prolonged procedure tests. These curves however, are expected to give unnecessarily pessimistic interference values. Since the results had dispersions of around 15 %, a more realistic representation would be given by taking sufficient readings to obtain statistical mean values. This would give lower prolonged values with which to compare the stepped results. On this basis the agreement between the 2 procedures is closer than suggested by the maximum prolonged procedure curves.

Thus it is concluded that, with further work this accelerated, stepped procedure could be developed to provide a method suitable for standardising in addition to the constant voltage one. Particular attention needs to be paid to ensuring that readings are only taken when the insulator surface is saturated but before any of the pollutants have been washed off.

8.2.4. Variation Of RIV With Pollution Severity And Voltage

From the dry state results on the 2 different insulator types, it is concluded that in dry, normal operating conditions, these insulators will not emit interference of any measurable consequence. This is in agreement with CISPR results [28] and with the operational experience of the 2 insulators.

If the maximum values of all the dry readings at each voltage are considered, an increasing trend of RIV with applied voltage was found. This was expected as the degree of electric discharge activity is in general known to increase with electric field strength. However, other unexpected results were also recorded. These were the very low RIV values recorded in some of the supposedly dry condition tests. For instance, on the glass disc insulator, background noise levels were recorded for tests at voltages as high as 16.5 kV (9.8 mm/kV specific creepage) whereas the maximum value at 16.5 kV was 40 dB.

It was concluded that these unexpectedly low RIV values, that gave the dry state tests poor repeatability (large dispersion of results for similar tests) were recorded when the insulator was not actually completely dry. This would agree with the CISPR findings that increases in relative humidity (RH), from a completely dry state up to about 50 %, can cause up to 30 % drop in the RIV produced by a polluted insulator. Once very high RH levels around 80 % are attained the RIV increases again to above the dry state values.

For the nominally dry state tests, no special precautions were

taken to ensure that the humidity was zero or very low. Neither was any humidity measurement made. It was merely noted that the polluted insulator appeared not to be wet. Thus, readings were almost certainly taken with RH levels in the range up to 50 %, where low readings of RIV can be expected.

The results obtained for both insulator types when polluted and wet were in general agreement with the CISPR results. The comparison between the glass disc results and the CISPR ones however, is the most valid since the CISPR ones were also obtained for a glass disc insulator. It had a similar profile but had an approximately 8 % longer creepage path. The CISPR results are based largely on the work done by Bernadelli [45]. He mainly tested 9 unit strings of these disc insulators. In the present study only single disc tests were done. Nonetheless, the 2 studies covered similar ranges of specific creepage and so could be compared on that basis.

It is also noted that for the 9 unit insulator strings RIV readings were recorded at 0.5 MHz, whereas here the measurement frequency was 1 MHz. As illustrated in figure 12 of Bernadelli's paper, the RN level from polluted insulators tends to decrease with frequency above 0.5 MHz. A decrease of some 5 dB is noted as the frequency increases to 1 MHz. Thus, to compare results at the 2 different frequencies, a factor of 5 dB needs to be added to the 1 MHz values. No correction is required for the meter characteristics, since both sets of readings were taken using CISPR compatible radio noise meters.

Bernadelli draws 3 main conclusions for the RN from polluted, wet

insulators. Firstly, he found that such insulators can cause very high degrees of interference of up to 90 dB to 110 dB. The maximum values measured here (on both insulators) were of the order of 80 dB to 90 dB. With the 5 dB frequency difference factor, this gives a similar though slightly lower range of magnitude.

There is no apparent reason for these values being lower. One factor that could have affected the RIV is the relative air density. Although its effect on the production of polluted insulator RIV is not known, its effect is inherent in comparing the results of this investigation with CISPR results. This investigation was done at roughly 1400 m altitude and the CISPR results apply mainly to sea level. This difference in relative air densities however, would be expected to yield higher RIV at the high altitude and not lower values as were recorded. This is because electric discharge activity is known to occur more readily at reduced air density.

Bernadelli secondly, recorded little variation in RIV with either pollution severity or with applied voltage. Only at low values of both was there a significant decrease in RIV of 20 dB to 30 dB. Here, in both insulator cases, the curves of RIV versus pollution severity were virtually flat from light to heavy pollution severity. Although for the glass discs, the RIV versus voltage curves have similar increases in RIV of around 30 dB for a similar range of specific creepage, they do not illustrate the sharp knee points that Bernadelli reported. The line post insulator results on the other hand, showed more definite knee points at around 8 kV test voltage at all severities.

The third conclusion drawn by Bernadelli, was the one concerning the time fluctuation of the RIV from wet, polluted insulators when energised at high voltage. A similar effect was observed in both the line post and glass disc insulator tests. There was usually a more steady basic level about which these fluctuations occurred. It was in these basic levels that the repeatable trends were noted.

These same conclusions are also borne out by work done in Japan in 1973 [20]. These measurements were done on 154 kV, 275 kV and 500 kV strings of glass disc insulators of similar shapes as those tested by Bernadelli. The Japanese study recorded large increases in the RIV for contaminated and wet insulators, also with large fluctuations. Again RIV variation with voltage and ESDD severity was not very great. Depending on the type of disc insulator, an increase of less than 20 dB was found over a range of ESDD from 0.02 mg/cm² to 0.2 mg/cm², i.e. from light to heavy pollution severity. An ANSI measurement system was used in that work. Thus, as mentioned in Chapter 4, a 2 dB correction factor has to be added to the ANSI values to make them comparable with the CISPR ones.

If the test results are used to directly compare the 2 insulators in terms of their RN performances, it appears that the glass disc is the superior unit. The respective curves given in Chapter 7 indicate that, for a similar specific creepage to the line post insulator installed on a 22 kV system, i.e. at 12.7 kV test voltage or 24 mm/kV, the glass disc unit (at 6.5 kV test voltage or 24.9 mm/kV) emits some 15 to 20 dB less interference.

This comparison however, is not entirely fair or valid and it cannot be concluded that the glass disc is a better insulator to use in polluted areas for improved RN performance. The reason for this is that, the curves on which the comparison is based, are drawn from the maximum steady values recorded from a varying number of tests at each point.

For the glass disc unit, in most cases, sufficient readings were taken at each point to calculate average values. For the line post one however, at many of the points only 1 reading was taken. Where more than 1 value was recorded, the dispersions tended to be much higher than for the glass disc tests. Thus, if more line post readings were obtained, so that average values could be determined for both units, the line post average values would drop by more than the glass disc ones from their respective maxima. In other words, the difference between the 2 sets of readings is expected to decrease. From the curves of figure 7.3 for the line post prolonged procedure results, characteristic values 15 dB to 20 dB lower than those indicated by the maximum curves could be more realistic.

A further conclusion can be drawn from the results of the RIV variations with voltage for the 2 insulators. Only for the glass disc case is increasing the specific creepage a feasible means of reducing pollution related interference. For the line post insulator it is not a practical option since the creepage length of each unit is fixed and no more than one can be used in series. Therefore, the specific creepage can only be increased by reducing the system voltage. This, for other considerations such as the quality of supply, is unlikely to be possible, especially

as a large voltage reduction is required to achieve significant RIV reduction. Significant RIV decreases could only be achieved by using this 22 kV line post insulator in 11 kV applications. The working voltage would then be equivalent to approximately a 6.5 kV test voltage which falls below the knee points of the RIV versus voltage curves.

For the glass disc insulator case, at fixed system voltage the specific creepage can be increased by using extra discs at each insulation point. On 22 kV systems 2 disc strings of U70BL insulators are most often employed. This gives a 25.5 mm/kV specific creepage. If a third disc is added, the specific creepage is increased to 38 mm/kV. This is equivalent to a 4.2 kV line-to-ground test voltage across a single disc. However only if uniform voltage distribution is assumed, can the single disc results be extrapolated on this basis to the extended strings. Then from the graphs of Chapter 7, this increase from 2 to 3 discs would give a 10 dB to 15 dB decrease in the RIV level. This is a significant decrease, especially in view of the CISPR criteria for the setting up of radio noise limits [12]. The relevant criterion there is that, for the RN from fittings, for example line insulators, to be negligible compared with the conductor corona noise, the fitting noise must be kept 10 to 18 dB below the corona noise level. A reduction by 15 dB therefore, could ensure this condition.

8.3. Review Of The Methodology

Possibly the main limitation of the results is that insufficient

tests were done to provide complete RIV versus voltage and pollution severity data for both insulator types. In the available time it might have been better to have only run tests on one insulator type. Had this been done, there would have been time to systematically take enough readings, using both procedures, at each severity and voltage to calculate statistically meaningful averages at each point.

The results might also have been improved if greater care was taken to ensure the similarity in test conditions for different tests at the same nominal severities and voltages. The test voltage, which was set by the primary input voltage to the step up transformer, would have been accurately set for all tests. The other conditions however, were not so easy to check.

The pollution severity was nominally given according to the salinity of the artificial pollution slurry. The actual severity value (ESDD) however, was not checked during any of the tests. Greater accuracy could have been ensured had systematic checks been done. For example, at each severity and voltage, where 3 prolonged tests were done on the glass disc insulator, an additional test could have been done. This test would involve polluting the insulator and measuring its ESDD without any exposure in the fog chamber. If this ESDD was within 10 % say, of the value indicated by the initial series of ESDD tests, the RIV tests at that point could be accepted. If not the tests should be repeated.

Variation in the ESDD however, is not expected to greatly influence the RIV results. This arises from the finding that the

RIV at fixed voltage was relatively insensitive to pollution severity. Certainly greater improvement in the reliability of the RIV values as a function of voltage and pollution severity would have been obtained by taking readings at more points, than by being more certain of the ESDD value of each test run.

Other test conditions that could have affected the results are the insulator surface and the mist temperatures and the RH in the tent during the test runs. Only the mist or ambient temperature at a point approximately 2 m away from the test insulator was measured. Both the initial and final temperatures varied over a range of some 20 °C between all the tests. Although it is not known what effect on the RIV production these temperature variations will have, they do represent differences in the test conditions. The temperature difference between the incident fog on the insulator surfaces and the insulator surface itself is certainly expected to effect the wetting of the insulator. This difference will determine how much steam condenses on the insulator. For this reason it was attempted to ensure that initially, before the steam application there was no difference, i.e. the insulator was at room temperature and so at least in thermal equilibrium with its initial ambient condition.

The RH measurement would have been particularly useful for the nominally dry state tests. It would have enabled curves to be plotted as a function of humidity for comparison with the CISPR results. This is not very important for practical purposes however, as the RIV was always insignificantly low except when the insulator was clearly very wet even if not saturated.

Another measurement that could have been included was a direct measurement of the 50 Hz leakage current. This can be done by inserting a resistor in series with the test insulator ground connection and measuring the voltage across it. It would be interesting to determine the exact relationship between this leakage current and the RIV. Monitoring the leakage current could serve to indicate when the pollution layer is completely saturated and so when the maximum RIV should be measured.

Any of these additional measurements could have increased the usefulness of the measured data. They would however, also have complicated the experiments and reduced the number of tests that would have been done in the available time. Including them however, could be investigated in further work in this field as discussed in the next section.

8.4. Suggestions For Further Work

There are four main areas where it is envisaged that further work on this laboratory measurement of the interference produced by artificially polluted insulators might be useful. These are,

1. To improve the interference measurement procedures to a level where the method can be standardised.
2. To measure and correlate leakage current with RIV.
3. To determine the RIV versus voltage and severity for other different insulator types.

4. To relate the practical interference effect or nuisance value of polluted insulator interference in the field to the laboratory measured RIV values.

8.4.1. Standardisation Of The RIV Measurement Procedure

Although the results of the investigation showed that test repeatability could be obtained to at least 15 %, in many cases much greater errors arose. Further work needs to be done particularly with regard to controlling the wetting rate in the tests. The effect of too low a wetting rate was clearly demonstrated in the stepped tests done with the reduced wetting rates. Also more attention needs to be given to determining the optimum step durations in accelerated tests, so that the pre-conditioning effects of previous step voltage levels do not prevent characteristic, repeatable RIV values being recorded.

The prolonged test procedures could be shortened in time and made more definite if a means, other than observing when washing begins, could be developed to indicate that the maximum RIV state should have been reached. It is surmised that if the wetting rate can be optimised, then the prolonged test could be well enough defined for standardisation. The procedure would be to specify the required wetting rate. Then the insulator, energised to the desired test voltage, would be subjected to the wetting condition for a specified length of time before the RIV level is measured. This would be the characteristic interference value.

The other aspect of the procedure that would need to be further developed is the quantification of the pollution severity. The

method of using the artificial pollution slurry salinity, as used in this investigation, is probably the simplest. However, the problem of the dependence of the relationship between ESDD and slurry salinity on operator judgement needs to be overcome. To be able to incorporate this severity parameter into a standard clean fog test procedure, it needs to be made operator independent. To do this, a purely mechanical artificial pollution application method is required. The dipping method is believed to be most suitable for such development.

8.4.2. Leakage Current Measurements

Another related avenue of research to follow would be to monitor the leakage current while recording the RIV in these pollution tests. Of interest would be the highest current values that occur for any given pollution condition, defined in terms of pollution severity and voltage. If a characteristic relationship between RIV and leakage current is found, a diagnostic tool could be developed.

This would be most useful if in addition the RIV emitted could be related to the radiated interference component at the same frequency. Then, theoretically, the presence of polluted line or even station insulators could be detected simply by a field radiated interference measurement. If the interference levels can be correlated to the highest values of leakage current, then by a comparison with the insulation's theoretical I_{max} , a flashover probability can be estimated. The alternative approach would be to directly measure and correlate in the laboratory both leakage current and radiated interference. The difficulty of relating the

laboratory radiated measurements to expected field levels is still envisaged.

The practical use of this would be to contribute towards optimising line maintenance procedures. It could be used as an early warning system to indicate critical pollution build up on line insulators. Warning obtained in sufficiently good time would permit a preventive washing or greasing operation to be done before a flashover and possible resulting line outage occurs. Conversely it could eliminate the need for routine insulator washing. This is sometimes done regardless of the degree of pollution build up, which may result in unnecessary maintenance costs being incurred. Instead, with a reliable pollution severity indicator, maintenance is only done when essential.

8.4.3. RIV Characteristics Of Different Insulator Types

A logical extension of the work would be to measure the RIV versus voltage and pollution severity characteristics for further different insulator types. This however, would be most useful if a more well defined RIV measurement procedure were first developed. Although, as mentioned in the introduction of Chapter 1, polluted insulator RI is seldom a problem at present, it could become so in the future. This is particularly so in areas where large expansions of 22 kV and lower voltage reticulation systems is proposed. Non-ceramic type insulators are expected to have the best RN performances under polluted conditions but an extended laboratory test program could quantitatively verify this.

8.4.4. The Nuisance Value Of Polluted Insulator Interference

To make the laboratory measurements of real practical use from the interference viewpoint, would require a correlation between the laboratory RIV and the nuisance value of interference practically experienced. The difficulty is expected to be that, in the laboratory the maximum possible RIV levels are measured. In the field the maximum level is seldom expected to occur for any significant time, except under rare ideal interference producing wetting conditions. Nonetheless, some field measurements of the radiated interference arising from polluted insulators on practical lines could greatly add to the usefulness of the data for purely practical interference purposes.

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APPENDIX A: ESDD MEASUREMENT PROCEDURE

To measure the ESDD of a polluted insulator involves determining the mass of salt (NaCl) that, when completely dissolved in a given volume of low conductivity distilled water, gives the same solution conductivity as would be obtained if all the solid pollutants on the insulator were thoroughly mixed up in the same volume of distilled water, at the same temperature. Once this mass of salt is known, the area over which the pollution is distributed needs to be known so that the ESDD can be given (in mg/cm^2) by the mass of salt divided by the area.

To determine the conductivity value, the solid pollutant is removed from the insulator surface into the specified volume of distilled water. Then the resulting solution conductivity and temperature are measured. The conductivity is converted to a resistivity value and the salt solution concentration at that temperature is determined from tables of the resistivity of aqueous NaCl solutions [31]. This gives the required equivalent mass of salt, since the volume of wash water is known.

The solid pollutants are removed from the insulator by carefully wiping the surface with a damp piece of cotton cloth or tissue paper and then rinsing all the solids out of the swab cloth into the water. The detailed procedure for performing the measurements and the final ESDD calculations are described in the following sections.

A.1. Equipment Required

1 x dry polluted insulator

1 x 500 ml measuring cylinder

1 x 500 ml beaker

0 - 2 mS/cm conductivity meter

0 - 50 °C thermometer (Not needed if the conductivity meter
applies automatic temperature correction.)

Absorbent cotton or clean paper tissue

Supply of low conductivity (<5 microsiemen/cm) distilled water

- each measurement will require approximately 1 litre

A.2. Procedure

It is important to note that, if the conductivity meter readings are automatically corrected to some reference temperature, (usually 20°C or 25 °C) then no temperature readings are required. All references to the thermometer in the following procedure description can then be neglected.

a) Thoroughly rinse the measuring cylinder and beaker with distilled water.

b) Ensure that the hands are clean and rinse them, the conductivity meter probe and the thermometer with distilled water. Place the probe and thermometer into the 500 ml beaker.

c) Measure 500 ml of distilled water into the measuring cylinder and pour it into the beaker. Using the conductivity meter, measure and note the conductivity of the water. This should be

less than 5 microsiemen/cm.

d) Take a piece of the absorbent cotton or tissue paper and swirl it around in the beaker until it is thoroughly wet. From this moment until the conductivity measurement is complete, the hand used to swirl the swab with should only be used to wipe down the insulator and should not touch any other object. This is to prevent other particles not from the insulator surface from going into the swab water and contaminating the measurement.

e) Measure and record the conductivity (C_1) and temperature (t_1) of the swab water with the cloth in it.

f) Remove the cotton or tissue swab from the beaker and squeeze it out over the beaker ensuring that no water drops splash out of the beaker. Use this damp swab to wash the pollution off the insulator area that is to be tested. Care must be taken to only wash the insulating surface and not to touch any of the metal fittings or cement areas at the insulator caps and pins.

It is best to systematically wash off small parts of the total area separately. Once each small section is done the swab should be returned to the swab solution and swirled around to ensure that all the pollution washes out into the water.

g) When the whole surface has been thoroughly washed and the solution and cloth have been well stirred up, measure and record the new conductivity (C_2) and temperature (t_2) of the swab solution.

h) If the area (in cm^2) of washed insulator is not known, this should now also be measured. If the whole insulator surface is used, usually only a rough approximation of the area is possible as a result of irregular shed shapes.

A.3. The ESDD Calculation

E.S.D.D. = equivalent mass of salt (M) on insulator surface ..A.1.
insulator surface area (A)

The equivalent mass of salt is that mass of salt (NaCl) that would need to be dissolved in 500 ml of distilled water to give the same conductivity (at the same temperature) as the pollution gave when washed off into the 500ml of distilled water.

M is determined from a set of tables [31], that give the resistivity (in ohm.cm) of low concentration salt solutions as a function of solution concentration (given as a % NaCl solution, i.e. g/100ml). This is a temperature dependent relationship and the tables are specifically given for 18 °C. Thus, if conductivity readings are given for any other temperature, a correction factor has to be calculated and applied.

The calculation of M proceeds as follows. First correct the conductivity readings, C_1 and C_2 at temperature t °C to 18 °C. From [31], the corrected values are given by equation A.2.

$$C_{18} = \frac{C_t}{1 + b_t(t - 18)} \quad \dots\dots A.2.$$

C_t = Measured Conductivity
 at t °C.
 b_t = Temperature resistivity
 co-efficient obtained
 from table 2 of [31].

From these 18 °C corrected conductivity values, determine the conductivity at 18 °C due to the pollution only, i.e. exclude the initial conductivity of the swab water and the effect of any soluble components from the swab material. This is given approximately by the difference between the initial and final conductivity readings.

Therefore, $C_{18} = C_{2\ 18} - C_{1\ 18}$, which is only valid for $C_1 < 20$ microsiemen/cm or for $C_2 > 10C_1$. From C_{18} the equivalent resistivity at 18 °C (R_{18}) is determined.
 i.e. $R_{18} = 1/C_{18}$.

Then from the tables in [31] of concentration versus resistivity look up the concentration of salt solution (X - in g/100ml) that has this same resistivity at 18 °C. Therefore,

$$M = \frac{X * V * 1000}{100} \text{ (mg)} \quad \text{where } V = \text{volume of wash water (ml),}$$

and

$$ESDD = M/A$$

$$= \frac{X * V * 10}{A} \text{ (mg/cm}^2\text{)} \quad \dots\dots A.3.$$

A

APPENDIX B. RESULTS OF RIV MEASUREMENTS

B.1. EP303 Line Post Insulator Results

B.1.1. EP303 Tests 1 - 5

a) Dry State Results

Readings were recorded on a decreasing voltage run from 13.5 kV.

Voltage (kV)	RIV (dB/ μ V.300 Ω)			
	Test 1	Test 2	Test 4	Test 5
13.5	11	16	26	30
12.0	10	8	6	17
10.5	7	6	4	4
9.0	7	0	2	0
7.5	0	0	0	0
6.0	0	0	0	0
4.5	0	0	0	0
3.0	0	0	0	0
1.5	0	0	0	0

b) Polluted Wet State Results

Time (min)	Test 1 40:5		Test 2 40:5		Test 3 40:5	
	KV	RIV	KV	RIV	KV	RIV
0.0	13.5	80	13.5	69	13.5	74
1.0		80		75		76 \pm 2
4.0		80		76		75
5.0		80		74 \pm 2		75
6.0	12.0	77	12.0	73	12.0	70
8.0		76.5		71 \pm 3		70 \pm 3
9.0	10.5	71.5	10.5	67	10.5	62
11.0		72.5		69		67
12.0	9.0	68.5	9.0	57	9.0	52.5
14.0		68.5		62 \pm 2		55
15.0	7.5	64.5	7.5	51	7.5	44.5
17.0		65 \pm 1		51		46.5
18.0	6.0	59	6.0	49	6.0	41.5
21.0		62 \pm 1		56		42
22.0	4.5	55	4.5	50	4.5	32.5
24.0		58		57		34
25.0	3.0	43	3.0	37	3.0	30
27.0		45		44		36
28.0	1.5	2	1.5	0	1.5	0
30.0	3.0	42.5	3.0	44	3.0	41 - 43
31.0		46		45.5		38 - 46
32.0	4.5	57	4.5	63	4.5	49
35.0		62		56.4		48 - 50
36.0	6.0	68.5	6.0	62	6.0	52.5

EP303 Tests 1 - 3 Continued

38.0	6.0	65.5	6.0	59.5	6.0	50
39.0	7.5	72	7.5	68	7.5	62.5
41.0		70		65		57
42.0	9.0	74	9.0	70	9.0	66.5
45.0		71		68		67
46.0	10.5	76	10.5	74	10.5	74.5
48.0		74		72		71.5
49.0	12.0	78.5	12.0	77	12.0	76
51.0		77		73.5		73
52.0	13.5	80 ± 1	13.5	75	13.5	75
54.0				63		64.5
55.0					14.2	64
56.0		77.5		50	13.5	48
57.0	12.0	71.5	12.0	40		43
58.0						39
59.5		71				34
60.0	10.5	64.5		11		31
60.5			10.5	0		24
61.0			9.0	0		23
62.0			6.0	0		13
63.0		67.5	4.5	0		0
64.0	9.0	61	3.0	0		
65.0					15.0	20
66.0		63			16.5	45
67.0	7.5	56.5			18.0	52
68.0						52.5
69.5		59.5				
70.0	6.0	52				49
71.0						42
73.0		55				36
73.5	4.5	43.5				
74.0						25
75.0			12.0	0		17 - 27
76.0		52.5			16.5	0
77.0	3.0	40			13.5	0
78.0						(III)
80.0		35 - 45				
81.0	1.5	12				0
82.0						22
83.0						31
84.0		14 ± 2				43
84.5						
86.0						44
88.0						59
89.0						62
91.0						64
91.5						62
95.0						63
99.0						61.5
104.0						62
109.0						63

Time (min)	Test 4 40:20		Test 5 40:20	
	KV	RIV	KV	RIV
0.0	13.5	69 - 75	13.5	72
0.0				(27.0)
1.0		74		73 ± 2
3.0		72		70 - 73
5.0		71.5		
5.5	12.0	64		69
6.5		63.5		67.5
7.5		63.5		
8.0	10.5	56		
8.5				65.5
9.0		56.5		
10.5		56		64
11.0		56		(26.5)
11.5	9.0	46		
12.5		47		62
13.5		47		61.5
14.0	7.5	28	12.0	48
15.0		30.5		54
16.0		35 - 37		
17.0		33		53 - 55
18.0		33	10.5	0
18.5	6.0	-4		
20.0	3.0	-2		
21.0	7.5	33		
22.0		33		
23.0	9.0	49		
24.0		48		
25.0		46		
26.0	10.5	57.5		
27.0		55.5	10.5	0
28.0		54.5	10.8	49
29.0	12.0	61.5		
30.0		60		46 ± 2
31.0		59		
31.5	13.5	66	11.1	47 ± 2
33.0		64	11.4	50.5
34.0		63		
35.0		62.5	11.7	50.5
37.0		61.5		0 - 35
38.0	12.0	51.5		
38.5			12.0	50.5
39.0		52		
41.0		52.5		49 ± 2
41.5	10.5	34	12.3	51
42.0		0		
43.0		33		
44.5				48
45.0		33	12.6	48.5
46.0	9.0	0		
48.0				44
48.5			12.9	45
49.0		5		
50.5				0
53.0	13.5	61.5		

EP303 Tests 4 - 5 Continued

54.0	13.5	60	12.9	
55.0		59	18.0	65
57.0		58		
58.5				63
59.0		58		
61.0		57.5		60.5
62.0		57	16.5	52
65.0				49.5
66.0			15.0	39.5
67.0		55.5		
67.5	12.8	50.5		33
68.5		51.5	13.5	7
69.5		51.5		15
70.0				17
70.5				26.5
71.0		51.5		32
72.0		51.5		35
72.5	12.0	42		38
73.0		38		42
73.5				48
74.0		39.5±1		54.5±2
75.0		38		64
76.0				65
77.0		38		66
78.0	11.3	22		66 ± 2
78.5				68.5
79.5				69
80.0		0		
81.0		18		68.5
82.0				68
83.0				68.5
84.0				69.5
86.0				68.5
88.0	10.5	10		67.5
89.5	13.5	54		
90.5		55.5		
91.0				68.5
91.5		54		
93.0		53.5		
93.5	12.8	49.5		
94.0		50.5		
95.0				68
97.0		49 - 52		67.5
97.5	12.0	45.5		
98.0		46		67
99.0		48	12.0	63
100.5		46.5		64.5
101.5	11.3	6		
103.0		9 - 15		
104.0	10.5	9		
105.5	13.5	54		
106.0	Off			64
109.0		(28.0)		65.5
110.0			10.5	59
112.5				58.5
120.0				60.5
123.0			9.0	45.5
131.5				38 - 40

EP303 Tests 4 - 5 Continued

136.0				54
137.0	13.5	70	7.5	-2
138.0		70		
139.0		68		13
144.0		63		31.5
147.0				33
149.0		58.5	6.0	0
154.0				20
155.0		54	4.5	0
155.0				(26.5)
158.0			6.0	29
160.0		50		
165.0		37		31.5
166.0			7.5	49

B.1.2. EP303 Tests 6 - 40

a) Dry State Results

Voltage (kV)		23.5	21.0	19.5	18.0	16.5	15.0	13.5	12.0	10.5	9.0
Test 6	Down	21.5	15.5	9	4	2.5	2				
	Up	23	21	11.5	6	2.5					
	Down		13.5	11.5	5	2	2				
Test 7	Down	15	0	0	0						
	Up	45	25	0							
	Down		20	20	0						
Test 8	Down	38	35.5	33.5	28.5	25.5	22	20			
	Up	39.5	39.5	37	32.5	28	26				
	Down		36.5	33.5	30.5						
Test 9	Down	39.5	34.5	27	24	22	19.5	11.5			
	Up	40	37	30	25.5	21.5	19				
	Down		36	31.5	23.5						
Test 10	Down	20	16	8	4.5	3.5	2.5	1			
	Up	20	14.5	14.5	7.5	6.5	5.5				
	Down		10	7	6	4.5	1.5	1			
Test 11	Down	20	10	13	11	7	1	0			
	Up	19	17	15.5	15.5	8	6.5				
	Down		10.5	10	7	5	0.5	0.5			
Test 12	Down	47	45	43.5	42.5	29	27.5	21.5	20	15	10
	Up	45	45	44.5	42.5	27.5	25.5	22	19	15.5	
	Down		42.5	44.5	43	41.5	40.5	17	13.5	11	4
Test 13	Down	44.5	43.5	42.5	41.5	39	38	26	13.5	3.5	0
	Up	45.5	44	43	41.5	40.5	38.5	29	14.5	9	
	Down		43.5	42.5	41.5	41	39.5	36.5	26.5	21	6.5
Test 14	Down	31.5	26	17.5	13	10.5	5	0			
	Up	24	22.5	17.5	12.5	5	5				
	Down		12.5	6	5	0					

EP303 Tests 6 - 40 Dry Tests Continued

Test 15	Down	45	42.5	42	41	38	34	31	28	19	7
	Up	45	43.5	42.5	41.5	40	35	32	26	17.5	
	Down		42	41.5	40.5	36	33	28.5	25	20	12
Test 16	Down	15	7	0	0						
	Up	30.5	13	10.5							
	Down		14.5	12	6	0					
Test 17	Down	53	50	45	43	39	36.5	10	10	10	10
	Up	50	52	44.5	43.5	39	25	10	10	10	
	Down		47.5	45	40	38	34.5	25	0		
Test 18	Down	47.5	44.5	44	42.5	40.5	35	31	25	8	3
	Up	45.5	44.5	43.5	43.5	42.5	38	36.5	17	12.5	
	Down		44.5	43	42	41	39	34.5	30	10	0
Test 19	Down	41	40.5	39.5	38.5	35.5	33.5	31.5	27.5	24.5	19
	Up	42.5	41.5	39.5	37	36	34	30.5	27.5	24.5	20.5
	Down		38.5	36	33.5	30.5	28	25.5	21	16	10
Test 20	Down	46	40.5	37.5	36	36	27.5	23.5	18.5	17.5	11
	Up	50	47.5	47	43	41.5	38.5	36	23	15.5	9
	Down		45.5	43.5	38						
Test 21	Down	45	43.5	40	39	36.5	34	27.5	21.5	16.5	2
	Up	42	41.5	40	39	35	27.5	23.5	20	14.5	
	Down		37.5	36	34						
Test 22	Down	41	37	36	19.5	16	3.5	1.5			
	Up	39.5	38	36.5	18	15	3.5				
	Down		35.5	33	31						
Test 23	Down	15	9.5	7	4	2					
	Up	5	4	3	2						
	Down		2.5	1	0.5	0.5	0.5	0.5			
Test 24	Down	44	42	33.5	31	30.5	28.5	26.5			
	Up	42	43.5	42	34.5	32.5	30.5				
	Down		40.5	39	36						
Test 25	Down	15	2	2	2	2	2	2			
	Up	15	0	0	0	0	0	0			
	Down		0	0	0	0	0	0			
Test 26	Down	42	39.5	38.5	38	35.5	29.5	25	12.5	4.5	4.5
	Up	44.5	42.5	39	38	37	31.5	28	14	4.5	
	Down		42	40	37.5	33.5	30.5	27.5	22.5	5	
Test 27	Down	36	32	28	25.5	23.5	21.5	16	13.5	10	7
	Up	34	31	27	24.5	21.5	19	18	12	9.5	
	Down		32	25	23	20	16	14	10.5	6.5	6.5
Test 28	Down	45	42.5	40	37	33	26	22	19.5	15.5	13
	Up	46.5	44.5	42.5	37.5	34.5	30.5	23.5	19	16.5	
	Down		41.5	38.5	36	31	21.5	16	11	6	3

EP303 Tests 6 - 40 Dry Results Continued

Test 29	Down	20	0	0	0	0				
	Up	20	8	4	0					
	Down		13	6	0	0				

Test 30	Down	33	27	23.5	22	20	15.5	12.5	10	10
	Up	33	31	28	25.5	22	18.5	13.5	6.5	
	Down		28.5	24.5	21.5	17	14.5	7	7	7

Test 31	Down	33	23.5	22.5	21.5	14	6.5	2.5	1	
	Up	33	25	23	22	21	16.5	10.5		
	Down		30	32	33	32	29.5	26	17	

Test 32	Down	44	5	5	5	5	4.5	4.5		
	Up	30	30	30	30	15	15			
	Down		15	5	5	5	5	5		

Test 33	Down	29.5	25.5	19.5	16.5	13	10	10		
	Up	30	27.5	24.5	17.5	15	10.5			
	Down		25.5	20.5	18.5	11.5	10			

Test 34	Down	40	36	33	31	24	15	13	11	10
	Up	40.5	38.5	36	32.5	28	16	12.5	10	
	Down		37	34	31	23				

Test 35	Down	40	20	0	0					
	Up	50	45	20						
	Down		40	40	35					

Test 36	Down	40	5	5	5					
	Up	20	5	5						
	Down		5	5	5					

Test 37	Down	41	37	21.5	20.5	2	0			
	Up	42	37.5	20.5	20	0				
	Down		36	26	21	0	0			

Test 39	Down	15	3	3	3					
	Up	4	4	3						
	Down		4	4	3					

Test 40	Down	20	18	11	10	1	0			
	Up	22	13	12	2	0				
	Down									

b) 40:5 Severity - Wet Results

Time (min)	Test 6		Test 7		Test 8		Test 9	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	9.0	39	18.0	44	18.0		18.0	23
1.0		37.5		41 - 45		2		22
2.0		37.5		34		2		26
2.5		38		43.5		2		23
3.0		54		45		2		19
3.5		53		40 - 47		2		29

EP303 Tests 6 - 9 Continued

4.0	53	45	2	34
4.5	51	50 ± 2	2	33
5.0	62	60	12	48
5.5	67	61	52	60.5
6.0	71	68	56	68
6.5	72 ± 1	72 - 74	58	69
7.0	71	72 - 75	65	54
7.5	71 - 74	72.5	72 ± 2	53
8.0	71	73	70	56 - 62
8.5	70	73.5	72 - 77	64
9.0	70 - 75	73	75	70
9.5	71 - 74	73.5	75 - 78	70 - 73
10.0		73 - 76	73	71.5±2
10.5	71 - 74	74 - 77	73 ± 2	70 ± 3
11.0	71 - 74	74	74 ± 2	68 - 73
11.5	72	74	74 - 77	70 ± 4
12.0	72	74	74 ± 2	70 ± 4
12.5	72	73	72 - 76	66 - 70
13.0	72	73 - 76	72 - 77	64
13.5	72.5	73		62 - 68
14.0	72	73	73 - 80	64 - 74
14.5	72.5	72.5	74 - 80	73
15.0	72	72.5	72 - 80	73 - 78
15.5	72.5	72	74 - 78	71 - 78
16.0	72	72	74 - 78	72 - 79
16.5	72	71.5	72 - 76	73
17.0	71.5	71.5	74 - 78	73
17.5	71.5	72	70 - 76	73
18.0	72.5	72 ± 3	70 - 77	73.5
19.0	71.5	71 - 75	74 ± 3	73.5
19.5	71.5	71.5		72
20.0	71	72 ± 2		73
21.0	71.5	71.5±2	74 ± 4	72.5
22.0	72	71	74 ± 4	72
23.0	72	71.5	74 ± 4	72
24.0	71	71	74 ± 4	72
25.0	71	71		72
25.5	71.5	70.5		
26.5		71	74 ± 4	72
28.0		70.5		
28.5		71		
29.0	72	71	74 ± 2	21.0 74
30.0	71		74 ± 3	74
31.5	70.5	70.5	73 ± 3	73.5
32.0	71			74
34.0	71	70	73 ± 2	19.5 71.5
36.0			73 ± 2	72.5
40.0	70.5		73 ± 3	18.0 69
44.0	70		70 ± 4	70.5
46.0	69.5			16.5 67
49.0	68			68.5
49.5				15.0 64.5
50.0				65
50.5				65
51.0				66
52.0				66
52.5				66
53.0				13.5 61

EP303 Tests 6 - 9 Continued

53.5		61.5
54.0	70	61.5
55.0		62.5
55.5		62.5
56.0		62
56.5		57
57.0		57.5
57.5		58.5
58.0		58.5
59.0		59
59.5		59.5
60.0		59.5
62.0		61
66.0		61
76.0		63
83.0		63
88.0		62
90.0		63
92.0		63

12.0

c) 40:20 Severity - Wet Results

Time (min)	Test 10		Test 11		Test 12	
	KV	RIV	KV	RIV	KV	RIV
0.0	9.0	28	9.0	-5	9.0	20 - 28
1.0		28		27.5		0
2.0		28		27.5		-5
3.0		28		27.5		-5
3.5		27.5		27.5		-5
4.0		27.5		43		-4
4.5		27.5		53		6
5.0		27		65		11.5
5.5		27.5		72		12
6.0		27.5		75.5		12
6.5		27.5		77.5		10
7.0		27		77 - 79		11
7.5		27		77		10.5
8.0		27.5		75 - 77		11
8.5		43		76		15
9.0		57		76		35
9.5		61		75		43
10.0		69		75.5		45 - 50
10.5		73.5		75 - 77		53
11.0		72 - 74		76 - 78		51
11.5		72 - 77		75 - 79		55
12.0		77		79 ± 2		67
12.5		76 - 80		80 ± 2		67 - 70
13.0		76.5		80		64 ± 2
13.5		75		80		70
14.0		75 ± 1		77 - 81		70 ± 2
14.5		75 ± 2		77 - 81		73
15.0		75 ± 2		75 - 80		75
15.5		78		72 - 79		78

EP303 Tests 10 - 12 Continued

16.0	76.5	79 ± 2	76 - 79
16.5	74 - 80	79 ± 2	78 - 70
17.0	78	72 - 81	77
17.5	77 - 80	77 ± 3	76 - 79
18.0	79 ± 2	77	76 - 81
18.5	79 ± 2	77	
19.0	79 ± 2	77 ± 2	76 - 81
19.5	77 - 82	79 ± 2	77 - 82
20.0	80 ± 1	79 ± 2	77 - 81
20.5	80 ± 2	77 ± 2	76 - 82
21.0	80	72 - 78	76 - 84
21.5	80	72 - 80	76 - 84
22.0	80 ± 2	72 - 77	74 - 81
22.5	80 ± 1	72 - 77	75 - 81
23.0	79	72 - 77	75 - 81
23.5	77 ± 2	72 - 77	79
24.0	76 - 79	74 ± 2	79 ± 3
24.5	76 - 81	77	79 + -3
25.0		72 - 77	74 - 82
25.5	70.5	72 - 77	73 - 82
26.0	80 ± 1	73 ± 2	
26.5		72 - 77	
27.0	80 ± 2	69 - 77	73 - 81
27.5		74 ± 3	73 - 81
28.0		70 - 77	
28.5		74 ± 3	73 - 80
29.0		75 ± 3	73 - 80
30.0	77 - 82		
31.0		70 - 77	
32.0		72 ± 3	72 - 81
33.0		74 ± 4	73 - 79
34.0	79 ± 2		76 - 83
36.0	77 - 81	50	80 ± 3
37.0		41	80 ± 3
38.0	75 - 81	41	72
39.0		40	52
40.0	76 ± 1	31 - 42	47
41.0		30 - 45	
42.0	65	39	45
43.0	57	51	
43.5		39	39
44.0	57		41
45.0	51 - 55		
46.0			26
47.0	47 - 50		35
49.0	42.5		35
51.0	32 - 42		26

EP303 40:20 Wet Tests Continued

Time (min)	Test 13		Test 14		Test 15		Test 16	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	12.0	20 - 28	12.0	6	12.0	23	12.0	0
1.0		20 - 26		15		22		0
2.0		18 - 26		40		22		0
3.0		27.5		51				40
3.5		28.5		62		30		48
4.0		29.5		63.5		29.5		47
4.5		29		64				54
5.0		28		66		31		50 - 54
5.5		27		65				47
6.0		30		58		29		40
6.5		30		56 - 60				44
7.0		35		51		29		
7.5		32		53 ± 3				0 - 40
8.0		33				25		60 ± 5
8.5		36.5				23.5		60
9.0		39.5				37		
9.5		43				41.5		64
10.0		47.5				43		
10.5		55		50		49		
11.0		64				56		62 - 65
11.5		72		53		60		
12.0		77				67		
12.5		79 ± 10				71		
13.0		79				70		64 ± 2
13.5		79.5				70.5		
14.0		79.5				69.5		
14.5		79.5				68		64
15.0		80				65		
15.5		79				63		
16.0		79.5		46.5		54		
16.5		79.5				51		65.5
17.0		79				56		
17.5		78.5						
18.0		78.5		42		61.5		
18.5		78.5				63 - 70		
19.0						62.5		
19.5						61.5		
20.0		80		40				
21.0		80				64.5		
22.0				40 ± 5		63.5		
22.5		80.5				63		
23.0						63 - 70		
23.5		80.5				65 - 70		
24.0						63		
25.0		81.5				62		
25.5								61
26.0		80.5						
26.5								63
28.0		80.5		40 ± 5		66		
28.5			13.5	50		66		
29.0				51				
30.0				50		62 - 69		
30.5		79.5		50.5				

EP303 Tests 13 - 16 Continued

31.0			50.5		
32.0	79	15.0	54.5		
32.5			56.5	62 - 70	62
33.0	79		55.5		
34.0			55		58
35.0	78	16.5	52.5	60 - 70	58
36.0			52.5		
37.0	77		48	63	
38.0		18.0	51		
39.0	75.5		48		55 - 63
40.0	75.5		26		
41.0	74.5	7.5	6	63	
42.0	74.5			61	
43.0	72.5		6		
43.5	66.5				
44.0	63	1.5	0	60.5	
45.0	61			62.5	
46.0	50				53 - 59
47.0	54				
48.0	51				51
49.0	50.5				56
50.0	50			60	54
51.0	49				
52.0	50.5			58 - 60	
53.0	47.5	12.0	58	60	
54.0	49.5		48.5		
55.0	51.5		34	60 ± 2	
56.0	49		32		50 - 58
57.0	47.5		36.5		
58.0	49		34		53
60.0	49			60	

Time (min)	Test 17		Test 18		Test 19		Test 20	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	15.0	34.5	15.0	40	15.0	22	15.0	0.5
1.0		33		39.5		23		0.5
2.0						26		0.5
2.5				35		4		
3.0		31		40		49		38
3.5						40		0.5
4.0		25 - 35				60		49
4.5		39				68		63
5.0				39.5±1		75		78.5
5.5		37				75.5		73 - 79
6.0		36.5						67
6.5		42.5		73.5				54
7.0		43		40.5				52
7.5		42.5						52
8.0		45		33		72		59
8.5		45.35						69
9.0				31 - 32		72.5		68
9.5				34				68 - 73
10.0				39				69
10.5				44.5		70.5		69

EP303 Tests 17 - 20 Continued

11.0			53		68.5
11.5			60	67.5	68.5
12.0	76		62		70
12.5	79		70	58	67 - 75
13.0	80.5		75.5		69
13.5	82		77	64	68.5
14.0	82			66	70
14.5			78	67	70
15.0			71		70
15.5	81.5		64	68.5	70
16.0			60		68
16.5			58		69
17.0	79.5		>70		68
17.5			62	66 - 74	
18.0	74.5		65		68
18.5			>70		68.5
19.0	74		67 - 70		69
20.0	72				69
20.5			68		69.5
21.0	70				70
21.5				70 ± 1	
22.0	68		69	67	71
23.0	64		68		70.5
24.5	57		68 - 71		
25.0	65				69.5
26.0			68	60	69
27.0	65				69
27.5					69.5
28.0	64			58.5	68
29.0	63			62	67.5
29.5				59	67
30.0					67
31.0			68 ± 5		66
32.0	59				66
33.0	56 - 60			58 - 62	
34.0	55		67 ± 5	56	67
36.0					65.5
37.0	61		67 ± 5	57	
38.0	60		67		65
39.0	59			51	
40.0	60				65.5
41.0	57			49.5	
42.0	55.5				63.5
43.0	51			47.5	
44.0	47				65 ± 1
45.0	40			40	
46.0	35		66	34 ± 2	
47.0	38			25 - 35	60.5
48.0				13	
49.0			66		58
50.0			65	5 - 30	
52.0			64	10	59
55.0			64		
60.0			58		
62.0			55		
63.0			52		

EP303 40:20 Wet Tests Continued

Time (min)	KV	Test 21	Test 22	Test 23	Test 24	Test 25
		RIV	RIV	RIV	RIV	RIV
0.0	18.0	37.5	28	24.5	40	0
1.0		40		25.5	35	0
2.0		39.5	27	17 - 25	33	0
2.5		50			34	
3.0		52	23	19.5	39	
3.5	54 - 58		32	30	57	50
4.0	45		31	20	59	60
4.5	45 - 55			43	52	72
5.0	35	15 - 30		60	59	76
5.5	42			66	65	72
6.0	51.5	41		66	69	70
6.5	66			66	71	65
7.0	63.5	47		60	71	64
7.5		54		56 - 61	71 ± 2	66
8.0	71	57		56	72 ± 2	68
8.5	71.5	63.5			71.5	68
9.0		73		64	72 ± 2	66
9.5	75	79		66.5		66
10.0	74.5	70			72	66 - 68
10.5		66		68		65 - 70
11.0	75.5	62		69.5	73.5	61 - 70
11.5	Trip			69.5	73	66
12.0	Trip	64	71 - 75		73	65
12.5		67	71 - 75		73.5	65 ± 1
13.0		69	71		74	66
13.5					74	65.5
14.0	75	70 ± 2	73 - 80		74	64
14.5					74	64
15.0	74.5	69 - 75	73		74	62
15.5					74 - 77	63
16.0			73 - 80		73 - 77	62
16.5		75 ± 5			72 - 76	62
17.0		75 ± 5			74.5	61
17.5		75 ± 5				5 - 70
18.0	74.5		73		74	58
18.5			75			59
19.0					72 - 79	57
20.0					74	55
20.5					73	
21.0		72 - 80	73 - 80		73	
21.5					74 ± 1	57
22.0	74	73	72 - 78		73	58
23.0					73	57
23.5					73.5	57
24.0					72.5	54.5
24.5	73				72.5	55
25.0		72 - 80	72		72	55
26.0	73.5	72			73.5	
27.0		72				56 ± 2
27.5					72	55.5
28.0					71.5	57
28.5		71			71.5	57
29.0		71			71	56

EP303 Tests 21 - 25 Continued

30.0				71 ± 1	52
31.0	72			71	51 - 57
32.0		71		71	48 - 57
33.0				70.5	52
34.0				70	48 - 56
35.0					
36.0		71			54
37.0	70.5			70.5	53
38.0				70 ± 1	45 - 52
39.0				70	
40.0			71		47
41.0	68	71		69.5	
42.0	69			69.5	35 - 45
43.0		71		69 - 74	30 - 45
44.0				69 ± 1	40
45.0			71	69 ± 1	
46.0	67.5	70 ± 1			22
47.0	67			69.5	
49.0	67	69			
50.0	66		70.5	69.5	
52.0	65.5	68			
55.0	64.5	68	70	69	
60.0			69.5	69	
62.0					
63.0	63	68 ± 1		69	
64.0	63				
65.0			69		
66.0		68			
68.0	62				
76.0		68			

d) 40:40 Severity Results

Time (min)	Test 26		Test 27		Test 28	
	KV	RIV	KV	RIV	KV	RIV
0.0	9.0	4.5	9.0	6.5	9.0	2.5
1.0						3
2.0		4.5		4		3
2.5						3
3.0		4		4		2
3.5		1.5		4		2
4.0		4		9		2
4.5		2		11		11
5.0		1.5		10		22.5
5.5		4		8.5		30
6.0		4.5		22		35
6.5		16		40		42.5
7.0		17		46		45.5
7.5		16.5		55		51
8.0		18		61		52.5
8.5		20		60		56
9.0		19		66		57
9.5		20		74		60

EP303 Tests 26 - 28 Continued

10.0		23	74	61.5
10.5		26	74	62
11.0		28	75	62.5
11.5		45	76	78
12.0		52	75	79 ± 1
12.5		48.5	75	77
13.0		60	76	77
13.5		65	75.5	78 - 81
14.0		73	76	78
14.5		68	76	79 ± 1
15.0		70	77	78 ± 3
15.5		72	71	78
16.0		69 - 73	78	78
16.5		70	79	78
17.0		75	78.5	78
17.5		77.5	79 ± 1	78
18.0		76	80	78
18.5		77	80	
19.0		78	80	78
19.5		79 ± 1	79	
20.0		79 ± 1	79	78
20.5		76	78 - 81	
21.0		77	79	77
21.5		77	79	
22.0		77 ± 1	78	77.5
22.5		77		
23.0		76		77
23.5		76		
24.0		77		78
24.5		78		
25.0				78.5 ± 1
26.0		80		
29.0		77.5		78 ± 2
30.0		79		
31.0		81		
32.0		82 - 83		80 ± 5
33.0		82 ± 1		81 ± 4
34.0		82 ± 2		
42.0		83		
49.0		78 - 82		
52.0		80 ± 2		
52.5	7.5	76		
53.5	6.0	71		
55.5		76		
56.0	4.5	67		
60.0	6.0	76		
59.0	4.5	71		
64.0		66 - 68		
65.5	3.0	54		
66.0		57		
71.0		60		

EP303 40:40 Wet Tests Continued

Time (min)	Test 29		Test 30		Test 31		Test 32	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	12.0	0	12.0	5	12.0	10	12.0	5
2.0				5		6.5		5
3.0				5		7		5
3.5						27		5
4.0		35		5		38		5
4.5		37		12		47		25
5.0		45		24		51		35
5.5		51		35		55		38
6.0		58		40		62		55
6.5		60		43		61		53
7.0		59		67		70.5		50
7.5		65		68		72		57
8.0		64		73		76.5		61
8.5		66		75		77 - 81		62
9.0		69		76		77 - 81		64
9.5		70		78		79		63
10.0		72		79 - 81		76 - 83		60 - 64
10.5		75		79		80 - 83		64
11.0		76		79		83		65
11.5		78		79 - 82		82		65
12.0		78		80 - 83		79 - 85		64 - 68
12.5		78		82 - 83		82		64
13.0		77 - 81		79 - 83		82		65
13.5		80 - 83		80 - 85		83		65
14.0		80		82.5		82		>70
14.5		82 - 84		81.5		82		65
15.0		82		83.5		82		63
15.5		82		82.5		81		63
16.0		79 - 84		83		81		65
16.5				82.5		79 - 82		66
17.0				83		80 - 83		67
17.5				83		83		65
18.0				83		81 - 83		63
18.5				83		82.5		65
19.0						83 ± 2		64
19.5		78 - 83		83		83		65
20.0						81 - 85		66
20.5						83		65
21.0		78 - 82				83		65
21.5						83 - 86		62
22.0				83		81 - 85		63
22.5				83		83		63
23.0				83		80 - 85		
23.5						63		
24.0						81		63
24.5		76 - 83				81		63.5
25.0				83		81 ± 2		65
29.0		77 - 84				78 - 85		
30.0								64
33.0				80				
34.0		76 - 80				80 ± 2		65
35.0		76 - 82		78 - 80				
39.0		76 - 82		78		77 - 82		

EP303 Tests 29 - 32 Continued

40.0	77	78	
44.0		75	79
49.0			79
50.0		68	
54.0		66	79
59.0		60	79
64.0		57	80 ± 1
69.0			79
74.0			79 - 81
79.0			80 ± 1
84.0			79 - 84

Time (min)	Test 33		Test 34		Test 35		Test 36	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	15.0	23		24	18.0	40		5 - 20
1.0		34		24		45		
1.5						46		
2.0		35		22		45.5		
2.5		40		30		46		18
3.0		40		52		41		23
3.5		46		61				40
4.0		44 ± 4		62		48		50
4.5		38		58		49.5		53
5.0		45		60 - 63		51		61
5.5		40 ± 2		61.5		53		63
6.0		44		63 ± 1		60		62.5
6.5		56		63		70		65
7.0		60		63		73		67.5
7.5		63		64				68
8.0		67		64		72		
8.5		67		67				70
9.0		68 ± 5		68				73.5
9.5		70		70.5		73		72.5
10.0		70.5		71 - 74		73		72.5
10.5		70.5		72				
11.0		71		73		74		73.5
11.5		71.5		73.5				
12.0		72		73				75.5
12.5		71.5		73				
13.0		72		73				75
13.5		71.5						
14.0		72		73		74		
14.5		75	18.0	77				
15.0		76		77				
15.5				77				
16.0		77		74				
16.5		73.5		76.5				
17.0		73		76				
17.5		73		76.5				
18.0	12.0	61.5	Trip					
18.5		66						
19.0		68				75		75.5
19.5		67	15.0	74.5				
20.0		67.5		72.5				

EP303 Tests 33 - 36 Continued

20.5		68		73		
21.0		68		73		
21.5	9.0	45	18.0	76		
22.0		50.5		75.5		
22.5		53		75		
23.0		57		75		
23.5		59		75		
24.0		60		75	74	75
24.5		60		74		
25.0	6.0	6		66		
25.5		6	15.0	67.5		
26.0		6		68.5		
26.5	9.0	65				
27.0		61.5		70		
27.5		62		70		
28.0		61.5		69.5		
28.5		62	18.0	73		
29.0		63		73.5	75	74
29.5		60		73.5		
30.0	12.0	66		73.5		
30.5		65.5		73.5		
31.0		66.5		73.5		
31.5		65.5		73.5		
32.0		66	15.0	62.5		
32.5		64		65.5		
33.0		64		66		
33.5				66.5		
34.0				66.5	74	73
34.5				67		
35.0				67		
35.5			12.0	49		
36.0				51.5		
36.5				53.5		
37.0				54.5		
37.5				55.5		
38.0				56		
38.5				57		
39.0			9.0	30	73	73
39.5				35		
40.0				36	72.5	
40.5				40		
41.0				41.5		
41.5				42.5		
42.0				42.5	72.5	
43.5				44		
44.0				45		72.5
45.0				46		
47.5				50		
49.0				51.5	72	
51.0				54		
54.0				55		
56.5				54.5		
59.0				55	72.5	
64.0				54		
67.0					72.5	
69.0					72.5	

EP303 Wet Tests Continued

e) Clean State Results

Time (min)	Test 37		Test 38		Test 39		Test 40	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	15.0	0	15.0	0	18.0	2 - 11	25.5	22
1.0		(24.5)		(25.0)		(24.8)		(23.8)
2.0				< 20		0		24
3.0								33
4.0								35
5.0								47
6.0				6.5				34
7.0		0		6.5				25
8.0								30 ± 5
9.0		19		6 - 10				30
10.0		24.5				7		25
11.0		20.5				7		35
12.0		32.5				7		5
13.0		26						5
14.0		20 - 33						5
15.0		0 - 5						
16.0				6 - 10				
17.0		28						
18.0		29						
18.5		22.5						
19.0		11		6 - 13				< 5
20.0		0 - 5				0		
21.0				6.5				
22.0						7		
24.0				< 20				
25.0						7		
26.0		0						
29.0				< 20				
30.0						7		
32.0								
33.0						7		
39.0		0						
40.0						7		
31.0				< 20		7		
42.0						7		
47.0						7		
69.0		0						

B.1.3. EP303 Tests 41 - 62

a) Dry State Results

Voltage. (kV)	RIV (dB/ μ V 300 Ω)										
	Test 41	Test 42	Test 43	Test 44	Test 45	Test 46	Test 47	Test 48	Test 49	Test 50	Test 51
22.5	49	47	49	43	47	48	51.5	50	43	49	
21.0	25.5	43.5	41	30	45.5	46	38	48	34.5	43.5	
19.5	20	37	27	21	43	42	37	47	30	40.5	
18.0	16	31.5	23	19	41	38.5	36	45	17	34.5	46.5
16.5	11.5	26	18	17	31.5	32		33	16	28.5	35
15.0	3.5	18	9	16	28	24		29	16	23	29
13.5	3.5	7	6	15	3.5	17		20.5	11.5	17.5	16
12.0	3	5.5	3	13.5	3.5	12		15	7	11.5	14
10.5	3	3	3	11.5	3.5	10		5	5	6	11
9.0	3	2.5	1	1	3.5	4		5	5	5	4
7.5	3	2.5	-3	1	3.5	4		5	5	5	
6.0	3	2.5	-4	1	3.5			5	2		
4.5	3	2.5	-4	1				5	2		
3.0	3	2.5	-4					5	2		

Voltage. (kV)	RIV (dB/ μ V 300 Ω)										
	Test 52	Test 53	Test 54	Test 55	Test 56	Test 57	Test 58	Test 59	Test 60	Test 61	Test 62
22.5	20	40		42	51.5	48	46	45	48	57	58
21.0	11	35		24	46	40	40.5	43	33		
19.5	0	33		22	44.5	34	38.5	39	31		
18.0		29		20	42	32.5	36.5	38	30		
16.5		17.5		19	32.5	29	28.5		22		
15.0		14		17		16	26.5		20		
13.5		7		15		13.5	25		17		
12.0		2		8		11	22		15		
10.5		2		4.5	25	3	2		12		
9.0		1		0		0.5	2		6		
7.5		0				0.5	2		0		
6.0		0				0.5	2		0		
4.5		0				0.5	2		0		
3.0		0				0.5	2		0		

EP303 Wet Tests Continued

b) 40:5 Severity Results

Time (min)	Test 41		Test 42		Test 43	
	KV	RIV	KV	RIV	KV	RIV
0.0	1.5	3	3.0	2.5	3.0	-4
0.5		3		2.5		
2.0				2.5		-4
4.0				2.5		-4
5.0		3		15		9
5.5		10		34		9
6.0		17		42		7
6.5		20		43.5		7
7.0		23		46		7
7.5		27		44 - 48		7 - 10
8.0		27		52		15
8.5		32		52		30
9.0		34 - 39		54		35
9.5		36		58		37
10.0		34 - 37		59		40.5
10.5		36 ± 2		59		46
11.0		36		59.5		48
11.5		38		59.5		
12.0		40		60		52
12.5		37 - 41				
13.0		40 ± 1		60.5		55
13.5		40.5				
14.0		40.5		60		57
15.0		42		59.5		58
16.0		43 ± 2		60 ± 1		59.5
17.0		43 ± 2		60 ± 1		60
18.0		42 ± 1		61		60.5
20.0				60.5		61
22.0		42		61		61.5
23.0		42		61 ± 1		61.5
24.0		42				
25.0	3.0	66		61		63
26.0		65		58		
26.5	6.0	77				
27.0		80		58 - 60		63
28.0		78				
29.0	12.0	79 - 84		60 ± 1		63
29.5		85				
30.0		85				
31.0		85		61		62
32.0	18.0	83 ± 2				
33.0		82				60
34.0		82 ± 2				56 - 59
35.0		82				58 ± 2
36.0						57
37.0				48		57 ± 2
39.0				48		54
40.0						50
41.0				47		
44.0				46		

EP303 40:5 Wet Tests Continued

Time (min)	Test 44		Test 45		Test 46		Test 47	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	4.5	1	6.0	3.5	7.5	4	18.0	33.5
0.5		1		3.5				33.5
2.0		1		3				33
3.5		15		3				25
4.0		39		3		4		45
4.5		50		3		5		40
5.0		51		25		11		52
5.5		54		35		30	48	57
6.0		56		42		42		52
6.5		63.5		44		58	54	60
7.0		65.5		53		62		66
7.5		67		56		67	69	± 1
8.0		67		59		72	71	± 2
8.5								78
9.0		67		70		76		81
9.5								82.5
10.0		68.5		74		79 ± 1		85
10.5							86	± 1
11.0		69 ± 1		75		79	86	± 1
11.5								86
12.0		69 ± 1		77.5		79 ± 1		87
12.5								86
13.0		70		77		79 ± 2	86	- 92
13.5							85	- 89
14.0		69		76		79 - 81	84	- 88
15.0		69		76.5		79 ± 2	86	± 3
16.0				76		79 ± 2	86	± 3
17.0		69		76 ± 1		80 ± 2	84	± 2
18.0		69 ± 1					83	- 87
20.0		68		77		81 ± 1		
22.0				79		81.5 ± 1		83
23.0		70		78		81.5	81	- 87
24.0		69					84	± 2
25.0				78.5		80 ± 2	19.5	86
25.5								86
27.0				78		78 ± 2		84
27.5							21.0	86
28.0								83
29.0				77		78		80 ± 5
29.5							22.5	80 ± 5
30.0								80 ± 5
31.0						75 - 80		70 - 85
31.5							24.0	87
32.0								85 - 89
33.0						77 ± 2		85 - 89
33.5							25.5	90
34.0								89 - 93
35.0						74		92
36.0							18.0	53
38.0								31 - 55

EP303 Wet Tests Continued

c) 40:20 Severity Tests

Time (min)	Test 48		Test 49		Test 50	
	KV	RIV	KV	RIV	KV	RIV
0.0	1.5	5		6		5
1.0				2		
3.5						5
4.0						30
4.5				2		32
5.0				10		50
5.5				42		50
6.0				45		58
6.5				47		63
7.0		5		46		67
7.5		10		46		70
8.0		25		46		71 ± 1
8.5		32		54		73
9.0		32		56		77
9.5		32 ± 2		56		81
10.0		20		58		81
10.5		20		66		
11.0		22		68 - 70		81 ± 1
11.5		32				
12.0		31		67 - 71		78 - 80
12.5		36				
13.0		40		71 ± 2		78.5±2
13.5		44				
14.0		47 ± 2		70 - 73		77 - 81
14.5		51				
15.0		53		74 ± 1		78
15.5		55				
16.0		55		74 ± 1		79
17.0		56		74 - 80		78
18.0		58 ± 2		74 ± 1		
19.0		59		74 - 76		78
20.0		59				
21.0		59		75		78
22.0		58				
23.0		58		72 - 74		77
25.0		55		71		
27.0		52 ± 5				
28.0		54 ± 5		72		
29.0				70		
29.5				66		

EP303 Wet Tests Continued

d) 40:40 Severity Tests

Time (min)	Test 51		Test 52		Test 53	
	KV	RIV	KV	RIV	KV	RIV
0.0	1.5	4	1.5	0	2.25	10
1.0		4				0 - 10
2.0		4				0 - 15
3.0		4				0 - 15
4.0		4		3		37
4.5						44
5.0				0 - 13		44.5
5.5		24				44
6.0		28				44
6.5		30				44.5
7.0		34		3		44.5
7.5		31		0		46
8.0		33 - 35		0		
8.5		35		0		46.5
9.0		35		0		46.6
9.5		36		0		49.5
10.0		36		0		49.5
10.5		40		0		55
11.0		40		0		58 ± 4
11.5		40 - 43		0		60
12.0		40 - 45		0		62
12.5		50 - 55		0		65
13.0		46 - 51		0		64.5
13.5		46 - 50		0		67
14.0		46 - 50		0		66 - 69
14.5		46 - 50		0		69 ± 2
15.0		50 - 56		0		69.5
16.0		52 - 58		0		72
17.0		53 - 58		3		67 - 73
18.0		57 - 59		3		67 - 73
19.0				2		69
20.0						69
21.0				12		
22.0				12.5		67
23.0				12.5		
24.0				12 - 37		67
25.0					3.0	75
26.0				12 - 47		72 - 76
26.5					4.5	74
27.0						70 - 76
28.0						70 - 78
28.5				57 - 59		
29.0				54		74 ± 5
29.5					6.0	83
30.0				56 ± 2		80 - 83
31.0				57 ± 1		81
31.5				56 - 61	7.5	85
32.0				56 - 65		81 - 85
33.0						82
33.5				55 - 60	9.0	86
34.0				61		83

EP303 Tests 51 - 53 Continued

34.5		63	
35.0		60	83
35.5			10.5 86
36.0		59	85 ± 3
37.0		59 ± 2	80 - 86
37.5			12.0 86
38.0		59	85
39.0			84 ± 3
39.5			13.5 87
40.0			80 - 87
41.0			84 ± 3
41.5			15.0 85
42.0			85
43.0			80
44.0			78
44.5			76
46.0			76
48.0			74
50.0			74
50.5			3.0 0 - 10
51.5			18
52.5			35
53.0			44
54.0			46
57.5			54
63.0			60
76.0		1.5 31	
76.5		2.25 39	
77.0			43
78.0			42
78.5		3.0 47	
79.0			45
79.5		4.5 53	
80.0			51
80.5		6.0 60	
81.0		64 ± 5	

Time (min)	Test 54		Test 55		Test 56	
	KV	RIV	KV	RIV	KV	RIV
0.0	9.0	3	9.0	0	18.0	39.5
1.0		71.5		0		39.5
2.0		72		0		39.5
3.0		74		9		39.5
3.5		78		25		36.5
4.0		79		41		37
4.5				58		
5.0				66		33
5.5				70		34
6.0				73		34
6.5		81		75		36
7.0				77		36
7.5				79		37
8.0				79 - 83		48
8.5		81.5		80 - 84		57

EP303 Tests 54 - 56 Continued

9.0		80 ± 3	82 ± 2	53.5
9.5				63
10.0			82	70
10.5				73
11.0				77
11.5				79
12.0			81	81
12.5				81.5
13.0		80 ± 4	82	
13.5				80
14.0			82	79
15.0			80	
16.0				75.5
17.0				76
18.0			82	77 ± 2
19.0				75
20.0		78 ± 2	80	77 - 80
23.0			79	
24.0				79.5
25.0			81	77 - 80
28.0			81	77
29.0		78	80	
32.0		77		
33.0			81	
36.0		73		73
37.0	12.0	84	80	73
38.0		84		
39.0		82 ± 2	77	
40.0			78.5	70.5
40.5				>80
42.0			80	69 - 80
44.0			76	<44
45.0				60 - 65
49.0				55 - 80
57.0			75	
64.0			74	40
70.0			73	
76.5			7.5	63
77.0			6.0	53
77.5			4.5	43
78.0				50
79.0				56
79.5			60 ± 4	
80.0			3.0	43
80.5				48
82.0				54
83.0				56
84.0				58
85.0				62
86.0				63.5
87.0				67
88.0				68
90.0				68
91.5				67.5
92.0			1.5	39
93.0				44
94.0				47

EP303 40:80 Wet Tests Continued

Time (min)	Test 57		Test 58		Test 59	
	KV	RIV	KV	RIV	KV	RIV
0.0	1.5	0	3.0	2	18.0	38
2.0						38
4.0						59
6.0		0		45		77.5
6.5		5		48		79
7.0		5		47		80 ± 3
7.5		20		48		80 - 83
8.0		25		48		82 ± 2
8.5		27		48		82 ± 2
9.0		27		48		82 ± 2
9.5		25 - 28				80 ± 2
10.0		25 - 28		49		80 ± 2
10.5		25 - 30				79 ± 1
11.0		32		51		79
11.5		32 ± 2				79
12.0		32 ± 2		54		79 - 85
12.5		32				80 ± 1
13.0		30 - 36		55.5		80 ± 1
13.5		30 - 36				80 ± 1
14.0		32 ± 2		60		82 ± 2
14.5						81
15.0		32 - 37		67 ± 3		81 - 85
15.5						79.5
16.0		33 ± 2		70 - 73		80 ± 2
16.5						77
17.0		35		74		79
17.5		44				
18.0		50		76 ± 1		70
19.0		60		75 ± 2		
20.0		56 ± 2				
20.5		58 ± 2				
21.0		59 ± 2		72 - 75		78
22.0		57 ± 2				
23.0		56		70 - 75		76 - 80
23.5		57 - 61				78
24.0		55 - 61				
25.0		59		70 - 75		
26.0		59				
27.0		58 - 62		69 - 73		
28.5	3.0	55 - 60				
29.0		50 ± 5		72		
30.0		40 - 60				
30.5	6.0	80				
31.0		82				
32.0		82				
32.5	12.0	85				
33.0		84				
34.0		82 - 85				
34.5	18.0	86				
35.0		84 - 87				
36.0		82				

EP303 Wet Tests Continued

f) 40:10 Severity Test

Time (min)	Test 60	
	KV	RIV
0.0	3.0	-4
5.0		-4
5.5		4
6.0		7
6.5		13
7.0		22
7.5		30
8.0		39
8.5		45
9.0		45
10.0		46
11.0		52
12.0		64
13.0		68.5
14.0		68.5±1
15.0		69 - 70
16.0		70
17.0		71
19.0		72
21.0		72
23.0		72 ± 1
25.0		72 ± 1
27.0		72 ± 1
29.0		71
31.0		70 ± 1
32.0		60 ± 5
32.5		60 - 63

g) Clean State Tests

Time (min)	Test 61		Test 62	
	KV	RIV	KV	RIV
0.0	22.5	45	22.5	47
1.0		44		47
2.0		43		46
3.0		27		45
4.0		26		40
5.0				35
6.0				32
7.0		24		29
8.0				27
9.0		26		26
10.0		27		27
11.0		28		26
12.0		30		24
13.0		32		26
14.0		32		27
15.0		32		27
16.0				28
17.0				28
18.0				29
19.0				29
20.0				28.5
21.0				28
22.0				29
23.0				30
24.0				30
25.0				29
26.0				29.5
27.0				30
28.0				29.5
29.0				29.5
30.0				28
31.0				24 - 27
32.0				
33.0				24
34.0				30
35.0				31
36.0				31
37.0				29.5
38.0				
39.0				29.5
40.0				29

B.1.4. EP303 Tests 63 - 67

Test No. Severity	63 40:5	64 40:5	65 40:10	66 40:20	67 40:80	
Time (min)	KV	RIV	RIV	RIV	RIV	
0.0	Off	(23.5)	(22.0)	(24.5)	(24.5)	(23.0)
15.0		I	St Off	I	I	I
19.0		(27.0)	(26.0)	(28.5)	(28.5)	(26.8)
20.0	0.0					
20.5	6.0	80	75	82.5	81	79
21.0		80	75 ± 2	82.5	81 ± 2	84
21.5		79	77 - 79	81	82	85
22.0		80.5	80	80.5	81	84.5
22.5		80	80	80	80 - 83	
23.0		80	80	80	80.5	83
23.5		79.5	80	80 ± 2	80	82.5
24.0	9.0	83	80	83	84	88
24.5		79 - 84	80 - 83	81	83.5	83 - 88
25.0		82	82.5	80.5	83	83
25.5		82	83	80	83	83
26.0		82	83	79 - 84	84	82.5
26.5		82.5	83.5	82	83.5	80
27.0	12.0	83	83	81.5	83	80
27.5		85	87	84	83 - 85	88
28.0		82	85.5	80 - 85	83 - 86	79
28.5		82	84	80 - 85	84	78.5
29.0		82	82	82 ± 2	83	78
29.5		82.5	82.5	81 ± 2	82	77
30.0		82	83.5	81 ± 2	81.5	77
30.5		82	82	81 ± 2	80 - 82	77
31.0	15.0	87	87	87	<85	80
31.5		84	85	85	80	78
32.0		81 - 85	84	83.5	78	77.5
32.5		83	82	83	77	77
33.0		82	81	82	77	76.5
33.5		82	79 - 83	82.5	76.5	75
34.0		82	79	81.5	76.5	75
34.5	18.0	86	86	86	78	74
35.0		79 - 84	75 - 80	82	74	72
35.5		78	76	80	74	70
36.0		78	75	80	73	67
36.5		78	74	80	72	65
37.0		78	73 - 78	80	69	64
37.5		79	72	80	68	63.5
38.0			(24.0)	(27.5)	(27.5)	(25.5)
38.0		(26.8)	71	78	67	62
38.5		77	71	77	66	61
39.0		77	70	77	65	61
39.5		73	69	74 ± 3	64	60
40.0	15.0	71	66.5	62	60.5	58.5
40.5		74	66	65.5	60	58.5
41.0		74	66	65.5	60	58.5
41.5		74	65	65	59	58
42.0		74	65.5	66	56	57
42.5		74	65	66	54	56
43.0		74	64.5	64 - 66	54	56.5

EP303 Tests 63 - 67 Continued

43.5	12.0	56	41.5	51	51	51
44.0		56.5	55	49	50	51
44.0		56.5	55	49	50	51
44.5		59	57	54	50	51
45.0		60	55	59	50	52
45.5		58 ± 4	53 - 57	54	50	53
46.0		64	53 - 57	50	49.5	53.5
46.5		66	55	58	48.5	53
47.0	9.0	50	37.5	43	42	47
47.5		50	38	44	42	48
48.0		50	39	44.5	41	49
48.5		50	40	44.5	40	48
49.0		49	40	44.5	40	48
49.5		48.5	41	44.5	40	48
50.0		49	40.5	44	40	48 ± 1
50.5	6.0	42	33	37	25	20 ± 8
51.0		45	33.5	38.5	28	28
51.5		45	36	40.5	30.5	32
52.0		46	37	42	31	36
52.5		46	37	41.5	31	40
53.0		46	38.5	42.5	34	40 - 44
53.5		45.5	40	42	34	44
54.0		45	39	42.5	36	45
54.5		45	39	43	36	46
55.0		45	39 I	43	36	47
55.5		47	40	43	37	46
56.0		47	40	43.5	37	47
56.5	9.0	51	46	54	42	53
57.0		50.5	46	54 ± 2	41.5	56
57.5		50	45	55	41.5	55
58.0		50	44.5	52	41.5	53.5
58.5		49.5	44.5	50	41	53
59.0		49	44	45	40.5	52
59.5		48.5	44	45	41	52
60.0	12.0	78	64 ± 5	62	44	57.5
60.5		76	60 ± 5	56	42	56
61.0		74 - 80	45 - 55	54	42	55
61.5		77	50 - 60	54	41	55 ± 3
62.0		77	40 - 60	52	41	53
62.5		77	40 - 60	51	41	51
63.0		77.5	55 - 60	50	40	49
63.5	15.0	84	79	66	43	56
64.0		80	72 - 79	61	45	55
64.5		81	72 - 79	59	40	54.5
65.0		80	71	59 - 65	40	54
65.5		79.5	70.5	60 ± 5	39	49.5
66.0		79	70	55	38	30
66.5		77	69	55	37.5	5
67.0	18.0	84	75 - 80	72	39	61
67.5		81	73 - 78	68	38	59
68.0		79.5	71	68	38	56.5
68.5		78	70	68	36	56
69.0		78	68	66	36	56
70.0		70 - 78	66	67.5	34	56
70.5		60 - 74	66	67	33	55
71.0		(25.0)	(24.0)	(26.0)	(26.0)	(25.4)
72		64	64	67		

B.2. U70BL Results

B.2.1. U70BL Tests 1 - 8

Voltage	Test 1		Test 2		Test 3		Test 4	
	Up	Down	Up	Down	Up	Down	Up	Down
28.5			84					
27.8	90							
27.0			71					
26.2					81		58	
					78		61	
25.5	87							
22.5	81		58	35	54	53	52	51
	79		55		53	52	51	50
	79		50					
21.8	74	74		52	53	52	49	49
		71						
21.0	65	67	45	55	53	50	47	48
	68	65	44	50		45		48
		56						
20.2	52	53		40	48	46	46	47
		50						
19.5	53	53	40	49	43	40	44	43
	50	48	24	25		40		45
		48						
18.8	51	52	53	40	44	35	47	41
	51	46	38	24	40	35	42	
	45	46						
18.0	43	43	23	23	35	25	41	39
		42				35		38
17.2	23	39		22	30	25	39	37
		20						
16.5	25	32	28	29	23	24	39	36
	15	17	21	22		23		34
		11						
15.8	5	5		21	23	23	37	34
15.0	38	1	40	27	21	23	40	30
			27	20	23	23	33	25
			18					
14.2				19	23	22	32	29
13.5			26	25	23	22	26	24
			17	17				20
12.8				15	22	21	22	22
12.0			7	5	20	21	21	22
11.2			22	21	19	20	20	20
				0				
9.0			6	6	17		18	18
7.5	0		0	0	11	10	22	0

U70BL Dry Tests Continued

Voltage (kV)	RIV		
	Test 5	Test 6	Test 7
7.5	-4	-4	0
15.0	7	0	3
	6		
22.5	17	15	16
	17		
30.0	21	20	20

Test 8.

Time (min)	KV	RIV
	0.0	-4
	7.5	14
	15.0	0
	16.5	9
	18.0	30
	19.5	51
	21.0	58
	22.5	78
	26.2	85
	22.5	72
0.0	22.5	Steam
0.5		62
1.0		62
2.0		80
3.0		77
4.0		79
5.0		79
6.0		73
7.0		71
8.0		71
9.0		69
10.0		67
11.0		66
12.0		63
13.0		62
14.0		61
15.0		60
16.0		58
18.0		58
19.0		58
22.0		55
25.0		49
27.0		48
28.0	Off	

B.2.2. U70BL Tests 9 - 18

a) 40:10 Severity Tests

Test No. Severity		9 40:10	10 40:10	11 40:10	12 40:10	13 40:10
Time (min)	KV	RIV	RIV	RIV	RIV	RIV
0.0	12.0	18	20	62.5	56	0
1.0		20	35	62.5	51	
2.0		19	53		46	<25
3.0		37	55	62.5	50	
4.0		42	55		55.5	<40
5.0		48	48	62.5	53	
6.0		59	60		54	49
7.0		62	60	66	57	
8.0			58		59.5	48
9.0		65	61	74 - 76	61	
10.0		67	63	71.5	61	62.5
11.0		67	65	71.5	64	67
12.0		65	70	72.5		68.5
13.0		65	73 - 75	71.5	64.5	71.5
14.0		66	73 - 75	71	64 - 67	72.5
15.0		67	74	72	65	72.5
15.5	12.8	69	77	74.5	67.5	76
16.0		71	77.5	75	66.5	75.5
17.0		72.5	77.5	74 - 80	68	76
18.0		72	76.5	74	69.5	78
18.5	13.5	75	78	76 - 80	73.5	80.5
19.0		74	78	76 - 80	73.5	80
20.0		74.5	77.5	76 - 80	75	80.5
21.0		75	78 - 80	75 - 80	76	80.5
21.5	13.8	77	80	78	77.5	82.5
22.0		77.5	79	77.5	77.5	81.5
23.0		78	79.5	77	75.5	81.5
24.0		78	79.5	77.5	75 - 80	81.5
24.5	15.0	80	80.5	80	76	83 - 85
25.0		80	>90	78	73.5	83 - 86
26.0		79 - 82	Trip	78	75	83.5
27.0		80		78.5	75 - 80	83
27.5				Trip		
28.0		80			74.5	83.5
29.0		80			75	83.5
29.5	13.5	75.5	76	76	68	80
30.0		76.5	71.5	76	71	80
31.0		76 - 79	70	74.5	70 - 73	80
31.5	12.0	71	65.5	67.5	65.5	77
32.0		70.5	66	69	66	77.5
33.0		71.5	67 - 71	69.5	67	78.5
33.5	10.5	64.5	60.5	62.5	62.5	73
34.0		66 - 68	61 - 65	67	63	74.5
35.0		66.5	62	66.5	64	75.5
35.5	9.0	61	57	59.5	57.5	70
36.0		61	59 - 63	60	59	71
37.0		63 - 66	59 - 62	61.5	59.5	71.5
37.5		61.5		62		
38.0	7.5	56	54.5	56.5	54	65

U70BL Tests 9 - 13 continued

38.5		57.5	55 - 56	57	55.5	65.5
40.0		57.5	55 - 62	57	55.5	67.5
40.5	6.0	49	49	48	48.5	58
41.0		50	51.5	50	49	59.5
42.0		51.5	52 - 55	51	50	60.5
42.5	7.5	60	64	61	56	68.5
43.0		60	58.5	59	55.5	66
44.0		59	58 - 64	58	54	66.5
44.5	9.0	64.5	68	66.5	64	73
45.0		64.5	65	64.5	62.5	72.5
46.0		64	61.5	63.5	61.5	71
46.5	10.5	68.5	71	71.5	68	76
47.0		68.5	66	70		74.5
48.0		69	67 - 70	68	66	74.5
48.5	12.0	74.5	72.5	74.5	72.5	79
49.0		73.5	71	73	71	78
50.0		72.5	69.5	72.5	72	77.5
50.5	13.5	77	73	77.5	74	82
51.0		76.5	69	76.5	72.5	80.5
52.0		76	68 - 70	76.5	73	80.5
52.5	15.0	81	75 - 80	80	78	85.5
53.0		79.5	74 - 80	79	77	84.5
54.0		79	74 - 80	78.5	77	84.5
55.0				80		
56.0			74 - 80	79.5		
57.0			74 - 80			
58.0			73			
59.0			73 - 76			
60.0			74 - 80			
61.0			74			
62.0			74			
63.0			73.5			
64.0			74			
57.0	12.0			66		
58.0				68.5		
59.0	9.0			57.5		
63.0				60		
63.5	6.0			45.5		
64.0				48.5		
65.0	3.0			19		
66.0				28		
67.0				30.5		
68.0				33		

Test 14 (40:10)

Time	KV	RIV	Time	KV	RIV
0.0	3.0	-5	44.5	6.0	47
6.0		-5	45.0		49
11.0		-5	46.0		52
19.0		28	46.5	3.0	5
20.0		27	47.0		14
21.0		27	48.0		27
22.0		26	49.0		27

U70BL 40:10 Accelerated Wet Tests Continued (Test 14)

23.0		24	49.5	6.0	63
24.0		20	50.0		59
25.0		15 - 20	51.0		57.5
26.0		20	52.0		56.5
27.0		20	52.5	9.0	69
28.0		22	53.0		67
29.0		24	54.0		66
29.5	6.0	59	55.0		66
30.0		52	55.5	12.0	76
31.0		45 - 50	56.0		74
31.5		46	57.0		75
32.0	9.0	71	58.0		75
33.0		69	58.5	15.3	79
34.0		67	59.0		78 - 85
35.0		67	60.0		77
35.5	12.0	71	61.0		78
36.0		75	61.5	16.5	84
37.0		72	62.0		82
38.0		72 - 75	63.0		82 - 87
38.5		73	64.0		82
40.0		73	64.5	18.0	87
40.5	9.0	57	65.0		87
41.0		60	66.0		84
42.0		62	67.0		84
43.0		62.5	70.0	22.5	101
44.0	6.0	41.5			

b) 40:20 Severity Tests

c)

40:20 Severity Results

Time (min)	Test 15		Test 16		Test 17		Test 18	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	12.0	66	12.0	52 - 56	12.0	-5	12.0	-5 - 20
2.0						-5		10
4.0		66		42 - 67		-3		50
6.0		69		75.5				65
7.0						55		
8.0						63		71 - 76
9.0						68		
10.0		72.5		78.5		80		73 - 76
11.0		73.5						
12.0						79 - 83		68 - 75
13.0		73		79		78		
13.5	12.8	76.5						
14.0		76		79.5		77 - 81		
14.5					12.8	80	10.5	70 - 75
15.0						80 - 69		56 ± 4
16.0		76		79.5		71		55 ± 4
16.5	13.5	78						
17.0		76				75		50 - 62
17.5					13.5	73		
18.0		76.5		79.5		75		50 - 70
19.0		76.5		79		75		50 - 70
19.5	12.0	70	9.0	66.5	Trip			

U70BL Tests 15 - 18 Continued

20.0		71		68	12.8	76		50 - 70
20.5							9.0	-5
21.0		73				72		
22.0		72		73	Trip			35 - 55
22.5	10.5	62.5						
23.0		65			12.0	77		40 - 60
24.0		66		74 - 75		68		40
25.0		65.5				71 - 74		35 - 50
25.5	9.0	58						
26.0		61		72 - 76		74		50 - 55
27.0		63				74 - 76		50 - 65
27.5							7.5	-10
28.0		63		73		76 - 81		-10
28.5	7.5	51						
29.0		53			Trip	76		40
29.5					10.5	66		
30.0		56		73		62		46
30.5			6.0	54				
31.0		57				60 - 63		44
31.5	6.0	44						
32.0		49		58.5		65		44 - 47
33.0		48				68 - 73		44 - 60
34.0		50 - 52		60 - 68		70		59
34.5	7.5	61						
35.0		60				70 - 75		<60
35.5							6.0	-5
36.0		58		58 - 62		70		-5
36.5					9.0	56		
37.0		58				59		<40
37.5	9.0	65						
38.0		64.5		60		62		<40
39.0		63		60		61		<40
40.0		64		60 - 64				<40
40.5	10.5	69.5	3.0	21				
41.0		69		30				
42.0		67.5		40				
43.0		67.5						
43.5	12.0	73.5						
44.0		71.5		42 - 45		61 - 70		
46.0		71.5		46.5				
48.0				48				
50.0				49				
52.0				51.5				
55.0				51				
55.5			12.0	79				
58.0				78				
60.0				76				
60.5			9.0	61				
61.0				63				
64.0				64				
66.0				65				
66.5			6.0	49.5				
67.0				52				
68.0				53.5				
69.0				54				

B.2.3. U70BL Tests 19 - 82

a) 40:5 Severity Tests

Time (min)	Test 19		Test 20		Test 21	
	KV	RIV	KV	RIV	KV	RIV
0.0	0.0	0	0.0	0	0.0	5
0.5	3.0	3	3.0	22	3.0	34
1.5				10		
2.0		III		III		III
4.0						19
5.0		3		16		
6.0						25
10.0		<20		15 ± 2		32
12.0						32
14.0						33
15.0				13 ± 2		
20.0		23		22		34
22.0		27 ± 1		20		34
24.0		29		23		35
26.0		29		<28		35
28.0		28 ± 1		28		36
30.0		31		32		36
32.0		32		27 - 33		36
34.0		32		30		
36.0		32		32		
38.0		32				
40.0		32				

U70BL 40:5 Wet Tests Continued

Time (min)	Test 22		Test 23		Test 24	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off	-10	Off	-5	Off	-10
0.5	0.0	0	0.0	0 ± 5	0.0	0
2.0	6.0		6.0	57	6.0	58
3.0		0 ± 5		52		
4.0		III				
5.0				45		39
8.0		5			10	40
10.0		5		35 - 38		37
10.5				III		III
11.0				38		37
12.0				43		
14.0		<20				
15.0		43		48		33
16.0		47				
18.0		50		54 ± 1		38 ± 2
20.0		52 ± 2		57		38 ± 2
22.0		51 - 54		58 ± 1		46 ± 3
24.0		52		58		47 ± 5
26.0		55		58		48 - 50
28.0		55		58		44 - 49
30.0		53 ± 2		58		42
32.0		54				44 ± 3
34.0		54				44
36.0		53				46 ± 2
38.0		52 ± 1				46
40.0		52				46 ± 3
42.0		50 - 52				

Time (min)	Test 25		Test 26		Test 27	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off	-5	Off		Off	-5
2.0					0.0	0
3.0	0.0	0	0.0	0	9.0	
4.0	9.0	47	9.0			
5.0				70		56
6.5		III				
7.0		<25		61		50
8.0		<25		54		
8.5						46
9.0						III
10.0		<45		52		43
11.5				52		
12.0				III		46
13.0				51		
14.0		55				48
15.0		55		52		
16.0		59				50
18.0		62		54		50
20.0		60 ± 1		54		50

U70BL Tests 25 - 27 Continued

22.0	59	55	55
24.0	58 ± 2	58	52 - 55
26.0	58		53 ± 2
28.0	58 ± 2	58	51
30.0		58	51
32.0	60	58 - 60	
36.0		59	
38.0		58 - 60	
40.0		59	

Time (min)	Test 28		Test 29		Test 30	
	KV	RIV	KV	RIV	KV	RIV
0.0	0.0	5	Off	-10	Off	
0.5			0.0	-10	0.0	10
1.0	12.0	73	12.0	76	12.0	
5.0		65		71		
5.5		III		III		
7.0						74
8.0		66				67
10.0		68		70		III
12.0		69		70		67
14.0		72		70		71
16.0		72				73
18.0		73		71		76 - 79
20.0		73		72		78 ± 1
22.0		74		72		79 ± 1
24.0		73 ± 1		72		79 ± 1
26.0		73		73		79 ± 1
28.0		72		73	15.0	86 - 89
30.0		71		73		86
32.0						86
34.0						86 - 90
36.0					18.0	92 - 94
38.0						90 - 93
40.0						90 - 93
42.0						90 - 93

Time (min)	Test 31		Test 32		Test 33	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off	-10	Off		Off	-10
0.5	0.0	-5	0.0	-5	0.0	
2.0	15.0	78	15.0	80	15.0	<40
2.5						III
3.0		76				<30
4.5		74				
5.0		III				
6.0						65
7.0		73				
8.0						78
10.0		74				81.5

U70BL Tests 31 - 33 Continued

12.0		74		82
14.0		75		84
16.0		76	79	84
18.0		76		85 ± 1
19.5			79	
20.0		77	III	85 - 86
22.0		76 - 79		86
24.0		76		86 - 87
26.0		75 - 80	80	87 ± 1
28.0		77		87
30.0		78		
30.5	12.0	67		
32.0		72 ± 2	82	
34.0		73 ± 2		87
35.0		70		
36.0		70		87
36.5	9.0	60		
38.0		58 - 66		
40.0		61		
42.0		61 ± 1		
44.0		61	80	
44.5	6.0	40		
46.0		46		
48.0		48		
50.0		50	79	
51.0		50		
52.0		51	18.0	87
52.5	3.0	12		
54.0		24		
56.0		29	85	
57.0		32		
58.0		33		
60.0		33 - 35		
62.0		35		
64.0			85	

b) 40:20 Severity Tests

Time (min)	Test 34		Test 35		KV	Test 36	Test 37	Test 38
	KV	RIV	KV	RIV		RIV	RIV	RIV
0.0	Off		Off		Off			
0.5	0.0	0	0.0	-10	0.0			-10
1.5			3.0	60	6.0	-5	60	70
2.0	3.0	43 ± 5		47		III		60
3.5		<40		38				
4.0		III		III		<10	50	53
6.0		10		36		<20	40 ± 5	49 ± 2
8.0		<40		36 - 40			III	47 ± 2
10.0		<50		36 ± 3		<45	<45	48
12.0		<40		40 ± 2			45 ± 5	45
14.0		40		42		<60	52 ± 2	III
16.0		35 ± 5		42 ± 2			54 ± 2	49
18.0		40 - 45		43 ± 2		45 - 60	56 ± 2	57 ± 3

U70BL Tests 34 - 38 Continued

20.0	40 ± 5		45	55	56 ± 2	52 - 57
22.0	40 ± 5		45	<60	54 ± 2	58 ± 2
24.0	40 ± 5		45	<65	54 ± 2	56 ± 2
26.0	40 ± 5	15.0	87 ± 3	60 ± 10	54	56 - 65
28.0	40 ± 2		87	60 ± 10	52 ± 2	58 - 65
30.0	40 ± 2		87	60 ± 10	52 ± 2	62 ± 2
32.0	40 - 50	18.0	89	57	52 ± 2	60 ± 2
34.0	40 - 50		88 ± 2	50 ± 10	52 ± 2	60
35.0		Trip				
36.0	42			50 ± 5		
38.0	40 - 45			57 ± 5		
40.0	40 - 45			55 - 60		
42.0				55 - 60		
44.0				55 - 60		

Time (min)	KV	Test 39 RIV	Test 40 RIV	Test 42 RIV	Test 43 RIV	Test 44 RIV	Test 46 RIV
0.0	Off	- 0					0
0.5	0.0	III	-10	-10	0	-10	
1.0	9.0	0	-10	-10	71	74	
2.0			III	III	III	73	
4.0			50	5	64	71	71
6.0			<45	<15	65 ± 1	69	
8.0			<50	<20		68	70
10.0			64 - 68	<35	64 - 69	68	68
12.0		0	60 - 64	52 ± 2	64 - 69	66	66
14.0		<30	61	54 ± 3	64 - 67	66	64
15.0							III
16.0		<40	50	60 ± 2	65 ± 1		64
18.0		35 - 45	45 - 53	62 - 65	64 - 67	66	66
20.0		<20	<35	62 - 70	65 - 67	III	68 ± 2
22.0		<20	33	66 ± 2	66 ± 1	65	68 ± 2
24.0		<20	35 - 20	67	66	66	70
26.0		<25	35 ± 2	67	65	66 - 69	70 ± 2
28.0		46	42	68	65	66	72
30.0		45 - 50	56	68 ± 2		69	73 ± 2
32.0		50 - 54	59	66 ± 2		69 - 72	73 ± 2
34.0		50 - 52	58	65 ± 2		71	71 - 76
36.0		50	56	65 ± 2		72 - 75	
38.0		48	53 - 56	66		72	73
40.0		48 - 54	53	67 ± 2		72 - 75	73
42.0		50 - 54	53 - 55	64		72 - 75	
44.0		56 ± 2	55			72 - 75	
46.0		54 ± 2	56			72	
48.0		49	56			71	
50.0		48	56			70 - 75	
52.0		48				70 - 72	
54.0		48 - 52				70	
56.0		52 ± 2				70	
58.0		54 - 56				69	
60.0		54 ± 2				69 - 71	
62.0		52				69	
64.0		52				69	
66.0		52				68	

U70BL Tests 39,40,42,43,43 And 46 Continued

68.0	67
70.0	67
72.0	67
74.0	67
76.0	67 - 68
78.0	66
80.0	66

Time (min)	Test. 41		Test 45	
	KV	RIV	KV	RIV
0.0	Off		Off	-5
0.5	0.0	-10		
1.0	9.0	73		
2.0		62		
4.0			9.0	78
6.0		59		71
8.0		58		68
10.0		56		65 - 69
12.0		54		68 - 70
14.0		III		68 - 72
15.0				70
16.0		52		70 ± 1
18.0		57		70 - 74
20.0		62		72 ± 2
22.0		62		72 ± 2
24.0		62		72 - 75
25.0				73
26.0		62 ± 2		74 ± 1
28.0		60		74 ± 1
29.0				74
30.0		60 - 63		74
30.5			6.0	52
31.0				57
32.0		60		59
34.0		60 - 63		62
35.0				62
36.0		60 - 63		62 - 65
38.0	18.0	85		62
40.0		83 ± 2		62
40.5			3.0	22
41.0				30
42.0		83		38
44.0	15.0	72 - 76		42
45.0				42 - 43
46.0		75 - 78		45 - 47
48.0		75 - 78		
50.0				45
52.0				45 - 46
52.5			9.0	77
53.0				76
54.0				73
57.0				72 - 73
60.0				71

U70BL 40:20 Wet Tests Continued

Time (min)	KV	Test 47 RIV	Test 48 RIV	Test 49 RIV	Test 50 RIV
0.0	Off				
0.5		-10	-5	-5	-5
1.0		-10			
1.5	12.0	0	70	76	82
2.0		III	55	76	80
4.0			III	75	76
6.0		0 ± 5	<35	72	76
8.0		53	<35	71	76
10.0		55 - 60	59	71	74
12.0		62	63	71	74
14.0		64	66 - 75	69	74
16.0		68	66 - 75	III	III
18.0		72	68 - 75	66	75
20.0		69	75 - 50	68	76
22.0		68	64 ± 3	72	77
24.0		66 - 70	63	72 - 74	79 - 81
26.0		67	63	73 - 77	78 - 80
28.0		67 - 72	63	73 - 77	79
30.0		67 - 74	60 - 74	75 ± 2	79
32.0		68		75	79
34.0		70		75	
36.0		69		75	
38.0		69			
40.0		69 - 74			
42.0		70			
44.0		70			

Test 51 : 40:20 severity, 12.0 kV constant voltage.

Time	RIV	Time	RIV
0.0	0	60.0	77
1.0	0	62.0	77
2.0	III	64.0	76.5
7.0	0	66.0	77
9.0	<35	68.0	76.5
10.0	<40	70.0	76.5
11.0	46	72.0	76.5
12.0	49	74.0	76.5
13.0	56	76.0	76
14.0	70	78.0	76.5
15.0	74	80.0	77
16.0	74.5	82.0	76.5
17.0	76	83.0	76.5
18.0	76 - 79	84.0	76.5
20.0	76	86.0	76.5
21.0	76 - 78	88.0	76.5
22.0	76 - 79	90.0	76.5
24.0	76 - 80	92.0	77

U70BL Test 18 Continued

26.0	76 - 78	94.0	76
28.0	76	96.0	76
30.0	76 - 79	98.0	76
32.0	77 - 80	100.0	76
34.0	78	102.0	75.5
35.0	78 - 81	104.0	76
36.0	78	106.0	75.5
38.0	78	108.0	75.5
40.0	77.5	110.0	75.5
41.0	77 - 79	112.0	75
42.0	77	114.0	76.5
44.0	77	117.0	76
46.0	77	122.0	75
48.0	77	127.0	75.5
49.0	76 - 78	132.0	75.5
50.0	77 - 79	137.0	76
52.0	77.5	142.0	78
54.0	76.5	145.0	78
56.0	76.5		
58.0	77		

Time (min)	KV	Test 52	Test 53
		RIV	RIV
0.0	Off		
0.5	0.0	-5	-10
1.5	15.0	67	87
2.0		66	86 ± 2
4.0		III	83
6.0		63	74
8.0		65	72
10.0		76	III
12.0		78 - 81	83
14.0		75 - 80	80 - 86
15.0		Trip	
16.0			83 ± 3
17.0			Trip
18.0	3.0	0	-10
20.0			-10
26.0		0	
28.0		0	
34.0		25 - 30	
36.0		<30	

c) 40:40 Severity Tests

Time (min)	Test 54		Test 55		Test 56		Test 57	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	Off		Off		Off		Off	
0.5	0.0	-5	0.0		0.0		0.0	
1.0	3.0	60			6.0	70		
1.5							6.0	65
2.0		56				50		51
4.0		III	6.0	-10		30 ±10		III
6.0		50		III		III		<40
8.0		35		-10		37 - 42		<55
10.0		40		0 ± 5		<50		<55
12.0		40 - 50		0 ± 5		40 - 50		50 ± 5
14.0		40 ± 5		<35		<55		<60
16.0		40 - 45		<50		<50		50 - 60
18.0		35 - 45		<55				55 - 60
20.0		35 - 45		60 - 65		<40		50 - 60
22.0		40 ± 2		50 ± 5				50 - 60
24.0		40 ± 2					3.0	-10
26.0								<30
28.0								25 - 35
30.0			9.0	70 - 57				25 - 35
32.0				57 - 70				
34.0				60 ± 5				
36.0			12.0	75 - 63				
38.0				55 ± 5				
40.0				<63				

Time (min)	KV	Test 58	Test 59	Test 60	Test 61	Test 62
		RIV	RIV	RIV	RIV	RIV
0.0	Off					
0.5	0.0				0 - 15	-10
1.0					71	72
2.0		-5		71	66	70
4.0					55	66
5.0	9.0			65		
6.0		III			53	63
7.0			10 - 30		53	
8.0				III	III	61
10.0				59	50 ± 3	61
12.0				58	55 ± 2	III
14.0					64 - 68	63
15.0		0 ± 5	III	60 - 63		61
16.0			10 - 15	64	56 - 66	64
18.0			<45	64	56 - 66	65 ± 1
20.0		50	<45	64 ± 2	60 ± 3	67 ± 1
21.0		58				
22.0		57	52	64	57 - 68	68
24.0		60 ± 2		64 - 70	60 - 68	68 - 73
26.0		62 ± 2		68	60	71 ± 3
28.0		62 ± 2		68 ± 1	58 - 60	71 ± 3
30.0		64	53 ± 2	66 ± 3	58 - 68	71 ± 1

U70BL Tests 58 - 62 Continued

31.0	67 ± 3			62	70
32.0	67 ± 3	53 ± 2	63		
34.0	70		63 ± 3		
35.0		<65			
36.0	67 - 72		58 - 65		
38.0	66 - 74	50 - 68	62 ± 3		
40.0	71 ± 3	66	62 ± 3		
42.0	62 - 71	58			
44.0	60 - 71	56			
46.0	67 ± 3	56			
48.0	68	56 - 66			
50.0	66	56 - 63			
52.0	64	56 - 63			
54.0	65	57			
56.0	62				
58.0	60				
60.0	57				

Time (min)	Test 63		Test 64		Test 65		Test 66	
	KV	RIV	KV	RIV	KV	RIV	KV	RIV
0.0	Off		Off		Off		Off	
0.5	0.0	0					0.0	-10
1.0	12.0	III					12.0	70
2.0		0	0.0	0				>79
3.0			12.0	0				65
4.0								III
5.0				III				
6.0						-5		72
7.5						III		
8.0		53			12.0	5 - 25		72 - 64
10.0		64		0 - 20				74 - 60
12.0								60 - 76
13.0		62						
14.0						-5		60 - 80
15.0				0 - 20				
16.0						III		65 - 75
18.0		71				-5		70 - 60
20.0				0 - 20		<20		60 - 79
21.0				55				
21.5				41				
22.0				51				60 - 70
23.0				45				
24.0						45	9.0	<40
25.0		66						
26.0		70 ± 2		<55		<30		54
27.0		60 - 70						
28.0						57		54
29.0		70		62				
30.0				66		62		
31.0		79 ± 3		67				
32.0						62		
32.5	Trip							
33.0				67 - 69		66		
34.0	10.5	57						

U70BL Tests 63 - 66 Continued

34.5	12.0	64			
35.0			67		67
36.0					74
37.5					60 - 70
38.0		62	67 - 75		
40.0		63	68		75 - 54
41.0			70 - 75		
42.0			53		53 - 75
43.0		63			
45.0			57		55 - 75
46.0			59	9.0	0
48.0		63 - 65	45		<30
49.0					
49.5		63 - 75			
50.0		63	45		44
52.0			58		46
53.0		64			
54.0		67	50 - 64		47
55.0			55 - 62		
56.0					47
56.5				6.0	-3
58.0		67			<35
60.0			56 ± 2		<35
60.5			9.0 0		
62.0			<22		<35
63.0		63			
64.0			<25		36
64.5		73			
65.0		57	42		
66.0			42		36
67.0					36
68.0		64	43		
70.0		64	41 - 44		
70.5			6.0 0		
73.0		63	0		
74.0			<25		
75.0			<25		
77.0			20		
78.0		64	20		
79.0			<20		
80.0			<27		

d) 40:80 Severity Tests

Time (min)	Test 67		Test 68		Test 69	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off	-10	0.0	-10	Off	
0.5	0.0	0			0.0	0
1.0			3.0	-10		
1.5	3.0	10		-10		
2.0		III		III	3.0	40 ± 5
4.0				<20		III
6.0				<40		45 ± 2

U70BL Tests 67 - 69 Continued

8.0		0 - 10	<35	47 ± 2
10.0			<30	48 - 50
12.0			<20	50 ± 3
14.0		0 - 10	<40	50
16.0		10	<35	45 - 50
18.0			<40	46 - 50
20.0		10	<30	6.0 75 - 55
21.0	6.0	65		
22.0		46 ± 5	<22	55 ± 2
24.0		<36	6.0 75 - 50	55 ± 2
26.0		<36	50 ± 3	9.0 75 - 63
27.0	9.0	63		
28.0		64	45 - 50	63 - 67
30.0			9.0 55 ± 3	63
32.0			45 - 50	
33.0		50		
34.0		45	45 - 50	

Time (min)	Test 70		Test 71		Test 72	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off	-10	Off	-10	Off	
0.5	0.0	5	0.0	<30	0.0	-5
1.5	3.0	0	3.0	30		
2.0					3.0	0
4.0		5		5		III
5.0		III		III		
6.0						0
8.0				5		<35
10.0		0		5		<20
12.0		<15		<15		<25
14.0		<25		<20		0
16.0		<30				<50
18.0		51 ± 3		<30		<45
20.0		49 ± 5		<20		0
22.0		49 ± 5		0 - 15		0
24.0		50 ± 1		<10		<35
25.0		53		<20		
26.0		52	6.0	74		52 ± 4
28.0		55 ± 3		68		52
30.0		41		63 ± 5		<52
32.0		31		60 ± 5		<42
34.0		30 - 33	3.0	10		<42
35.0		28		20		
36.0				<30		42
38.0						45
40.0						45 ± 3
42.0						43
44.0						<45
46.0						25
48.0						<45
50.0						<43
52.0						<25
54.0						<25

U70BL 40:80 Wet Tests Continued

Time (min)	Test 73		Test 74		Test 75	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off		Off		Off	
0.5	0.0	5	0.0	-10	0.0	
2.0		III	6.0	60	6.0	
4.0				<40		III
6.0				III		
8.0	6.0	20 ± 5		<30		
10.0		0 - 30		30		
12.0		<40		<42		
14.0		<20		<45		
16.0		<30		<50		<50
18.0		<20		<50		<52
20.0		10		<45		45
22.0		<40		<45		<45
24.0		0 ± 10		<45		<30
26.0		0 ± 10	9.0	70 - 67	9.0	50
28.0	9.0	70 - 58		67 - 50		50
30.0		50		50 ± 3		<52
32.0		50 - 53		50 ± 3		<40
34.0		50 - 53				
36.0	12.0	75 - 58				
38.0		54 - 65				
40.0		53 - 57				
42.0	6.0	-10				
44.0		-10				
46.0		-10				

Time (min)	Test 76		Test 77	
	KV	RIV	KV	RIV
0.0	Off	-10	Off	
0.5	0.0	0	0.0	-10
1.5	6.0	56	6.0	-10
2.0		10		III
4.0		III		0 - 20
6.0		0		<30
8.0		<40		<30
10.0		10 - 40		40
12.0		0 - 20		40 - 50
14.0		<40		40 - 50
16.0				45 ± 5
18.0				0 - 50
20.0		<40		<45
21.0	12.0	72		
22.0				<40
24.0		65 ± 5		<40
26.0		65 ± 5		55 ± 5
30.0				55 ± 3
34.0				55 ± 5
36.0				55 - 60

U70BL 40:80 Wet Tests Continued

Time (min)	Test 78		Test 79		Test 80	
	KV	RIV	KV	RIV	KV	RIV
0.0	Off		Off		Off	
0.5	0.0	5	0.0	-10	0.0	-5
1.5	12.0	85 - 70			12.0	<30
2.0		67				III
3.0		III	12.0	75		
4.0		67		70		<50
6.0						<55
8.0		65 ± 5		71		<55
10.0				71		<60
12.0		60 - 80		III		60
14.0		<60		70 - 75		72
16.0		<65		65 - 70		71 - 76
18.0	Trip			70 - 60		74 - 82
20.0	9.0	58 - 52		68		73 - 80
22.0		50		68 - 80		73 - 80
24.0		48 ± 2		<74		71
26.0		50 ± 5		64 - 80		72
28.0		50 - 60		64 - 74		66
30.0	6.0	0		64 - 74		70 - 80
32.0		<38	9.0	0 - 53		70 - 75
34.0				54		73 - 80
36.0				54 - 60		76 - 85
38.0		0	6.0	0 - 46		80
39.0					Trip	
40.0		<25		48		
42.0		<25		48		
44.0		33	3.0	0 - 20		
46.0	Off			29 ± 1		
46.5	6.0	65				
48.0		34 ± 2		34		
50.0		32 ± 2		34 ± 2		
52.0		32 ± 2		34 ± 2		
54.0	3.0	0		34 ± 2		
56.0			6.0	66 - 59		
58.0				57		
60.0		28 - 31		57 ± 2		
62.0		30 ± 2		53		

e) 40:10 Severity Results

Time (min)	Test 81		Test 82	
	KV	RIV	KV	RIV
0.0	Off		0.0	
2.0			12.0	0
3.0	9.0			III
4.0		67		0
5.0		64		
6.0		III		

U70BL Tests 81 - 82 Continued

8.0		61	0
10.0		62	51
12.0		64 ± 1	59
14.0		65	
15.0		65	
16.0		65	70.5
18.0		66	
20.0		63 - 67	69.5
20.5	6.0	49	
21.0		53	
22.0		55	72
24.0		56 ± 1	73
26.0		56	73.5
28.0		56 ± 1	75
29.0		57	
30.0		56 - 58	75
30.5	3.0	20	
31.0		29	
32.0		39	75
33.0		42	74
35.0			75
36.0		42.5	75
38.0		43 - 45	
40.0		45	74
41.0	9.0	75	
42.0		71	
45.0		68	73
46.0		67	
48.0		65.5	
50.0		66	73
52.0		66	74
54.0		65 - 67	75
55.0			77
56.0		66	72 - 78
58.0		64	
60.0		63 - 64	72 - 74
62.0			72
67.0			71
73.0			71
77.0			70
79.0			70
82.0			69.5
87.0			68
92.0			68.5

APPENDIX C : TRANSFORMER VOLTAGE CALIBRATION

Applied Primary Voltage (Volts rms)	Measured Secondary Voltage (kV rms)	Values Read From The Graph Of Figure C.1.	
		Test HV (kV)	Input LV (V)
10	1.38	1.5	11.44
25	3.68	3.0	21.2
50	7.38	4.5	30.9
75	11.29	6.0	40.6
100	15.19	7.5	50.4
125	19.05	9.0	60.1
150	22.80	10.5	69.8
175	26.86	12.0	79.6
200	30.81	13.5	89.3
225	34.31	15.0	99.0
250	38.15	16.5	108.8
275	42.21	18.0	118.5
300	42.71	19.5	128.2
325	49.66	21.0	138.0
350	53.72	22.5	147.7
375	57.33	24.0	157.4
385	59.59	25.5	167.2

Table C.1 : Test Transformer Secondary Versus Primary Voltage

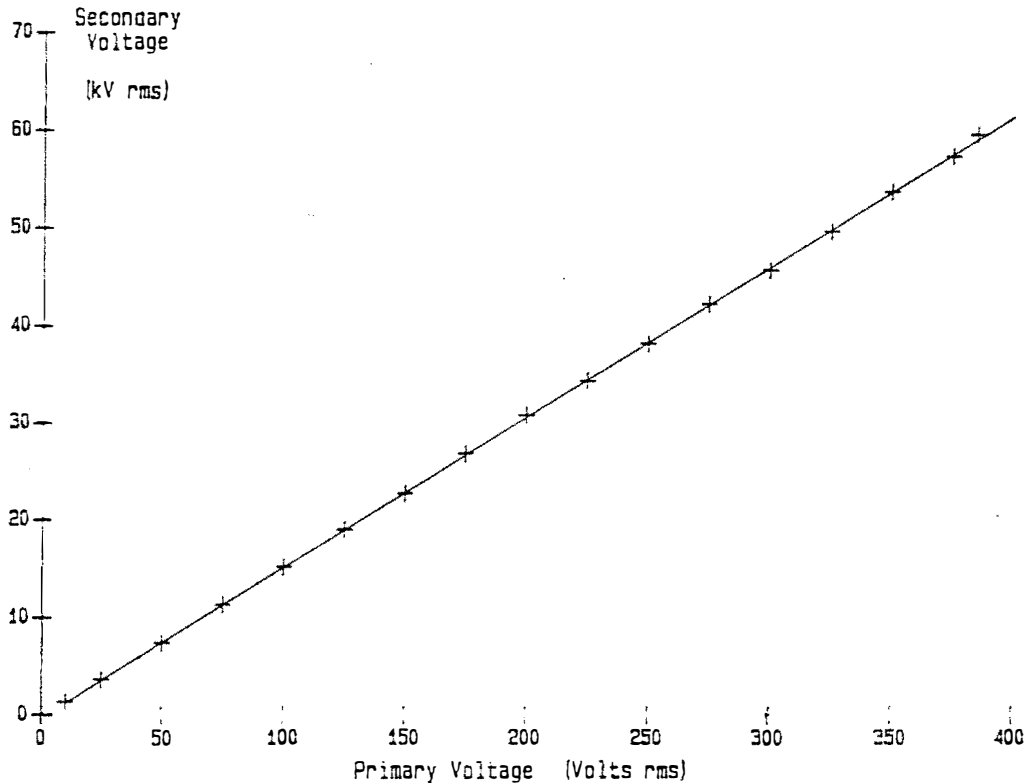


Figure C.1 : Secondary Voltage Versus Primary Voltage