

PUNCTURE TESTING OF PORCELAIN

CAP AND PIN INSULATORS

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PAGE 1

I hereby declare that this is my own work and has not
been submitted before to any university for a degree.

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ABSTRACT

This dissertation describes the work performed to assess the usefulness of a withstand test for determining the quality of porcelain cap and pin insulators.

Porcelain cap and pin insulators have been in use on high voltage transmission lines for close on one hundred years. Despite this long period of service not all problems associated with this kind of insulator have been ironed out. This is true for both the quality of the insulator itself and the method that is employed to determine its electrical characteristics.

The experimental work performed is in the form of dielectric puncture tests. To this purpose the insulators were immersed in SF_6 . Several batches of insulators were tested in accordance with differing criteria.

The results are analyzed statistically and are compared to the outcome of puncture tests performed in oil in accordance with SABS specification 177 of 1973.[1]

A modified withstand test is proposed which gives meaningful results

In memory of my late father Hans K.O.Dietz 1919 -1982.

To my mother for all her patience and encouragement.

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Messrs.R.Macey and P.Sneddon from Cullinan Electrical for providing me with technical information on cap and pin insulators.

S.A.G.Ceramics for supplying free of charge all the insulator specimens required for the experimental work.

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1 INTRODUCTION

Cap and pin insulators of various shapes and sizes have been used since the end of last century, concurrently as mechanical supports and electrical insulators on pylons of high voltage transmission lines.

Although the replacement of insulator strings by long rod insulators has been en vogue in Europe and the Middle East since 1945, cap and pin insulators are still widely used elsewhere. [14] Strings of cap and pin insulators are in general more economical than the former. Also the replacement of damaged specimens is simple.

The main disadvantage of cap and pin insulators is their susceptibility to dielectric breakdown when subjected to high voltage stresses. Verification in the form of a quality assurance test is therefore required to prove adequate resistance to puncture under service conditions. The "Puncture Test in Oil" as prescribed by SABS-177, BSS-137 and IEC-383 is employed to do this. [1]

The very fact that puncture of the insulators does take place is an indication that a number of inherent faults are unresolved. This concerns both the design of the insulator and the demerits of the standard puncture test.

The purpose of this dissertation is to establish meaningful parameters and test conditions for conducting dielectric strength tests on cap and pin insulators.

The dissertation begins with a review of the physical event of dielectric breakdown or puncture of solid dielectrics. Particularly puncture in porcelain is of interest. The design and structure of cap and pin insulators is such that additional factors which decrease the intrinsic puncture strength of the porcelain become perceptible.

This review is followed by a discussion on the limitations of the puncture test in its present form. Problems of both a general nature and those pertaining to specifics of the puncture test in oil will be considered.

A second method of performing puncture tests is by using steep fronted impulse voltages. This method has been tried out in various laboratories but does not enjoy unreserved support. [9, 10, 11]

The experimental work is exclusively centered around a method for performing puncture tests with the insulator or test specimen

immersed in SF_6 . Various procedures to this end are investigated. The desired result is finally obtained by performing voltage withstand tests at various discrete voltage levels. In total 233 insulators were punctured.

There are no published authoritative statements on breakdown mechanisms within porcelain. An in depth investigation of these mechanisms will require a major effort on the part of electrical engineers and material scientists and is beyond the scope of this dissertation. An identification of the causes leading to head punctures in cap and pin insulators is however beneficial to the experimental work. To this purpose variables such as the current of the insulator and the partial discharge activity inside the insulator are recorded as a function of the applied voltage.

The experimental work is followed by a statistical evaluation of all the relevant data and a discussion of the results. Of particular interest is the comparison of puncture in oil with puncture in SF_6 .

Puncture tests in oil are not part of the experimental work of this dissertation. Tests using oil as immersing medium were performed by two parties outside the Department of Electrical Engineering of the University of the Witwatersrand, namely:

- 1) The Department of Electrical Engineering, University of Cape Town. [2]
- 2) Die Instituut vir Elektronika, Universiteit van Stellenbosch. [4]

Both parties employed the same type of insulators as was used by the author of this dissertation. A direct comparison of the results is therefore possible.

N.B. Unless stated specifically otherwise all voltages and currents are expressed in effective or R.M.S. values.

2) DIELECTRIC BREAKDOWN OF PORCELAIN INSULATORS

2:1) Puncture or Dielectric Breakdown of Solids

The definition of puncture as given by SABS specification 177 is: "Puncture is a disruptive discharge through the insulating parts (of a glass or ceramic overhead line insulator) that produces permanent loss of dielectric strength.[1]"

A more apt explanation of the phenomenon of puncture or dielectric breakdown in solids is given by R.Coelho [2]:

"In a sufficiently high electric field, materials break down, either abruptly or gradually, with the formation of one or several conducting spots in the sample. This process is irreversible in a solid. The breakdown field depends inter alia on the nature and composition of the sample, its shape, on its environment and on the way in which the electric field is applied.

For solid insulators the breakdown fields usually observed range from below 10^5 V/cm to about 5×10^6 V/cm. Although apparently large on a macroscopic scale, these fields are in fact very low on the atomic scale. 10^6 V/cm represents 10^{-2} V/ Angström and this clearly indicates that except under very special laboratory conditions breakdown never results from the direct action of the field on the atoms and molecules of the material.

Thus, electrical breakdown is a collective phenomenon, whereby energy is communicated to the constituent molecules by other particles such as electrons or ions which have acquired enough energy in the field."

In practice this means that the intrinsic strength of most solid materials is seldom obtained due to the presence of impurities which markedly lower the electric strength.[4]

Two basic processes which could initiate breakdown are thermal instability and collision breakdown.

For thermal instability the current density and power generated in a local region of high resistance increases out of bounds if the heat dissipation exceeds the rate at which heat is conducted away from the region.

Collision breakdown is a heading used to describe intrinsic breakdown processes such as the purely intrinsic and avalanche breakdown.

In the actual collision process ionizing collisions produce electron avalanches which constitute high electron density paths.

R.Coelho [3] further suggests that it is not known beyond all doubt as to which breakdown mechanism occurs. Regardless of the initial step, the development of the breakdown event involves a local dissipation of energy from the excited carriers into heat through excitation of lattice vibrational modes.

The failure itself is in the nature of a fused path, the size of an ordinary pin, through which the current discharges. [7]

2.2 Factors determining the Intrinsic Strength of Porcelain Insulators

The quality of porcelain used for high voltage insulators is determined by its electrical and mechanical breakdown strengths. The factors governing these two parameters are interdependent and can conflict with one another. In practical terms this means that if any parameters are changed to improve the electrical characteristics, then this is at the expense of mechanical strength and vice versa.

The quality of porcelain is influenced in particular by the composition, porosity and firing temperature of the raw material as well as the density of the finished product. Other factors to be considered are the dielectric constant, the loss angle $\tan \delta$ and the electrical resistance.

The short time dielectric strength in particular depends on the density of the ceramic, its thickness and porosity. The dielectric strength of poorly vitrified bodies is reduced by as much as 25% because of the minute voids contained in their structure. The ionization voltage of entrapped gas contained in the structural pores is lowered by the presence of moisture. Once initiated, the ionization and partial electrical discharge within the pore leads to localized heating with resultant localized degradation in the resistivity, leading to the

ultimate failure of the insulation. While this process needs time to develop it can be accelerated by applying a sufficiently high voltage and by a localized high concentration of electric field.[5]

F. Clarke [5] distinguishes between intrinsic puncture and puncture caused by thermal runaway. To separate the regions in which each kind of puncture occurs the concept of a "Transition Temperature" is used. This is that temperature above which an abrupt change in the temperature/property relationship of the ceramic is observed. Above the transition temperature specific properties of the porcelain degrade at a faster rate. Distinction must be made between the mechanical, conduction and dielectric breakdown transition temperatures. Only the latter two quantities are of interest here. The actual transition temperatures determined for dielectric breakdown and resistance vary from 85°C to 127°C with an average value of 103°C . Above this temperature the porcelain is characterized by a conducting rather than insulating property and the puncture is of a thermal nature. Below the transition temperature breakdown is of an intrinsic nature.

2.5) Puncture of Cap and Pin (Clevis and Tongue) Insulators

Cap and pin insulators consist of a single shed of porcelain or toughened glass with several skirts underneath, the no. of skirts used being dictated by operating environments.

Each insulator is cemented to a metal cap above and a metal pin below, such that several units can be joined together in ball and socket joints to form an insulator string. The no. of units in the string is chosen to suit the system voltage and the level of pollution likely to be experienced.[22]

According to SABS 177 [1] both "Cap and Pin" and "Clevis and Tongue" insulators are Class B insulators. This implies that the length of the shortest path through the insulating material does not exceed half the length of the dry arcing distance. Insulators of this kind are not puncture proof and need verification by testing to prove adequate resistance to puncture under service conditions.

For purposes of this dissertation "Cap and Pin" insulators are considered to be identical to "Clevis and Tongue" insulators. This assumption is certainly justified as far as the respective electrical characteristics are concerned and also holds for the pertinent physical dimensions. The only discernible difference between the two types of insulators is in the shape of their respective suspension couplings as is suggested by their designation.

Before proceeding to elaborate on the electrical attributes of these insulators it is useful to list the main specifications of the test specimens used in the subsequent experiments. These are given in TABLE 1 below. A cross section of this insulator together with its main dimensions is given in Fig. 2:1 on Page 7. [6]

Insulator type:

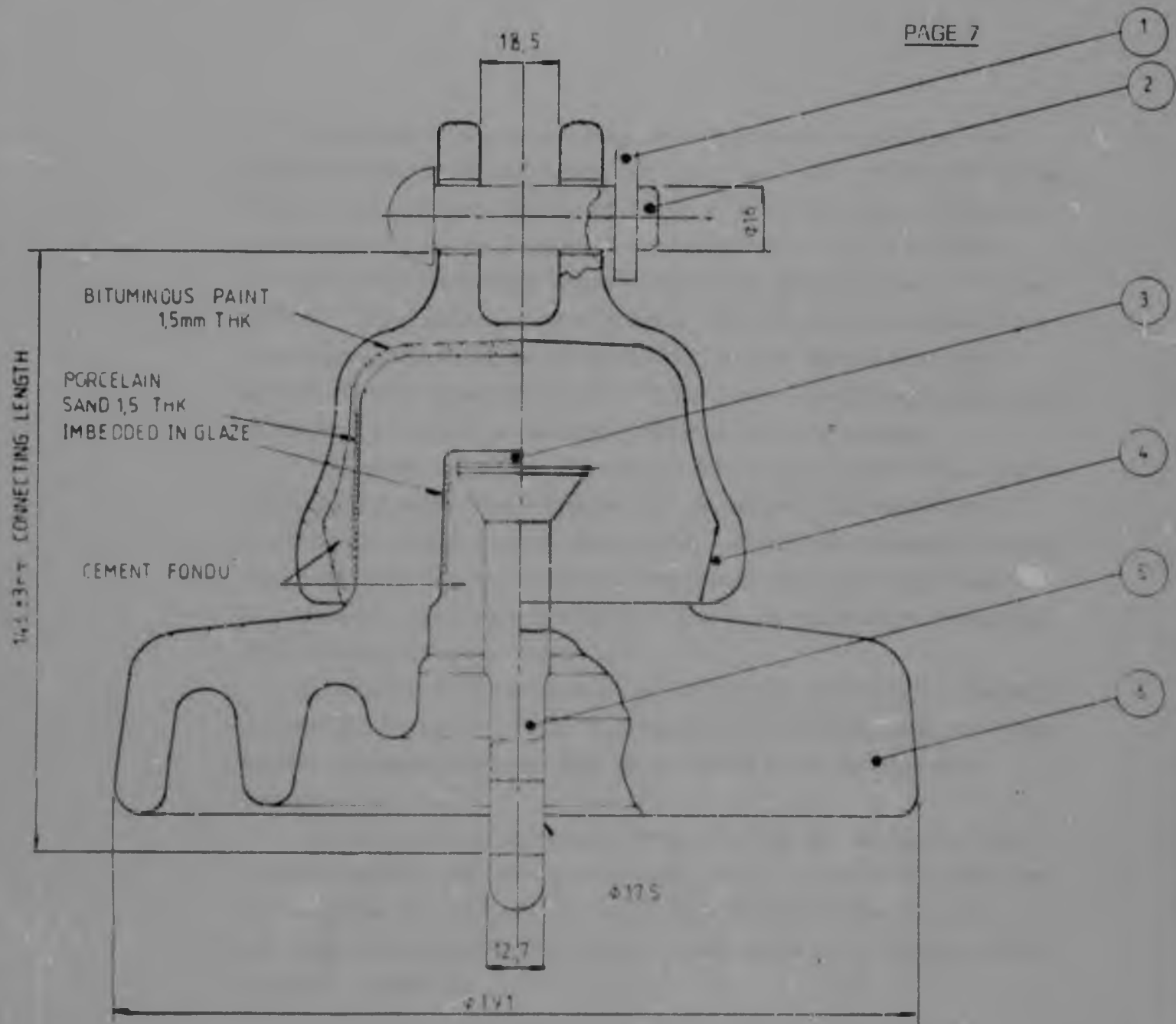
U 70 LC Clevis & Tongue with limited movement. SAG order No. 19-0345.

Diameter	191 mm
String spacing	146 mm
Leakage distance (min)	210 mm
Net weight	4,3 Kg
Rated Mechanical load	70 KN
Average flashover voltage	Dry 3 KV
	Wet 35 KV
Low frequency punct.voltage	90 KV

Composition of Porcelain

Ball clay	30%
Klaus clay	13%
FelDSPar	27%
Silica	30%

TABLE 1: Mechanical and Electrical Characteristics of Insulator
SAG 19-0345. [6]



1	SPLIT COTTER	STAINLESS STEEL/PHOSPHOR BRONZE
2	CLEVIS PIN	STEEL (51-0025)
3	RESILIENT PAD	CORR.
4	CAP	MALLEABLE STEEL (53-0005)
5	TONGUE PIN	FORGED STEEL
6	INSULATOR BODY	PORCELAIN

Fig.2:1 Cross section of Insulator SAG 19-0345 (U 70 LC) [6]

(Diagram supplied by manufacturer.Vide Reference 6, APPENDIX 1 .Page A2)

A thorough literature survey on the subject of puncture in cap and pin insulators as well as related topics was conducted by the author. None of the engineers and ceramists who contributed their findings and conclusions to the journals and books consulted by the author has identified "The Mechanism" which causes puncture in cap and pin insulators. The question whether punctures in cap and pin insulators are of an electro-mechanical nature, are initiated by partial discharge activity or are caused by any of the more conventional mechanisms such as thermal instability or intrinsic failure is still unanswered.

This seems to confirm the notion of R.Coelho [3] that for practical purposes the mechanism initiating the breakdown process differs significantly in the various cases, but as soon as this initiating step has occurred, breakdown develops in a very similar way and observation of the breakdown spot does not help very much in establishing what type of breakdown has taken place.

In addition to what has been said about the breakdown of solids in general and that of porcelain in particular, cap and pin insulators have certain constructional features which affect their resistance to dielectric breakdown.

A study of Fig.2:1 on Page 7 shows that the top surface of the insulator pin and the area surrounding the sharp edge of the same can be identified as a multiple boundary value problem. Dielectrics of different relative permittivities are involved. These are formed by the following substances:

- 1) The actual body of porcelain between cap and pin.
- 2) The cork or felt pad between the pin head and the bottom surface of the insulator head.
- 3) The concrete interstices
- 4) The concrete interstices are not of uniform quality and contain oval air pockets up to 5 mm long. These are due to assembly procedures. A thin layer of air is also present between the felt pad and the bitumen layer in the insulator head.

The problem becomes even more complex when it is considered that porcelain by its very nature is a non homogeneous substance.

In addition to the above mentioned points, the sharp edge of the pin is simultaneously the point of highest mechanical and electrical

stress.[13] The probability is therefore high that a local defect in the porcelain at or near the sharp edge of the pin will initiate breakdown. Some of the factors causing such a defect have been mentioned in Ch.2:2. This breakdown will occur at a voltage which is lower than that at which puncture would occur at other spots in the insulator.

In practice three paths of dielectric breakdown occur in cap and pin insulators. These are shown by tracks A to E in the following sketch.

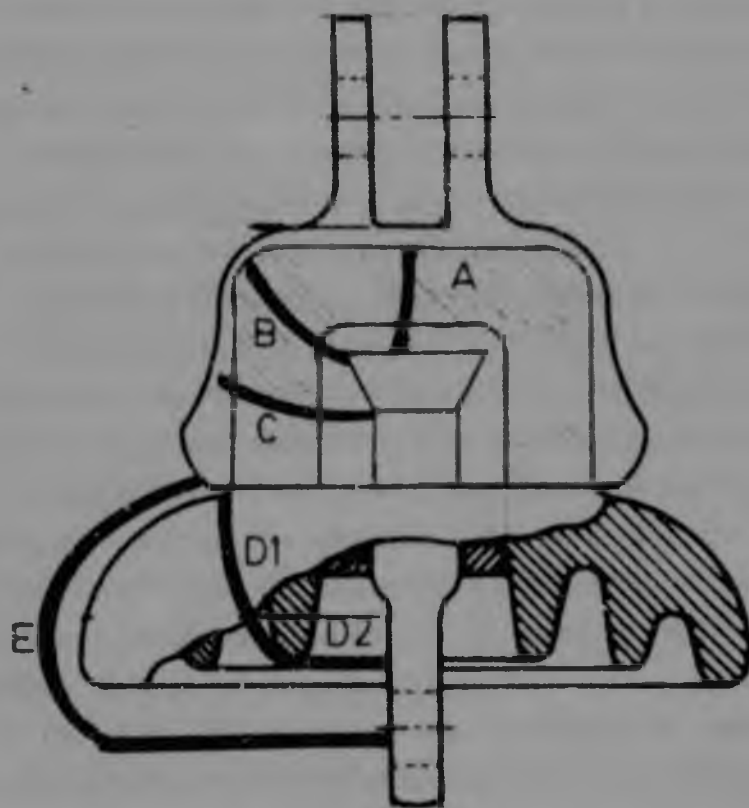


Fig.2:2 Discharge-tracks in Cap and Pin Insulators

1) Head punctures

Vide tracks A,B,C

Puncture tracks following the above three or similar tracks originate at the pin and proceed to the cap by "eating" their way through the porcelain.

2) Shed Punctures

This is a composite puncture path which goes partially through the porcelain of the insulator shed and partially along the surface. (Flashover).

Its presence can be explained as follows: The sheds of cap and pin insulators are designed in such a way that under normal operating conditions in air, puncture is preceded by breakdown in the form of flashover.[13]

In determining the short time dielectric strength of solid insulations it is therefore practice to immerse the dielectric test assembly in an insulating liquid such as mineral oil. The oil or other insulating medium raises the flashover level of the test specimen to the extent that now in all cases except at voltages in excess of 130 KV puncture precedes flashover. This assessment is valid for insulator type U 70 LC and differs for the various types and sizes of insulators.

Hopwood [18] makes the following comments on this phenomenon:

"Insulating oils of low permittivity, such as transformer oils, are not suitable. (as immersion medium) since the division of voltage between the oil and the much higher permittivity porcelain results in overstressing the oil which can break down and the ensuing discharge results in failure of the porcelain, external to the cap and pin, by a combination of localized electrical and thermal stresses." While at first sight this comment appears to be restricted to flashover it is nevertheless also valid for shed punctures.

The flashover voltage of the insulator when immersed in mineral oil is higher than the combined partial puncture voltages of the oil in the vicinity of the insulator pin and the porcelain of the insulator shed nearest the edge of the cap.

The end result is a discharge as per path D1-D2 as is shown in Fig.2:2. The breakdown path consists of two dielectrics in Series, namely the porcelain and the immersing medium. This failure mode usually starts when partial breakdown of the oil takes place.

To minimize the occurrence of this kind of puncture the relative permittivity of the insulating medium should be more or less equal to that of the insulator porcelain.

3) Surface Flashover:

Vide track E.

This is the third kind of breakdown caused by the electrical collapse of the immersion medium. The flashover arc follows a crazed path across the insulator, spanning cap and pin. In some instances this severely damages the glazing of the shed. Although this is no breakdown in the sense of puncture, the electrical symptoms are identical, namely a short circuit once the arc is established.

Here it should be noted that damage to the rim of an insulator shed resulting from a fragment breaking away, and damage to the insulator by the heat of a flashover are not considered to be a puncture.[1]

In western Europe and the Middle East cap and pin insulators have been widely replaced by long rod insulators as the standard insulation employed on high voltage transmission lines.

The undisputed advantage of longrod insulators is that by virtue of their construction i.e. a solid stalk of porcelain they are puncture proof. Another advantage is that of long creepage distances. Longrod insulator assemblies are however more expensive than equivalent strings of cap and pin insulators. This accounts for the popularity of the latter elsewhere. The replacement of damaged cap to pin insulators in service is simpler than when the same procedure has to be performed on a longrod insulator assembly.

Compared to toughened glass, porcelain insulators do not shatter when puncture occurs. Dielectric breakdown merely results in a narrow discharge channel. The mechanical stability of the insulator is reduced but not to the extent that an imminent mechanical collapse of the insulator string assembly takes place, bringing down the line.

3 DIFFICULTIES ASSOCIATED WITH THE ELECTRICAL PUNCTURE TEST

3.1 General Drawbacks of the Electrical Puncture Test

The puncture test is a sample test performed on insulators taken at random from batches offered for acceptance by the electricity supply authorities in order to verify the characteristics of the insulators and to determine the quality of the material used.[6]

The main drawback of the puncture test irrespective of which method is used to employ it is that it is a random sample destruction test. The voltage across the test specimen is raised until breakdown takes place. This is done to compare the quality of the specimen's withstand characteristics to a preset norm.

Routine production testing of newly manufactured insulators involves subjecting them to a voltage withstand test. This test which is conducted in air on a pass or fail basis has to be conducted at a voltage which is lower than the flashover voltage of the insulator concerned. Here it must be remembered that the design of an insulator shed is such that the puncture voltage is higher than the flashover voltage.

Consider for example insulators of type U 70 LC which will be used in the subsequent experimental work. The nominal puncture and dry flashover voltages for this insulator are given as 90 and 65 KV respectively.[6]

The routine withstand test is conducted at 70 KV and the voltage is applied for an uninterrupted interval of 4 minutes. The pass rate varies between 82% and 98% and differs significantly from hatch to batch.[19]

Whereas the afore-mentioned test eliminates all faulty insulators which puncture at a voltage of 70 KV or less, no exclusion is given for insulators which would puncture at voltages between 70 and 90 KV. To eliminate these, a puncture test using a dielectric immersion medium (e.g. mineral oil) needs to be performed. This approach is impractical for routine production testing because of the elaborate procedure that is involved. See Chapter 3:2 below.

Specification SABS 177 [1] is not helpful in resolving the above mentioned contradiction apart from stating that the specified puncture voltage of a Class B insulator must exceed its dry flashover voltage by an "acceptable" margin.

Two standard methods of performing dielectric breakdown tests are en vogue: Both have certain drawbacks as regards their implementation.

3.2 The puncture test in oil

As mentioned in Ch.3:1 it is necessary to immerse the insulator test assembly in a dielectric insulating medium when performing a puncture test. The reason for doing this is to suppress the development of corona and electrical discharge which is invariably formed even at voltages substantially below the puncture voltage, and ultimately cause flashover.[5]

The procedure for implementing the puncture test in oil is detailed in SABS-177. Details of how to perform this test are given in Appendix 2 on Page A.5.

The following problems are observed when performing puncture tests in mineral oil or related dielectric substances:

- 1) Impurities in the oil cause tracking leading to the deformation of the electric field. This can bring about premature flashover at a voltage below that at which breakdown of the insulator would otherwise occur.
- 2) Under the given testing conditions, corona and electrical discharge preceding the dielectric breakdown is not eliminated, although the actual inception voltage of its formation is much higher than observed when similar tests are carried out in air. Once started, however, corona growth in oil is much more rapid and intense than in air. Again, this can cause premature flashover.[5]

The problems of tracking and corona can be suppressed by increasing the conductivity of the oil or by increasing its relative

permittivity. (The ϵ_r of oil is 2-3 compared with 6 for porcelain.) Ideally the ϵ_r of the insulator is equal to that of the immersing dielectric. Several methods can be employed to achieve this:

- 1) Steam treat the oil so as to obtain a more highly conductive oil water emulsion. It is however almost impossible to keep the properties of this emulsion unchanged for any length of time. Water particles tend to agglomerate and precipitate over the surface of the insulators and on the wall of the vessel.[8]
- 2) Use additives such as Creosote and Para-Cresol to improve the conductivity of the oil. Problems are experienced with the medium and long term chemical stability of the resultant mixtures.[4]

3.2) The Steep Fronted Impulse voltage Puncture Test.

Air and other gasses have the property that there is a finite time lag between the instant of application of sufficient voltage to cause breakdown (of the gap) and the actual physical breakdown.[16] The same is true for solid dielectrics. However the time lag of the latter is generally much smaller than that of air.

This property is used to perform puncture (and flashover) tests by applying steep fronted impulse voltages to solid insulators. If the voltage-time gradient of the applied voltage is steep enough then in theory breakdown of the solid dielectric should occur before flashover.

The following observations were made when employing this technique:

- 1) The puncture breakdown rate varies greatly with the type of insulator.
- 2) Puncture breakdown never occurs at the first application of impulse voltage; in all cases it occurs after several pulses have been applied repeatedly.
- 3) The initial application of the voltage due to the steep fronted rise causes discharges within the insulator which penetrate the porcelain. This growth of internal discharges continues if similar impulse voltages are supplied in succession, which finally lead to breakdown. This gradual erosion with each application of voltage

also leads to a decrease of the time delay when compared to puncture on a single voltage application. After a multiple voltage application the effective thickness in the final stage of breakdown is very small due to the accumulated erosion.[9,11]

- 4) When flashover occurs, a large fraction of the surge generator energy during discharge goes into the arc over the surface of the insulator. The heat of this arc causes a crazed path over the surface and thereby possibly reduces the insulator flashover voltage by virtue of forming a slightly conducting track in the glazing.[10]
- 5) The fact that several voltage applications are necessary for puncture to occur seems to confirm the notion of Park and Cones [10] that it is the initial rate of rise of voltage which matters rather than the greatest rise.

The puncture breakdown of an insulator is considered to take place in that region of the V-t curve where the puncture voltage of an insulator is lower than the flashover voltage. If such a steep fronted voltage is applied that this requirement is met then puncture breakdown is expected to occur without fail by the first impulse voltage. The maximum attainable voltage-time gradient is limited by the available energy of the employed impulse generator.

Also this way of performing puncture tests has several shortcomings some of which have already been mentioned in the above observations. No relevant standards on how to perform the test are available in any of the Standards publications. Parameters such as the voltage-time gradient to be used and the no. of voltage applications are not specified.

4 OBJECTIVES AND TECHNIQUES OF THE EXPERIMENT

4.1 Objectives of the Experimental Work

The objectives of this dissertation are to establish a relevant experimental technique that enables a manufacturer to set quality standards concerning the electrical withstand capabilities of cap and pin (or clevis and tongue) insulators.

As has been specified in Ch.2:2 on Page 4 the quality of the porcelain mix employed directly determines the electrical strength of the finished product. The mechanical requirements are primarily dictated by the physical stress exerted on the insulator assembly by the weight of the transmission line conductor. This consideration is of utmost importance in assessing the overall performance of the insulator. In the ensuing experimental work the emphasis is however purely on the electrical characteristics.

Some of the problems that lead to the dielectric breakdown of cap and pin insulators have already been discussed. Despite various shortcomings inherent in the puncture test, it is at present the only significant means available for inspecting the electrical withstand characteristics of solid insulators. A non destructive quality assessment would be infinitely more preferable but is as yet unavailable.

Problems that are encountered when conducting the test in oil are the presence of corona and the concomitant flashover, as well as partial breakdown of the dielectric immersant around the insulator shed. Therefore the search is on for an immersing medium in which these undesirable side effects can be eliminated entirely or suppressed to a degree so as not to affect the puncture tests.

To the knowledge of the author no puncture tests of this nature have been performed in insulating gas other than air. The following experiments were therefore conducted in Sulphur hexa-fluoride (SF_6) at a pressure of 400 kPa, abs. SF_6 has a high dielectric breakdown strength despite a low relative permittivity of approximately 1.

4.2) Experimental Procedure

The bulk of the experimental work took the form of voltage withstand tests which were conducted at various discrete levels in accordance with the following criteria:

- 1) Start at 80 KV and increase the voltage in steps of 10 KV for each following test.
- 2) Use a two minute ON / two minute OFF or 1:1 duty cycle at each test level.
- 3) Repeat this cycle until puncture occurs.

The rate of voltage rise is clamped to either 5 KV/sec. or 10 KV/sec. Of the 233 insulators that were tested in total, 160 were subjected to the above mentioned routine.

The following variables were recorded so as to assess their influence on the dielectric behaviour of the insulators.

- 1) The applied voltage level V_s
- 2) The current of the insulators, I_L , as a function of the applied voltage.
- 3) The corona inception and flashover voltages.
- 4) Partial discharge activity within the insulators.
- 5) Observation of breakdown current waveshapes.
- 6) Time to puncture.
- 7) Influences on the puncture voltage, as caused by the rate of rise of voltage.

To determine the influence of factory "Pollution" on the puncture voltage of the insulators, tests comparing 60 clean to 50 polluted insulators were conducted.

According to manufacturer's information there are appreciable quality differences between the various batches of insulators. [19] To investigate this point comparative studies were performed on sets of insulators from three different batches.

A post mortem was carried out on 70 insulators which punctured in the head. These insulators were cut open such that the puncture path

was laid bare. In this way the exact locality of the discharge channel was established. Normally no post mortem was required on shed punctures because the extent of damage caused by the discharge current was discernible to the naked eye.

A statistical analysis of the following variables was performed:

- a) The frequency distribution of head punctures as a function of the applied voltage.
- b) The frequency distribution of shed punctures as a function of the applied voltage.
- c) The current of the insulators as a function of the applied voltage.

Porcelain Insulators of the type U 70 LC were chosen as test specimens because of their ready availability from manufacturer's stock.

For convenience the insulator test specimens are divided into eight Series. This somewhat arbitrary division is determined by the order in which various aspects of the experimental work were carried out.

The following identification procedure has been used for both the experimental work and the listing of the individual results as given in Appendix 5.

<u>Series No.</u>	<u>Batch size</u>	<u>Insulator numbering</u>
1	15	1:1 - 1:15
2	16	2:1 - 2:16
3	11	3:1 - 3:11
4	20	4:1 - 4:20
5	30	5:1 - 5:30
6	30	6:1 - 6:30
7	30	7:1 - 7:30
8	81	8:1 - 8:76 8:A - 8:E

N.B. There is no correlation between manufacturer's batch no. and the designation adopted above.

Except for tests which were performed on "polluted" insulators, the test specimens were prepared by "washing dishes." To this purpose the insulators were cleaned in a warm water bath using a detergent. (TELPOIL) To remove traces of detergent the cleaned insulators were rinsed thoroughly in warm water. A minimum drying period of 24 hours was observed prior to testing.

For tests performed on polluted insulators the test specimens were taken as is; ie, in the factory soiled condition in which they were delivered by the manufacturer.

4.3 Choice of suitable Test Parameters

In compliance with BS specification 923 (Section 2:1), [12] for "Assured disruptive Discharge Voltage Tests" the voltage should be applied to the test object starting at a value sufficiently low to prevent any effect of overvoltages due to switching transients. It should be raised sufficiently slowly to permit accurate reading of the measuring instrument but not so slowly as to cause unnecessary prolongation of stressing the test object near to the test voltage." These requirements are in general met if the rate of rise of voltage above 75% of the estimated final test voltage is approximately 2%/second of this voltage.

The voltage should be raised in this manner until a disruptive discharge occurs on the test object. The value of the test voltage reached just prior to the disruptive discharge should be noted.

The above procedure assumes certain prerequisites which can not always be adhered to when performing high voltage tests in practice. Puncture tests in oil using U 70 IC insulators [2] have yielded breakdown voltages varying from 102 to 160 KV. It is therefore impossible to meet the requirement that the rate of rise of voltage should be 2% / sec. of the 75% puncture voltage.

Similarly, a voltage withstand test performed at one single voltage level as is commonly done in routine production tests is inconclusive in itself. The only data that can effectively be garnered from this test is whether the insulator has passed or failed.

Since the emphasis here is on the establishment of an "Experimental Technique", various approaches using different criteria were explored. The withstand test method described in Ch.4:2 was finally adopted because:

- 1) Two different modes causing head puncture were identified. The first one leads to an almost instantaneous breakdown of the insulator. This mode appears to be of an intrinsic nature and is triggered by impurities or mechanical faults in the insulator head. Because of their almost instantaneous nature these punctures are unaffected by the rate of rise of voltage.

Observation of the ellipse on an ERA discharge detector has identified the second mode as one which appears to cause a "Treeing" process in the porcelain insulator head. This mode is characterized by the presence of well developed partial discharge activity, which all of a sudden increases rapidly and steadily; i.e. it "lifts-off" when puncture is imminent, up to the instant that breakdown actually occurs. The time from "lift-off" of the partial discharge activity until failure of the insulator takes place is finite. Dependant on the magnitude of the applied voltage this varies from a few seconds at 80 KV to a fraction of a second at 120 KV. The voltage at which this mode is initiated is easily passed by and missed entirely when the applied voltage is raised continuously at a rapid rate.

It is therefore preferable to set the voltage at a fixed level and to perform a withstand test. Nevertheless it must be remembered that withstand tests performed at voltage spacings of 10 KV lead to rounding errors of ± 5 KV of the chosen setting when determining the puncture voltage.

- 2) Apart from the applied voltage a whole battery of variables was monitored. (Vide Ch.4:2 Page 16 for details.) The recording of this data was simplified using voltage withstand tests. It was at times near impossible to observe all the instruments simultaneously when the voltage was raised continuously.
- 3) Tests conducted early on in the experimental phase showed that

with the voltage clamped to a fixed voltage level puncture occurred within two minutes of applying the voltage or not at all. This was the case irrespective of how long the voltage was maintained in excess of two minutes. For this reason a two minute ON cycle was chosen.

- 4) The two minute OFF cycle served as a rest period between the various withstand tests performed on the same insulator.
- 5) Voltage withstand tests furnish puncture voltage data in discrete form. It is therefore possible to draw up histograms which depict the frequency distribution of puncture occurring at a certain voltage.

Various other avenues of performing puncture tests were explored before the author decided to settle for the above mentioned procedure. In particular the puncture tests of Series 6 Insulators should be mentioned here. These tests were performed using a continuous 1 min. ON vs. no OFF time duty cycle; i.e. The voltage was applied continuously for a duration of 1 min. and was then raised in increments of 4 KV to the next level without observing a rest period.

A comparison of the results using the two methods is given in Chapter 5.

4.4 The Puncture Test in SF₆.

The somewhat greater ease with which gas can be handled is a convenience when using SF₆ as the immersing medium for puncture tests. There are no messy residues when an insulator is retrieved as is the case with oil. This advantage is offset by the higher capital outlay for gas handling and recycling equipment.

At a pressure of 400 Kpa absolute the breakdown strength of SF₆ is more or less equal to that of mineral oil. However, the relative permittivity of gas is unity. The electric field around a cap and pin insulator immersed in SF₆ is higher than in oil under identical circumstances. This infers that partial breakdown of the gas will occur at a lower voltage than in oil.

4.5) Specifications of Test Circuit and Power Supply

The experimental work is carried out by testing one insulator at a time in a pressure vessel of 2.2 m^3 volume which is filled with SF_6 . All tests were carried out at a gas pressure of 400 kPa abs.

The maximum output voltage of the test transformer is 325 KV.

The insulator or test specimen is suspended inside the test vessel by means of a girder made from angle iron.

A pictorial representation of the test vessel and gas handling equipment is given in Figs.4:1 and 4:2 on Page 23.

The principal piece of equipment of the electrical test circuit is the power supply. This is in the form of a single phase high voltage transformer which is mounted on the top right hand side of the pressure vessel as shown in Fig.4:1. The main specifications of the transformer are listed in Appendix 4 on Page A7.[20]

The test transformer is fed by a motor controlled supply transformer, with a secondary voltage range from 0 to 1000 V.

The test circuit which was employed in the following experiments is given in Fig.4:3 on Page 24. The following details should be noted:

The high tension terminal of the secondary winding is connected to a set of busbars inside the pressure vessel. The return terminal of this winding which is earthed via current transformer CT 1 (Ratio 1:1) is formed by the casing of the pressure vessel. The secondary winding of CT 1 is wired to a milli-ammeter on the control desk. CT 1 is unfortunately connected in a way as to register not only the possible insulator current but also the parasitic capacitive current of the pressure vessel. The latter quantity is almost 10 times as large as the former. For this reason the basic transformer circuit was expanded to the configuration as employed in Fig.4:3.

In the circuit of Fig.4:3 on Page 24 the current through the test specimen is isolated from the total current by the insertion of a second current transformer CT 2 (Ratio 1:1). CT 2 is mounted physically inside the test vessel. The primary winding is wired between the pin of the insulator specimen and the wall of the pressure vessel. The secondary winding is terminated by an insulated gasket on the pressure vessel. The connection between the test vessel and the control desk is achieved by means of a co-axial cable.

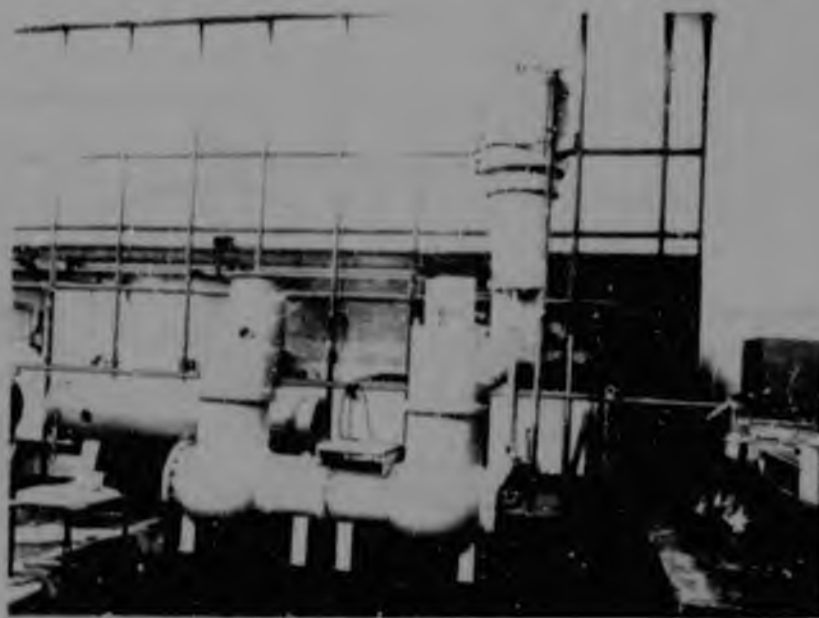


Fig.4:1 Test vessel in the "SIEMENS High Voltage Test Facility" of the University as used for the Experimental work.

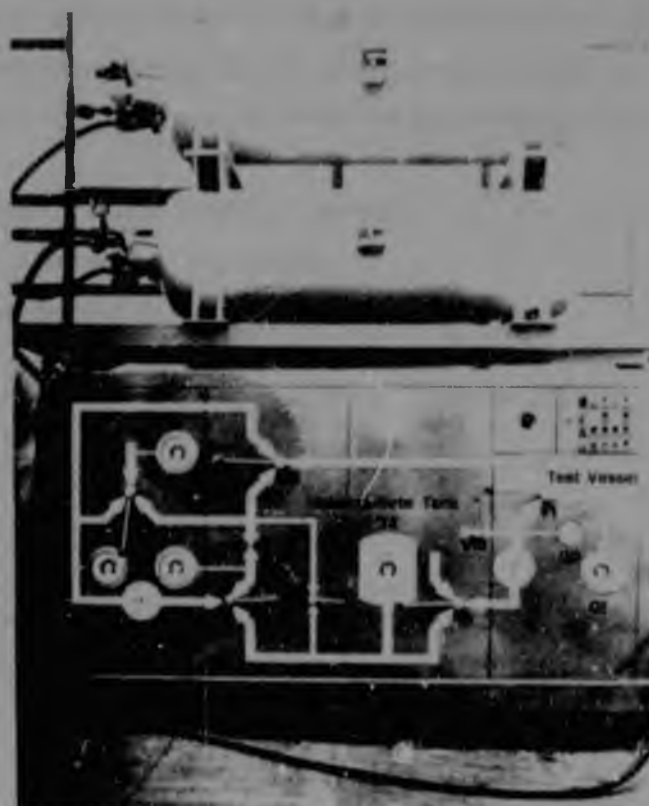


Fig 4:2 Gas Recycling Equipment

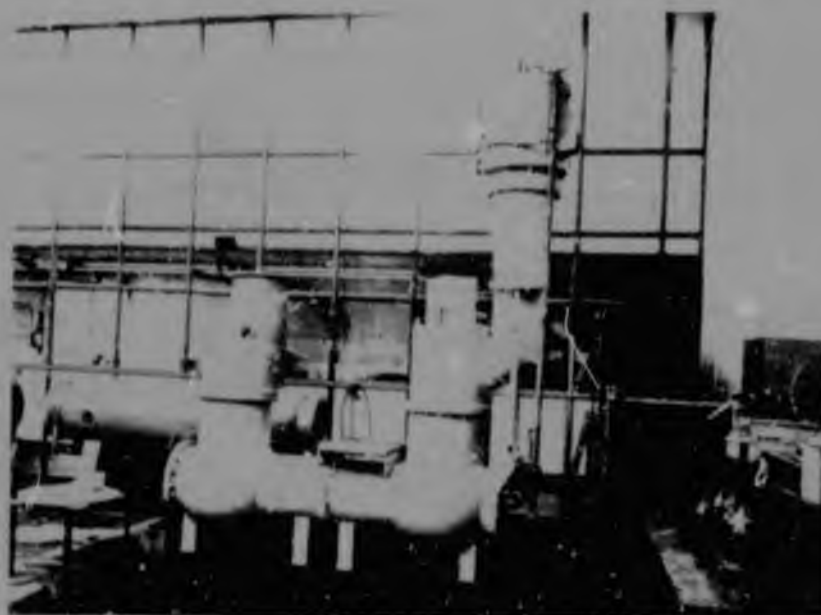


Fig. 4-1 Test vessel in the "SIEMENS High Voltage Test Facility" of the University as used for the Experimental work.

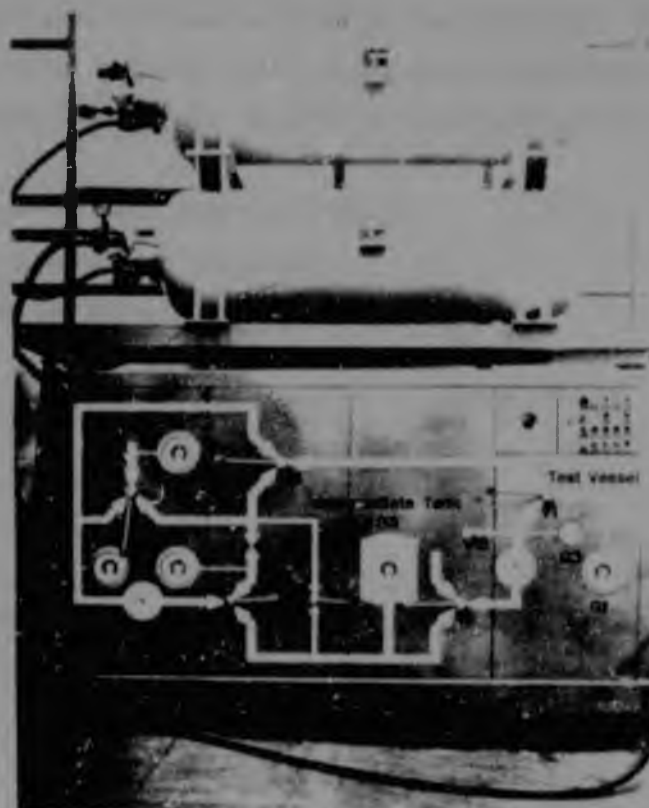


Fig. 4-2 Gas Recycling Equipment.

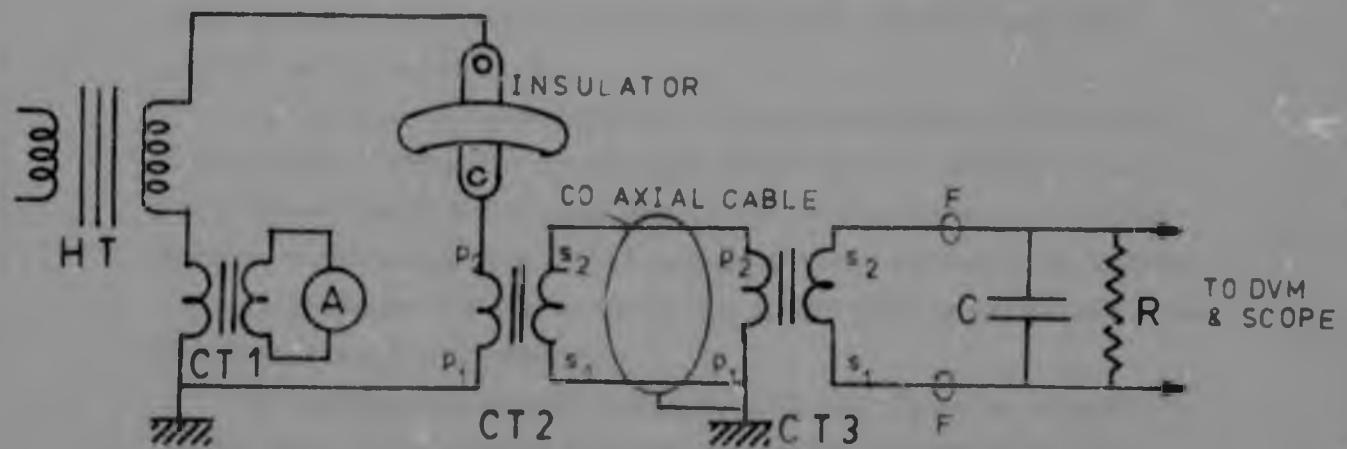


Fig 4.3 Test circuit

- HT High voltage test transformer
- CT1 Current transformer installed by manufacturer (Ratio 1:1)
- CT2 Current transformer which is physically installed in test vessel.(Ratio 1:1)
- CT3 Isolation transformer at point of instrumentation (Ratio 1:1)
- F Ferrules (Black Ferrite Beads)
- C Surge suppression capacitor
- R Voltage sampling resistor

A summary of the pertinent specifications of these instruments is given in Appendix 4 on Page A 7.

Insulation between the high tension circuitry and the recording instrumentation is improved by terminating the coaxial cable with a third CT ie. CT 3 of ratio 1:1.

CT 3 in turn is terminated by a surge suppression circuit and a 10 Ohm shunt resistor. The surge suppression circuit consists of two black ferrite beads and a capacitor of 100 pF. The voltage across the resistor is monitored by a digital voltmeter and a storage oscilloscope.

To eliminate leakage currents due to differering earth potentials selective grounding is employed.

All auxiliary equipment is energized through a mains isolation transformer so as to shield the instrumentation against di/dt and dV/dt spikes.

These elaborate protection measures were adopted because the employed digital voltmeters continually failed and malfunctioned on the occurrence of a puncture. The problem was finally traced to the power supply of the instruments concerned which lacked any form of surge protection. The use of battery operated DVM's overcame this problem.

A list of the auxiliary equipment employed together with the main specifications of the individual instruments is given in Appendix 4 on Page A 7.

4.61 Partial Discharge Measurements

Partial discharge measurements were performed on 80 insulators so as to establish in what measure such activity is responsible for initiating dielectric breakdown. These measurements were performed using an ERA Model 3 discharge detector.

The test circuit employed is shown in Fig. 4:4 below. The following factors must be borne in mind when taking readings. C_m is the high voltage arm of a capacitive voltage divider. This capacitor is mounted inside the gas tank of the high voltage supply transformer. ($C_m = 9pF$). For maximum sensitivity of reading $C_m \gg C_x$ where C_x is the capacitance of the test specimen, in this case a cap and pin insulator. C_x is given as 364 pF. when the parasitic capacitance of the test vessel is taken into consideration. The resultant sensitivity is therefore low. [21]

The correction factor $Q_{act} = 4.62 \times Q_{nom}$ was determined by using a discharge simulation unit.

Procedure of calibration and other relevant data concerning the partial discharge readings are given in Appendix 5 on Page A 4.

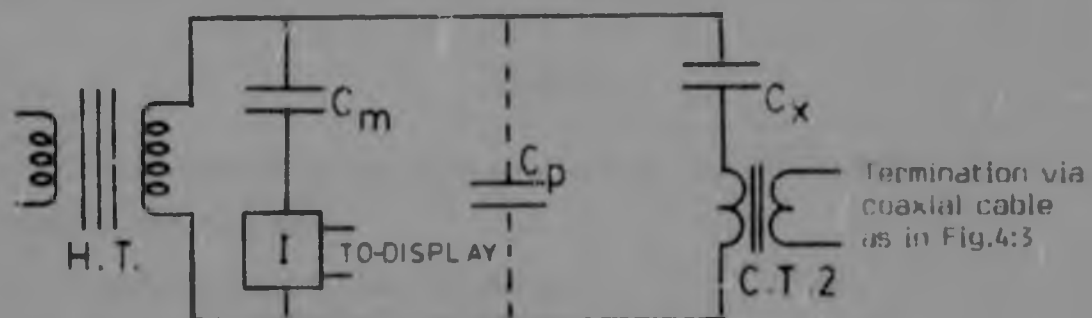


Fig. 4:4 Circuit employed to measure partial discharges

H.T.	High tension transformer
C_m	High tension arm of capacitive voltage divider
C_p	Parasitic capacitor formed by test vessel and HT
I	Input unit of ERA discharge detector.
C_x	Capacitance of test object ie. Insulator

5) OBSERVATIONS AND RESULTS

5.1) Frequency Distribution of Punctures as a Function of the Applied

Voltage

The following results were obtained for the 233 insulators which were tested experimentally:

Ratio of head to shed punctures	175:48
Average puncture voltage of all insulators	118,1 KV

Ten insulators did not puncture at all due to steady state flash-over at voltages in the vicinity of 120 KV. These are therefore not reflected in the following statistics.

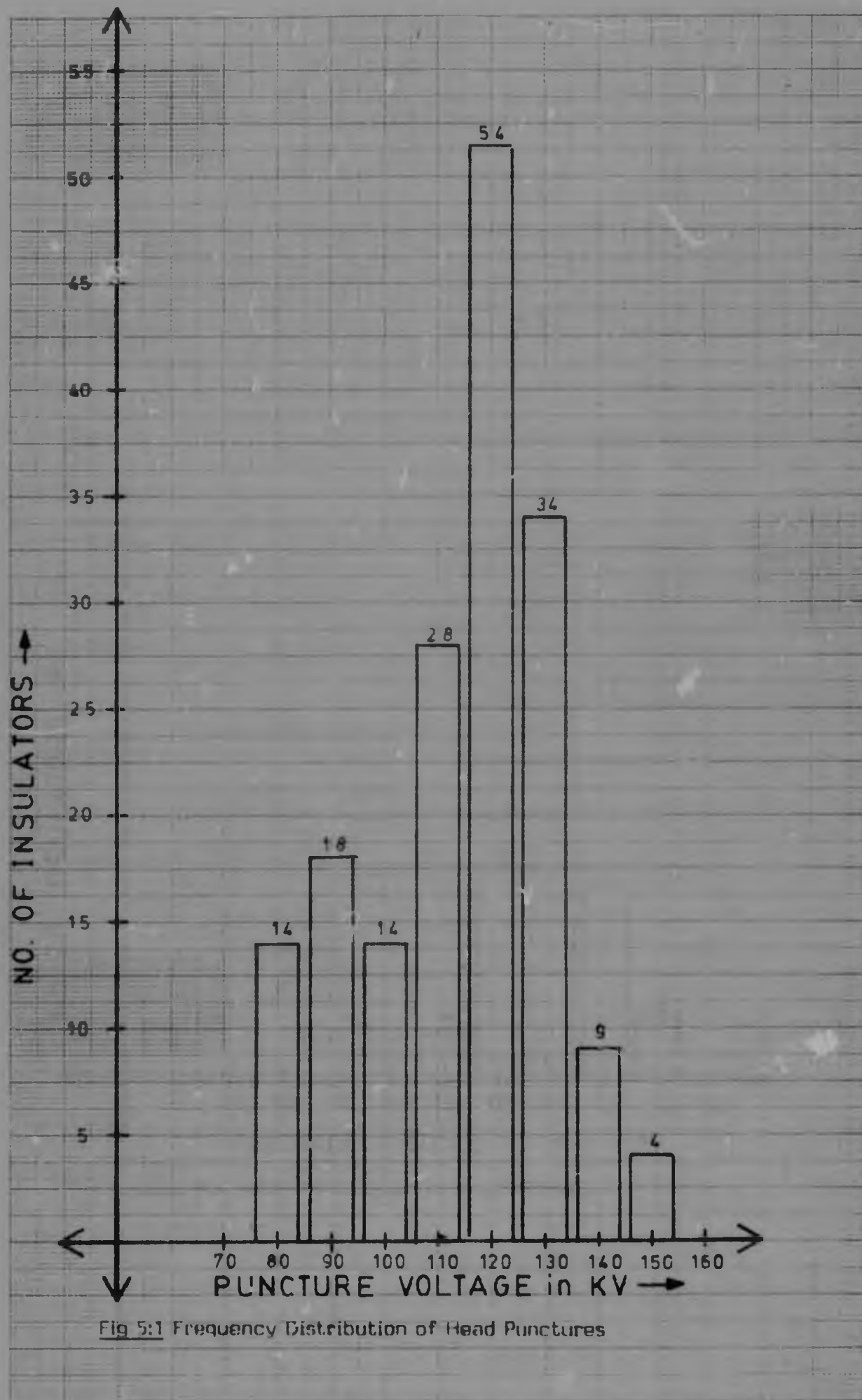
a) Head Punctures

No. of punctures	175
Minimum puncture voltage	80 KV
Average puncture voltage	114,2 KV
Maximum puncture voltage	150 KV
Standard deviation	17,2 KV

b) Shed Punctures

No. of punctures	48
Minimum puncture voltage	110 KV
Average puncture voltage	131,7 KV
Maximum puncture voltage	150 KV
Standard deviation	9,7 KV

Vide Figs. 5:1 and 5:2 on Pages 28 and 29 respectively for the frequency distributions of the above results.



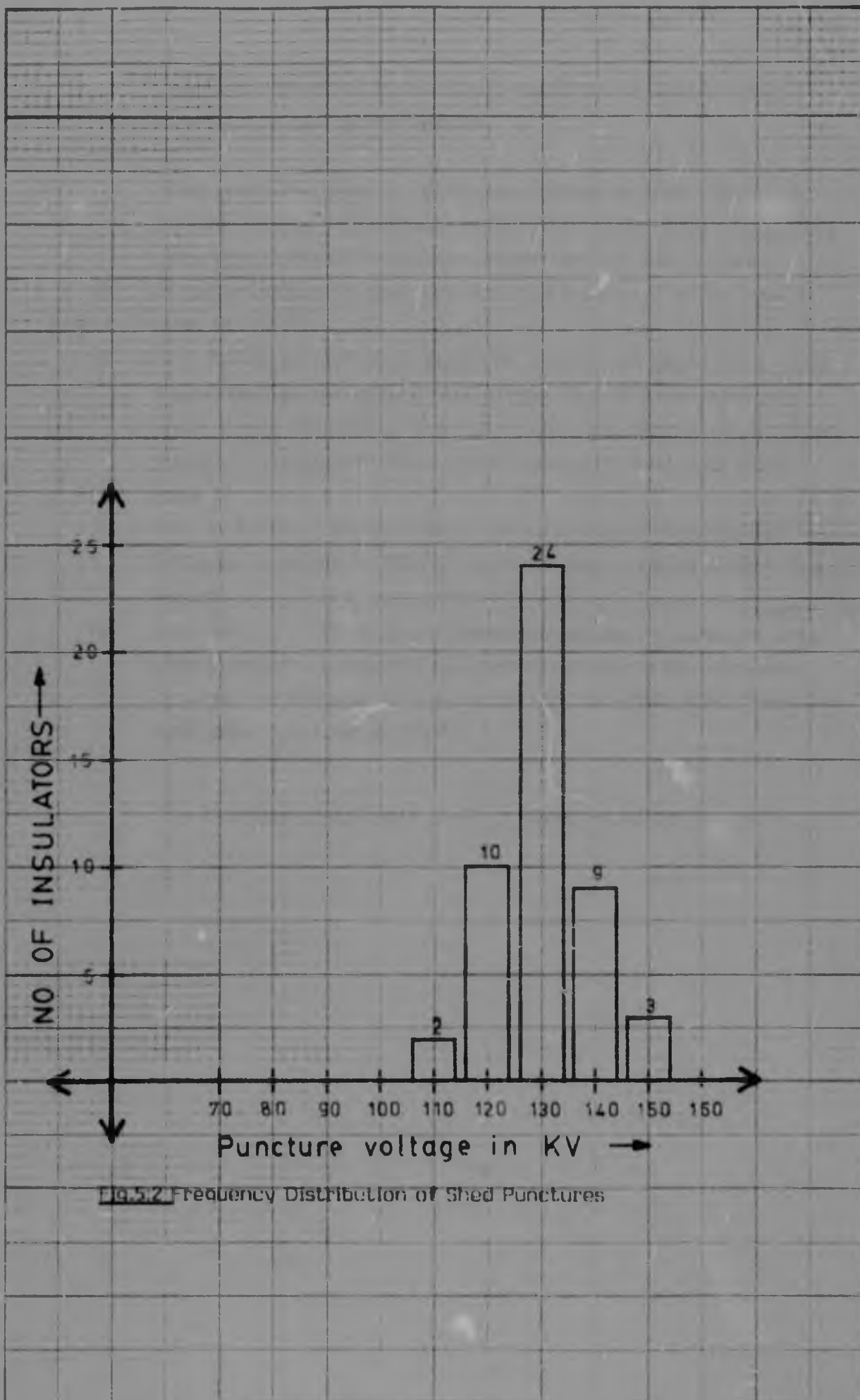


Fig. 5.2 Frequency Distribution of Shed Punctures

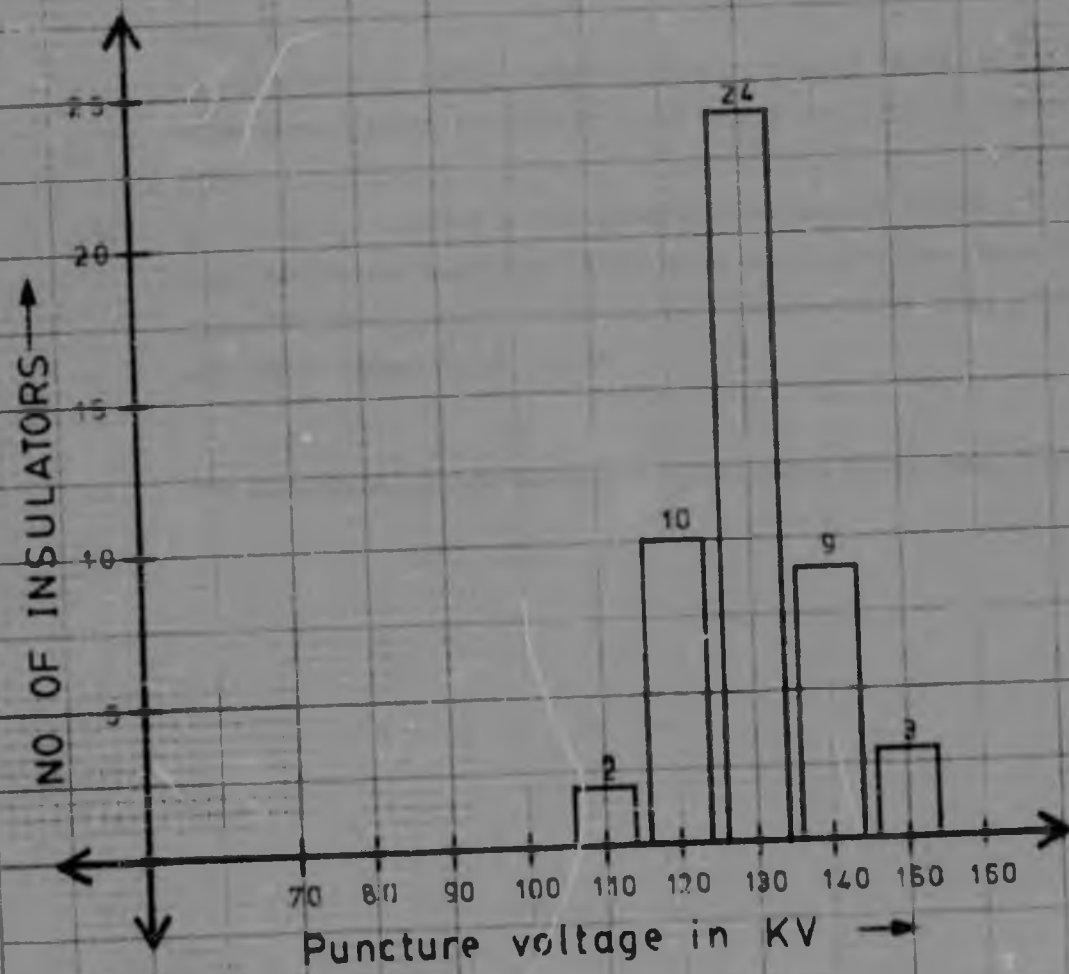


Fig. 5.2 Frequency Distribution of Shed Punctures

The following points have been noted from the histograms of Figs.5:1 and 5:2 as well as the results.

- 1) Head punctures peak at 120 KV, the voltage at which 30% of all failures namely 54 punctures occurred. The frequency of puncture occurring drops off rapidly on either side of this voltage.
- 2) A similar pattern is observed for shed punctures which have a peak at 130 KV.
- 3) Only 20% of all punctures occurred at voltages below 110 KV. This figure ignores the failure rate of the routine production test which easily amounts to 10 @ 15% of the total number of insulators tested. For details of the routine production test Vide Ch.3:1 Page 12.
- 4) No punctures of either head or shed type were recorded for voltages in excess of 150 KV; ie. All insulators failed at or below 150 KV.
- 5) As a rule $V_p = 130$ KV is the threshold voltage in excess of which shed punctures invariably occur. Head punctures have however occurred at voltages as high as 150 KV. Conversely, shed punctures have been observed at 110 KV.

The individual results are given in Appendix 6:1 on Page A 13.

5.2) Statistical Analysis of $I - F(V)$

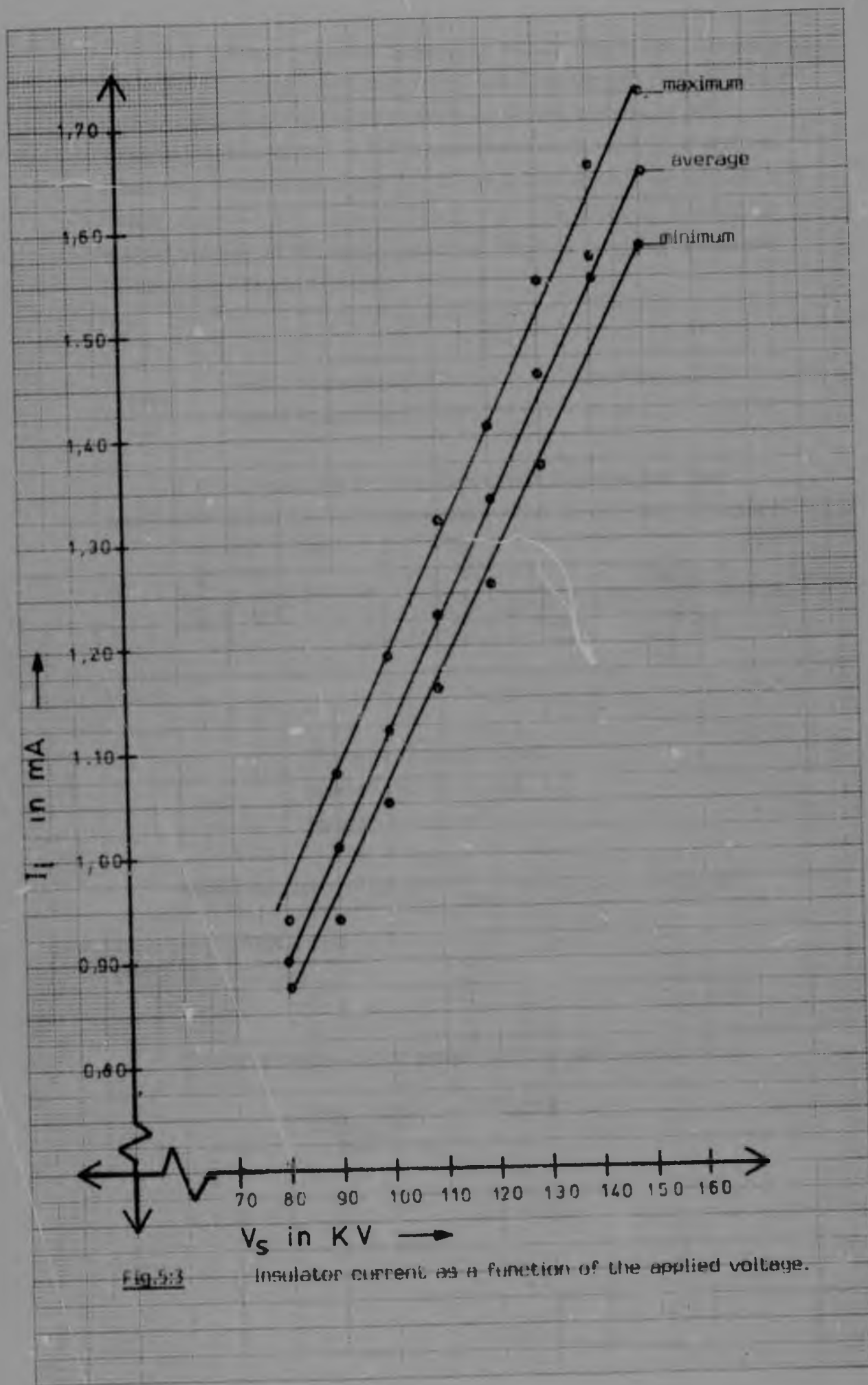
The current of each insulator of the batches 4 to 8 was measured so as to establish a link between current flow and puncture mechanisms.

V_{lev}	N_I	I_{min}	I_{av}	I_{max}	I_{sd}
80	166	0,85	0,90	0,94	0,021
90	155	0,94	1,01	1,08	0,028
100	142	1,05	1,12	1,19	0,031
110	127	1,16	1,23	1,32	0,034
120	100	1,26	1,34	1,41	0,039
130	47	1,37	1,46	1,55	0,045
140	12	1,55	1,57	1,66	0,051
150	2	1,58	1,65	1,73	-

TABLE 2: Statistical evaluation of insulator current as a function of the applied voltage.

V_{lev}	applied voltage withstand level in KV
N_I	no. of samples used in computing the average current and the standard deviation.
I_{min}	minimum current
I_{av}	average current
I_{max}	maximum current
I_{sd}	standard deviation of current

Curves depicting I_{min} , I_{av} , I_{max} as a function of the applied voltage are given in Fig.5:3 on Page 32.



The insulator current is made up of two components, namely a small conduction current which is in phase with the applied voltage and a dominating capacitive current which leads the voltage by 90° . To establish the magnitude of these components, capacitive and $\tan(\delta)$ measurements were recorded for 15 insulators using a logarithmic LCR bridge. $C_{av} = 32.5 \pm 0.5$ pF. $\tan(\delta)$ averages out at 0.04. For an applied voltage of 120 KV the average insulator current is 1.34 mA. (Vide Table 2, Page 31), hence:

I_{cond}	$1.34 \times \sin[\arctan(0.04)]$	$= 0.05 \text{ mA or } 50 \text{ uA}$
I_{cap}	$1.34 \times \cos[\arctan(0.04)]$	$= 1.34 \text{ mA}$

If the conduction current component is neglected then $I_l = I_{cap}$ and the measured insulator capacitance can be verified as follows:

$$Z = \frac{V}{I} = \frac{1}{\omega C} \longrightarrow C = \frac{I_l}{\omega V_{app}} = \frac{3185 I_l}{V_{app}}$$

where:

I_l	insulator current in mA
V_{app}	applied voltage in KV
C	capacitance in pF.

Again consider the case of $V_{app} = 120$ KV and $I_l = 1.34$ mA

$$\text{then } C = \frac{3185 \times 1.34}{120} = 35.6 \text{ pF}$$

The discrepancy in the result for the two methods is :

$$\frac{35.6 - 32.5}{35.6} = 8.7 \%$$

The insulator current is made up of two components, namely a small conduction current which is in phase with the applied voltage and a dominating capacitive current which leads the voltage by 90° . To establish the magnitude of these components, capacitive and $\tan(\delta)$ measurements were recorded for 15 insulators using a logarithmic LCR bridge. $C_{av} = 32,5 \pm 0,5$ pF. $\tan(\delta)$ averages out at 0,04. For an applied voltage of 120 KV the average insulator current is 1,34 mA. (Vide Table 2, Page 31), hence:

$$\begin{aligned} I_{\text{cond}} &= 1,34 \times \sin(\arctan(0,04)) = 0,05 \text{ mA or } 50 \text{ } \mu\text{A} \\ I_{\text{cap}} &= 1,34 \times \cos(\arctan(0,04)) = 1,34 \text{ mA} \end{aligned}$$

If the conduction current component is neglected then $I_1 = I_{\text{cap}}$ and the measured insulator capacitance can be verified as follows:

$$Z = \frac{V}{I} = \frac{1}{\omega C} \longrightarrow C = \frac{I_1}{\omega V_{\text{app}}} = \frac{3185 I_1}{V_{\text{app}}}$$

where:

$$\begin{aligned} I_1 & \text{ insulator current in mA} \\ V_{\text{app}} & \text{ applied voltage in KV} \\ C & \text{ capacitance in pF.} \end{aligned}$$

Again consider the case of $V_{\text{app}} = 120$ KV and $I_1 = 1,34$ mA

$$\text{then } C = \frac{3185 \times 1,34}{120} = 35,6 \text{ pF}$$

The discrepancy in the result for the two methods is :

$$\frac{35,6 - 32,5}{35,6} = 8,7 \%$$

The results in TABLE 2 and Fig.5:3 show that the insulator current is an almost linear function of the applied voltage. The insulator current does vary as a function of V_s but is stable; i.e. There are no hysteresis or other factors present which distort the readings when the voltage is lowered and reraised. As can be seen from the individual results in Appendix 6:2 on Page A 18, this does not imply that the current readings for the various insulators are necessarily identical. The $I_i = f(V_s)$ curve on Page 32 shows that variations of ± 0.05 mA occurred around the average values curve over the whole range of test voltages.

Up to and until puncture occurred no appreciable increase in the current readings was discernible to the naked eye. Once puncture had taken place the current rose sharply to the steady state short circuit current. The transition from maximum voltage stress to steady state short circuit current takes place within one quarter cycle of the supply voltage frequency; i.e. in less than 5 ms. This pattern of development was observed for punctures of both the "instantaneous" and "freeing" type.

The current waveforms of both the insulator current and the transition into short circuit were observed on a storage oscilloscope. I_i is sinusoidal and leads the applied voltage by 90° . Fig.5:4 on Page 35 shows the events leading to a head puncture. The magnitude of the resultant short circuit current which is also sinusoidal is limited by the impedance of the power supply. In this case $I_{pp} = 600$ mA or $I_{rms} = 215$ mA.

The short circuit current waveform of a shed puncture is distorted by the flashover as is shown in Fig.5:5.

On both of these figures the high frequency damped oscillations are caused by corona discharges.

The individual results of I_i as a function of V_s are given in Appendix 6:2 on Page A 18.

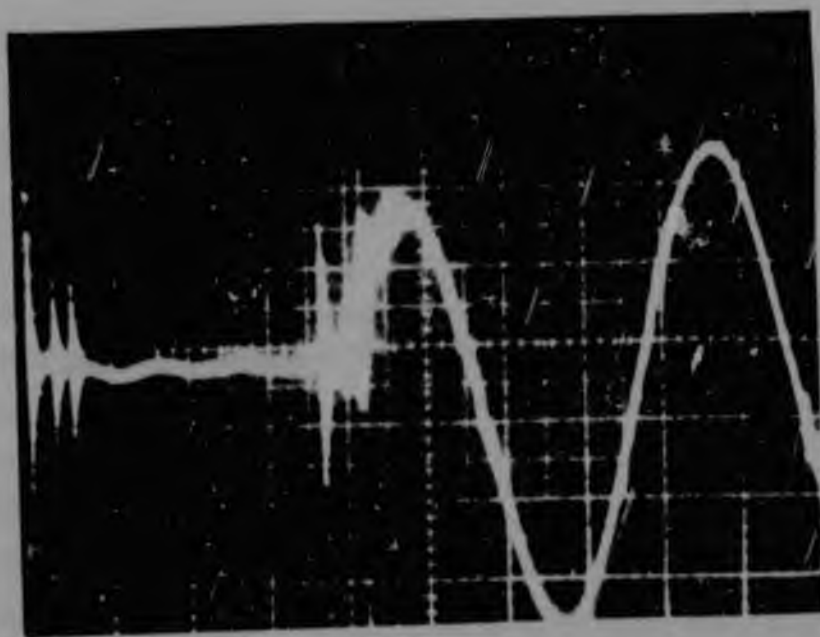


Fig 5:4 Current waveform of a head puncture

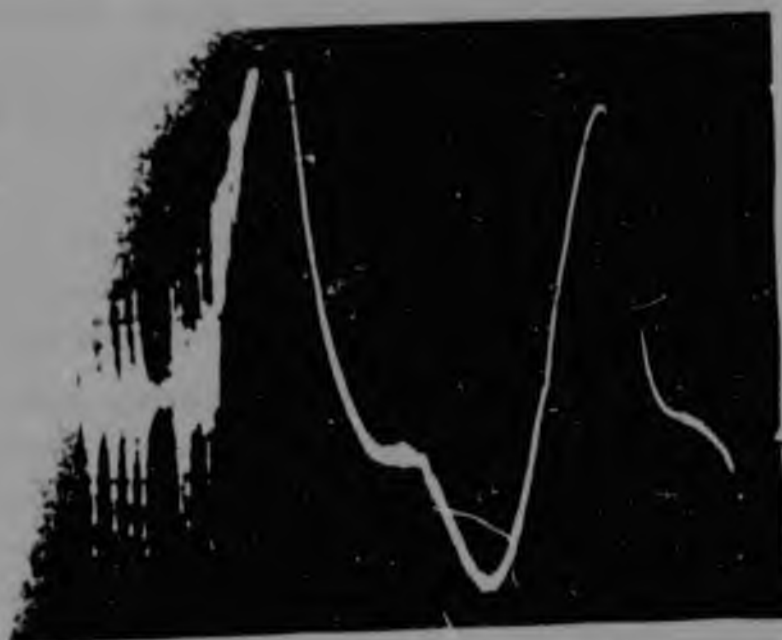


Fig 5:5 Current waveform of a shed puncture.

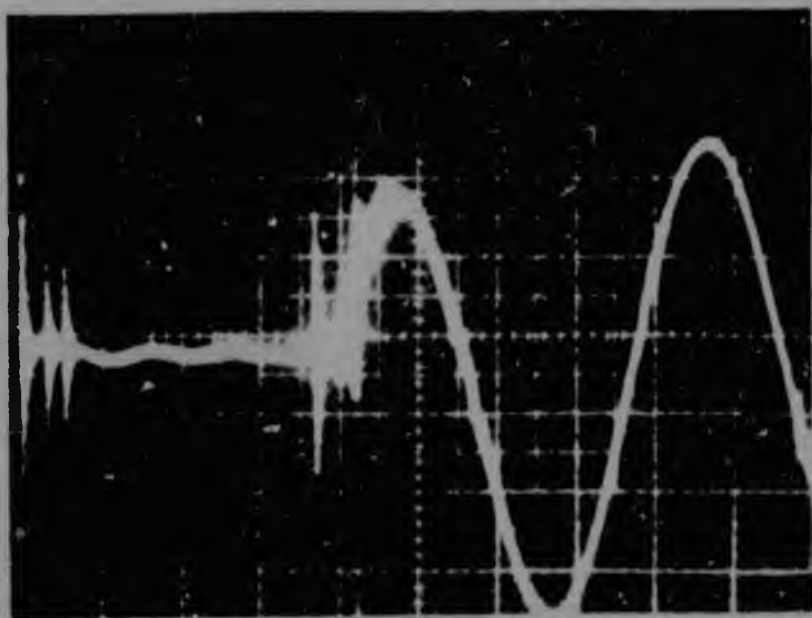


Fig 5:4 Current waveform of a head puncture

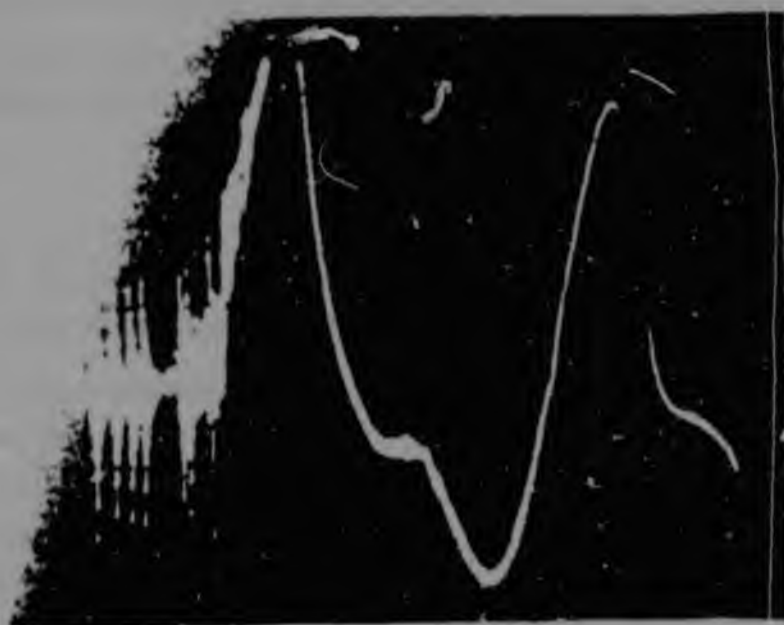


Fig 5:5 Current waveform of a shed puncture.

5.3) Flashover and Corona Inception Voltages

a) Flashover

The flashover activity of all 233 specimens was investigated giving the following results:

No. of insulators which flashed over	80
Minimum inception voltage	100 KV
Average inception voltage	120.0 KV
Maximum inception voltage	152 KV
Standard Deviation	9.7 KV

"Flashover Inception Voltage" implies that voltage at which partial flashover occurs; i.e. Flashover occurs with subsequent extinction of the arc.

Sporadic flashover was observed on 80 insulators for voltages ranging from 100 to 150 KV. Once flashover had been initiated at a withstand voltage level it re-appeared in the following tests which were performed at higher voltages. Sporadic flashover with attendant extinction of the arc provided no obstacles to puncture testing. Once the 140 KV withstand level was reached flashover however appeared in the form of a short circuit power arc which encompassed both cap and pin by following a crazed path across the surface of the insulator.

b) Corona

The coronaic behaviour of a sample of 141 insulators comprising all the insulators from batches 6, 7 and 8 was recorded.

No. of ins. on which corona was observed	44
Minimum inception voltage	70 KV
Average inception voltage	106.4 KV
Maximum inception voltage	120 KV
Standard Deviation	9.17 KV

The presence of corona could be heard but was also visible on the storage oscilloscope in the form of damped sinusoidal oscillations of short duration. An example of this are the oscillations on the left hand side of Fig. 5.4 on Page 35.

Corona appeared at voltages below the flashover level in the range from 90 to 110 KV. As the results of Appendix 6:3 show, corona is in many instances a precursor to flashover. For 8% of the tested insulators an excessive build up of corona was observed at voltages as low as 90 KV. The resultant level of activity was such that the readings on the DVM and oscilloscope went wildly out of control. The applied voltage was then lowered to zero and reraised after the two minute OFF time interval. By then this phenomenon had disappeared. Occasionally however it reappeared with undiminished intensity. The ultimate puncture voltage was not affected. This is possibly a conditioning effect associated with the presence of dust particles on the insulator surface.

5:5) "Clean" vs. "Polluted" insulators

Puncture tests were performed on 50 "Polluted" insulators. The results are compared to a representative batch of 5 "Clean" insulators. "Polluted" insulators for the purposes of the experiment implies factory soiled, unwashed insulators.

Ratio of head vs. shed punctures:

Clean insulators

43:11

Polluted insulators 39:11

<u>Ins.</u>	<u>N</u>	<u>V</u>	<u>V_{min}</u>	<u>V_{av}</u>	<u>V_{max}</u>	<u>V_{sd}</u>
CI hp	43		80	113,7	140	14,8
CI sp	11		120	134,5	150	8,2
PI hp	39		80	105,4	130	17,6
PI sp	11		110	126,4	140	10,3

TABLE 3:

Comparison of puncture voltages "clean" vs. "Polluted" insulators

CI hp Clean insulators, head punctures

CI sp Clean insulators, shed punctures

PI hp	Polluted insulators, head punctures
PI sp	Polluted insulators, shed punctures
N	No. of samples
$V_{p \min.}$	minimum puncture voltage (in KV)
$V_{p \text{ av}}$	average puncture voltage (in KV)
$V_{p \max}$	maximum puncture voltage (in KV)
V_{sd}	standard deviation (in KV)

The frequency distribution of these results is given in Figs. 5:6 to 5:9 on Pages 39 and 40 respectively

V_{lev}	N_1	I_{min}	I_{av}	I_{max}	I_{sd}
80	47	0.87	0.90	0.94	0.018
90	44	0.97	1.02	1.06	0.021
100	40	1.08	1.13	1.17	0.022
110	37	1.21	1.25	1.29	0.025
120	33	1.32	1.36	1.41	0.029
130	11	1.44	1.49	1.52	0.027
140	2	1.61	1.615	1.62	-
150	1	-	1.73	-	-

TABLE 4: Evaluation of $I_1 = f(V_s)$ for clean insulators

V_{lev}	N_1	I_{min}	I_{av}	I_{max}	I_{sd}
80	46	0.87	0.91	0.95	0.016
90	42	0.98	1.03	1.08	0.022
100	35	1.09	1.14	1.19	0.025
110	27	1.22	1.26	1.32	0.028
120	20	1.34	1.38	1.42	0.024
130	7	1.48	1.51	1.55	0.024
140	2	1.63	1.65	1.66	0.021

TABLE 5: Evaluation of $I_1 = f(V_s)$ for polluted insulators

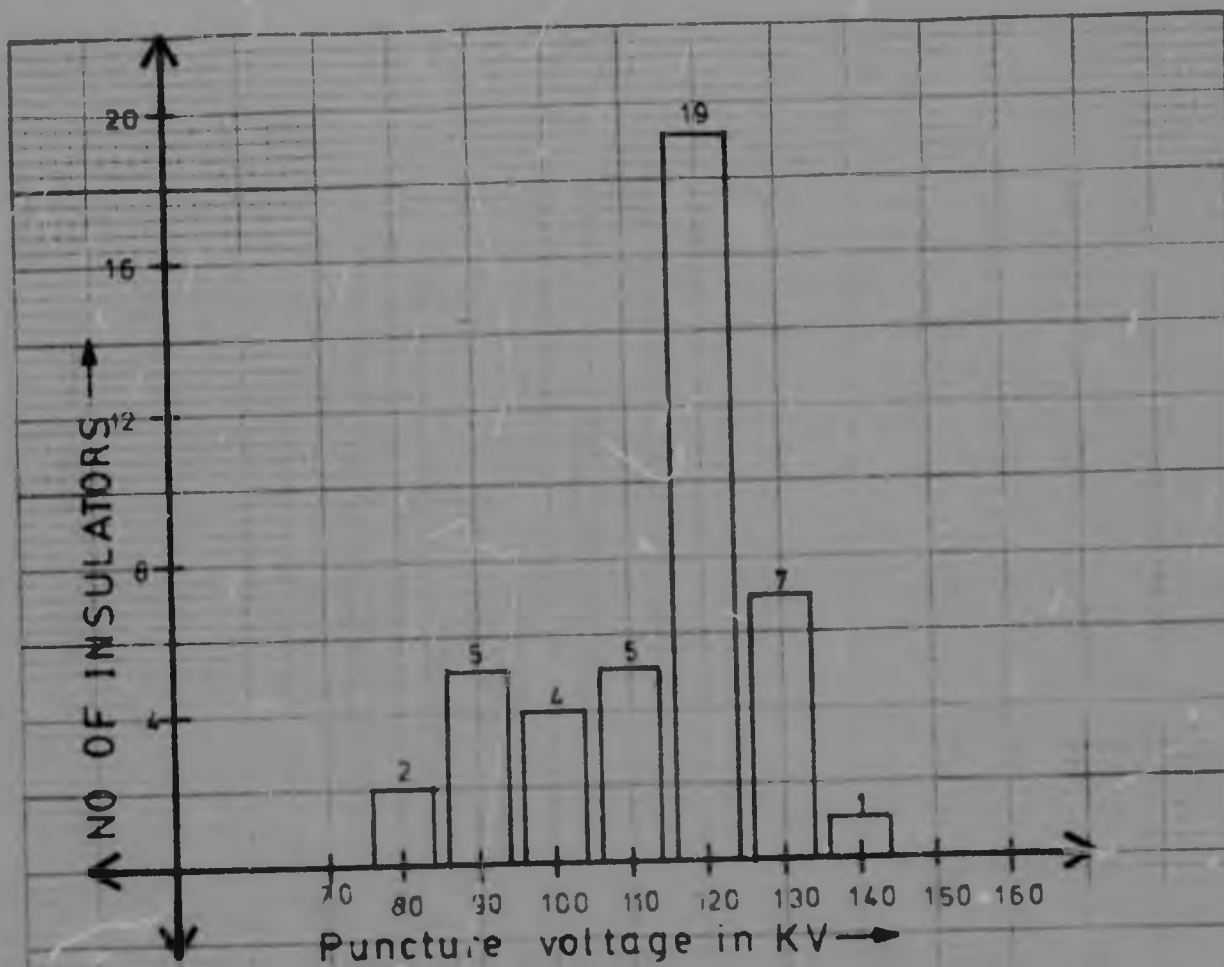


Fig.5:6 Frequency distribution of head punctures for "clean" insulators

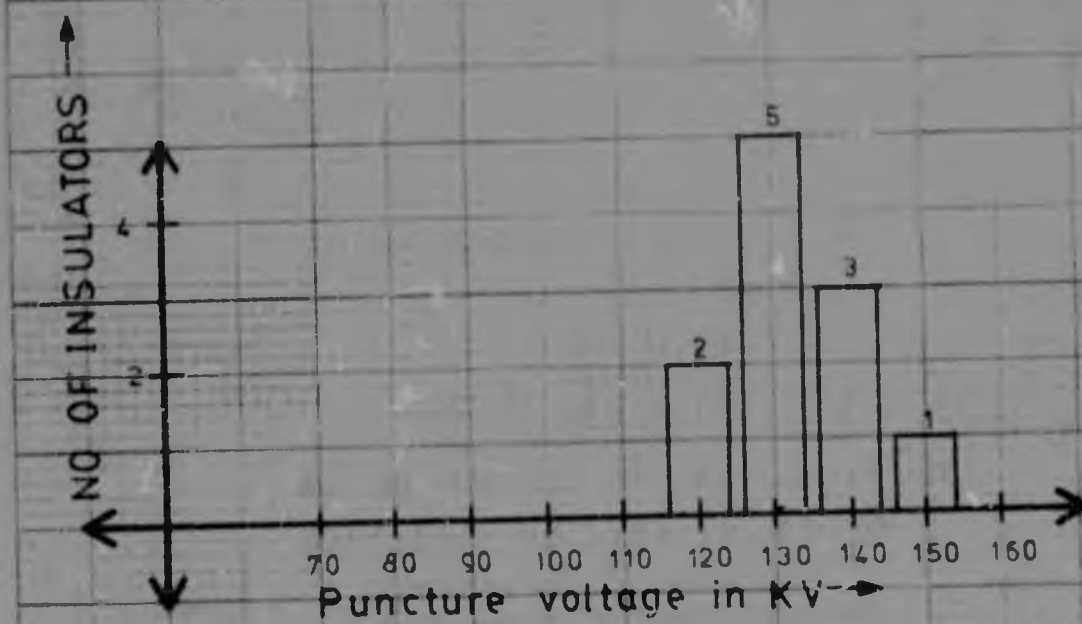


Fig 5:7 Frequency distribution of shed punctures for "clean" insulators.

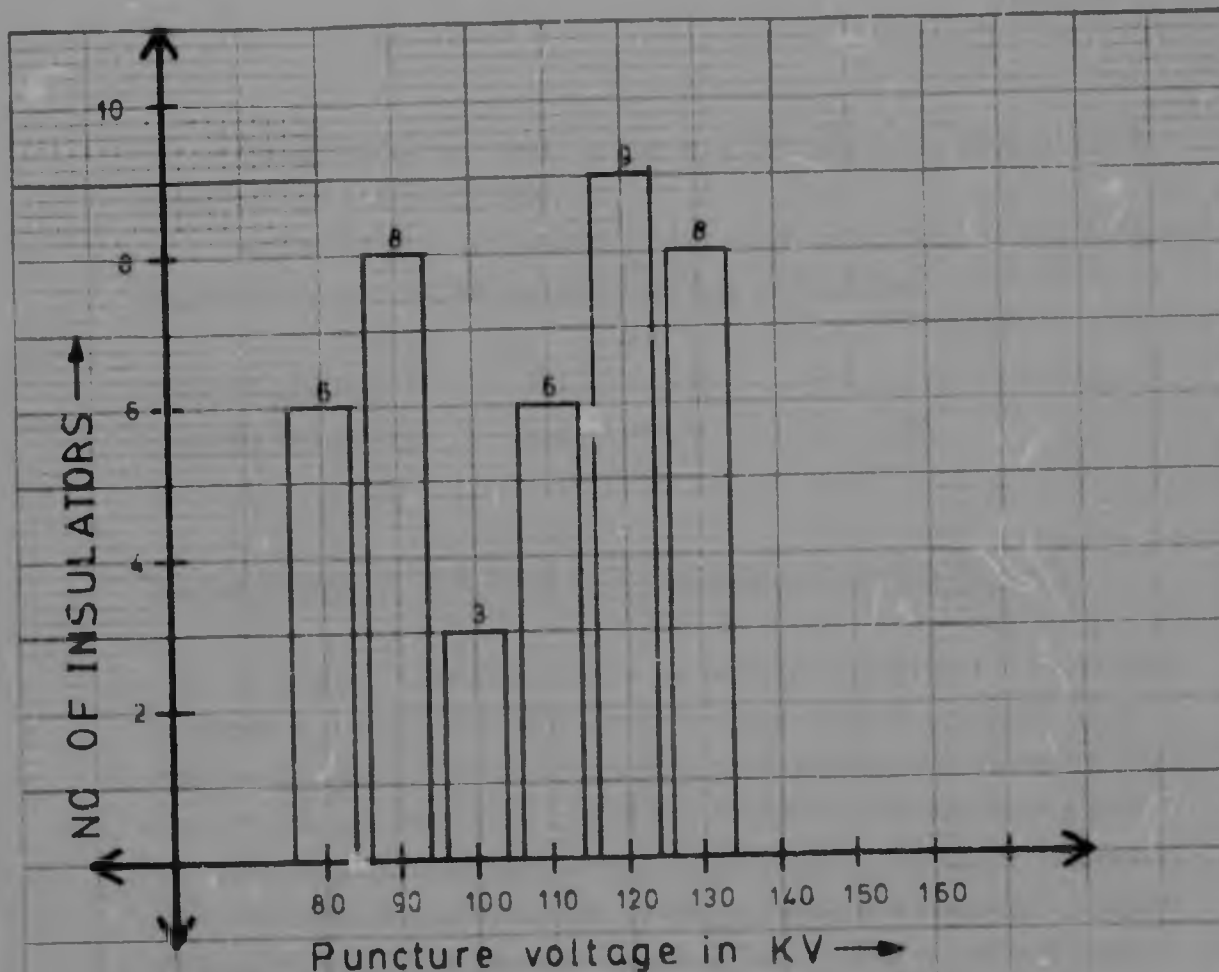


Fig. 5.8

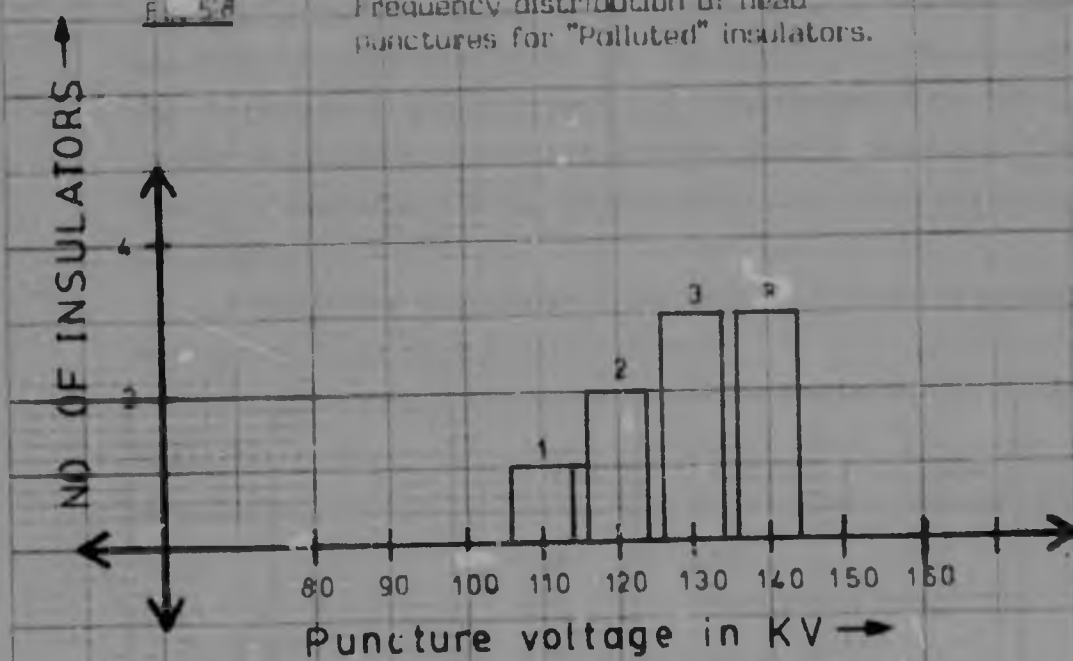


Fig. 5.9

The abbreviations used in Tables 4 and 5 are the same as those employed for Table 2 on Page 31.

With reference to Batches 1 to 8 as given on Page 18 the following insulators were used in performing these experiments.

<u>Clean Insulators:</u>	Nos.4:1 - 4:30	5:21 - 5:30	7:1 - 7:24
<u>Polluted Insulators:</u>	Nos.5:1 - 5:20	6:1 - 6:30	

5.5) Breakdown of Test Data in Accordance with Batch Numbers

A record of manufacturer's lot numbers was kept for insulators of Series 8. The 81 insulators which comprise batch 8 are made up of insulators coming from 21 different manufacturing lots. The no. of samples per lot was therefore too small to produce any meaningful statistics. 44 insulators belonging to three different lots were however identified and tested. Fourteen of these insulators belonged to batch 7M while 15 insulators each belonged to lots 7C and I5 respectively.

All of these insulators were manufactured in 1979. The year of manufacture together with the lot no. are printed on the insulator shed. The characters of the lot numbers are interpreted in the following manner: The numeral indicates the month whereas the alpha numeric character identifies the day of manufacture. eg. 7M is the 13th working day in July.

A statistical evaluation of the results obtained from testing batches 7M, 7C and I5 is given in Table 6.

<u>Batch No</u>	$\frac{N}{V}$	$\frac{V}{min}$	$\frac{V}{av}$	$\frac{V}{max}$	$\frac{V}{sd}$
I5 hp	5	80	120	150	26.5
I5 sp	5	120	134	150	11.4
7C hp	13	80	113	140	18.0
7C sp	2	120	120	120	0
7M hp	10	80	115	140	16.5
7M sp	4	130	130	130	0

TABLE 6: Evaluation of Data in accordance with manufacturer's lot nos.

The abbreviations used are the same as those employed in TABLE 3 on Page 37.

Five insulators from batch 15 and one from batch 7M did not puncture at all. Flashover made further testing impossible beyond the withstand level of 150 KV. The following insulators were used in performing the above experiments:

<u>Batch 15:</u>	8:08 - 8:22	
<u>Batch 7C:</u>	8:07	and 8:32 - 8:45
<u>Batch 7M:</u>	8:01 - 8:05	and 8:23 - 8:31

The individual results are recorded in Appendix 6:1 on Page A 16.

5.6) Partial Discharge Activity within the Insulator as a Function of the applied voltage

In addition to the recording of other data partial discharge measurements were carried out on all insulators of batch 8. The results do not lend themselves to a rigorous analysis but have yielded some very interesting observations on the internal behaviour of the insulator.

Partial discharge activity in one form or another was observed in 60% of the insulators tested. No definite pattern between puncture voltage and p.d. activity could be established. The observed p.d. activity was usually very sporadic and random.

The following points were noted:

- 1) The magnitude and density of the observed partial discharges was distributed equally between both +ve and -ve cycles of the sinusoidal voltage wave.
- 2) In some instances p.d. activity in the +ve half cycle exceeded that in the -ve half cycle either in magnitude or frequency and occasionally both.
- 3) Certain insulators have a p.d. inception voltage of less than 50 KV. Once initiated p.d. activity is well developed.
- 4) The presence of p.d. activity on its own is not sufficient evidence that breakdown is imminent. This point is discussed in more detail in the following Chapter.

5.7) Physical Damage of the Insulator due to Puncture

A post mortem was conducted on 70 insulators which punctured in the head.

To this purpose the insulator shed was knocked off and the metal cap was cut open. Depending on how well it was developed, the discharge channel caused a localized mechanical weak spot. This channel was laid bare by applying several blows from a heavy hammer. Occasionally the insulator shattered in such a manner that the discharge channel could not be located.

An analysis of the location of puncture paths yielded the following frequency of occurrence:

1)	Corner of cap to sharp edge of pin	44
2)	Centre of cap to centre of pin	7
3)	Centre of cap to sharp edge of pin	3
4)	Side of cap to stem of pin	3
5)	Side of cap to sharp edge of pin	2
6)	Exact location not established	11

Fig.5:10 shows the various locations which were identified. (The key to the numbering is in accordance with the above list.) It is seen from the above dissection data that 85% of all punctures start or terminate at or near the sharp edge of the pin. Some typical discharge tracks are shown in Figs.5:13 on Pages 44 and 45 respectively.

The thickness of porcelain in the insulator head varied from 17.0 to 19.0 mm. The following frequency distribution was observed for 55 head punctures.

d in mm	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5
No. of ins.	10	3	8	11	10	16	4	2

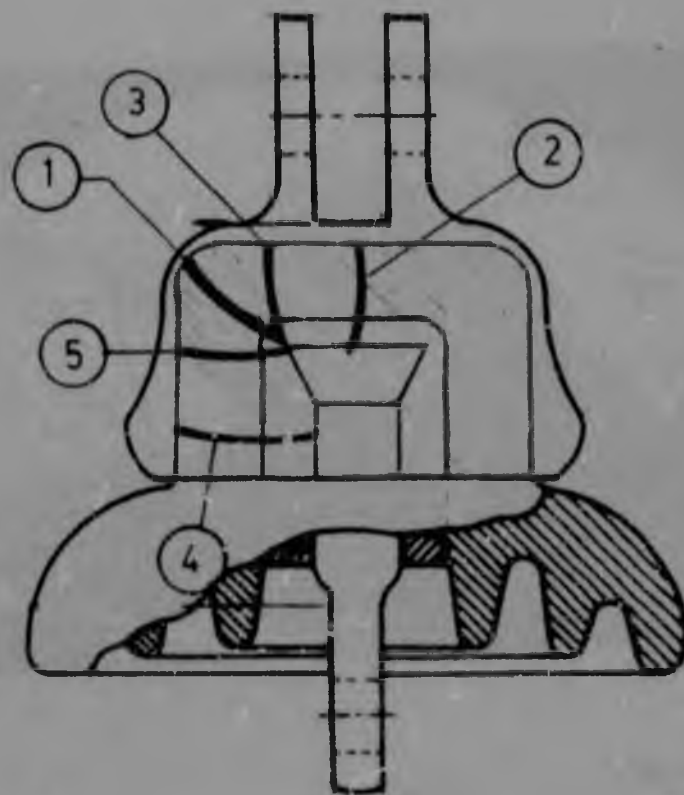


Fig.5:10 Specific locations of head punctures



Fig.5:11

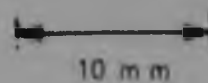




Fig.5:12

10 mm



5 mm

Fig.5:13

Figs.5:10,5:11,5:12 and 5:13: Discharge tracks in cap and pin insulators



Fig. 5:12

10 mm



5 mm

Fig. 5:13

Figs. 5:10, 5:11, 5:12 and 5:13: Discharge tracks in cap and pin insulators

5:8) Comments on other recorded Data

The rate of rise of voltage is fixed at either 5 KV/sec. or 10 KV/sec. For the insulator withstand tests as performed, the voltage was raised in a random manner by alternatively using the fast and slow modes. The following points were noted:

- 1) When the voltage was reraised after a withstand test no insulator broke down at a voltage below that of the last performed test, irrespective of the rate of rise of voltage.
- 2) The breakdown voltage of head punctures is unaffected by the rate of voltage rise.

The insulators of Batch 7 were subjected to the standard test; routine of 2 mins.ON / 2 mins.OFF up to 120 KV. Those insulators which had not punctured by then were retrieved and subjected to a new series of tests. This time withstand tests using a 5 min.On / 5 min.OFF duty cycle were performed at 100, 110 and 120 KV respectively. The test cycle for 120 KV is repeated until puncture occurs. None of the test specimen failed at 100 or 110 KV. All failed at 120 KV with times varying from 1 to 20 minutes. The ratio of head vs. shed punctures is 5:1

The individual results that were recorded for this procedure are given at the end of Appendix 6.1 on Page A 15.

As has already been mentioned in Ch. 4.3 on Page 21, Insulators 6:1 to 6:20 were subjected to withstand tests using a 1 minute On / no rest period or continuous duty cycle while the voltage was raised in increments of 4 KV. The following results were obtained:

Total no. of punctures	30
Ratio of head vs. shed punctures	75.0 or (7:3)

(i) Head Punctures

No. of punctures	21	
Minimum puncture voltage	80	KV
Average puncture voltage	104.5	KV
Maximum puncture voltage	132	KV
Standard deviation	17.0	KV

b) Shed Punctures:

No. of punctures	9	
Minimum puncture voltage	112	KV
Average puncture voltage	128.9	KV
Maximum puncture voltage	140	KV
Standard Deviation	8.9	KV

Early experimental work showed that punctures occurred within two minutes of clamping an insulator to a fixed discrete voltage or not at all. The results confirm this hypothesis.

The only exception to this rule are insulators from Batch (or Series 7) which were subjected to the routine described on Page 46.

The individual results that were recorded are given in Appendix 6:5 on Page A 30.

6) DISCUSSION

6:1) Assessment of the Experimental Procedure: The Puncture Test in Oil vs.that in SF₆

As has been mentioned in Ch.3:1 the puncture test despite all its shortcomings is at present the only means available to perform electrical quality tests.

The significance of the reported experimental work is that puncture tests have been performed in SF₆ instead of oil.

The problems that are encountered when conducting the puncture test in SF₆ are the same which are present when performing it in oil. Specifically these are the presence of corona and the concomitant flashover, as well as the partial breakdown of the dielectric immersant around the insulator.

Before discussing the effect of these phenomena on the breakdown voltage of insulators in more detail, the puncture tests as performed in SF₆ will be compared to puncture tests in oil. The latter tests were performed by two independent parties outside of the "Department of Electrical Engineering" of the University of the Witwatersrand, namely:

- 1) The Department of Electrical Engineering, University of Cape Town [2].
- 2) Die Instituut vir Elektronika, Universiteit van Stellenbosch [4].

In both cases insulators of the type SAC 19-0345 or U 70 LC were used in performing the experimental work. These are of the same type as used by the author. A direct comparison of results is therefore possible. The following points should however be considered:

- 1) Neither of the other two parties performed withstand tests but raised the applied voltage in accordance with BS-923 which procedure is detailed in Ch.4:3 on Page 19.
- 2) The number of test samples is small, 37 for Stellenbosch and 2 x 11 for Cape Town. No record of manufacturer's lot No.s is kept by either party. Neither is it known whether the insulators belonged to one and the same batch or not.

- 3) The results of Stellenbosch are somewhat misleading in that they have been combined with those obtained by Croucher [2] from UCT, although the latter used different test conditions.

TABLE 7 on Page 50 compares the results obtained for puncture tests in oil vs. those performed in gas. The experimental conditions have been reconstructed as far as possible. The following points were observed:

- 1) The ratio of head to shed punctures for SF_6 compares well with the results obtained for oil.
- 2) The range of puncture voltages, the average puncture voltage and the standard deviation are identical in all three cases. This is true irrespective of whether SF_6 or oil was used as the immersing medium and despite the differing test criteria that were employed by each party.
- 3) The average voltage for shed punctures was found to be 130 KV for SF_6 . Croucher [2] obtains values of 132 and 154 KV for 2 series of test. The resistivity of oil in each case was 3×10^{11} and $4,7 \times 10^9$ Ohm-m respectively.

The following four points are observations of a more general nature.

- 1) Gas is easier to handle than oil. This has already been postulated in Ch.4:4 on Page 21 and is substantiated by the experimental work.
- 2) Irrespective of the measures that are adopted to maintain the purity of the oil, it ultimately becomes polluted with use. In contrast hereto the impurities in the gas can be filtered out during transfer from storage tank to test vessel and vice versa.
- 3) The presence of a power arc across the insulator occasionally causes partial dissociation of the SF_6 and the formation of free fluorine.
- 4) Flashover in air does not attack the surface of the insulator whereas flashover in oil badly injures the insulator surface. [8] The same event takes place in SF_6 . The dry flashover voltage in air for insulators of the type SAG 19-0345 is given as 65 KV. In contrast hereto flashover in oil and SF_6 were observed only

LABORATORY	CAPE TOWN 1	CAPE TOWN 2	Stellenbosch	Wits
Insulator Type	SAG 19-0345	SAG 19-0345	SAG 19-0345	SAG 19-0345
Batch size	11	11	37 ?	233
Insul.medium	Transf.oil	Transf. oil	Sunfl.Oil	SF gas
Resistivity of oil in Ohm-m	$4,7 \times 10$	3×10	8×10	-
Rel.Permitt. of ins.medium	2,0	2,0	3,25	1,0
$V_{p \text{ min.}}$	102	100	70	80
$V_{p \text{ av.}}$	127	121	?	118,1
$V_{p \text{ max.}}$	150	162	155 +	150
$V_{p \text{ sd}}$	17,7	15,9	-	17,2
Ratio of head to shed punct.	9:2	5:6	2:1	175:48

TABLE 7: Comparison of puncture tests in Oil vs.SF [2,4 19]

N.B. The $V_{p \text{ av}}$ for Stellenbosch is meaningless since Insulators with $V_{p \text{ max}}$ 155 KV were considered to be "Unpuncturable"

The abbreviations have the usual meanings employed in TABLES 1 to 6.

for voltages which were in excess of 110 KV.

The damage to the insulator shed can be accounted for in the following manner: The flashover arc is better developed at the higher voltage due to the bigger short circuit current. The resultant power arc follows the path of least resistance which due to the high breakdown strength of the oil and SF_6 is across the surface of the shed. The end result is a crazed path of damaged glazing.

The problems associated with the puncture test in SF_6 are much the same as when the test is performed in oil.

As is borne out by the above comparison between oil and SF_6 , corona and the electrical discharges preceding the dielectric breakdown are not eliminated when using SF_6 . Clarke [5] claims that the actual inception voltage of corona formation is much higher in oil than observed when similar tests are carried out in gas, in particular air. The observed corona formation voltage in SF_6 varies from 70 KV to 120 KV with an average value of 106 KV. (Vide Ch.5:3b, Page 36 for details).

Unfortunately neither N.F. Croucher [2] nor J.P. Holtzhausen [4] from Stellenbosch paid any attention to this aspect so that comparative figures for oil and SF_6 are not available. Nishi [8] found that corona in oil starts at approximately 100 KV and develops rapidly. He does however not mention whether this value is fixed or varies with the model of insulator.

What has been said above for corona can be applied mutatis mutandis to flashover. The range of flashover voltages varies from 100 to 150 KV. However 40 of the 80 insulators which displayed flashover, did so sporadically at the average value of 120 KV. (Vide Ch.5:3a, Page 36 and Appendix 6:3 for details.) Again comparative values for flashover voltages in oil and SF_6 are not readily available.

The average breakdown voltage for shed punctures is 132 KV with a range from 110 KV to 150 KV. Hopwood [18] and others have shown that with the relative permittivity of SF_6 equal to unity the electric field in the gas will be higher than in oil. Partial breakdown of the gas (and hence shed punctures) will therefore occur at a lower voltage. (Vide Ch.2:3, Page 5 for a more detailed discussion of this problem.)

Nevertheless as has been mentioned earlier on in this Chapter the breakdown voltages for shed punctures compare well to identical results of puncture tests performed in transformer oil. [2] A study of TABLE 7 shows that the above results also compare well with puncture tests conducted in sunflower oil.

It will be shown in Ch.5:2 that the maximum applied voltage for a quality assessment of insulator U 70 LC need be no higher than 100 KV. That value is below the flashover level of the insulator and the partial breakdown voltage of SF_6 at 400 kPa, while the possible presence of corona can be ignored.

From the above mentioned results and comparisons it can be inferred that the breakdown qualities of SF_6 are not inferior to those of transformer oils despite the differing values in the relative permittivities of the two substances.

6:2) Analysis of the Frequency of Punctures as a Function of V_s

According to the information given to the author by a leading South African ceramist [19], the frequency distribution of insulator punctures as a function of the applied voltage should have the characteristics of a normal distribution.

Figure 5:1 on Page 28 shows that this is only partially true since the frequency distribution for head punctures has the features of a bimodal frequency curve with maxima at 90 and 120 KV respectively.

To assess in how far the recorded data differs from that of a normal distribution the following technique is employed.

A study of the histogram of Fig.5:1 reveals that the frequency distribution of head punctures over the voltage range 100 - 150 Kv is that of a normal distribution with a peak at 120 KV. That this hypothesis is justified can be verified in the following manner:

- 1) Calculate the average puncture voltage and standard deviation for head punctures using only the data recorded for the voltage range from 100 to 150 KV. This gives the following results:

No. of punctures	143
Minimum puncture voltage	100 KV
Average puncture voltage	120,6 KV
Maximum puncture voltage	150 KV
Standard Deviation	11,55 KV

- 2) Draw a normal curve with $\mu = 120,0$ KV and $\sigma = 11,55$ KV which is superimposed on the histogram of Fig.5:1. The peak value of this normal distribution coincides with the no. of punctures at $\mu = 120$ KV; i.e. 54 punctures.

Vide Fig.6:1 on Page 53 for the result. The details of derivation procedures are given in Appendix 7 on Page A 32.

N.B. The histograms of Figs.5:1 and 6:1 are identical.

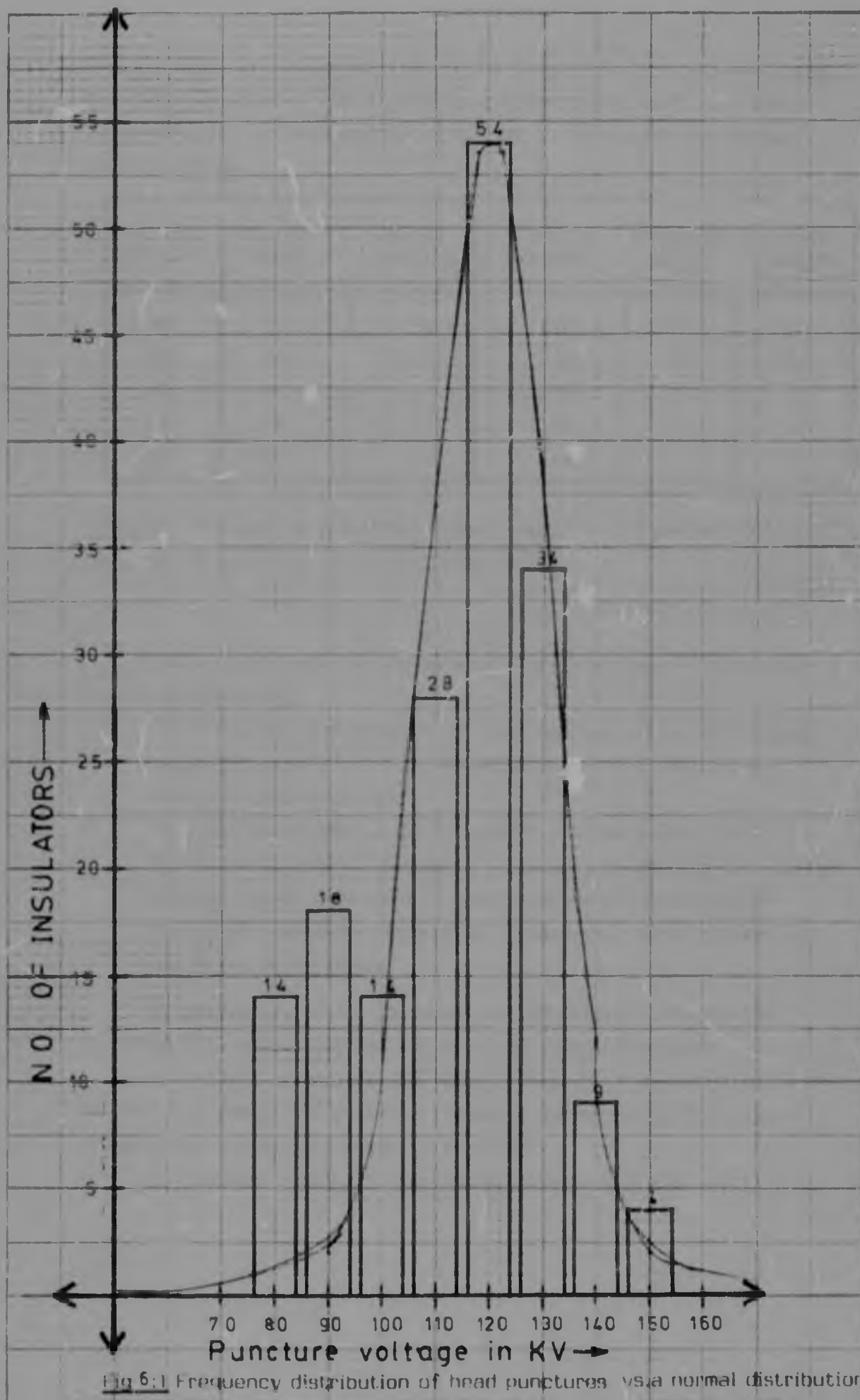


TABLE 8 below gives a comparison of the frequency distribution of head punctures as drawn in Fig.5:1 and the corresponding no.of punctures calculated for the same voltage according to the normal distribution derived above.

Puncture voltage	Recorded Data	Normal Distribut..	Puncture Voltage	Recorded Data	Normal Distrib.
80	14	0	120	54	54
90	18	2	130	34	37
100	14	12	140	9	12
110	28	37	150	4	2
120	54	54	160	-	0

TABLE 8: Frequency distribution of head punctures. Comparison of the recorded data to that of a normal distribution.

From TABLE 8 and the histogram of Fig.5:1 on Page 28 the following points can be noted:

- 1) The frequency distribution (of head punctures) for the voltage range 100 to 140 KV is fully encompassed by the curve of the derived normal equation.
- 2) The no.of punctures at the fringes of the spectrum ie for $V_p < 100 \text{ K}$ and $V_p > 140 \text{ KV}$ exceeds the value calculated for the normal distribution. An inspection of TABLE 8 reveals that the worst discrepancy between recorded and calculated values occurs at the 80 and 90 KV levels.

At the top end of the spectrum any differences between the recorded data and calculated values are of little importance.

In contrast hereto the well defined peak of 18 insulators at 90 KV at the lower end of the spectrum indicates the presence of irregularities in the quality of the tested insulators.

Two factors distort the results at either end of the spectrum.

- 1) No punctures occurred at voltages below 80 KV. This is to be expected since all test specimen had been subjected to and passed the routine production test as detailed in Ch. 3:1 on Page 12. This test is however only performed at a voltage of 70 KV and therefore gives no indication of the frequency distribution for punctures occurring at voltages below that level.
- 2) At the top end of the spectrum the results are distorted by the presence of shed punctures.

In contrast to what has been said about the frequency distribution of head punctures that of shed punctures follows a normal distribution with $\mu = 132$ KV and $\sigma = 9,7$ KV; i.e. very steep flanks

The purpose of a quality test is to eliminate faulty specimens, in this case cap and pin insulators whose dielectric puncture strength is below a pre-set norm. The question arises: What is this norm?

The analysis of data pertaining to insulator punctures is by its very nature a statistical process as can be deduced from the results and the subsequent discussion. It is therefore logical to specify quality criteria which have been derived from statistical parameters. In the above mentioned exposé an attempt is made to assess how far the recorded data confirms with the requirements of a normal distribution. Consider the following specification:

Raise the test voltage of the routine production test to 90 KV. A routine production withstand test performed at 90 KV may not eliminate all the faulty insulators. However, all the insulators which either because of an inhomogeneity in the porcelain mix or mechanical defects are responsible for the inordinately high number of punctures at or below 90 KV are dispensed with.

Furthermore the frequency distribution of Fig. 6:1 for voltages between 100 and 140 KV follows that of a normal distribution.

By coincidence 90 KV is the puncture voltage specified by the manufacturer for insulator 19-0345 or model I 70 LC.[7]

6.3) The Influence of auxiliary Parameters on the breakdown Strength of Insulators

6.3.1) The Insulator Current: Observation of both the magnitudes and waveshapes of the insulator current yields no information as to the actual puncture mechanism. The insulator current is a very stable parameter of the applied voltage up to and until puncture occurs. It is of little use in identifying the short term breakdown mechanism.

6.3.2) Partial Discharge Activity: The partial discharge mechanism that was observed when testing insulators has already been described in Ch.4:3 on Page 20.

The presence of partial discharge activity has led to the identification of punctures caused by Freeing. This mode was observed in five insulators prior to puncture.

In all five cases partial discharge activity was initiated at approximately 20 KV and was well developed in both half cycles of the voltage wave once the first voltage withstand test was performed at 80 KV. For example, a peak discharge level of 165 pC was measured for insulator 8:51 at 80 KV. The partial discharge activity remains stable for a few seconds once the voltage has been raised to the desired level, then suddenly increases very rapidly in both magnitude and density; i.e. "Lifts-Off". This increase is maintained up to and until puncture actually occurs. Although the increase happens very rapidly the time to puncture is finite. For example, insulator 8:7 needed 5 seconds to complete the cycle from "Lift Off" to puncture. This time becomes progressively less the higher the voltage at which the "Freeing" mode occurs. At no instance in time was an increased insulator current observed during the "Lift-Off" cycle.

This phenomenon can be accounted for in the following manner:

When a sufficiently high voltage is applied between the insulator electrodes, then the presence of a minute air filled crack in the porcelain head leads to the inception of partial discharges. The relative permittivity of the gas (air) in the cavity is lower than that of the surrounding porcelain. The field strength in the cavity is therefore higher than in the dielectric. Accordingly under normal working stress of the

insulation, the voltage across the cavity may exceed its breakdown value and partial discharges occur in the cavity. (26) When the gas in the cavity breaks down, the surfaces of the insulation form the cathode and anode and the full applied potential appears across the remaining thickness of the porcelain. The partial breakdown in the cavity is of a sporadic and intermittent nature since it is dependant on the instantaneous value of the applied voltage.

The breakdown of the remaining porcelain in the head is therefore due to "Treeing" or crack propagation rather than overstressing of the dielectric. As the crack propagates and the thickness of the porcelain decreases partial discharge activity increases in both magnitude and density.

Since the electric field between the cap and the pin is highly non linear the identified Treeing mode is a complex interaction between the applied voltage and the concomitant partial discharges as well as the presence of cracks or voids in the porcelain.

5:3:3 "Clean" vs. "Polluted" Insulators: The results as analyzed in Section 5:4 seem to indicate that the performance of polluted insulators is inferior to clean ones. Two observations appear to confirm this:

- 1) The average puncture voltage is reduced by pollution for both head and shed punctures.
- 2) The frequency distribution of puncture voltages is more scattered for polluted insulators than for clean ones. (Vide Figs. 5:6 to 5:9 on Pages 39 and 40 respectively.)

Pollution promotes the growth of corona. Hence the no. of shed punctures is likely to be higher for polluted insulators than for clean ones. The ratio of head to shed punctures is 43:11 and 39:11 for clean and polluted insulators respectively.

Surface pollution has nothing to do with the puncture performance of insulators. The inference is therefore valid that a batch of poor insulators was tested.

The comparative values of average insulator currents are identical for both clean and polluted insulators. The minimum and maximum insulator currents for voltages in excess of 110 kV are higher for polluted than clean insulators. There is however no correlation between these increased current values and the puncture voltage.

6:3:4) Divergences in Puncture Voltages between Insulators from different Manufacturing lots: The purpose of these experiments is to establish whether there is a noticeable divergence in the frequency distribution of puncture voltages when the test results of insulators taken from various manufacturing lots are compared to one another. A study of Table 6 on Page 41 does not confirm this.

Fifteen insulators each, taken from three different manufacturing lots ie. a total of 45 insulators were tested. It is therefore debatable how representative and reliable the results are.

Insulators of batch 15 were found to be exceptionally puncture proof. This is confirmed by the high average puncture voltages for both head and shed punctures. The minimum puncture voltage of 80 KV is somewhat misleading since only one insulator punctured at that value. Apart from a second insulator which punctured at 110 KV, the puncture voltage for all insulators of lot 15 was in excess of 120 KV.

Insulators of batch 15 also differed physically from other insulators by virtue of their dark glazing.

Insulators from batches 7C and 7M also proved to be exceptionally puncture resistant when compared to the overall results.

The results of this experiment are at odds with its initial purpose. The author wanted to isolate a lot of poorly manufactured insulators which give consistently low puncture voltages.

6:4) 4,0 vs. 10,0 KV Interval withstand tests ?

The choice of whether to use intervals of 10,0 KV or 4,0 KV intervals between adjacent voltage withstand tests was determined by practical considerations.

The testing of an insulator which punctures at 130 KV involves the performance of voltage withstand tests at 80, 90, 100, 110, 120 and 130 KV respectively; ie. six tests lasting four minutes each. (2 min. ON / 2 min. OFF). The time required to degas the test vessel and retrieve the insulator is an additional thirty minutes. The performance of a post mortem varies from fifteen to thirty minutes. The testing of one insulator (depending on the puncture voltage) therefore effectively lasts from 60 to 90 minutes.

If in contrast hereto the withstand voltage interval is reduced from 10,0 KV to 4,0 KV the no.of test intervals ie.the sample rate, is increased 2,5 times.The testing time for an insulator which punctures at 132 KV is increased from 30 to 32 minutes and the total turn around time is approximately two hours.In an effort to limit the effective duration of each test cycle to managable proportions the 10,0KV interval was preferred.

For purpose of comparison insulators 6:1 to 6:30 were subjected to withstand tests conducted at 4,0 KV intervals using a 1 min.ON / 0 Off duty cycle as described in Ch.5:8 on Page 46.The average puncture voltage of these insulators (head punctures) is 10 % less than the total average puncture voltage. This is due to any of the following reasons:

- 1) The 4,0 KV intervals give a narrower spread between puncture voltages than the 10,0 KV intervals.
- 2) The maximum puncture voltage of insulators 6:1 to 6:30 is 132 KV, whereas the overall maximum puncture voltage is 150 KV.This reduces the average voltage.
- 3) The small size of the sample (30 insulators).

7) CONCLUSIONS

The aim of this dissertation is to establish a quality control test for cap and pin insulators that yields consistant results.

An experimental test method has been developed which establishes the dielectric breakdown or puncture voltages of these insulators.

- 1) Puncture tests are performed using SF_6 pressurized to 400 kPa, absolute as the immersing medium instead of mineral oil. The correlation of results between the two methods is good. The main problems which are encountered when performing puncture tests in oil are also present in SF_6 . These are:

- 1) The presence of corona and the concomitant flashover at voltages in excess of 120 KV.
- 2) The partial breakdown of the dielectric immersant around the insulator.

The main advantage of performing puncture tests in SF_6 is the somewhat greater ease with which the gas can be handled and the high level of gas purity that can be maintained over the long term. There are no messy residues when retrieving an insulator after a test. This advantage is offset by the greater capital outlay for gas handling equipment.

A quality test aims to eliminate insulators which are defective in manufacture. The frequency distribution of head punctures as a function of the applied voltage peaks at 120 KV. Defective insulators puncture at a voltage below this level so that corona, flashover and shed punctures are of little consequence.

- 2) Eliminate defective insulators by raising the voltage level of the routine production test to the nominally specified puncture voltage. For insulator type SAG 19-0345 this implies an increase from 70 to 90 KV.

The main drawback in doing this is that the routine production tests can no longer be performed in air because the nominal puncture voltage of a Class B insulator exceeds its dry flashover voltage.

The frequency distribution of head punctures has the characteristics of a bimodal frequency curve which peaks at 90 KV and 120 KV respectively. The peak at 90 KV is caused by defective insulators. By raising the test voltage to 90 KV these "poor" insulators are eliminated.

- 3) The recorded results while consistent are nevertheless statistical in nature. Punctures were observed over a range of voltages from 90 to 150 KV. The problem is to be sought in the insulator itself rather than the method of test. There are a number of unanswered questions as regards the quality of the porcelain in general and the design of cap and pin insulators in particular. It has for example been suggested to manufacturers to replace the pin head by a round ball so as to eliminate the high field region at the sharp edge of the former. Consultation with experts in the field has shed little light on these problems. A thorough search through the available literature on the subject was equally fruitless.
- 4) The actual cause of puncture is the great unknown. To gain some insight into the mechanisms which cause dielectric breakdown "secondary" parameters and variables were recorded.

The current of the insulator as a function of the applied voltage is a very stable quantity up to and until puncture takes place. The transition from maximum applied voltage to steady state short circuit current takes place in less than 5 msec.

Partial discharge activity inside the insulator has enabled the author to make distinction between "instantaneous" puncture and a "Treeing" mode which is correlated to partial discharges; i.e. A flaw or crack in the insulator porcelain propagates when voltage is applied. This differentiation gives however no indication of the actual puncture mechanism.

Inspection of the discharge channel revealed no information apart from confirming that the sharp edge of the pin is a high field region, because 85% of all head punctures start or end here. This ties up with the findings of R.coelho [3] as quoted in Ch.2:1 on Page 3.

- 5) A withstand test performed at discrete voltage levels separated by fixed intervals, for example 10 KV, is preferable to a straight raising of the voltage, because:
- 1) It gives a puncture caused by freering a chance to develop without masking the true inception voltage of this mode.
 - 2) It facilitates the drawing up of puncture frequency distributions.
 - 3) It facilitates the recording of data and the monitoring of current waveforms.
 - 4) Routine production tests of insulators are for practical purposes withstand tests.

APPENDICES

APPENDIX 1

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APPENDIX 2The Power Frequency Puncture Test in Oil

The following two paragraphs and the note are extracted from SABS specification 177 [1] (Section 8:14 Page 37).

"Clean and dry the insulator and then immerse it completely in a tank containing a suitable insulating medium to prevent surface discharges.

Ensure that there are no air pockets under the sheds.If the tank is made of metal its dimensions shall be such that the shortest distance between any part of the insulator and the side of the tank is at least 1.5 times the diameter of the largest insulator shed.The insulating medium shall be at approximately room temperature.Apply the test voltage between the metal connecting parts.Increase the voltage to the assigned or specified (as relevant) puncture voltage as rapidly as the value of the increase can be recorded by the measuring instrument and note whether puncture occurs.

Note: It is not possible to define exactly the properties of the insulating medium,but one desirable property is a slight conductivity. (resistivity of the order of 10^6 Ohm-m to 10^8 Ohm-m).

APPENDIX 3Test Parameters employed for various Series of Insulators

As was mentioned in Section 4:3 various procedures were adopted for testing insulators from different batches (or Series).The numbering of the insulators is in accordance with the convention adopted in Ch.4:2 on Page 18.A detailed breakdown of the various test constraints is as follows:

Series 1

Insulator Nos. 1:1 to 1:15

- a) Perform a withstand test of 15 minutes at 120 KV.
- b) Re-apply the supply voltage and raise to puncture level, i.e. the voltage is raised to the point where the voltmeter reading collapses and the short circuit current starts to flow.

Series 2

Insulator Nos. 2:1 to 2:16

- a) Perform a withstand test of 5 minutes duration at 110 KV.
- b) Re-apply the supply voltage and raise slowly to puncture level.

Series 3

Insulator Nos. 3:1 to 3:11

Raise the voltage smoothly until puncture occurs. These experiments were performed so as to iron out problems experienced with the leakage current measurements.

Series 4, 5, 6 and 8.

Insulator Nos. 4:1 to 4:20, 5:1 to 5:30, 6:1 to 6:30, 8:1 - 8:76 and 8A to 8E.

These insulators were tested according to the 2 min.ON/ 2 min.OFF routine as described in Ch.4:2 on Page 17.

Series 6

Insulator Nos. 6:1 to 6:30

Series 7

Insulator Nos. 7:1 to 7:30

The test parameters of the above two mentioned insulator series are given in detail together with the relevant results in Chapter 5:8 on Page 46.

APPENDIX 4Specifications of auxiliary Equipment.1) High Voltage Test Transformer [20]

Model: Meßwandlerbau TES 325/30, single phase operation

Ratings based on 15 minute continuous operation

S = 30 KVA $V_{sec} = 325 \text{ KV}$ $I_{sec} = 92 \text{ mA}$

For 2 minute short time operation the ratings increase to:

S = 70 KVA $V_{sec} = 325 \text{ KV}$ $I_{sec} = 215 \text{ mA}$

A downtime of 24 hours is stipulated after operating the transformer at full load 2 minute ratings for 2 minutes.

2) Digital Voltmeter

Model Fluke 8050 A

Mains operated digital multimeter with battery option.

3) Storage Oscilloscope

Model Tektronix 7633

Fitted with modules 7A11, 7A18 and 7B50A

Probe Tektronix P6106 13pF, 10M Ω m,
10:1 attenuation

4) Partial Discharge Calibration Unit.

Model: ENRAF Nonius Delft

Nominal discharges of 5, 50, 500 5000 p

Internal Capacitance 1, 10 100 1000 pF

5) ERA Discharge Detector (21)

Model FCR Model 3, Type 652
 Amplitude of Calibration Step Wave (CSW) = 100 V
 Attenuation range of CSW = 0-120 dB

6) Logarithmic LCR Bridge

Model Wayne and Kerr B 500
 Ranges
 Capacitance 0-16 mF
 Inductance 0-16 KH
 Resistance 0-160 MOhm

The individual ranges are divided up into 10 logarithmic scales.

7) Current Transformer 2

Model Harper Set No. COQ 29
 Current ratio = 0.1 / 0.1 Burden = 1 VA
 Accuracy = 0.5% Insulation level = 3 KV
 Primary Resis. = 15.1 Ohm Secondary Resis. = 21.2 Ohm

A test of I_{in} vs. I_{out} shows that the regulation is less than 1.5% for currents as low as 0.5 mA.

Manufactured in accordance with BSS 3938 of 1973.

8) Current Transformer 3

Model own design
 Current ratio = 0.1/0.1 A Burden = 1 VA

This transformer is an "Off the Cuff" design which was subsequently tested and modified to meet the desired requirements.

The main criterium is the consistency of current transfer.

Core: SIFERIT EC 70 Conductor diameter D = 0.15 mm

$N_{\text{primary}} = 1000 \text{ turns}$

$N_{\text{secondary}} = 1000 \text{ turns}$

$R_{\text{primary}} = 79,8 \text{ Ohms}$

$R_{\text{secondary}} = 99,8 \text{ Ohm}$

A test of I_{in} vs. I_{out} shows the regulation to be better than 1.0% for an $i_{\text{in}} = 0,5 \text{ mA}$.

APPENDIX 5

Settings of Partial Discharge Measuring Equipment.

Settings on the ERA Discharge detector

Set rotate ellipse to 60° .

Initial setting of step wave is not important and depends on each individual measurement.

A calibration measurement using a needle and plate electrode conf. gave the following results.

- Discharges in the top half of the ellipse as seen on the ERA detector emanate from the H.T. terminal ie. insulator pin.
- Conversely discharges in the bottom half of the ellipse emanate from the ground terminal ie. the cap.

Test measurements to establish C_{par}

- C_{par} = parasitic capacitance of the pressure vessel.
- C_x = average capacitance of the insulator = $32,5 \text{ pF}$
- C_m = measuring capacitor inside the H.T. transformer.
- $C_{\text{eq}} = C_{\text{par}} + C_x$

<u>V in KV</u>	<u>I in mA</u>	<u>C_{par} in pF</u>
80	8,34	331,83
90	9,35	330,7
100	10,40	331,0
110	11,47	331,9
120	12,50	331,6

For the purposes of conducting these experiments the test vessel was filled with SF_6 but no insulator was inserted.

TABLE A1: Calibration measurements for determining the parasitic capacitance of the pressure vessel.

C_{par} is calculated via $C_{\text{par}} = \frac{3183 \times I}{V}$ I is in mA
V is in KV

$C_{\text{av}} = 331,4 \text{ pF}$ $C_{\text{sd}} = 0,53 \text{ pF}$
 $C_{\text{max}} = 331,8 \text{ pF}$ $C_{\text{min}} = 330,7 \text{ pF}$

Average capacitance of the insulator $C_x = 32,5 \text{ pF}$

The effective test capacitance is: $C_{\text{eff}} = C_x + C_{\text{par}}$

hence: $C_{\text{eff}} = 331,4 + 32,5 = 360,4 \text{ pF}$

Calibration of circuit using the Discharge Simulator

The magnitude of the discharge detector response is determined by the magnitude of the vertical step voltage applied to its terminals. For the infinitesimal length of time occupied by the vertical step, the discharge detector circuit, which is inductive, will behave as an infinite impedance and may therefore be regarded as an open circuit. The step voltage appearing on the terminals is thus determined entirely by the capacitances in the circuit.

<u>Q_{nom.}</u>	<u>C_b</u>	<u>Q_a</u>	<u>V in dB</u>	<u>V in V</u>
5000 pC	1000 pF	1334 pC	42	794 mV
500 pC	100 pF	392 pC	52	251 mV
50 pC	10 pF	48 pC	71	28 mV
5 pC	1 pF	5 pC	92	2 mV

TABLE A 2: Overleaf on Page A 10 Calibration of test vessel using ENRAF NONIUS Discharge simulator.

Correction factor for the discharge q of the calibration unit is:

$$Q_a = \frac{C_a}{C_a + C_b} q_{\text{nom.}} = \frac{364 \times q_{\text{nom.}}}{364 + C_b}$$

Hence: $Q_{\text{dis}} = \frac{\text{magnitude of discharge from simulator} \times Q_a}{\text{measured magnitude of same discharge}}$

C_a = capacitance of the sample Q_a = sample discharge
 C_b = capacitance of the calibrator unit $Q_{\text{nom.}}$ = nom. discharge

Calculation of the correction factor: C

Q_a	=	1334 pC	V	=	42 dB	C =	4,62
Q_a	=	392 pC	V	=	52 dB	C =	4,29
Q_a	=	49 pC	V	=	71 dB	C =	4,74
Q_a	=	5 pC	V	=	92 dB	C =	5,46

C = Correction factor

The last value is somewhat suspect. Averaging out over the first three values yields $C = 4,55$. A rounding off to $C = 4,5$ is justified.

Readings were taken for four different insulators to verify the calibration values.

Hence: $Q_{\text{act}} = 4,5 \times 364 \times V$ pico Coulomb
 with V expressed in Volts.

A value of $C = 4,62$ was used for calculation purposes.

N.B. The abbreviations and symbols are the same as used in the instruction booklets and application manuals of the respective apparatus.

APPENDIX 6Experimental Results

List of employed abbreviations

V_s	•	High tension supply voltage in KV
I.No.	•	Insulator No.
L.No.	•	Manufacturer's lot no.
V_p	•	Puncture voltage of insulator in KV
Punc.	•	Type of puncture,where:
H.P.	•	head puncture
S.P.	•	shed puncture
Flash	•	Flashover, no puncture has occurred
I_l	•	Leakage current in mA This is the total insulator current
C.I.V.	•	Corona inception voltage in KV
F.L.	•	(Sporadic) Flashover voltage level in KV
m	•	Massive build up of corona
n.r.	•	not recorded
p.d.i.v.	•	partial discharge inception voltage in KV
p.d.a.	•	partial discharge activity in pC
m.p.d.a.	•	maximum value of partial discharges in pC
V_{lm}	•	Voltage level and range at which maximum partial discharge activity occurs in KV
T	•	Time in seconds to failure at V_p

The puncture voltages obtained for insulators of Series 1,2,3,and 6 are not all multiples of 10 KV.To streamline the data for the drawing up of frequency distributions the following key is used:

A range from 76 to 85 KV corresponds to	V_p	-	80 KV
A range from 86 to 95 KV corresponds to	V_p	-	90 KV
A range from 96 to 105 KV corresponds to	V_p	-	100 KV
A range from 106 to 115 KV corresponds to	V_p	-	110 KV
A range from 116 to 125 KV corresponds to	V_p	-	120 KV
A range from 126 to 135 KV corresponds to	V_p	-	130 KV
A range from 136 to 145 KV corresponds to	V_p	-	140 KV

APPENDIX 6:1

Puncture as a function of the applied voltage

<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>	<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>
1:01	120	S.P.	3:01	90	H.P.
1:02	135	H.P.	3:02	130	H.P.
1:03	120	H.P.	3:03	150	S.P.
1:04	115	H.P.	3:04	130	H.P.
1:05	100	H.P.	3:05	150	S.P.
1:06	145	S.P.	3:06	120	H.P.
1:07	120	H.P.	3:07	120	H.P.
1:08	120	H.P.	3:08	140	H.P.
1:09	135	S.P.	3:09	130	H.P.
1:10	110	H.P.	3:10	130	H.P.
1:11	110	H.P.	3:11	140	H.P.
1:12	120	H.P.			
1:13	120	H.P.	4:01	130	H.P.
1:14	120	H.P.	4:02	150	S.P.
1:15	110	H.P.	4:03	120	H.P.
			4:04	130	S.P.
2:01	135	H.P.	4:05	140	S.P.
2:02	110	H.P.	4:06	130	S.P.
2:03	128	H.P.	4:07	130	H.P.
2:04	134	H.P.	4:08	90	H.P.
2:05	105	H.P.	4:09	140	S.P.
2:06	136	S.P.	4:10	120	H.P.
2:07	80	H.P.	4:11	120	H.P.
2:08	130	H.P.	4:12	130	H.P.
2:09	128	H.P.	4:13	140	H.P.
2:10	110	H.P.	4:14	140	S.P.
2:11	128	H.P.	4:15	130	S.P.
2:12	126	H.P.	4:16	80	H.P.
2:13	128	H.P.	4:17	130	H.P.
2:14	152	H.P.	4:18	110	H.P.
2:15	132	S.P.	4:19	100	H.P.
2:16	110	H.P.	4:20	130	S.P.

APPENDIX 6:1 continued

Puncture as a Function of the applied Voltage

<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>	<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>
5:01	130	H.P.	6:01	140	S.P.
5:02	90	H.P.	6:02	104	H.P.
5:03	110	H.P.	6:03	120	H.P.
5:04	110	H.P.	6:04	128	S.P.
5:05	90	H.P.	6:05	132	S.P.
5:06	120	H.P.	6:06	132	H.P.
5:07	130	H.P.	6:07	128	H.P.
5:08	90	H.P.	6:08	108	H.P.
5:09	80	H.P.	6:09	116	H.P.
5:10	90	H.P.	6:10	80	H.P.
5:11	110	H.P.	6:11	140	S.P.
5:12	130	H.P.	6:12	116	H.P.
5:13	100	H.P.	6:13	124	H.P.
5:14	120	H.P.	6:14	92	H.P.
5:15	120	S.P.	6:15	128	S.P.
5:16	140	S.P.	6:16	80	H.P.
5:17	120	H.P.	6:17	84	H.P.
5:18	90	H.P.	6:18	108	H.P.
5:19	90	H.P.	6:19	132	S.P.
5:20	120	H.P.	6:20	88	H.P.
5:21	120	H.P.	6:21	128	H.P.
5:22	100	H.P.	6:22	84	H.P.
5:23	110	H.P.	6:23	128	S.P.
5:24	80	H.P.	6:24	96	H.P.
5:25	130	S.P.	6:25	96	H.P.
5:26	130	H.P.	6:26	116	H.P.
5:27	100	H.P.	6:27	88	H.P.
5:28	110	H.P.	6:28	120	S.P.
5:29	130	H.P.	6:29	112	S.P.
5:30	130	H.P.	6:30	80	H.P.

APPENDIX 6:1 continued

Puncture as a Function of the applied Voltage

<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>	<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>
7:01	120	H.P.	7:16	120	H.P.
7:02	120	H.P.	7:17	90	H.P.
7:03	120	H.P.	7:18	120	H.P.
7:04	90	H.P.	7:19	120	S.P.
7:05	120	H.P.	7:20	100	H.P.
7:06	120	H.P.	7:21	120	H.P.
7:07	110	H.P.	7:22	120	H.P.
7:08	120	H.P.	7:23	110	H.P.
7:09	120	H.P.	7:24	120	H.P.
7:10	120	H.P.	7:25	-	-
7:11	120	H.P.	7:26	-	-
7:12	120	S.P.	7:27	-	-
7:13	90	H.P.	7:28	-	-
7:14	90	H.P.	7:29	-	-
7:15	120	H.P.	7:30	-	-

Take the insulators which have passed the withstand test at 120 KV and subject them to a battery of withstand tests of 5 minute duration at voltages of 100,110 and 120 KV respectively.Repeat the cycle at 120 KV until puncture occurs.

Ins.No.1	Failure after 1 min.	H.P.	All of these punctures occurred at 120 KV.
Ins.No.2	Failure after 6 min.	H.P.	
Ins.No.3	Failure after 5 min.	H.P.	
Ins.No.4	Failure after 3 min.	H.P.	
Ins.No.5	Failure after 18 min.	H.P.	
Ins.No.6	Failure after 20 min.	S.P.	

N.B. Insulators 7:25 to 7:30 all passed the 120 KV withstand test of 2 Min.ON / 2Min.OFF .As the follow up tests were not conducted in the sequence in which the insulators were retrieved a new system of numbering as adopted above was used.

APPENDIX 6:1 continued

Puncture as a Function of the applied Voltage

<u>I.No.</u>	<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>	<u>I.No.</u>	<u>I.No.</u>	<u>V_p</u>	<u>Punc.</u>
8:01	7M	80	H.P.	8:31	7M	120	H.P.
8:02	7M	130	S.P.	8:32	7C	120	H.P.
8:03	7M	110	H.P.	8:33	7C	110	H.P.
8:04	7M	110	H.P.	8:34	7C	110	H.P.
8:05	7M	100	H.P.	8:35	7C	120	H.P.
8:06	7S	140	H.P.	8:36	7C	80	H.P.
8:07	7C	100	H.P.	8:37	7C	120	H.P.
8:08	15	130	S.P.	8:38	7C	120	H.P.
8:09	15	130	Flash	8:39	7C	120	H.P.
8:10	15	130	Flash	8:40	7C	80	H.P.
8:11	15	130	Flash	8:41	7C	140	H.P.
8:12	15	130	S.P.	8:42	7C	130	H.P.
8:13	15	130	Flash	8:43	7C	110	H.P.
8:14	15	120	Flash	8:44	7C	120	S.P.
8:15	15	130	H.P.	8:45	7C	130	H.P.
8:16	15	150	S.P.	8:46	7D	130	Flash
8:17	15	140	S.P.	8:47	7D	130	H.P.
8:18	15	120	S.P.	8:48	7D	130	H.P.
8:19	15	150	H.P.	8:49	7D	120	H.P.
8:20	15	80	H.P.	8:50	7D	110	H.P.
8:21	15	110	H.P.	8:51	7N	120	H.P.
8:22	15	130	H.P.	8:52	7N	100	H.P.
8:23	15	130	H.P.	8:53	7N	130	S.P.
8:24	7M	130	Flash	8:54	7N	140	H.P.
8:25	7M	120	H.P.	8:55	8I	140+	no punc.
8:26	7M	120	H.P.	8:56	7V	120	H.P.
8:27	7M	140	H.P.	8:57	7R	110	H.P.
8:28	7M	130	S.P.	8:58	7P	110	S.P.
8:29	7M	120	H.P.	8:59	8O	100	H.P.
8:30	7M	130	S.P.	8:60	6P	140	Flash

APPENDIX 6:1 continuedPuncture as a function of the applied voltage

<u>I.No.</u>	<u>L.No.</u>	<u>V</u>	<u>Punc.</u>	<u>I.No.</u>	<u>L.No.</u>	<u>V</u>	<u>Punc.</u>
8:61	8E	140	H.P.	8:72	6F	90	H.P.
8:62	8K	110	H.P.	8:73	7N	130	S.P.
8:63	8E	130	H.P.	8:74	7N	90	H.P.
8:64	7I	130	S.P.	8:75	7O	130	S.P.
8:65	7S	120	H.P.	8:76	8P	90	H.P.
8:66	7E	120	H.P.	8:A		110	H.P.
8:67	7E	120	H.P.	8:B	-	120	H.P.
8:68	7S	130	S.P.	8:C	-	140	S.P.
8:69	8M	90	H.P.	8:D	-	130	S.P.
8:70	6H	150	H.P.	8:E	-	130	S.P.
8:71	8P	130	flash				

APPENDIX 6:2

Insulator Current as a Function of the applied Voltage

I.No.	Voltage withstand level in KV							
	80	90	100	110	120	130	140	150
4:01	0.91	-	1.13	1.25	1.36	1.49	-	-
4:02	0.91	1.03	1.14	1.26	1.36	1.52	1.62	1.73
4:03	0.88	1.00	1.11	1.23	1.34	-	-	-
4:04	0.88	1.00	1.11	1.22	1.32	1.45	-	-
4:05	-	-	-	-	-	-	-	-
4:06	0.87	0.98	1.09	1.20	1.32	-	-	-
4:07	-	-	-	-	-	-	-	-
4:08	0.92	1.00	-	-	-	-	-	-
4:09	0.90	1.02	1.13	1.25	1.36	1.50	-	-
4:10	0.93	1.06	1.17	1.28	1.41	-	-	-
4:11	0.93	1.06	1.16	1.29	1.41	-	-	-
4:12	0.91	1.04	1.16	1.27	1.38	1.52	-	-
4:13	0.91	1.03	1.15	1.26	1.37	1.51	1.61	-
4:14	0.92	1.03	1.16	1.27	1.40	1.52	-	-
4:15	0.89	1.02	1.12	1.24	1.34	1.48	-	-
4:16	-	-	-	-	-	-	-	-
4:17	0.89	1.01	1.11	1.23	1.34	-	-	-
4:18	0.91	1.03	1.14	1.25	-	-	-	-
4:19	0.90	1.02	1.14	-	-	-	-	-
4:20	0.91	1.03	1.14	1.26	1.38	1.50	-	-

APPENDIX 6:2 continued

Insulator Current as a Function of the applied Voltage

I.No.	Voltage Stand level in KV							
	80	90	100	110	120	130	140	150
5:01	0,91	1,04	1,15	1,26	1,38	1,51	-	-
5:02	0,91	1,03	-	-	-	-	-	-
5:03	0,87	0,98	1,09	-	-	-	-	-
5:04	0,93	0,98	1,09	-	-	-	-	-
5:05	0,90	-	-	-	-	-	-	-
5:06	0,92	1,04	1,16	1,28	-	-	-	-
5:07	0,89	1,01	1,12	1,24	1,35	-	-	-
5:08	0,90	1,03	-	-	-	-	-	-
5:09	0,89	-	-	-	-	-	-	-
5:10	0,89	1,00	-	-	-	-	-	-
5:11	0,898	1,02	1,12	-	-	-	-	-
5:12	0,89	1,00	1,12	1,23	1,35	-	-	-
5:13	0,91	1,04	-	-	-	-	-	-
5:14	0,89	1,01	1,12	1,23	-	-	-	-
5:15	0,89	1,01	1,13	1,24	-	-	-	-
5:16	0,92	1,05	1,16	1,28	1,39	1,52	1,63	-
5:17	0,89	1,01	1,12	-	-	-	-	-
5:18	0,91	1,04	-	-	-	-	-	-
5:19	0,91	1,04	-	-	-	-	-	-
5:20	0,92	1,04	1,15	1,26	-	-	-	-
5:21	-	-	-	-	-	-	-	-
5:22	-	-	-	-	-	-	-	-
5:23	0,92	1,04	1,16	1,27	-	-	-	-
5:24	0,87	-	-	-	-	-	-	-
5:25	0,88	1,00	1,11	1,22	1,40	-	-	-
5:26	0,89	1,01	1,12	1,24	1,34	-	-	-
5:27	0,92	1,04	-	-	-	-	-	-
5:28	0,93	1,05	1,17	1,29	-	-	-	-
5:29	0,91	1,05	1,17	1,29	1,39	1,50	-	-
5:30	0,90	1,02	1,13	1,24	1,34	1,44	-	-

APPENDIX 6:2 continued

Insulator Current as a Function of the applied Voltage

I.No.	Voltage withstand level in KV							
	80	90	100	110	120	130	140	150
6:01	0.94	1.06	1.19	1.31	1.42	1.53	1.66	-
6:02	0.94	1.03	1.17	-	-	-	-	-
6:03	0.88	1.00	1.10	1.22	1.36	-	-	-
6:04	0.92	1.06	1.16	1.28	1.37	1.48	-	-
6:05	0.89	1.01	1.12	1.24	1.36	-	-	-
6:06	0.93	1.05	1.17	1.30	1.42	1.55	-	-
6:07	0.94	1.05	1.18	1.32	1.42	-	-	-
6:08	0.90	1.02	1.15	1.25	-	-	-	-
6:09	0.90	1.02	1.15	1.25	-	-	-	-
6:10	-	-	-	-	-	-	-	-
6:11	0.95	1.06	1.18	1.28	1.38	-	-	-
6:12	0.93	1.05	1.16	1.28	1.40	-	-	-
6:13	0.92	1.03	1.16	1.26	1.37	-	-	-
6:14	0.92	1.03	1.15	-	-	-	-	-
6:15	0.90	1.02	1.14	1.25	1.36	-	-	-
6:16	-	-	-	-	-	-	-	-
6:17	0.92	-	-	-	-	-	-	-
6:18	0.89	1.01	1.12	1.24	-	-	-	-
6:19	0.91	1.03	1.15	1.26	1.38	-	-	-
6:20	0.91	1.02	-	-	-	-	-	-
6:21	0.92	1.04	1.16	1.27	1.38	1.50	-	-
6:22	0.91	-	-	-	-	-	-	-
6:23	0.90	1.02	1.14	1.26	1.37	1.49	-	-
6:24	0.91	1.03	1.15	-	-	-	-	-
6:25	0.90	1.03	1.15	-	-	-	-	-
6:26	0.89	1.00	1.11	1.22	1.34	-	-	-
6:27	0.90	1.00	1.16	1.29	1.40	-	-	-
6:28	0.92	1.05	1.16	1.29	1.40	-	-	-
6:29	-	-	-	-	-	-	-	-
6:30	-	-	-	-	-	-	-	-

APPENDIX 6:2 continued

Insulator Current as a Function of the applied Voltage

Readings of $I_i = f(V_s)$ for Series 6 insulators have been taken at 4 KV intervals. Since $I_i = f(V_s)$ is more or less a linear function the obtained data has been smoothed out for 10 KV intervals by interpolation and extrapolation techniques. This was done so as to incorporate the data of Series 6 insulators in the overall statistical evaluation of $I_i = f(V_s)$ as given on Page 31.

<u>I.No.</u>	Voltage Withstand Level in KV							
	80	90	100	110	120	130	140	150
7:01	-	-	-	-	1,35	-	-	-
7:02	-	-	-	-	-	-	-	-
7:03	-	-	-	-	1,35	-	-	-
7:04	-	-	-	-	-	-	-	-
7:05	-	-	-	-	1,35	-	-	-
7:06	-	-	-	-	1,37	-	-	-
7:07	0,92	1,04	1,15	-	-	-	-	-
7:08	0,88	1,00	1,12	1,24	-	-	-	-
7:09	0,90	1,01	1,12	1,24	-	-	-	-
7:10	0,91	1,03	1,13	1,25	-	-	-	-
7:11	0,90	1,01	1,12	1,23	1,36	-	-	-
7:12	0,90	1,02	1,13	1,25	-	-	-	-
7:13	0,93	-	-	-	-	-	-	-
7:14	0,92	1,04	-	-	-	-	-	-
7:15	0,89	0,99	1,10	1,22	1,32	-	-	-
7:16	0,89	1,02	1,13	1,25	-	-	-	-
7:17	0,92	1,04	-	-	-	-	-	-
7:18	0,88	0,97	1,08	1,21	1,33	-	-	-
7:19	0,92	1,04	1,16	1,28	1,43	-	-	-
7:20	0,90	1,02	1,13	-	-	-	-	-

APPENDIX 6:2 continued

Insulator current as a Function of the applied Voltage

<u>I.No.</u>	Voltage Withstand Level in KV							
	80	90	100	110	120	130	140	150
7:21	0,90	1,02	1,13	1,24	1,36	-	-	-
7:22	0,93	1,05	1,16	1,29	-	-	-	-
7:23	0,91	1,04	1,14	-	-	-	-	-
7:24	0,94	1,06	1,17	1,29	1,41	-	-	-
7:25	-	-	-	-	1,35	-	-	-
7:26	-	-	-	-	-	-	-	-
7:27	0,88	1,00	1,12	1,24	1,35	-	-	-
7:28	0,88	1,01	1,11	1,24	1,34	-	-	-
7:29	0,87	0,99	1,12	1,21	1,33	-	-	-
7:30	0,90	1,04	1,14	1,26	-	-	-	-

<u>I.No.</u>	Voltage Withstand Level in KV					
	100	110	120	120	120	120
1	-	1,25	1,36	1,36	1,36	-
2	1,13	1,24	1,36	-	-	-
3	1,13	1,25	1,37	-	-	-
4	1,12	1,23	1,35	-	-	-
5	1,09	1,20	1,31	1,32	1,32	1,32
6	1,11	1,23	1,35	1,35	1,35	1,35

Results of Follow up experiments of Series 7B.

APPENDIX 6:2 continued

Insulator current as a Function of the applied Voltage

I.No.	Voltage Withstand Level in KV							
	80	90	100	110	120	130	140	150
8:1	-	-	-	-	-	-	-	-
8:2	0,88	0,98	1,09	1,21	1,32	1,43	-	-
8:3	0,91	1,00	1,11	1,24	-	-	-	-
8:04	-	-	-	-	-	-	-	-
8:05	0,95	1,08	-	-	-	-	-	-
8:06	0,89	1,01	1,11	1,18	1,29	1,43	1,54	-
8:07	0,86	0,96	1,07	-	-	-	-	-
8:08	0,86	0,96	1,07	1,19	1,30	1,43	-	-
8:09	0,85	0,96	1,05	1,15	1,26	1,37	-	-
8:10	0,83	0,94	1,04	1,16	1,26	-	-	-
8:11	0,86	0,96	1,06	1,17	1,28	1,39	-	-
8:12	0,88	0,98	1,09	1,20	1,30	1,42	-	-
8:13	0,88	0,98	1,09	1,19	1,30	1,42	-	-
8:14	0,86	0,96	1,07	1,18	1,30	-	-	-
8:15	0,86	0,96	1,06	1,17	1,27	1,38	-	-
8:16	0,87	0,97	1,08	1,20	1,30	1,41	1,51	1,58
8:17	0,86	0,95	1,05	1,16	1,27	1,41	1,52	-
8:18	0,88	0,98	1,09	1,20	1,31	-	-	-
8:19	0,86	0,97	1,07	1,18	1,29	1,40	1,50	-
8:20	0,86	-	-	-	-	-	-	-
8:21	0,86	0,96	1,07	1,18	-	-	-	-
8:22	0,87	0,97	1,08	1,19	1,30	-	-	-
8:23	0,91	1,01	1,12	1,24	1,36	1,47	-	-
8:24	0,90	1,00	1,11	1,22	1,33	1,44	-	-
8:25	0,88	0,99	1,11	1,21	1,33	-	-	-
8:26	0,91	1,03	1,14	1,24	1,36	-	-	-
8:27	0,90	1,00	1,11	1,23	1,36	1,45	1,59	-
8:28	0,90	1,00	1,11	1,23	1,36	1,50	-	-
8:29	0,89	1,00	1,11	1,23	-	-	-	-
8:30	0,91	1,01	1,13	1,24	1,35	-	-	-

APPENDIX 6:2 continued

Insulator current as a function of the applied voltage

I.No.	Voltage withstand Level in KV							
	80	90	100	110	120	130	140	150
8:31	0.90	1.01	1.13	1.24	1.35	-	-	-
8:32	0.87	0.96	1.07	1.19	1.28	-	-	-
8:33	0.90	1.00	1.12	1.23	-	-	-	-
8:34	0.89	1.00	1.11	1.22	-	-	-	-
8:35	0.90	1.00	1.11	1.22	-	-	-	-
8:36	-	-	-	-	-	-	-	-
8:37	0.87	0.98	1.08	1.19	1.27	-	-	-
8:38	0.89	0.99	1.11	1.22	1.34	-	-	-
8:39	0.89	1.00	1.11	1.22	1.33	-	-	-
8:40	0.89	-	-	-	-	-	-	-
8:41	0.88	0.99	1.10	1.21	1.33	1.45	1.56	-
8:42	0.88	0.98	1.10	1.21	-	-	-	-
8:43	0.89	0.99	1.10	-	-	-	-	-
8:44	0.89	1.00	1.11	1.22	-	-	-	-
8:45	0.88	0.98	1.09	1.21	1.29	-	-	-
8:46	0.90	1.00	1.11	1.21	1.33	1.45	-	-
8:47	0.90	1.00	1.12	1.23	1.34	-	-	-
8:48	0.88	0.98	1.08	1.20	1.31	1.41	-	-
8:49	0.90	1.03	1.13	1.25	1.36	-	-	-
8:50	0.88	0.99	1.09	1.21	-	-	-	-
8:51	0.90	1.00	1.13	1.23	-	-	-	-
8:52	0.89	0.99	1.11	-	-	-	-	-
8:53	0.90	1.00	1.12	1.23	1.34	1.45	-	-
8:54	0.86	0.97	1.07	1.18	1.29	1.39	-	-
8:55	0.89	0.99	1.10	1.21	1.33	1.44	1.55	-
8:56	0.88	0.98	1.08	1.20	1.31	-	-	-
8:57	0.91	1.02	1.13	1.26	-	-	-	-
8:58	0.93	1.03	1.15	1.27	-	-	-	-
8:59	0.92	1.03	1.14	-	-	-	-	-
8:60	0.91	1.01	1.12	1.24	1.35	1.44	-	-

APPENDIX 6:2 continued

Insulator current as a function of the applied voltage

I.No.	Voltage Withstand Level in KV							
	80	90	100	110	120	130	140	150
8:61	0,85	0,94	1,06	1,16	1,26	1,38	-	-
8:62	0,91	1,00	1,13	1,23	-	-	-	-
8:63	0,89	1,00	1,12	1,21	1,34	1,44	-	-
8:64	0,87	0,98	1,11	1,20	1,31	1,43	-	-
8:65	0,91	1,02	1,15	1,24	-	-	-	-
8:66	0,91	1,02	1,14	1,24	-	-	-	-
8:67	0,87	0,98	1,09	1,18	1,29	-	-	-
8:68	0,91	1,02	1,14	1,24	1,35	1,48	-	-
8:69	0,91	-	-	-	-	-	-	-
8:70	0,92	1,03	1,15	1,24	1,36	1,46	1,58	-
8:71	0,92	1,02	1,15	1,24	1,36	-	-	-
8:72	0,87	0,99	-	-	-	-	-	-
8:73	0,91	1,01	1,13	1,23	1,35	1,48	-	-
8:74	0,89	-	-	-	-	-	-	-
8:75	0,90	1,00	1,13	1,22	1,34	1,46	-	-
8:76	0,89	1,02	-	-	-	-	-	-

APPENDIX 6:3

Corona and Flashover Inception Voltages

<u>I.No.</u>	<u>CIV</u>	<u>F.L.</u>	<u>I.No.</u>	<u>CIV</u>	<u>F.L.</u>
1:08	n.r.	120	5:29	n.r.	120
1:13	n.r.	120	6:01	n.r.	120
2:01	n.r.	130	6:02	90	n.r.
2:08	n.r.	130	6:03	100	n.r.
2:11	n.r.	125	6:04	n.r.	120
2:12	n.r.	120	6:05	-	120
2:13	n.r.	120	6:06	120	-
2:14	n.r.	152	6:07	120	-
4:01	n.r.	130	6:08	110	-
4:02	n.r.	120	6:19	115	120
4:03	n.r.	120	6:26	100	-
4:04	n.r.	130	7:03	110	-
4:06	n.r.	120	7:09	n.r.	120
4:07	n.r.	120	7:15	n.r.	120
4:09	n.r.	120	7:16	n.r.	110
4:11	n.r.	120	7:19	120 m	120
4:12	n.r.	130	7:23	120 m	120
4:13	n.r.	140	8:06	120	-
4:14	n.r.	130	8:08	n.r.	120
4:15	n.r.	130	8:09	n.r.	130
4:20	n.r.	130	8:10	110	110
5:01	n.r.	120	8:11	n.o.	130
5:04	n.r.	120	8:12	110	120
5:06	n.r.	120	8:13	110 m	120
5:07	n.r.	100	8:14	110	110
5:12	n.r.	130	8:15	110	120
5:15	n.r.	110	8:16	n.r.	150
5:16	n.r.	140	8:17	n.r.	140
5:25	n.r.	120	8:18	110	110
5:28	n.r.	110	8:19	70	110

APPENDIX 6:3 continued

Corona and Flashover inception Voltages

<u>I.No.</u>	<u>CIV</u>	<u>F.L.</u>	<u>I.No.</u>	<u>CIV</u>	<u>F.L.</u>
8:21	110	-	8:46	110	120
8:23	110	110	8:47	100	100
8:24	110	120	8:48	110	120
8:26	110	-	8:49	100	120
8:27	100	120	8:53	110	110
8:28	100	120	8:56	n.r.	110
8:29	100	-	8:57	90	110
8:31	110	120	8:58	100 m	110
8:32	100	110	8:60	100	110
8:34	100	n.o.	8:61	110	120
8:35	110	-	8:63	n.r.	110
8:37	110	-	8:64	100	-
8:38	120	-	8:65	110	120
8:39	110	120	8:67	110 m	120
8:41	100	110	8:68	n.r.	120
8:42	90 m	110	8:70	n.r.	120
8:43	100	100	8:71	120	-
8:44	110	110	8:73	120 m	120
8:45	110	120	8:75	110	120

APPENDIX 6:4

Partial Discharge Activity

<u>I.No.</u>	<u>Pdiv</u>	<u>Mpda</u>	<u>V_{lm}</u>		<u>I.No.</u>	<u>Pdiv</u>	<u>Mpda</u>	<u>V</u>
8:06	50	147	90		8:47	50	30	80
8:07	n.r.	16	90		8:48	110	147	-
8:08	70	117	110		8:49	40	93	90-120
8:09	n.r.	165	110		8:50	50	117	90
8:10	n.r.	165	80-100		8:51	50	165	80-120
8:11	n.r.	16	100		8:52	65	165	100
8:12	n.r.	416	80-100		8:53	50	93	80-110
8:13	n.r.	165	80-100		8:54	120	29	120
8:14	n.r.	42	80-120		8:57	90	93	100
8:15	n.r.	30	110		8:58	50	52	80-110
8:16	n.r.	147	100		8:59	90	165	100
8:17	100	295	120		8:60	50	52	80-110
8:19	100	467	140		8:61	30	130	100-120
8:22	20	930	110		8:62	50	131	90-110
8:25	45	146	80		8:63	n.r.	52	80-120
8:26	n.r.	151	100-110		8:64	30	52	80-130
8:27	110	74	110		8:66	80	295	120
8:28	100	42	120		8:67	80	295	80-90
8:32	120	53	120		8:71	40	165	90
8:34	70	93	90-110		8:72	30	1000	90
8:35	110	93	110		8:73	60	415	80-130
8:37	50	52	110-120		8:74	15	93	80
8:45	80	165	80		8:75	55	117	90-120
8:46	40	52	80-130		8:76	80	415	80

APPENDIX 6:4 continued

Comments on the Partial Discharge Activity of Individual Insulators

- 8:08) Well developed in both amplitude and intensity.
- 8:15) P.d.a.could possibly be noise.
- 8:16) Amplitude of the P.d.a.varies randomly.
- 8:17) Flare up and dying out.Generally intermittent activity.
- 8:19) P.d.a.inception at 110 KV.Extinction at 120 KV.
- 8:22) Well developed p.d a. from 20 KV upwards.
- 8:25) Inception at 45 KV,Extinction at 80 KV.
- 8:26) Low level of intensity.
- 8:27) Inception at 110 KV,Flare-up.
- 8:28) High intensity,low amplitude.
- 8:32) Low amplitude
- 8:37) Low amplitude
- 8:45) Sporadic pda.
- 8:46) Well developed in both amplitude and intensity.but sporadic.
- 8:48) Bulk of pda in bottom half cycle of ellipse
- 8:49) Bulk of pda in bottom half cycle of ellipse.
- 8:50) Sporadic flares.
- 8:51) Increase of pda prior to puncture.
- 8:54) Flare up of pda for voltages in excess of 120 KV.
- 8:59) Increase of pda prior to puncture.
- 8:60) Inception at 50 KV.Extinction at 120 KV.
- 8: 1) Visible discharges could possibly be corona.
- 8:62) Pda is well developed in both amplitude and intensity.
- 8:64) Both the amplitude and intensity are well developed.
- 8:66) Both the amplitude and intensity are well developed.

APPENDIX 6:5

Time to Puncture

<u>L.No.</u>	<u>T</u>		<u>L.No.</u>	<u>T</u>		<u>L.No.</u>	<u>T</u>		<u>L.No.</u>	<u>T</u>
1:01	90		5:01	10		6:01	90		7:01	180
1:03	90		5:02	100		6:02	0		7:02	15
1:07	30		5:03	60		6:03	5		7:03	5
1:08	90		5:04	15		6:04	10		7:04	0
1:12	5		5:05	-		6:05	5		7:05	45
1:13	15		5:06	45		6:06	15		7:06	60
1:14	10		5:07	0		6:07	0		7:07	0
2:02	0		5:08	7		6:08	20		7:08	20
2:10	90		5:09	15		6:09	5		7:09	0
2:16	30		5:10	40		6:10	5		7:10	0
4:01	10		5:11	0		6:11	5		7:11	150
4:02	90		5:12	0		6:12	20		7:12	10
4:03	60		5:13	0		6:13	15		7:13	10
4:04	20		5:14	5		6:14	5		7:14	30
4:05	60		5:15	10		6:15	0		7:15	240
4:06	5		5:16	15		6:16	0		7:16	5
4:07	5		5:17	10		6:17	15		7:17	75
4:08	10		5:18	20		6:18	10		7:18	110
4:09	15		5:19	10		6:19	5		7:19	110
4:10	5		5:20	15		6:20	5		7:20	15
4:11	20		5:21	20		6:21	60		7:21	165
4:12	35		5:22	0		6:22	5		7:22	10
4:13	30		5:23	10		6:23	5		7:23	20
4:14	3		5:24	60		6:24	30		7:24	220
4:15	10		5:25	5		6:25	15		7:25	60
4:16	5		5:26	0		6:26	35		7:26	360
4:17	5		5:27	2		6:27	5		7:27	300
4:18	10		5:28	20		6:28	30		7:28	180
4:19	10		5:29	15		6:29	30		7:29	1080
4:20	45		5:30	75		6:30	20		7:30	1200

APPENDIX 7Derivation of the normal curve as used in Ch.6:1

Consider all insulators with puncture voltages in excess of 90 KV.
For this group of insulators the following data is obtained.

No. of punctures	143
Average puncture voltage	120,6 KV
Standard Deviation	11,6 KV

Fit a Gauss or normal distribution curve with $\mu = 120$ KV and
a standard deviation of 11,6 KV. [24,25]

<u>X</u>	<u>P(X)</u>	<u>No. of insulators</u>
80	$1,05 \times 10^{-3}$	<1
90	$1,404 \times 10^{-2}$	2
100	$9,008 \times 10^{-2}$	12
110	0,275	37
120	0,3989	54
130	0,275	37
140	$9,008 \times 10^{-2}$	12
150	$1,404 \times 10^{-2}$	2
160	$1,05 \times 10^{-3}$	<1

The corresponding no. of insulators for each value of $P(x)$ is
calculated as follows:

$$\text{Ins.No.} = \frac{P(X) \times 54}{P(X) \text{ at } 120 \text{ KV}} = \frac{54 \times P(X)}{0,3989}$$

$$\underline{\underline{135,4 \times P(X)}}$$

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